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Paleoseismic Studies along the Warm Springs Valley fault system

Craig M. dePolo and Alan R. Ramelli
Nevada Bureau of Mines and Geology
University of Nevada, Reno, NV 89557
(775) 784-6691 ext.149
cdepolo@unr.edu

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Abstract

The Warm Springs Valley fault system is a major earthquake threat to the northern part of the Reno-Carson City urban corridor that previously lacked any direct studies of its earthquake hazard. The system is up to 96 km long and commonly inlcudes two or more fault traces. We compiled a map of the fault system and annotated it with tetonogeomorphic features. Using this map two sites were deemed potentially to be the most informative for trench exploration. Four trenches (two at each site) were excavated, logged, sampled, and interpreted to gain information on the paleoseismic history of the Warm Springs Valley fault system (WSVFS). Several paleoearthquakes were identified, mostly from Trench 1, the southernmost trench at the Mid-Valley site. Trench 1 is located along the southeastern part of a small, tilted push-up mound along the fault. This site was briefly inundated by the high stand of Lake Lahontan leaving deposits of fluvial and lacustrine sands. Pre-lake and post-lake sandy clays and sands were also exposed in the trench.

Trench 1 exposed evidence for the four last paleoearthquakes in sequence and other earlier, but potentially out of sequence, events. The youngest event offsets mid to late Holocene deposits and has relatively small (25 cm) apparent normal separations. This kind of small event occurring earlier in the record could be difficult to detect because of overprinting by larger events. The second event back occurred after Lake Lahontan high stand. This event created a fault scarp 60 to 70 cm high and juxtaposed Lahontan and pre-Lahontan sediments with >1 m right-lateral slip. Paleoevent 3 (the third event back) occurred during the Lake Lahontan high stand, at about 15 ka; this is occasionally referred to as the "inundation event." This paleoearthquake locally uplifted and tilted the west side of the fault to the west. This liquefied and laterally spread Lake Lahontan sediments off this uplift resulting in highly contorted and soft-sediment deformed sediments. Paleoearthquake 4 is evidenced by down-dropped fissure material that was in turn faulted by Paleoearthquake 3. Paleoearthquakes have uplifted older, faulted sediments which provide evidence for earlier paleoearthquakes, possibly up to three more.

Trenches 2, 3, and 4 provide structural insights into the WSVFS and support the paleo-history from Trench 1. Trench 2 had evidence for the last three paleoearthquakes, particularly Paleoearthquake 1. Trench 3 was 91 m long and spanned two stepping, fault traces. Both apparent normal and apparent reverse displacements were seen across the eight faults encountered in Trench 3. Trench 4 exposed a sequence of colluvial/distal fan deposits that likely represent paleoearthquakes. An interpretative model for the origin of these deposits is that major earthquakes cause sedimentary trapping of the distal fan sediments, which are relatively rapidly deposited, and in between events the colluvial slope from the adjacent linear ridge gradually develops across the fault and onto the east side, pushing fan sedimentation to the east. Collaborating tectonic evidence is needed to develop confidence for a tectonic origin for this secondary evidence.

This research demonstrated that the WSVFS is a major late Quaternary (Holocene) fault that is an active earthquake threat with substantial surface offsets. The study identified several paleoearthquakes (possibly seven), all which have occurred since ~21 "2 ka luminescence date,

one of these occurring during the Lake Lahontan high stand and one to two occurring in the Holocene. Earthquakes with magnitudes up to 7.3 are possible for this system based on fault lengths.

Introduction

The Warm Springs Valley fault system (WSVFS) is a major northwest-striking, right-lateral fault system in western Nevada. The system lies within the northern Walker Lane belt, a broad area of right-lateral shear along the western edge of the Basin and Range Province. The WSVFS is up to 96 km long, and is one of four prominent, northwest-striking fault systems that make up the northern Walker Lane belt. These systems appear to be the principal structures accommodating tectonic translation measured in the western Great Basin, such as measured by GPS (Bennett and others, 1998; Hammond and Thatcher, in press).

The WSVFS threatens the Reno-Carson City urban corridor, and the southern portion of the system crosses Warm Springs Valley, which is undergoing moderate urban development. Yet our knowledge of this system was poor and there was no direct seismic hazard data available prior to this study. This research has generated the first set of recurrence information for the WSVFS and compiled a detailed tectonogeomorphic map of the system. This research project was able to trench an excellent site that will be lost to developed in the near future, recovering perishable paleoseismic data.

This project compiled a Quaternary fault map of the WSVFS, at a scale of 1:24,000, annotated that map with tectonic geomorphic features, and conducted four trench investigations of the southern part of the fault. The results give an excellent structural view of the system, with geomorphology indicating the “active” traces, and a first cut at the paleoearthquake history for the southern part of the system.

Warm Springs Valley Fault System

The Warm Springs Valley fault system is up to 96 km long including a likely northern extension into Honey Lake Valley (Figure 1). We studied the southern 54 km of the system within Nevada. Overall this portion of the WSVFS has well developed geomorphic expression, although it varies with geologic setting. The southern half of the system creates large- to small-scale linear valleys, side-hill benches and swales, and immediately north of Warm Springs Valley, a spectacular series of aligned linear ridges.

The WSVFS typically includes two or more fault traces in parallel and anastomosing patterns. Overall, the system is transtensional and is dominated by right steps at both large and small scales. An estimated 5- to 10-km bedrock offset (Gross, 1984; Henry and others, 2002; Henry and Faulds, 2004 personal communication), combined with an age of 3.6"0.2 Ma for an ash in possible pre-fault deposits (Henry and others, 2002), yields a long-term slip-rate estimate of 1.3

to 2.9 km/My (same ratio as mm/yr).

Structural Geology

The WSVFS commonly includes two or more fault traces in parallel and anastomosing patterns. The width of the fault zone is commonly 1 km, but can be up to 2 km at complexities, such as pull apart basins. In the Virginia Mountains section, the system is a bedrock fault that has been recently mapped in detail (Faulds and others, 2003; Henry and others, 2003). This section commonly lacks burial by young sediments, and larger, older geomorphic features are preserved. Combined with the geomorphic analysis, it can be seen in Plate 1 that the connections between major subparallel fault traces is through secondary cross faults that have 10E to 30E angles with the major faults. The ends of the major faults become indistinct and/or die out, and are inferred, questioned, or buried. Throughout most of the system as mapped in Plate 1, there does appear to be a single, most important fault trace based on geomorphic expression. This dominant trace is likely the locus of most of the activity during latest Pleistocene, has the largest offsets, and moved during the most recent event.

Although the WSVFS is fairly continuous, it appears to have two overall orientations, ~N40EW along the southern portion, and ~N55EW along the northern portion (although more mapping in California is needed to confirm the latter).

At a fault trace scale and at a fault system scale, right and left steps and bends with their associated extension and contraction are common along the WSVFS. Right steps and bends, however, dominate indicating an overall transtensional nature to the system. This is consistent with the azimuths of geodetic deformation in this part of the Walker Lane belt, which tend to be slightly more westerly than the orientations of the WSVFS, especially the southern half of the system (c.f., Hammond and Thatcher, in press).

Tectonic Geomorphology

The WSVFS creates large- to small-scale linear valleys, linear depressions, and a series of aligned linear ridges immediately north of Warm Springs Valley. The local geomorphic expression of the WSVFS is related to geologic setting. Three distinct settings are present: alluvial basins, piedmonts, and bedrock areas. Based on these settings and the associated differences in geomorphic expression, five geomorphic sections of the WSVFS are distinguished

A 1:24,000 scale tectonogeomorphic map of the WSVFS was created to document the fault traces and geomorphic expression (Plate 1). The map was created by compiling fault traces from geologic maps, examining different scales of photographs noting features, conducting two aerial reconnaissance flights in low- and mid-sun-angle positions, and making limited field reconnaissances. The initial map was compiled from the Fraiser Flat and west ½ Moses Rock

Quadrangles (Garside and others, 2003), the Tule Peak Quadrangle (Faulds and others, 2003), the Dogskin Mountain Quadrangle (Henry and others, 2003), and the Stateline Peak Quadrangle (Grose, 1984). Photographs used consisted black and white U2 photography (~1:60,000 scale), color Bureau of Land Management photographs (~1:24,000 scale), and color Intrasearch photographs (~1:24,000 scale).

The WSVFS is rich with geomorphic features, as might be expected from a major strike-slip fault in a semi-arid region. The system has geomorphic expression of multiple parallel or anastomosing fault traces, except in alluvial-basin deposits, where only single trace is usually distinct. Table 1 is an alphabetical list of the features observed along the system. A unique aspect of the WSVFS is that it traverses three geologic settings (alluvial basin, piedmont, and bedrock). Each geologic setting has different sets of geomorphic features, which are easily understood in context of burial and erosion processes.

C **Alluvial basins**: Only features related to latest Pleistocene or Holocene events are visible, and there are large areas of late Holocene alluvium that obscure the fault. The features that exist are in relatively erodible young basin sediments and are related to the last few earthquakes.

C **Piedmont areas**: Mid- to late Pleistocene features, such as linear ridges, are nearly continuous, whereas evidence of the last few events is commonly subtle, buried, or eroded away, and is discontinuous and commonly indistinct.

C **Bedrock**: Geomorphic expression reflecting long-term activity is abundant and continuous, whereas evidence of recent activity is scarce; this is possibly because the offset ground is in sheared, fault zone materials and is relatively easily eroded. Large features include pull-apart basins, large-scale stream deflections, and linear ridges.

Table 1 Geomorphic Features along the Warm Springs Valley Fault System

aligned range front-alluvial fan contact
broad fault scarp
back-facing fault scarp
bedrock fault scarp
closed depression
deflected drainage
disturbed ground lineament - likely a moletrack or eroded surface rupture
drainage lineament
drainage pattern change lineament
fault escarpment (feature larger than a fault scarp)
fault facet
flared drainage
hillslope fault scarp
lineaments (undefined)
linear drainage
linear ridge
large fault scarp (compound)
linear valley (fault controlled)
mismatched drainage (juxtaposed different sized drainages or basins)
offset alluvium
oversteepened hillslope base
ponded alluvium
pull-apart basin
push-up mound
right-deflected stream channel
right-laterally offset alluvium
right-laterally offset channel margin
fault scarp
saddle in ridge or hilltop
side-hill bench (hillslope bench)
sidehill swale (hillsope cross swale)
fault-controlled spring
shutter ridge
swale
tonal lineament
topographic lineament
uplifted alluvium
vegetation lineament
warm spring

The geomorphic sections of the WSVFS are delineated on Plate 1 and are (south to north): Pah Rah Range section, Warm Springs Valley section, Winnemucca Valley section, Virginia Mountains section, and Honey Lake Valley section. The characteristics of these sections are described below:

Pah Rah Range section

This section is a bedrock fault, and may include a buried fault in alluvium adjacent to the range. The section is about 12 km long, and appears to end at the south in a small pull-apart basin within the Pah Rah Range. Geomorphic features consist mostly of side-hill benches and swales. Activity may be less than along the rest of the system because slip along the southern WSVFS is distributed on additional faults (e.g., Western Warm Springs Valley fault).

Warm Springs Valley section

This section crosses the floor of northern Warm Springs Valley, which was inundated by the high stand of latest Pleistocene Lake Lahontan. The 9-km-long section has small fault scarps, vegetation lineaments, and push-up mounds in latest Pleistocene and Holocene deposits. The subtle expression was caused by the last few earthquakes. Fault traces are indistinct for most of this section due to Holocene erosion and sedimentary burial.

Winnemucca Valley section

This 12-km-long section crosses alluvial fans, and includes linear ridges cored by alluvium and/or bedrock that are up to 1½ km long. Geomorphic expression is nearly continuous, but higher erosion and burial rates associated with the common hill-slope location of the fault obscures much of the expression of recent events.

At the Piute Canyon fan trench site smaller single-event scarplets can be seen on the shoulders and in between the larger linear ridges indicating that even at small scales the WSVFS is complex and likely has a multi-trace character. A direct analog would be the way secondary faulting during the 1986 Chalfant Valley earthquakes (M6.4) occurred along the White Mountains fault system, California; there small ruptures were present on and crossing linear ridges, along the bases and flanks of the linear ridges, and out-board of the ridges where sediment was ponded over fault traces. The area around the Piute Canyon fan trench site has similar types of ruptures, larger in size that in 1986, but smaller than the larger ruptures that are envisioned for this portion of the system, based on length and position.

Virginia Mountains section

This 21-km-long section is in bedrock. Geomorphic features include side-hill benches and swales, linear valleys, saddles in ridges, and fault facets. A butressed pull-apart basin 5½-km long and 1-km wide has a closed depression in its central part. It is described as "butressed" because part of this basin is formed by the juxtaposition of a group of small hills western part of the fault zone (sort of a giant, breeched shutter ridge). Because of the large scale of this feature, this basin's formation may coincide with the inception of strike-slip activity.

Honey Lake Valley section
This 42-km-long section was not examined in this study. The northern part of Honey Lake is elongate parallel to the system, and is likely related.

The WSVFS is an excellent case study for understanding the geomorphic expression of strike-slip faults in the semi-arid Basin and Range Province, because of the different geologic settings it crosses, and its relatively high rate. Unfortunately it is gradually being developed over limiting access and destroying features.

Trenching Studies

Four trenches were excavated along the southern portion of the WSVFS, with the objectives of delineating faults and associated structures, and obtaining a paleoseismic history of the system. The trenches were located along the Warm Springs Valley (Mid-Valley site, Trenches 1 and 2) and Winnemucca Valley sections (Piute Canyon fan site, Trenches 3 and 4).

Mid-Valley site

The Mid-Valley site is where the WSVFS crosses the lowest part of Warm Springs Valley. This site has a very low deposition rate (mostly eolian input and local alluvial reworking) and very low erosion rates (very flat with minor erosion (shallow gullies) at ephemeral streams). The site is a little below the high stand of latest Pleistocene Lake Lahontan, and was inundated only during the brief period that the high stand existed. Thus we anticipated that we would encounter lacustrine sediments in the trenches at this site, and could use them as a reference datum. Not only did we encounter lacustrine sediments, but a paleoearthquake appears to have occurred during the Lake Lahontan's last high stand.

The Mid-Valley site is being developed for homes and much of it will be lost within the next few years. Already runways have been constructed across the fault wiping part of it out, and Trench 2 is located in the corner of two runways. Thus it has been important to document what we can at this site. The geomorphic expression of small mounds and lineaments was questioned as to its origin and tectonic significance prior to this trenching.

Trench 1

Trench 1 is 43 m long, and was excavated on the southern side of a small push-up mound, with an east-facing scarplet on its eastern flank. The trench was oriented N45EE across an approximate scarp strike of N55EW. A GPS location of the survey reference point is 39E50.880' N, 119E40.954' W; the location of Trench 1 is shown on Plate 1. Initially the north side of the trench was logged to relate structures directly to the push-up mound, but because the paleoseismic evidence was clearer on the south side, 9 m of the south wall around the main fault was also logged. The trench logs are presented in Plate 2 and descriptions of the units are given in Appendix C.

Stratigraphy

Sediments in Trench 1 range from clayey deposits to sandy deposits with gravel lenses, and are alluvial, colluvial, eolian, and lacustrine in nature. Trench 1 can be described as having three basic parts, a western, central, and eastern section. The western and eastern sections can further be described as having three fundamental packages in a sediment stack, older pre-Lake Lahontan deposits (silts and sands), Lake Lahontan sand deposits, and post-Lake Lahontan silts and sands. These generally flat lying latest Pleistocene and Holocene deposits mantle and are faulted against uplifted and internally faulted older sands and silts in the central portion of the trench. Holocene deposits that are about a half a meter thick overlie the entire trench, but show lateral variations in texture and structure within them.

The eastern part of the trench, defined as east of the main fault, has three packages of sediments. The lowest package consists of brown muds (Unit 7a) that are warped proximal the fault and are of uncertain orientation. An unconformity was eroded across the top of Unit 7a after warping, including a channel that crosses the trench roughly parallel to the fault. This unconformity is overlain by 80 to 130 cm of well- to moderately sorted sands from latest Pleistocene Lake Lahontan. In the easternmost part of the trench the sediments have weak stratification and local soft-sediment deformation (Unit 5c). These are overlain by sands with abundant well-developed fluvial structure (fine layering and cross laminations)(Unit 5b). These sediments fill the channel in Unit 7a and appear to be early Lake Lahontan high stand lacustrine deposits (subaqueous fluvial, possibly near-shore deposits). These deposits are overlain by a coarse sand (Unit 4a) that was deposited over Units 5a and 5b. The depth of water over the Mid-Valley site at the high stand was about 44 m (site 1286 m, vs high stand 1330 m). Unit 4a in turn is overlain by a 10- to 20-cm thick, greenish gray clay-rich deposit (Unit 3) possibly from a shallow post-Lake Lahontan lake or wet playa. The Lake Lahontan deposits are overlain by about 80 cm of silty and fine sandy sediments. The lower part of these deposits (Unit 2) thicken at the fault in a wedge shape and appear to have been deposited following the formation of a small scarp from an earthquake. Locally parts of Unit 2 are diatom rich and may be deposited in local shallow ponds or lakes. The uppermost sediments (Unit 1) are silty sands and sandy silts with discontinuous fine platy structure and local small coppice dunes around small shrubs; these sediments appear to subaerial and deposited in an environment similar to what exists today.

The western portion of the trench, west of the faulted and uplifted block, is overall similar to the geologic history of the eastern portion, but with some differences in detail. The oldest sediments consist of three packages of deposits (Units 7, 8, and 9), with Units 8 and 9 deformed in a small antiform, and Unit 8 was deposited after this deformation. The oldest deposit in the western portion is Unit 9, a pebbly coarse sand. Unit 9 is overlain by Unit 8, an 80 to 120 cm thick sandy clayey silt. The top of Unit 8 has well formed prismatic structure with black humic staining and is a paleosol, that partly pre-dates Unit 7. Unit 7 was deposited on a warped and eroded Unit 8, and thickens to the west to up to 1 m in the exposure. A paleosol with weak prismatic structure and organic staining is formed on top of Unit 7. This paleosol is interpreted to be the surface that was inundated by the high stand of Lake Lahontan, and gently slopes to the west due to tectonic tilting. Lake Lahontan sand deposits can be broken into two packages, Units 4 and 5. The lower deposits, Unit 5, are fine to coarse sand, with three thin intercalated lighter layers, and pronounced evidence of spectacular soft-sediment deformation. These deposits are interpreted to have liquefied from an earthquake along the WSVFS and to have laterally spread to the west from the uplift and tilting occurring along the fault. The lower part (Unit 5a) appears to have acted as a detaching horizon and was locally injected into the overlying sands. A massive sand layer 20 to 50 cm thick (Unit 4) covers the liquefied deposits and fills fissures from lateral spreading. The top of Unit 4 and part of Unit 5 was eroded, and a thin greenish gray clay (Unit 3a) was deposited on top in the westernmost part. The entire sedimentary package was buried in the latest Pleistocene and Holocene by nearly horizontal layers of silts and sands (Units 1 and 2).

The central part of the trench is a faulted block of older geology uplifted by the last several earthquakes along the WSVFS. This block can be further divided into a western imbricated fault zone and a down-dropped and filled portion adjacent to the main fault. The westernmost wedge of deposits bounded by faults is a sliver of the easternmost lower part of the western portion of the trench (Units 8 and 9). These deposits are offset 1.5 m in an apparent down-to-the-west normal separation across a westerly dipping fault. This sliver is faulted against sands to the east of an unknown age. The down-dropped portion shows evidence of a paleoearthquake creating the down-dropped area, and the erosion of a scarp from that event. The lower part of the is area is a mud (Unit 10) that has been wrenched and has well-formed Reidel fractures and several small faults. This is overlain by pebbly sands that have been warped up on their west side by faulting. This event down-dropped the central portion and pebbly sands that were west of the fault were shed off to the east and interfinger with finer-grained sands filling the down-dropped area. A thin deposit of the Lake Lahontan sand (Unit 4) covers the central portion, as do Holocene deposits Units 1 and 2. The uplifted sediments in the central portion of the trench underlie the small push-up mound that was trenched, but do not get closer than 0.5 m of the surface and are covered by younger sediments.

The deposits in Trench 1 are latest Pleistocene to latest Holocene. Two pre-innundation radiocarbon ages, dendrocalibrated at 2 sigma are cal 18-19 kybp and 13.6-14.8 kybp. The high stand of Lake Lahontan was about 14.7-16 kybp (2 sigma dendrocalibration of a high stand date from Adams and Wesnousky, 1999). A photon-stimulated luminescence date collected by Dr. Glen Berger from the Desert Research Institute from the liquefied sediments, presumably from early inundation sediments, is 15.3 "2 ka (1 sigma). Earlier deposits are only limited by one date, a photon-stimulated luminescence date of 21 "2 ka in Unit 8; this date is significant because it predates all paleoearthquakes identified (possibly up to seven).

Structure

The structures exposed in Trench 1 include vertical strike-slip faults, apparent reverse and apparent normal separation, tectonic fissures and fissure fills, Riedel fractures, and near-fault warping.

A vertical main fault zone and several secondary/older faults to the west of the main fault were encountered in Trench 1. The main fault is the most pronounced and best developed in the trench, offsets the youngest units and is the highest reaching in the section, and was the locus of deformation during at least the last few earthquakes. The main fault coincides with the small geomorphic features, such as fault scarplets and pronounced vegetation lineaments. The main fault (Fault F1) is a vertical fault zone that splays upwards with flower structure of secondary faults within the upper two meters. Near the base of the trench exposure the fault zone is a 10 cm wide zone of sheared sediments bounded by pronounced faults. The fault trace in the trench strikes N75EW, dips 88E-90EE, and bounds the east side of the push-up mound that was trenched. Internally the fault zone has evidence of fissure forming and filling events (interpreted as paleoearthquakes), zones of sheared alluvium, and discrete fault surfaces. The upwards-splaying flower structure, vertical nature, and juxtaposition of units across Fault F1 indicates it is a strike-slip fault.

Secondary faults lie within a six-meter-wide zone to the west of the main fault. These faults lie in an older core of a push-up mound that has been brought up (and over) by the WSVFS. Four of the larger faults have been numbered (faults F2, F3a, F3b, F3c). The secondary faults appear to strike 10E to 17E more westerly than the main fault, and are vertical or dip to the west. Faults F3a, F3b, and F3c all likely converge on Fault 3c below the base of the trench. These faults have both apparent normal and apparent reverse separations. There also appears to be a small, broad anticline formed immediately west of fault F3c in the older sediments (Units 8 and 9), which seems likely related to movement along this zone. Fault F2 may be related to this zone as well because of its proximityu, but its connection is less clear.

A further west fault also exists (Fault F4), but the excavation was not deep enough to appreciate it’s significance. In addition there are a significant number of tertiary and higher order faults adjacent to the main fault and in the tectonically uplifted block to the west of Fault F1. The east side of the fault is relatively undisturbed by faults, although some small carbonate-coated fractures exist. Between faults F1 and F2 several relatively evenly spaced fractures opened 1 to 2 mm exist in the lower muds (Unit 10). These fractures had north-south strikes, vertical dips, and appear to be classic Riedel fractures. This orientation supports a right-lateral component of displacement along the WSVFS.

Trench 2

Trench 2 was excavated across a small mound along the fault zone, with a scarplet bounding its eastern side. This 2 m high mound, which likely contains other fault traces, is the largest of the mounds along the fault at the Mid-Valley site. Trench 2 is 38 m long. Trench 2 is oriented N53EE, the scarp was oriented about N47EW, and a GPS location of the reference datum for the trench is 39E51.056' N, 119E41.174' W; the location of Trench 2 is shown on Plate 1. The southern wall was logged because it was shadowed most of the day, making it easier to view. The trench log is presented in Plate 3 and the unit descriptions are given in Appendix D.

Trench 2 will only be discussed in a limited fashion here because most of the emphasis was placed on Trench 1, which had clearer cross-cutting tectonic relationships, more paleoevents exposed, and consequently was the focus of the dating constraints. Trench 2 exposed the same general section and relationships that were found in Trench 1, older muds, Lake Lahontan lacustrine sands, and Holocene silty sands and sandy silts. The log and unit descriptions are included. There are two features of note in Trench 2: 1) the most recent event (Paleoearthquake 1) is the well exposed, and 2) a sandblow, likely from Paleoearthquake 3, was exposed.

Fault breaks associated with Paleoearthquake 1 offset Unit 2a and Unit 2b. This break corresponds closely to the fault scarplet at the surface. A small colluvial wedge (Unit 1c) formed from this scarplet. Unit 2b is small colluvial wedge associated with Paleoearthquake 2; this unit is sheared within 20 cm of the main fault zone (Fault 1), and worked down into the fault zone by Paleoearthquake 1.

Two faults are exposed in Trench 2, both bounding a 10-m-wide push-up mound. The faults show apparent reverse displacement, and both are thought to be dominantly right-lateral strike-slip faults; the later is supported by the juxtaposition of facies in Unit 3. The most recent event only occurred along the eastern fault (Fault 1), and both faults appear to have been involved in Paleoearthquake 2, as evidenced by colluvial deposits buttressed against the faults. Paleoearthquake 3 likely occurred along these faults as well, but without fissure fills or liquefaction that can be tied specifically to the earthquake in the trench exposure, no direct connection was made.

Paleoearthquake history - Mid-Valley Site

Trench 1 exposes evidence for four paleoearthquakes along the eastern side of a 7-m-wide fault zone, and two or three older events along the western part of the zone. Characteristics of the fault zone (e.g., flower structure, vertical orientation of the main fault trace, and apparent reverse offsets) indicate dominantly right-lateral strike-slip displacement, even though recent events consistently have had a down-to-the-east vertical component. Juxtapositions of facies within units also supports the strike-slip sense-of-displacement.

Paleoearthquake 1: Small down-to-the-east offset of Holocene deposits (~25 cm of apparent vertical offset), including scarp colluvium of Paleoearthquake 2. In Trench 2, the colluvial deposit from Paleoearthquake 2 (Unit 2b) was sheared and offset, and a small colluvial wedge was formed from Paleoearthquake 1. Fault scarplets formed from Paleoearthquake 1 indicate a youthful, likely mid to late Holocene age for this event which is consistent with the fault in trench exposures. In Trench 1 faulted deposits are apparently overlain by 20 to 30 cm of eolian/alluvial deposits that include the active surface. No offsets of these upper deposits were seen, but fault scarplets to the south at Trench 2 indicate some surface breakage likely occurred nearby, possibly within some of these upper deposits. Paleoearthquake 1 is mid to late Holocene based on a lack of soil development in overlying deposits, and may be only a few thousand years old based on the freshness of the fault scarplets.

Paleoearthquake 2: The primary evidence for Paleoearthquake 2 is a colluvial deposit from a small west-side-up scarp formed by Paleoearthquake 2, and an apparent fault juxtaposition of a post-Lake Lahontan(?) clays against Lake Lahontan sands that remains after removable of Paleoearthquake 1. In the north and south walls of Trench 1, Unit 2a thickens on the east side of the fault, and has a fanning sedimentary fabric with the lower part derived largely from erosion of the underlying Unit 3, which was eroding off the west, upthrown side; this deposit is interpreted to be a colluvial wedge formed from a small fault scarp that was about 60 to 70 cm high (approximate thickness of the wedge). Apparent vertical offsets were less at Trench 2 (25 to 30 cm), but unlike Trench 1 where only the easternmost fault was involved in Paleoearthquake 2, both sides of the push-up feature exposed in the trench appeared to rupture. Soil development is limited in the section above Unit 2a in Trench 1, and a Holocene or latest Pleistocene age is possible for Paleoearthquake 2; the age is after the high stand of Lake Lahontan (14.7-16 k ybp cal C14).

Paleoearthquake 3: The "inundation event" displaced late Pleistocene lacustrine deposits vertically by >1 m, formed fissures along the main fault zone, and liquefied and laterally spread lacustrine deposits to the west of the fault. This vertical offset tilted the west side of the fault and caused the liquefied sands to laterally spread to the west. Shortly after the event, younger lacustrine sands filled fissures and buried the liquefied sediments. At an elevation of about 1300 m, Warm Springs Valley was inundated only when Lake Lahontan was near its high stand, so this event occurred at about 14.7 to 16 ka.

Paleoearthquake 4: Evidenced by fault-fissure deposits juxtaposed against subaerial deposits in the central part of the fault zone.

Older paleoearthquakes:

In the western part of the fault zone in Trench 1, three major faults and a myriad of secondary faults indicate three or more events pre-dating Paleoearthquake 4.

C The easternmost major fault (Fault 3a), with 0.8 m of apparent reverse separation, faults older brown-gray sands against brown subaerial sands in the central part of the fault zone. Deposits eroded from the upthrust block interfinger with the subaerial sands. In the south wall of Trench 1 a surficial silt overlies these subaerial deposits, and was subsequently partly involved in the fissure fill from Paleoearthquake 4, thus this event is older than Paleoearthquake 4.

C The middle major fault (Fault 3b) also appears to have relatively upthrust the west side, but details about this event are less clear. It could have moved during one of the other paleoearthquakes or it could be a separate, earlier event.

C The westernmost major fault (Fault 3c) has 1.5 m down-to-the-west apparent normal offset of some of the oldest deposits exposed in Trench 1, Units 8 and 9.

All of these paleoearthquakes occurred since the deposition of Unit 8, which has a photo-stimulated luminescence age of 21"2 ka (1 sigma).

Piute Canyon Fan site

Two trenches were excavated at the Piute Canyon Fan site, where fine-grained distal fan sediments intersect coarser sediments shed from linear ridges formed by the WSVFS. These trenches were dug to look for paleoseismic information and to examine the structural pattern of the faults in an area where there is a right step in tectonic linear ridges. The area is close to an area of Native American occupation. An archeological study was commissioned to make sure the trench sites were free of artifacts or evidence of occupation, and an archeologist was present during excavation; no artifacts or evidence of occupation was found at the surfaces trenched nor in the trenches.

Trench 3

Trench 3 is 91 m long and was located to cross the fault exposed in Trench 4 with overlying unfaulted deposits, to cross a fault to the west bounding a linear ridge, and to view what kind of structures might exist in the apparent right step between these faults. Scarps are poorly defined in this step-over area of the fault; the general trend of the western linear ridge front is N50EW. The trench is oriented N40EE. A GPS location of the trench reference point is 39E53.725' N, 119E44.095' W; the location of Trench 3 is shown on Plate 1 Over seven faults were exposed in the Trench 3 exhibiting right-lateral strike-slip, and apparent reverse and apparent normal dip-slip separations. As targeted, fine-grained distal fan deposits and coarse-grained colluvial deposits from the adjacent linear ridge were found in the trench, but deciphering the paleoearthquake history form these deposits has proved to be difficult and interpretive. The southern wall of the trench was logged and is presented in Plate 4 and unit descriptions are given in Appendix E.

Stratigraphy

Trench 3 can be described in three sections, a western, older alluvium part (deposits making up the linear ridge), a central part of older distal fan deposits, and younger distal fan deposits that are east of the easternmost fault.

The older, westernmost deposits are carbonate-cemented alluvial cobble and pebble conglomerates (Unit 14) and sandy deposits (Unit 15). These were overlain by a bouldery clay (Unit 12) that is tilted(?) to the east and has a tapered thickness that increases eastward (downward). The conglomerate and sands have numerous faults within them that locally rotate clasts into shear zones. The upper part of the conglomerate locally has old argillic or reddened horizons (Unit 13) that can be seen to be down-dropped and offset by some of the faults within the conglomerate. Overall, these older deposits were offset along the fault, and formed a substantial soil within them at some time, possibly in part related to Unit 12. Before burial, Unit 12 appears to have been the surficial soil on a slope on the flank of a linear ridge. This slope was progressively buried by distal-fan deposits of the Piute Canyon fan.

The central part of Trench 3 principally consists of two depositional packages (Units 10 and 11) of distal fan alluvium with a likely eolian contribution. The units are moderately cemented with silica(?); the matrix of most of the unit does not effervesce with HCl. These packages are offset by several faults and have many fractures. Fractures in Unit 11 are better developed, being wider and with fault breccia within them than their upward continuation in overlying Unit 10; these fractures in Unit 10 are commonly thin and carbonate filled. These deposits are generally massive coarse medium sands, coarse, medium, very fine sands, and silts, with local weak stratification. Unit 10 has some moderately developed paleosols within it. There is one near the base within an apparent graben structure (Unit 10c) possibly formed in a thin deposit overlying Unit 11. There is a weak paleosol near the top in the eastern part of the unit (Unit 10a), and there is a mantling soil over Units 10a and 10b that may be a latest Pleistocene soil that was buried by Holocene deposits. Units 1 and 3 (Holocene distal fan and surficial deposits) make up the upper part of the central section of the trench. Near the western part of the central section the drainage axis between the modern distal alluvial fan and the slope of the linear ridge. The slope of the linear ridge is made up of clayey surficial deposits, mostly eroded from older soils that are further up slope, overlain by a thin veneer of silty very fine sand (mostly modern eolian and reworked eolian deposits). The clay from the slope is working into transitional deposits (Unit 3a and 10b) between the distal fan and linear ridge. Modern distal fan deposits are fine grained sands and silts.

The eastern section of Trench 3 is a sequence of distal fan, alluvial, and colluvial deposits adjacent to and some faulted by, Fault 1. The oldest deposits in this section that were exposed in the trench is a clay rich deposit (Unit 9) that is likely from the colluvial slope of a linear ridge; possibly correlative to Unit 12, or with another colluvial deposit. A small colluvial deposit (Unit 8) overlies this, likely derived from a small fault scarp. Unit 8 was either formed on a slope or, more likely, was tilted by faulting, and was buried by distal fan deposits (Unit 7). A discontinuous, weak argillic soil was formed in the top of Unit 7, and subsequently this unit appears to have been faulted and tilted by Fault 1. Unit 6 was deposited on the tilted Unit 7 giving it a wedge shape, and was subsequently faulted and buried by Unit 5. Part of Unit 6 is a gravel channel that crossed obliquely to the trench. Unit 5 is also offset by Fault 1. A paleosol formed in the upper part of Unit 5 crosses most of the trench, corresponds to the paleosol in Unit 10a, and is likely a latest Pleistocene soil, buried by Holocene deposits. This soil appears to be fractured in a warp of about 1 m over Fault 1. Subsequently this eastern part of this scarp was buried by Unit 4. The upper deposits of the western section (Units 1-3) are distal fan deposits, mostly sands, with eolian contributions of very fine sand and silt.

Structure

One of the objectives of Trench 3 was to explore the structure between two right-stepping linear ridges along the WSVFS; this is why the trench is 91 m long. Over eight faults were exposed in Trench 3. Fault 1 is the same structure that was crossed with Trench 4. This fault trace bounds the east side of a linear ridge to the north that is buried at this location, if it exists at all at the Trench 3 site. The Fault 3 complex is the best candidate for the fault bounding the western linear ridge. Several other secondary faults were also found between Faults 1 and 3 and within the older alluvium.

Fault 1 has an apparent reverse component, with ostensibly younger deposits in the footwall offset below older, more cemented deposits. The majority of the offset is likely right-lateral strike-slip, supported by the difference in character of deposits across the two sides of the fault. Fault 1 strikes N47EW, and dips about 30E W. The fault is less than 10 cm in width at the bottom of Trench 3, and widens upwards in a wedge shaped zone of sheared alluvium. A couple secondary faults splay upwards from the main fault with steep east dips, the westernmost of which is a small shear zone. There are two major truncations visible in the fault zone of Fault 1, the lower where most of the shear zone that is within Unit 7, is covered by undisturbed Unit 6. The upper truncation is by Units 3 and 4 covering faulted Unit 5. A few fault traces in the eastern part of the zone, including the upwards splaying secondary faults, appear to reach the latest Pleistocene soil on Units 5 and 10. This surface is also warped about 1 m down-to-the-east over Fault 1. An alternative explanation for this warp would be a fault scarp that was buried by Unit 3 and 4. Fault traces extend to the top of Units 5 and 10 and there does not appear to be a depositional signal of a fault scarp prior to the soil. Unit 4 only appears on the lower side (the eastern side) of the fault, and Unit 3 mantles the entire fault zone without disturbance.

Fault 2 is between the two main faults, and has an apparent normal dip-slip component along a steep westward dip, with a strike of N60EW. The fault is likely dominated by strike-slip displacement, but supports the notion of having extension between two right-lateral faults with a right-stepping arrangement. Specifically, Unit 10 appears to have a normal vertical separation. Fault 2 may merge with Fault 3 at a significant depth; the westward dip of Fault 2 should intersect the more vertical Fault 3, and the two faults appear to have strikes that will intersect to the north of Trench 3.

The Fault 3 complex is over 4 m wide with several discrete, vertical fault traces clearly offsetting Units 10 and 11. Fault traces within the complex strike N25-35EW. There are potential fissure fills that may indicate recent paleoevents, but the highest fault traces appear go nearly to the surface (Fault 3b), being covered only by the surficial Unit 1. This trace is roughly in line with a stepped projection of a small surface scarplet that appears to be from the most recent event; thus the most recent event likely occurred on Fault 3b. There are not enough young sediments over the Fault 3 complex to discern the younger sequence of paleoearthquakes; even movement during the most recent event is inferential because of prismatic structure in Unit 3a.

Paleoearthquake History

The paleoseismic history of Trench 3 is poorly understood at this time. It is hampered by a lack of younger sediments (i.e., younger record) over Fault 3 and the inferential nature of older paleoearthquakes. We can make some observations, but we lack completeness and, in some cases, confidence in interpretations.

The most recent event is indicated by small scarplets and lineaments immediately north of Trench 3. This event likely crosses through the trench at Fault 3b, where nearly the entire section exposed in the trench is faulted. The most recent event appears young enough to be contemporaneous with the most recent event at the Mid-Valley site, but there is no direct evidence for or against this.

The next oldest event that there is evidence for is the warping and faulting of the latest Pleistocene sediments and soil along Fault 1. The interpretation of this event is uncertain, but at minimum there was a latest Pleistocene scarp from an earthquake that was backfilled against and buried by early to middle Holocene deposits - Unit 4 (based on soils; only a weak cambic horizon is developed in the overlying section). Thus a latest Pleistocene-early Holocene paleoearthquake is indicated. Again, this is potentially similar to Paleoearthquake 2, or possibly Paleoearthquake 3, at the Mid-Valley site, but there is no specific evidence.

Clear evidence for a paleoearthquake comes from offset and deformation of Unit 7, overlain by deposits from Unit 6. Two paleosols have been formed since this event, the one on top of Unit 6 (eastern part of unit) and the one in the top of Unit 5. Thus this event should be older that Paleoevent 3 at the Mid-Valley site

Unit 8 appears to be a colluvial deposit from a local fault scarp, and is likely a post-earthquake deposit. This deposit overlies a thick clayey unit that might be part of a linear ridge colluvial deposit. Unit 8 is overlain by Unit 7, which is deposited on a sloping surface on Unit 8. This may have been an original slope, or may have been a more horizontal surface that has been tectonically tilted by a local event, that would post-date Unit 8 and predate Unit 7.

Older events are also likely recorded in Units 10 and 11, but discrete events are hard to discern. Faulted older deposits with soils (Unit 13) have evidence of paleoearthquakes that cannot be discerned, especially in age.

Trench 4

Trench 4 is a 28.5 m long excavation across a single fault zone that translates and uplifts a small linear ridge of older alluvium along and over distal fan deposits of the Piute Canyon fan. A striking lineament between many stones versus few stones crosses the site and a distinct facies contrast was anticipated in the fault zone area that might aid in distinguishing paleoearthquakes. The stone lineament/fault the was trenched strikes N50EW and the excavation is oriented N40EE. A GPS location of the monument used for surveying the trench is 39E53.756' N, 119E44.152' W; the location of Trench 4 is shown on Plate 1. Trench 4 exposed a single fault zone separating older alluvium from a late(?) Pleistocene and Holocene sequence of alluvial and colluvial deposits. Distinct textural packages were mapped in the footwall of the fault (eastern side) that are likely related to paleoearthquake history. The southern wall of Trench 4 was logged and the log is present in Plate 5, with the unit descriptions given in Appendix F.

Stratigraphy

Trench 4 exposes fine grained, sheared older alluvium in its western part, juxtaposed against an up-to-three meter wide shear zone. The shear zone is made up of sheared and pulverized alluvium with several discrete fault planes, capped by small pockets of down-dropped colluvium. The eastern half of the trench is made up of a sequence of sedimentary packages that have sandy lower parts and clayey upper parts and are separated by unconformities. In a couple of cases a weak stone line occurs at the unconformity.

The older alluvium is a fine-grained facies of the older alluviums making up the linear ridges along the WSVFS. It does not appear to be the primary source for the cobbles and boulders scattered over it, or for the clayey deposit mantling the surficial slope. This clayey deposit (Unit 2) may be an in-place surficial soil, but it seems more likely that it is largely mechanically translated downslope from older soils, with secondary soil formation in situ.

The eastern packages of sediments appear to be a combination of distal fan and surficial slope deposits. Local distal fan deposition is occurring at the site today, although at a very slow rate; this is because the site is at the northernmost margin of Piute Canyon fan, and only receives occasional overbank flood deposits and eolian input. These sediments are dominated by fine and very fine sands and silts. The other main constituent of these sedimentary packages is clay which in part is due to soil formation processes and in part due to downslope movement of clays that are on the slope of the linear ridge to the west. In the youngest cases (Units 2 and 3) these different deposits were mapped separately, but for older deposits they were lumped together as presumable time packages; in the older deposits the boundary between the two facies was gradational and commonly difficult to map. Four to five sets of alluvial packages were exposed (excluding the surficial deposit). These sets are a package including Units 2 and 3, and Units 4, 5, 6?, and 7 as individual sets. These sedimentary packages may each represent an earthquake displacement along the fault. A model for this would be that after an earthquake, a local sedimentary trap was created, filling relatively rapidly with overbank sands and eolian very fine sands and silts. As the local surface topography filled and eroded the linear ridge slope on the west side of the fault the site would prograde out across the fault and over the distal fan deposits. This then became a surface of stability because it was higher than the depositional surface and no longer received major input from the fan.

Structure

A single fault zone was exposed in Trench 4, a shear zone up to 3 m wide of sheared and pulverized alluvium with several discrete faults within it. The zone appears to dip moderately to the west near the bottom of the trench, and splays upwards towards the surface with vertical and westward-dipping faults; the zone near the bottom is about 1 m wide.

Paleoearthquake History

Only a partial record of faulting is likely preserved at Trench 4. Much of the potential earthquake history is from sediments to the east of the fault, and is largely based on a facies argument that can be inferred from the youngest event evident in the sediments. Units 1 and 2 cross the entire fault zone and do not appear to be disturbed. Unit 2 is a clayey unit that has a significant amount of input from the linear ridge to the west. Unit 2 buries a wedge shaped Unit 3 sediments that are sandy distal fan deposits. Unit 3 appears to bury a faulted landform on Unit 4. Unit 4 is faulted and disturbed, clearly involved in a paleoearthquake. The upper part of Unit 4 is clay rich with prismatic structure, similar to Unit 2. The lower part of Unit 4 is sandy similar to Unit 3, thus Unit 4 may be a Unit 2/Unit 3 package, where fan sediments fill the area following an earthquake due to new sedimentation traps or concentration, followed by times of relative stability, when a smoother, more stabilized landscape allows clays to wash eastward from the slopes of the linear ridge. Alternatively these clays are the result of soil formation processes, and to some degree, aspects such as the prismatic structure must be the result of these processes. These clays seem to well developed for their corresponding calcic horizons, however, and boulders and cobbles occur in some units, which also were transported eastward from the linear ridge. If the assumption is made that each package is an interseismic period, then earthquakes are indicated following deposition of Units 4, 5, 6?, and 7.

There are older events indicated in faulted colluvial deposits over the main fault zone. The relative age of potential events is not understood, although these deposits have significant carbonate development, possibly indicating they are older than footwall deposits and inferred events.

Conclusions

The Warm Springs Valley fault system is a major right-lateral fault that has generated at least four latest Pleistocene/Holocene surface-rupturing earthquakes. The third event back occurred during the high stand of Lake Lahontan (~15 ka) and caused liquefaction and lateral spreading of lacustrine sands. Paleoearthquakes are evidenced by faulted units, fissures and fissure fills, and fault-scarp colluvial deposits. At least five paleoearthquakes and has many as seven events have occurred since about 21 ka.

Lateral offsets during these paleoevents are not directly constrained, but were likely substantial given the juxtaposition of units across faults. Strike-slip offsets are likely greater than vertical offsets, the largest of which is 1.5 m. Net single-event offsets are therefore probably at least 2 to 3 m for the larger events. Such offsets would indicate earthquakes of about magnitude 7 or greater. Potential rupture lengths indicate events up to magnitude 7.3.

The active shear zone consists of multiple parallel and intersecting faults. This is best seen in the bedrock setting. Multiple active fault traces indicate a larger surface rupture hazard is present than just a single trace, and that multiple traces need to be trenched to get complete paleoseismic records.

This study confirms Holocene activity along the WSVFS, and indicates a higher level of activity than previously thought. The system should be considered a significant earthquake source and surface-rupture hazard. Further, the system likely accounts for a higher percentage of regional deformation than generally assumed.

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Appendix A

2003 INQUA Abstract:

The Warm Springs Valley Fault System, a Major Right-Lateral Fault of the Northern Walker Lane, Western Nevada

Craig M. dePolo
Alan R. Ramelli

The Warm Springs Valley fault system (WSVFS) is one of three major right-lateral faults in the northern Walker Lane. The system has well-developed, late Quaternary tectonic geomorphology over 35 km, but may be up to 95 km long with potential extensions in Warm Springs and Honey Lake Valleys. The system is typically made up of two or more fault traces in parallel and anastomosing patterns. The WSVFS is a quintessential transtensional fault with a strong tendency to step to the right at large and small scales, creating extensional areas. The WSVFS traverses several sedimentary environments, and has different geomorphic expression in each. In the basin sediment of Warm Springs Valley, fault scarps, vegetation lineaments, and small push-up features created by the last few events along the fault are visible (short-term geomorphic expression), and there are large areas where alluvial processes are young or active, and there is no convincing tectonic expression. Long-term geomorphology (mid to late Quaternary) is buried or not sustained. In the alluvial fan environment, long-term geomorphic expression, such as linear ridges, is nearly continuous, whereas expression of the last few events is subtle and sparse, and commonly is buried, eroded away, or indistinct. In the bedrock environment, long-term gemorphic expression is abundant and continuous, including linear ridges, valleys, and drainages, sidehill benches and swales, fault scarps, oversteepened hillslope bases, and fault facets. Similar to the alluvial fan environment, short-term geomorphic expression is sparse.

Four trenches excavated along the southern portion of the WSVFS expose at least three, and potentially more, latest Pleistocene paleoearthquakes. Evidence includes offset deposits, fault-fissure deposits, colluvial-wedge deposits, liquefied and laterally spread deposits, and a sandblow. One of these paleoevents appears to have occurred while Warm Springs Valley was inundated with water, possibly the high stand of Lake Lahontan, a latest Pleistocene pluvial lake.

Appendix B
2004 Basin and Range Province Seismic Hazard Summit II Abstract:

Quaternary Structure and Geomorphic Expression of the Warm Springs Valley Fault System, Western Nevada

Craig M. dePolo, Alan R. Ramelli, Christopher D. Henry, James E. Faulds,
Nevada Bureau of Mines and Geology, Univ. of Nevada, Reno, NV, 98557, cdepolo@unr.edu
Thomas L. Sawyer
Piedmont GeoSciences, 10235 Blackhawk Drive, Reno, NV, 89506-8527

The Warm Springs Valley fault system (WSVFS) is a major, northwest-striking, right-lateral member of the northern Walker Lane belt in western Nevada. This large, well-exposed strike-slip fault system consists of multiple parallel and anastomosing fault traces that exhibit different geomorphic expression in different geologic settings. The southern 54 km of the system has well-developed late Quaternary tectonic geomorphology and is the focus of this study. The system extends to the north into Honey Lake Valley, California, however, and may have a total length of up to 96 km. The WSVFS appears to have two overall orientations. The southern half of the system has an overall strike of ~N40EW. The northern half has a strike of ~N55EW, although more mapping of the system in California is needed to confirm this.

The structure of the WSVFS is complex and commonly includes two or more parallel and anastomosing fault traces. Although the system is fairly continuous, right and left steps, with their associated extension and contraction, are common. Right steps dominate the system at both large and small scales, however, likely caused by the overall transtensional nature of the fault.

The WSVFS creates large- to small-scale linear valleys, linear depressions, and a series of aligned linear ridges immediately north of Warm Springs Valley. The local geomorphic expression of the WSVFS is related to geologic setting. Three distinct settings are present, alluvial basins, piedmonts, and bedrock areas. Based on these settings, five geomorphic sections of the WSVFS are proposed (south to north): Pah Rah Range section, Warm Springs Valley section, Winnemucca Valley section, Virginia Mountains section, Honey Lake Valley section. The Pah Rah Range section is characterized by a bedrock fault and, outboard of the range front, a buried fault. The 12-km-long section has sidehill benches and swales, and ends to the south in a small, intermountain pull-apart basin; expression is subtler because the slip rate is likely lower than the rest of the system. Faults in the Warm Springs Valley section cross the floor of northern Warm Springs Valley, which was inundated during the high stand of latest Pleistocene Lake Lahontan. The 9-km-long section has discontinuous small fault scarps, vegetation lineaments, and push-up mounds in latest Pleistocene and Holocene deposits. This subtle expression was likely created from the last few events. For much of this section, geomorphic expression is buried and/or modified by Holocene fluvial erosion and burial, and fault traces are indistinct. In the 12-km-long Winnemucca Valley section faults cross Quaternary alluvial fans and Tertiary volcanic deposits. Spectacular, aligned linear ridges along this section are cored by older alluvium and bedrock and are up to 1.5 km long. Geomorphic expression is nearly continuous,

but erosion and burial tends to obscure expression of the most recent events. The Virginia Mountains section is a bedrock setting and is about 21 km long. Geomorphic expression includes side-hill benches and swales, linear valleys, saddles in ridges, and small fault facets. The northern portion of the section includes a pull-apart basin, with a central closed depression that is about 5½ km long and 1 km wide. We did not study the Honey Lake section, but it exhibits linear faults in a deep basin alluvial and lacustrine setting.

Appendix C

Warms Springs Valley fault system
Trench 1
Unit Descriptions

Unit 1

Light gray to light brownish gray (10YR 6-7/2) very fine sandy silt and silt, with very fine to medium platy structure, local granular structure, and local vesicles. Lower contact even and gradational over 1 to 2 cm. Eolian and alluvial sediments.

Unit 1a

Pale brown (10YR 6/3) fine and very fine sand, clay silt with fine to medium platy structure with minor vesicles. Lower contact even and slightly gradational. This unit make up the upper part of a small uplifted mound that has several sagebrush bushes and small copice dunes. Eolian and alluvial sediments.

Unit 1b

Pale brown (10YR 6/3) clayey, fine to very fine sandy silt; sandier under scrub brush in small copice dunes. Fine platy and granular structure. Even and slightly gradational lower contact. Eolian and alluvial sediments.

Unit 1c

Light gray (10YR 7/2) very fine sandy silt, slightly mottled with darker patches. Unit has thin platy structure and local weak columnar structure. Basin or playa floor deposits.

Unit 2

Very pale brown (10YR 7/3) very fine sandy silt and silt, with fine to medium platy structure, local medium blocky structure, and some vesicles. Lower contact even and very abrupt. Playa or shallow lacustrine deposits.

Unit 2a

Very pale brown (10YR 8/2) very fine sandy silt, overall fairly massive but inclusive of other blocks of silt, abrupt and even lower contact. Weak, slope parallel structure consistent with a colluvial wedge deposit

Unit 3

Light gray (10YR 7/2) fine sandy clay (unit has greenish appearance). Weak fine to medium blocky structure and minor weak platy structure. Unit is thin (#20 cm), has abrupt and even upper and lower contacts. Localized lacustrine or playa deposit?

Unit 3a

Light gray to light brownish gray (10YR 6-7/2) slightly sandy, clayey silt (unit has greenish appearance) with small to medium blocky, semi-massive, and minor thin to medium platy structure. Even, fairly abrupt lower contact. Deposit may be colluvium eroded from Unit 3 that covered the local uplifted mound and was eroded off shortly after subaerial exposure.

Unit 4

Light gray to light brownish gray (10YR 6-7/2) silty, very fine, medium, coarse sand. Massive and unstratified poorly sorted, but evenly distributed sand. Lower contact is abrupt and irregular, with deposit filling into fissures and the wavy surface on top of Unit 5 after it liquefied and laterally spread, due to Paleoearthquake 3. Deposit is likely lacustrine.

Unit 4a

Grayish brown (10YR 5/2) very coarse, medium, coarse sand with mica and magnetite (Fe-stained part - 10YR 5/4); sand grains are angular to subrounded. Moderately well developed sedimentary structure consisting of layers 1 to 1.5 cm thick, that locally have cross laminations. Abrupt, even lower contact. Lacustrine deposit?

Unit 5

Light gray, light brownish gray, brownish yellow, and yellowish brown (10YR 6-7/2; Fe-stained 10YR 5-6/6) fine, medium, coarse sand. Sand grains are rounded and subrounded, and are from granitic and volcanic (rhyolite and basalt) sources. The unit has three, notable thin whitish layers that serve as marked beds. This deposit is dominated by soft-sediment deformation in the trench exposure consisting of contorted (including folded), injected, and attenuated deposits. Relict sedimentary layers and weak fluvial sedimentary structures present. Lower contact is sharp, even, and locally titled. These deposits are latest Pleistocene Lake Lahontan lacustrine sediments, that have been liquefied and upon being tilted adjacent to the causative fault trace during Paleoearthquake 3, laterally spread to the east. A photon-stimulated luminescence date from this deposit is 15.3"2 ka.

Unit 5a

Light brownish gray (10YR 6/2) fine, coarse, medium sand, well sorted with local fine parallel laminae that appears to be flow structure, and injections into overlying Unit 5. Lower contact is sharp and even. Lacustrine deposit.

Unit 5b

Light brownish gray (10YR 6/2) medium and coarse sands, with well-developed fluvial structure consisting of fine layered bedding a mm to few mm thick, local cross laminations, and some cut and fill structure. Sand grains are subangular to well rounded, and are dominated by quartz, with minor mica and magnetite. Abrupt, even contact that onlaps onto Unit 5c. Lacustrine deposit.

Unit 5c

Light brownish gray (10YR 6/2) coarse, fine, medium sand, with local soft sediment structure, mostly evidenced by contorted sedimentary layering. Deposit is mostly massive, with local weak stratification. Lacustrine deposit.

Unit 6

Light brownish gray (10YR 6/2) poorly sorted pebbly, silty, very fine, fine, medium, coarse, very coarse sand. Moderately to well developed fluvial layering with gravelly lenses in the lower portion, and the upper portion is more massive and poorly sorted. Pebble clasts are up to 1½ cm diameter, and are dominated by volcanic clasts (rhyolite and basalt), with minor granitic and metamorphic rocks. Lower contact is abrupt and fairly even. These deposits are subareal and may have filled a localized tectonic depression associated with a paleoearthquake. Subaerial alluvial and colluvial deposits.

Unit 6a

Light gray (10YR 7/2) pebbly coarse to very fine sand, moderately sorted, cross laminations, inter-fingering relationships, moderately developed sedimentary stratification, even fairly abrupt lower contact. Fluvial and colluvial deposits.

Unit 6b

Light gray (10YR 7/2) pebbly coarse to very fine sand, unsorted, moderately developed sedimentary stratification, with a fairly even, abrupt lower contact. Sediments are tectonically folded, and are the apparent source of the inter-fingers of Unit 6a.

Unit 6c

Light brownish gray (10YR 6/2) pebbly, medium, very coarse, coarse sand. Moderately sorted and clast supported, with local pebble layers. Local soft-sediment deformation within unit.

Unit 7

Pale brown (10YR 6/3) clayey, very fine sandy silt, generally massive with minor horizontal sedimentary layering, and weak moderate prismatic structure along the upper contact. Some organic staining near the upper part of the unit (this likely is the pre-Lake Lahontan innundation surface). Lower contact appears to onlap onto a tilted(?) unconformity on Unit 8. One radiocarbon date has been collected from near the top of Unit 7, from the organics in the surface paleosol; the date is ^{14}C cal BP 18 to 19.1 ka (T1-RC1). Subaerial basin deposits.

Unit 7a

Brown (10YR 5/3) fine, very fine sandy, silty clay (mud), that is generally massive, with some crude sedimentary layering that was warped near fault F1. Unit was saturated and difficult to see. Subaerial basin deposits.

Unit 8

Light gray (10YR 7/2) fine, medium sandy, clayey silt, with a well-formed paleosol on top, where the unit is darker brown (light brownish gray - 10YR 6/2), has well formed medium and large columnar structure, and has brown to brown-black inclusions. A photon-stimulated luminescence date from Unit 8 is 21"2 ka.

Unit 9

Grayish brown (10YR 5/2) pebbly (10-20%), very fine, fine, medium coarse sand. Poorly sorted and matrix dominated. Moderately well developed sedimentary structure consisting of thin layers and small gravel lenses.

Unit 9a

Light brownish gray (10YR 6/2) pebbly (30-40%), medium, coarse sand. Poorly sorted and matrix dominated. Weak to moderately well developed sedimentary layering.

Unit 10

Pale brown (10YR 6/3) very fine sandy, clayey silt, with minor coarse sand. Massive with northerly striking Reidel fractures.

Appendix D

Warm Springs Valley fault system
Trench 2
Unit Descriptions:

Unit 1

White to very pale brown (10YR 8/2-3), medium to fine sandy silt, well sorted, poorly stratified - massive, with discontinuous vesicular structure, discontinuous fine to medium platy structure, and an abrupt lower contact. In part this is a playette deposit.

Unit 1a

White (10YR 8/2) very fine sandy silt, well sorted, weak to well-developed platy structure, moderate vesicular structure, especially near the top of the deposit, some granular structure, even but gradation lower contact.

Unit 1b

Light gray (10YR 7/2) silty, fine, very fine sand layer that is deposited across Fault 1 that is undisturbed. Very fine sedimentary laminae are present.

Unit 1c

Very pale brown (10YR7/3-4), fine sandy silt, well sorted, fine to medium blocky and single grain structure, effervesces wildly with HCl, sharp but gradational lower contact. Small colluvial deposit from the most-recent event.

Unit 2

Very pale brown (10YR 8-7/3), coarse sand to pea-sized gravel clasts in a matrix of silty medium to fine sand, poorly sorted, poorly stratified, massive with some disintegrated platy structure in the lower part. Matrix effervesces wildly with HCL.

Unit 2a

White (10YR 8/2), medium to fine sandy silt; effervesces wildly with HCL.

Unit 2b

White (10YR 8/1-2) upper, wedge-shaped part of unit made up of sandy silt, well sorted, weakly to moderately layered (stratification?), fine to medium block structure, and a weakly developed moderate platy structure. Effervesces moderately to strongly with HCL. The part this unit next to Fault F1 has shear structure, and the western contact is faulted. Lower portion of Unit 2b is a very pale brown (10YR7/3) pebbly, silty, medium to fine sand overlying lacustrine sands with an irregular, fairly abrupt contact. There is some minor Fe-staining in the lower part. Unit 2b appears to be a small colluvial deposit related to Paleoearthquake 2.

Unit 2c

Very pale brown (10YR 7/3), silty very fine sand with minor pebbles, strong well-developed thin to moderately thick platy structure, sharp abrupt lower contact. Possibly a colluvial/buttress deposit against small scarp along Fault 2 from the second-event back.

Unit 3a

White (10YR 8/2) pebbly, coarse to fine, medium sand, 1-3% subrounded clasts up to 2 cm diameter, stringers of carbonate and carbonate-rich top, poorly sorted, generally massive with some fine laminations and fluvial structure, minor gravel lenses up to 20 cm long.

Unit 3b

Light gray to very pale brown (10YR 8-7/2-3) pebbly, coarse to fine, medium sand, 1-3% subrounded clasts up to 2 cm diameter, and has a discontinuous layer of small silty sand inclusions, and vertical carbonate-filled fractures.

Unit 3c

Pebbly, coarse to fine, medium sand, 1-3% subrounded clasts up to 2 cm diameter, with horizontal stringers and areas of whitish silty medium to fine sand (similar to sandblow sand). This unit may be the lower part of Unit 3b with liquefied sand injected into it.

Unit 3d

Greenish brown, medium sand, with a few small pebbles 1 cm in diameter (1-2 %), massive with discontinuous, weak stratification. Fairly abrupt upper and lower contacts. This sand is likely a lacustrine sand associated with Latest Pleistocene Lake Lahontan, and is possibly post Paleoearthquake 3.

Unit 3e

Very pale brown to pale brown (10YR 6-7/3) and light gray (10YR 7/2) pebbly, granular medium to fine sand (5 to 15% clasts) and with some sandy, pebbly, granular gravels lens and layers. Clasts are rounded to subrounded and are metamorphic, granitic, and felsic volcanic rocks. Deposits are matrix supported, and have weak to moderately well developed sedimentary structure (mostly layers). Deposits are moderately to strongly indurated. Upper and lower contacts are fairly abrupt. Some carbonate stringers. Bioturbated areas are full of roots, loose, and mixed with discontinuous sedimentary structure (~10 to 15% clasts). These deposits are late Pleistocene Lake Lahontan deposits and immediately pre-lake alluvial deposits, and are likely pre-Paleoearhquake 3.

Unit 3f

Very pale brown and pale brown (10YR 6-7/3), silty, pebbly fine sand (upper part), and mottled rust colored and pale brown, pebbly medium fine sand (middle part), and pale brown sandy pebbly gravel (lower part).

Sandblow sand

White (10YR 8/1-0.5) silty medium to fine sand, massive filling vertical pipes and horizontal tongues into Unit 4 and the lower part of Unit 3.

Unit 4a

Very pale brown (10YR 7/3), silty fine sand, well sorted, massive with local soft-sediment structure and discontinuous relict platy structure.

Unit 4b

Very pale brown to light yellowish brown (10YR 6-7/4), sandy clayey silt with minor sand lenses, well to medium sorted, fine to medium blocky with local prismatic structure, some stratification, especially in western part of unit where sandy silts have parallel west-tilted ~1-cm-thick muddy beds every few centimeters.

Unit 4c

Very pale brown (10YR 7/3), mud with some rare carbonate stringers and local Fe-staining.

Appendix E

Warm Springs Valley fault system
Trench 3
Unit Descriptions

Unit 1

Light brownish gray to grayish brown (10YR 5-6/2) fine sandy silt and silty fine sands, with loose, massive character, and local weak platy and weak blocky structure. The eastern part of this deposit has three layers, a 2-5 cm surface sandy silt, a 10 cm silty sand layer in the middle, and a lower, slightly indurated 2-5 silty sand. The upper layer includes small coppice dunes around bushes, and continues to the west across the entire trench. This layer was formed from a combination of eolian and alluvial processes. Gradational, but even lower contact.

Unit 2

Brown (10YR 5/3) fine sandy silt with 1-5% pebbles, moderately indurated and massive; clasts are matrix supported. Pebbles are rounded to subrounded and are felsic and basaltic volcanic rocks. The upper part of this deposit has a 2- to 5-cm thick, weak cambic soil horizon. The deposit appears to have been formed by eolian and alluvial processes. Lower contact is gradational, and generally even, but locally irregular.

Unit 3

Brown (10YR 5/3), silty medium to very fine sand. Stage I to very weak stage II carbonate development. Some weakly indurated parts, but mostly loose. Some bioturbation; small borings and root disturbances. The unit is massive with little or no stratification, and may be a single depositional event. Very abrupt, even lower contact.

Unit 4

Pale brown (10YR 6/3) cobbly, pebbly, silty very fine sand with some distinct lenses of well sorted, layered alluvial packages of gravels, otherwise moderately sorted deposit with cobbles. The bases is notably cobbly, especially the east end. The lower part of this deposit may be a debris flow, and the upper part may be eolian. This deposit lies on a paleosol formed on the top of Unit 5 that is likely a latest Pleistocene soil. The deposit fills a low area east of a fault scarp over fault F1. Lower contact is fairly even, but has irregularities where the deposit intrudes into prismatic structure in the buried paleosol below.

Unit 5

Yellowish brown (10YR 5/4) cobbly, pebbly, silty sand (2-5% gravel). The upper part is a paleosol that is darker brown, has clay enrichment, and moderately developed prismatic structure. Some small carbonate filaments near the top, and some clasts have Stage II carbonate development; also some Fe staining and mottling. [structure - lower contact- even contact?]

Unit 6a

Yellowish brown (10YR 5/5) cobbly, pebbly sandy silt. The upper part of the unit is a paleosol and is a darker, redder sandy, silty clay, with fine to medium prismatic structure. Deposit is massive. Lower contact is an irregular, wavy surface.

Unit 6b

Pale brown to brown (10YR 5-6/3) sandy pebble gravel deposit in a 20- to 40-cm thick channel deposit. The trench exposure is a slightly oblique cross section of the channel. Channel fill has weak horizontal stratification. Clasts are subangular and subrounded volcanic rocks, and vary from being 20% to 70% of the deposit; deposit is both matrix and clast supported. A paleosol on top of the gravel has fine to medium prismatic structure and shows vertical interfingers of the overlying silt from bioturbation or vertisolic action. Deposit fines upward into a clayey, silty, fine, very fine sand with small carbonate stringers.

Unit 6c

Pale brown (10YR 6/3) clayey, silty coarse, medium fine sand. Overall similar to Unit 6a. Slightly pebbly lower part.

Unit 7

Dark yellowish brown (10YR 4-5/4) well-sorted, pebbly granular, coarse medium fine sand. Gravel is minor (<1%). Paleosol in the top of the unit has a darker argillic horizon with well-developed fine and medium prismatic structure.

Unit 7a

Light yellowish brown (10YR 6/4) pebbly, coarse, very fine, medium fine sand with slight iron staining. Unsorted, with weak stratification. Generally a lack of soil structure, but some local very weak, fine prismatic structure. Abrupt, slightly irregular buttress contact with Unit 8.

Unit 8

Pale brown to brown (10YR 5-6/3) cobbly, pebbly, silty, fine, very fine sand with fine blocky and prismatic structure and carbonate filled fractures. The unit is sheared locally. Poorly sorted and matrix supported. Colluvial deposit with some slope-parallel oriented clasts.

Unit 9

Yellowish brown (10YR 5/4) very fine sandy, silty clay with fine prismatic structure. Lower part not exposed; truncated against fault. Colluvial deposit from linear ridge?

Unit 10

Pale brown (10YR 6/3) granular, very coarse, coarse medium sand. Sands are generally massive with weak stratification. Sand is strongly cemented with silica(?); although there are carbonate stringers present, the matrix generally does not effervesce with HCl. Locally there is some whitening due to carbonate staining and light Fe staining.

Unit 10a

Yellowish brown to light yellowish brown (10YR5-6/4) coarse, fine, medium sand, with a local granular, pebbly sandy lower part. Weakly formed medium prismatic structure in the upper part; Bt or Bw, latest Pleistocene soil, lower contact is even and abrupt.

Unit 10b

Pale brown (10YR 6/3) clayey, coarse to very fine sand, massive with well-developed, medium prismatic structure, with a gradational irregular contact.

Unit 10c

Pale brown (10YR 6/3) clayey, very fine sand, massive with well-developed fine to medium blocky texture and carbonate stringers. Abrupt lower contact.

Unit 10d

Light yellowish brown (10YR 6/4) clayey, coarse to very fine sand. Colluvium with chunks of unit 10 in it.

Unit 11

Light yellowish brown (10YR 6/4) very coarse, very fine sandy silt and silty sand. Locally has a strong fine platy structure. Very unsticky when wet.

Unit 11a

Brown (10YR 5/3) coarse, medium, very fine sand; massive with a coarse platy structure. Sightly darker upper part of Unit 11.

Unit 12

Yellowish brown (10YR 5/4) coarse, medium sandy, silty clay (mostly clay) with a few boulders. Massive with well-developed medium prismatic (shrink-swell) texture. Whitish carbonate stringers and filaments are present, and the clays effervesce with HCl. This deposit is a relict slope soil developed on a linear ridge of older alluvium.

Unit 13a

Brown (10YR 4/3) pebbly, clayey, medium to very fine sand. Colluvial deposit.

Unit 13b

Yellowish brown (10YR 5/4) pebbly, clayey, coarse to medium sand. Colluvial deposit.

Unit 13c

Light yellowish brown (10YR 6/4) pebbly, coarse to fine sand. Colluvial deposit.

Unit 13d

Very pale brown (10YR 7/3) pebbly coarse to fine sand with stage II carbonate. Colluvial deposit.

Unit 14

Granular, cobbly, pebble gravel conglomerate with well-developed stage III carbonate development (80 to 90% gravel). There is local moderate stratification with several areas where clasts are rotated into fault zones. Gravels are subrounded to well rounded. Many clasts are basaltic Pyramid Sequence rocks. To some degree the carbonate horizon in this unit may be associated with Unit 12, the latter being a well-developed argillic horizon.

Appendix F

Warm Springs Valley fault system
Trench 4
Unit Descriptions

Unit 1

Brown (10YR 5/3) coarse, fine, medium sand and silty medium, fine, very fine sand with thin horizontal stratification. Some boulders and cobbles scattered about, especially on the surface and near the linear ridge. Local thin to medium platy structure. Locally massive or loose single-grained structure. Lower contact sharp, but slightly irregular. Local light effervescence with HCl. Lower contact sharp, but slightly irregular. Young and active surficial deposits.

Unit 2

Brown (10YR 4/3) medium fine sandy clay (mostly clay) with weak to moderate prismatic structure and moderate blocky structure; partly a Bt soil horizon. Weak horizontal stratification, especially in the lower part. Very sticky and very plastic. Lower contact is fairly even but has broad waves in it.

Unit 3

Pale brown (10YR 6/3) medium, very fine sandy silt and silty sands with whitish CO3 filaments and some ryzoliths. Massive with a few small pebbles (<<1%). Matrix lightly effervesce and the filaments wildly effervesce with HCl. Lower contact fairly even with a weak stone line that was buried by deposition of Unit 3. Contains a Bk soil horizon that corresponds to the Bt in Unit 2.

Unit 4

Pale brown to dark yellowish brown (10YR 4/3-4) clayey, medium sandy, silty, very fine sand that is generally massive with fine prismatic structure and weal medium blocky structure near the top. Minor CO3 filaments; with exception of the filaments, does not effervesce with HCl. Abrupt bu irregular lower contact with a weak stone line.

Unit 5

Dark yellowish brown (10YR 4/4) medium to fine sandy clay with some cobbles. Unit has well-developed fine to medium prismatic structure and fine to medium blocky structure. Unit is extremely sticky and extremely plastic. Some carbonate-coated fractures near the top of the deposit. Cobbles are felsic and mafic volcanic rocks eroded from the older alluvium to the west. The clasts are subrounded to subangular and have discontinuous carbonate coatings on them. This upper part of the Unit 5 package (Units 5 and 5a) is mostly derived from the older alluvium to the west.

Unit 5a

Yellowish brown (10YR 5/4) clayey medium, fine, very fine sand. Unit is massive with weak discontinuous blocky structure. Unit is very sticky and very plastic. Unit is early part of the Unit 4 package and may be dominated by distal facies sands from Piute Canyon fan.

Unit 6

Dark yellowish brown (10YR 4-5/4) clayey medium, very fine, fine sand with a few cobbles. Thin unit with massive to weakly and moderately developed blocky structure. Unit is very sticky and very plastic, and variably effervesces in HCl from non-effervescing to effervescing wildly. There is a weak stone-line near the top of Unit 6.

Unit 7

Dark yellowish brown (10YR 4/4) medium to very fine sandy clay. Unit has fine to medium prismatic structure and weak to moderately blocky structure. Unit is extremely sticky and very plastic. There is some carbonate staining and lining of ped faces. There is a weak stone-line near the top of Unit 7.

Qao

Older Quaternary alluvium. Very pale brown to pale brown (10YR 6-7/3) indurated, highly sheared, well sorted, coarse to fine sand with a few minor cobbles (<1%).

Colluvium III

Light yellowish brown (10YR 6/4) pebbly, coarse to very fine sandy silt with clasts of Unit Qoa within it. Unsorted and massive. Unit has Stage II carbonate development, strongly effervesces in HCl.

Colluvium IV

Very pale brown (10YR 7/3) pebbly, coarse to very fine sandy silt with clasts of Unit Qoa within it. Weak fine to medium platy structure. Unit has Stage III carbonate development and effervesces with HCl.

Colluvium IV?

Very pale brown to pale brown (10YR 6-7/3) pebbly, coarse to fine sandy, silty, very fine sand. Anastamosing medium platy structure with weak Stage III carbonate development that effervesces wildly with HCl.

Colluvium IV or V

Very pale brown (10YR 7/3) pebbly, coarse to very fine sand. Poorly sorted and massive. Stage III carbonate development.