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Determination of Fault Slip Rates, Paleoearthquake History, and Segmentation of the Warm Springs Valley Fault System

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Abstract

This research confirmed a right-lateral sense-of-displacement, measured the lateral offset of a buried stream channel deposit, refined the paleoseismic history, and determined preliminary fault slip rates along the Warm Springs Valley fault system (WSVFS). The WSVFS is one of the most active faults in western Nevada, and threatens the northern part of the Reno-Carson City urban corridor. The first three objectives were completed with the box-trench complex around the fault at the Mid-Valley site, and the fourth objective (fault slip rate) was developed at the Fort Sage Mountains site.

Six trenches (the Trench 5 complex and Trench 7) were dug, surveyed, and mapped at the Mid-Valley site. The Trench 5 complex is made up with five trenches, four making the box around the fault (two fault-perpendicular trenches and two fault parallel trenches), and a fault-perpendicular trench piercing the box to test the buried channel alignment. These were used to identify and measure the right-lateral offset of a distinct, buried channel deposit. The channel crossed the fault nearly perpendicular (controlled by push-up mounds) and has been offset by two events (Paleoearthquakes 2 and 3). The right-lateral offset of the channel across the fault, 2.5 ± 0.5 m, confirmed the right-lateral nature of the WSVFS. An estimate of single-event displacement along the southern part the system of 1.25 ± 0.5 m is made by dividing this total by two events. A 1 ± 0.25 m vertical offset, down-to-the-northeast, is measured from a cross-section projection of the channels into the fault (fig. 3); thus, in addition to the lateral offset, there was about 0.5 m of reverse dip-slip offset per event as well. An additional event to the original earthquake chronology was discovered in the more complete sections in the channel area; this event (Paleoearthquake 3) was missed because evidence was eroded away in previous trenches. Evidence for Paleoearthquake 3 includes severe liquefaction, injection of silts from a fault, evidence of a paleo-high area created by the event, and a possible angular unconformity between pre- and post-event deposits caused by it.

Eight probable paleoseismic events are identified at the Mid-Valley site, all since a luminescence date of 21 ± 4 ky (2 sigma). Only two of these eight events are since a radiocarbon date of 9,950 to 12,942 ^{14}C cal bp (2 sigma), whereas, five to six events occurred between ~21 and ~10 ky bp. Thus, earthquake activity has been significantly less in the Holocene than in the latest Pleistocene. This brings up the question, did earthquake activity (potential) recently dramatically decrease by about 75% along the WSVFS, or is the system ripe for an earthquake?

At the Fort Sage Mountains site an offset alluvial fan was used to develop a late Quaternary fault slip rate for the WSVFS. This site is along the north-central part of the system, on the main trace of the fault zone. The measured offset is 95 m right-lateral, with estimated uncertainties of +15 m and -11 m. A preliminary age of the offset surface is 80-130 ky , with a maximum estimated age of 300 ky and a minimum age of 50 ky. Thus, the preferred right-lateral fault slip rates are 0.7 - 1.2 m/ky (~1 m/ky), the minimum rate is 0.3 m/ky, and the maximum rate is 2.2 m/ky. There are other parallel fault traces that would have some contribution to the overall slip rate of the WSVFS that were not studied, so these rates should be considered minimums.
Potential earthquake magnitudes (moment magnitudes) along the WSVFS range from M6.5 to

M7.3, and the most likely maximum earthquake along the system is M6.9 to M7.1. Earthquake segments are difficult to confidently define along the WSVFS; a large (5-6 km long) pull-apart basin and a bend in the fault are used to divide the long system (96 km long total) into two parts that are tentatively used as earthquake segments. Poorly constrained Holocene average earthquake recurrence intervals are estimated as 6 ky, with maximum and minimum average recurrence intervals of ~13 ky to 3 ky, but we are likely much closer to the next earthquake along the southern WSVFS than these values would imply. This is because geomorphic expression of the system indicates a relatively high long-term slip rate and geodetic measurements show there are local high levels of lateral strain, but it has been a while since there has been a significant strain release event along the southern part of the system. Thus, it would be logical to expect another cluster of earthquakes along the WSVFS. Further, the most recent event (PE1) was relatively small enhancing the sense that the system is overdue or ripe for an earthquake.

Introduction

The Warm Springs Valley fault system (WSVFS) is a major northwest-striking, right-lateral fault system in western Nevada that threatens the northern part of the Reno-Carson City urban corridor. The fault system was demonstrated to be an active latest Quaternary fault by dePolo and Ramelli (2004) and is in the top five most active faults in Nevada. The WSVFS is as much as 96 km in length, extending from southern Warm Springs Valley northward into Honey Lake Valley in California (fig. 1). This system accommodates tectonic translation in western Nevada caused by motion between the Pacific and North American plates.

This research continued trenching investigations at the Mid-Valley site, including a box-trench to explore and document right-lateral strike-slip faulting, and mapped a right-lateral offset along the north-central part of the system. The results have refined the earthquake history of the southern part of the system, which is closest to the Reno-Carson City urban corridor, and defined a minimum latest Quaternary fault slip rate for the central part of the system. The box-trench site is in an area being built over with homes and this research saved these data which may have been impossible to gather in the future. This study also conducted the initial investigation into fan deposits offset by the main strand of the WSVFS, in southern Honey Lake Valley, Nevada. Preliminary estimates of slip rates based on the oldest of offset alluvial units (latest Pleistocene) confirms that the WSVFS is a very active fault system, and will likely have an earthquake in the near geologic future.

Figure 1. General location map of the Warm Springs Valley fault system. Sites 1 and 2 for this study are indicated on the map.

Trenching Studies

Trench exploration was continued at the Mid-Valley site along the WSVFS. Five trenches were excavated for the box trench (the Trench 5 complex) and an additional trench was placed on the northern nose of the push-up mound originally explored with Trench 1. Information and mapping gained from the first NEHRP study (dePolo and Ramelli, 2004) was used to identify the potential and location of the buried offset stream channel for the Trench 5 complex. Figure 2 is general map of the trench site.

Trench 5 Complex

The objective for the Trench 5 complex was to find a buried offset stream channel deposit between a pair of push-up mounds. The mounds were built or pushed up at least since Paleoearthquake 4 (PE4), which occurred during the high stand of latest Pleistocene Lake Lahontan. Local drainages are nearly orthogonal to the fault zone at the site, thus the possibility existed for a local channel to have been geologically preserved and offset right-laterally by the fault. The plan was to excavate a box around the fault, including two fault-parallel trenches, looking for laterally offset features. The box started with two fault-perpendicular trenches to define the fault location and its correspondence with surficial expression of the fault (Trench 5A - the northwestern trench and Trench 5B, the southeastern trench). A fault-parallel trench (Trench 5C) was started at the northern push-up mound (at Trench 5A) and was located on the up-thrown, up-drainage side of the fault to explore for channel deposits. When a distinct channel of sufficient age to have experienced some earthquakes was encountered, the trench was excavated through the channel and deposits surrounding it, and Trench 5C was ramped out. Excavation of Trench 5D along the other side of the fault was begun at it intersection with Trench 5B. This other fault-parallel trench (Trench 5D) was excavated until it encountered the same channel deposit and was dug to within 5 m of Trench 5A. The box was ~6 m wide and ~42 m long, with the main fault running down the middle of the long axis of the box. To confirm the channel did not have a possible bend in it at the fault that would contaminate the offset measurement, Trench 5E was excavated across the core of the box along the side of the channel.

Trench 5A

Trench 5A was 40.2 m long, was oriented N40°E, crossed the N56±2°W striking fault trace at a high angle, and had a maximum depth of 3 m. The trench was excavated to confirm the fault location, to look for paleoseismic information, to explore a small push-up feature, and to become the northwest side of the box-trench complex. The log of Trench 5A is shown in Plate 1.

The southern wall of Trench 5A exposed older deposits (Units 5c, 6?, and 7) from an eroded core of a faulted push-up feature, covered by a sequence of mostly post-Lake Lahontan, subaerial sands and silts, with a possible intercalated, clayey spring deposit (Unit 3). The older deposits in

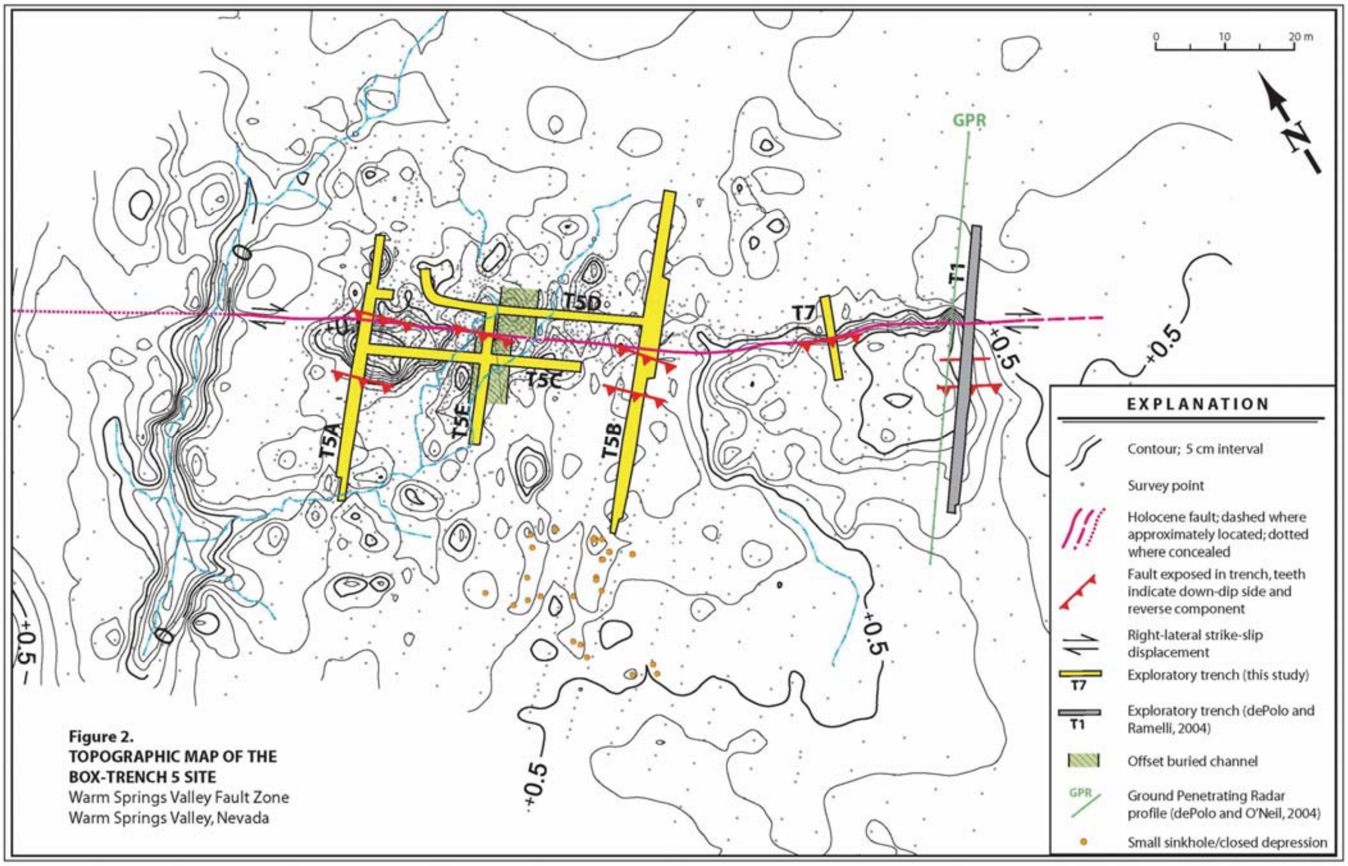


Figure 2.
TOPOGRAPHIC MAP OF THE BOX-TRENCH 5 SITE
Warm Springs Valley Fault Zone
Warm Springs Valley, Nevada

the push-up area are muddy and sandy pre-Lake Lahontan deposits (Units 6? and 7) northeast of Fault F2 and some lower Lake Lahontan highstand deposits (Unit 5c) to the southwest of Fault F2. The top of the older deposits in the push-up area is an unconformity on these clayey and sandy deposits, that was a surface for a while because of some weak prismatic structure in the top of Unit 7.

As much as 1.5 m of subaerial, fluvial and eolian sands and silts from Unit 4 were deposited on this surface; these deposits have cut-and-fill structures and interfingering bedding relationships. Unit 4b is identified from Fault F1 and to the southwest, but it is not ruled out from the other side of the fault; Unit 4b wasn't confidently identified on the northeast side. The thickness of Unit 4b is highly variable from 20 to 50 cm and increases away from the push-up core; some of this variation may be due to filling coseismic tectonic or liquefaction irregularities.

The greenish Unit 3 changes character over the buried push-up feature being more clay-rich on the down-thrown side of Fault F1, and on the back side of the push-up core increasing in thickness away from the core. Unit 3 has a variable thickness from 10 cm to as much as 60 cm where it thickens across Fault F1. Unit 3 appears to be deformed by Fault F1 as well. Unit 2 is a whitish deposit containing diatomaceous earth on the down-thrown side of the fault, whereas it more closely resembles a sandy silt with a weak carbonate soil in it over the top of the push-up mound. In the northeastern part of the trench Unit 2 has vertical, light brown mottles caused by bioturbation by plants, animals, or both. In Unit 2 there is a possible colluvial deposit (Unit 2b) and an apparent thickening of Unit 2 across the fault (as much as 70 cm thick); these are likely related to PE2. The youngest deposit (sandy silts and very fine sands of Unit 1) is about 20 to 40 cm thick and appears to drape over the landscape with local irregularities related to plants (e.g., coppice dune areas).

The mound crossed by T5A (stations 16 - 23) is only cored by uplifted older deposits and is subsequently buried by thickened younger deposits that have some coppice dune accumulation. Unit 2a most notably thickens, and Unit 1 thickens mostly on the leeward side of the mound possibly due to addition eolian input. It is unclear whether PE1 might have warped the mound up a bit as well. An additional factor in the geomorphology of this mound is it is somewhat of an erosional feature with floods eroding down the sides.

Two fault zones were exposed in Trench 5A, the main fault (F1a-c), and the main secondary zone (F2a-c). Both faults are primary strike-slip faults with reverse components as much as 40% of lateral displacements. The main zone (F1) is made up of three parallel faults with apparent total reverse offset of Unit 4b and 4c? of ~50 cm, and bounds a small uplifted block that may have been additionally tilted to the southwest during faulting events. Fault F1 strikes slightly more northerly (~6°) than the overall expression of the fault indicating the fault is likely part of a left-stepping fault set that stays within the Trench 5 complex box. Fault dips (both F1 and F2) at the trench are about 50° SW. Fault F1 has some possible evidence of Paleoearthquakes 2 and 3. Faults F1a-c offset deposits from Units 4 and 7, probably warped and possibly offset Unit 3, and induced a possible colluvial deposit (Unit 2b). Although the fault zone likely has as much as 2.5 m of right-lateral offset, some facies could be carried across individual fault traces, but they have different thicknesses across faults. Units 2 and 3 thicken at the fault, apparently caused by Paleoearthquake 2 (early Holocene). Fault zone F1 coincides with a small surface scarp, but does not appear to have a direct relationship with it. Thickening units have diminish the expression of the fault scarp, although units built up contemporarily on the southwest side as well, preserving a small fault scarp that is shifted slightly from the main fault into the hanging wall. The structural deformation of the top of Unit 4 is ~1 m of vertical offset (PE2 & PE3?), whereas the height of the present scarp is 0.3 m.

Trench 5A shows a significant amount of latest Pleistocene, post-Lake Lahontan erosion and subaerial fluvial deposition. This activity may have eroded down a small push-up feature on the southwest side of the fault and buried it with as much as 2 m of sandy deposits.

There was some moderate soft-sediment deformation in parts of Unit 4b indicating local liquefaction. Deformation consisted in wavy and contorted contacts, distortion of layer thicknesses, minor injection of one layer to another, and sinuous contortion of layers. The most severe of this deformation was localized to within 4 m of Fault F1. There also may be a sand dike within Unit 4b at station 34.

Evidence for two to three paleoearthquakes exists in Trench 5A. It is possible that there is evidence for PE4, but this was not definitive, just permissive, and involved Fault F2. Localized liquefaction of Unit 4b indicates movement of Fault F1 during PE3. These deposits are faulted, warped, and deformed by fault movement during PE2, and a possible colluvial deposit (Unit 2b?) formed. There is no unique evidence that there was discrete movement on the faults during PE1, but any anticipated offsets would be small and possibly completely manifested by broad deformation or local warping.

Trench 5B

Trench 5B was 50.2 m long, oriented N39°E, crossed the fault at a high angle, and was up to 3.1 m deep. The trench was excavated to confirm the fault location, to look for paleoseismic information, and to become the southeast side of the box-trench complex. The log of Trench 5B is shown in Plate 2.

The northern wall of Trench 5A exposed older deposits (Units 5c, 6, and 7) from an eroded, faulted, uplifted, and southwest-tilted older core, covered by a thin deposit from the highstand of Lake Lahontan (Unit 5c?; this unit is questioned because alternatively it could be Unit 5a), and a sequence of post-Lake Lahontan, subaerial sands and silts with an intercalated, possible spring deposit (Unit 3).

Brown muds and sands of Unit 7 make up the uplifted core and extend along the bottom the entire distance of the trench. Deposits within the core are highly faulted and deformed by many paleoseismic events. On top of the push-up core and older deposits (Unit 7) there is a substantial amount of Unit 6 (as much as 1 m thick), a pre-lacustrine subaerial, unsorted pebbly sand deposit. In some cases, Unit 6 appears to be coring small, soft-sediment, antiformal structures that involve Units 4b and 5c? (e.g., stations 11 and 19).

The uplifted core is overlain by discontinuous Lake Lahontan deposits or Unit 4b (a subaerial fluvial sand with intercalated silt layers). Layered, well-sorted Lake Lahontan sands (Unit 5a) 20 to 40 cm thick cover Unit 6 on the down-thrown side. Unit 4 is 0.5 to 1 m thick at the trench, and has soft-sediment deformation the entire length of the trench. The top of the deformed Unit 4b is truncated by a locally sharp angular unconformity and is discontinuously overlain by silty sands from Unit 4a.

Unit 3 deposits, latest Pleistocene - earliest Holocene, occur along most of the trench exposure, but pinch out in the northeastern part. These clay-rich deposits are thickest (50 to 60 cm thick) near Fault F1. In this trench, what appears to be Unit 3 clay-rich deposits continue down the main fault in a 10-cm-wide fissure and have the purest clays of Unit 3; Fault F1 may have been a spring feeder conduit for Unit 3 deposits. A tectonic depression created during PE 2 is filled by what appears to be part of Unit 3 (Unit 3a).

As in Trench 5A, Unit 2 is a whitish, diatomaceous deposit on the down-thrown side of the fault, whereas it more closely resembles a sandy silt with weak carbonate soil development over the top of the push-up mound. Unit 2 is as much as 1.1 m thick on the down-thrown side. It has the vertical bioturbation features on the down-thrown side and a group of low-angle internal shears (between stations 40 and 48). It is not entirely clear what caused these internal shears; they may be soft sediment failure of Unit 2 during or shortly after formation, or induced by strong shaking, possibly with the aid of some local liquefaction.

The youngest deposit (sandy silts and very fine sands of Unit 1) appears to drape over the landscape with local irregularities (10 to 30 cm thick), and a has little more blocky structure on the down-thrown side.

Two main fault zones were encountered in Trench 5B, but there are some additional secondary faults in the uplifted core and internal shears in the northeast part of Unit 2. Faults in the trench are ~6° to 11° more northerly striking than the main fault trace, supporting an overall left-stepping pattern of fault traces through the site; probably a set of Reidel shears breaking through the basin sediments. Fault F1 is the most northerly striking, and is open as much as 10 cm and filled with greenish clayey deposits (akin to and continuous with Unit 3 deposits). This is interpreted as a local usage of the fault as a spring conduit, which likely helped create the wet conditions that led to the greenish, reduced iron color of Unit 3. The spring must have been offset during PE2 or the fissure was filled from above; the later hypothesis is not favored because of the relative purity of the clay-rich infill deposits, lacking material that would have fallen in if it was an open fissure. Curiously, some layers in deposits of Unit 4b can be approximately matched up across the fault, despite presumable lateral offset of Fault F1 during paleoearthquakes PE2 and PE3. Fault F1 has ~20 cm of apparent reverse fault offset across it but including local warping the reverse offset could be as much as 60 to 80 cm.   Most of this feature is buried by Units 1 and 2. Fault F2 may have been active during PE4 to account for the pre-Unit 4 faulting of pre-Lake Lahontan deposits. Earlier activity along Fault F2 is indicated by buried deposits, such as Unit 7a, but they were too indistinct to unravel. The uplifted core itself has undergone severe deformation and faulting. The overall push-up structure is most recently behaving as a southwestward tilt block with some warping neat Fault F1.

Liquefaction during PE3 involves Unit 4b, as well as the Lake Lahontan deposits (Unit 5c?), and pre-Lake Lahontan deposits (Unit 6), indicating all these units were saturated at the time of PE3. The unconformity created by PE3 and overlying, relatively undisturbed Unit 4a anchors the time of liquefaction to PE3. The severity of liquefaction of Unit 4 diminishes in both directions away from Fault F1 indicating local movement of the fault during PE3.

Similar to Trench 5A, Trench 5B has evidence for two and possibly three paleoearthquakes. PE4 may have occurred along Fault F2, where it is truncated by an unconformity from erosion during Unit 4b time. Evidence for PE3 includes liquefaction of Units 4, 5, and possibly 6 over a wide section of the trench. Local deformation of Unit 4b adjacent to Fault F1 also indicates movement of this fault during PE3. Subtracting the apparent deformation of Unit 3 from the deformation of Unit 4b gives a possible 20 to 50 cm apparent reverse displacement during PE3. There is also support for PE3 by the unconformity, which is the approximate event horizon, and the capping deposit (Unit 4a?) over the liquefied sediments of Unit 4b. PE2 thrust up the uplifted core with about 20 to 50 cm of apparent reverse motion. The upper part of Unit 3 appears to fill a depression caused by PE2, which helps establish that this event occurred during latest Unit 3 and earliest Unit 2 times. There is no specific evidence for PE1, which may have been "absorbed" in deformation. The general depositional shape of Unit 6 might be supportive evidence of PE5; Unit 6 thickens towards Fault F1 from both sides of the fault, possibly indicating tectonic control.

Trench 5C

Trench 5C was 26.5 m long, oriented fault parallel at N56°W, and as much as about 3 m deep. This trench was dug to explore for a unique channel deposit crossing perpendicular to the fault zone that could be used to constrain lateral displacement. Such a channel was encountered between stations 17 and 22 (the log of Trench 5C is shown in Plate 3). Trench 5C is along the relatively up-thrown side of the fault, and shows an example of fault parallel relief on this side. Here the uplifted core is made up of muddy, pre-Lake Lahontan deposits, overlain by three sandy deposits attributed to the high-stand of Lake Lahontan, including a highly liquefied section attributed to PE4 shaking and movement. Unit 4 deposits have relatively prograded to the southeast across the uplifted side. A relatively coarse, energetic channel created a cut-and-fill deposit (Unit 4bc). This channel is used as a datum for determining the right-lateral offset. The creation of an unconformity overlain by Unit 4 deposits cut into strongly liquefied Lake Lahontan deposits helps distinguish liquefaction caused by PE4 from liquefaction created by PE3; the liquefaction below this unconformity is related to PE4.

The oldest deposits exposed in Trench 5C are Units 7 and 7a which are brown and green, very clayey in this trench. The deposits appear to be relatively horizontal with well developed blocky and prismatic structure. This is overlain by a well-bedded and undeformed section of highstand Lake Lahontan deposits (Unit 5d), which is overlain by a highly contorted and liquefied Unit 5c, which is as much as 80 cm thick. In the southeastern part of the trench, Unit 5b is overlain by an unconformity and Lake Lahontan deposits of Unit 5a (as much as 40 cm thick). This unconformity was post-PE4 and Unit 5a sediments were deposits following that event. The Unit 5a deposits also appear to be liquefied and are intruded by a sand dike, all attributed to PE3.

Unit 4, including the distinctive channel deposit, is as much as 1.6 m thick in the northwest part of the trench. The unit tapers to the southeast part of the trench, and is eroded into by Unit 1a. Unit 4 deposits are brown and gray, subaerial channel and overbank, silty sand and sandy silt deposits. Only a thin deposit of Unit 3 was noted in Trench 5C (<20 cm thick), in the northwestern part. Unit 2 is the silty variety common over the uplifts; it thickens coincident with the small mound at the northwestern end of the trench (as much as 50 cm thick). A more modern channel in Unit 1 deposits was mapped (Unit 1a), but it was difficult to explore for an offset because it was too broad of a feature and crossed the fault at an angle. Unit 1 is composed of light brown sandy silts that generally blanket the area (20 to 40 cm thick) outside of the channel.

The only possible structure exposed in Trench 5C is in the station 8 area where there are some abrupt lateral changes in deposits, possibly indicating that they are near a tip of deformation from a secondary fault.

There are two liquefaction events exposed in Trench 5C, one in Unit 5c overlain by an angular unconformity, and one in Unit 5a, 4b, 4c. In Unit 5c, the axes of most of the contortion folds are tilted to the northwest indicating some apparent lateral flowage of Unit 5c to the northwest during PE4, possibly within a paleochannel. This event occurred during the highstand of Lake Lahontan, so sediment saturation was likely. Subsequent to the PE4 liquefaction an angular unconformity was eroded across the deposit (which was probably soft and easily eroded), and Unit 5a was deposited. The second liquefaction event, PE3, liquefied Units 5a, 4b, 4c, and injected a sand dike across the contact of Units 5a and 5c near station 26. Soft-sediment deformation in Unit 4b is indicated between stations 8 and 14. Some minor soft-sediment deformation and local injection structures indicate the channel (Unit 4bc) was also shaken and predated by PE3.

Trench 5D

Fault-parallel, Trench 5D was dug from Trench 5B northwestward in search of the channel found in Trench 5C. It was the deepest trench (as much as 3.5 m deep) to capture the channel, which was relatively down-dropped as well as shifted laterally. The trench was 32.5 m long and oriented N58°W. The log of Trench 5D is shown in Plate 4. This down-thrown view along the fault shows greater relative thicknesses in Units 2, 3, and 6 all possibly related to paleoearthquakes.

Older deposits (Units 6 and 7) occur in the bottom part of the southeastern end of the trench and are apparently slightly tilted to the north. These deposits are on-lapped near station 15 by Unit 5c, but are largely overlain in the exposure by Unit 5a. The gray sands of Unit 5c are locally severely liquefied and are overlain by an angular unconformity.

Unit 4 generally blankets the southeastern end of the Lake Lahontan deposits, but appears to erode more deeply into the Unit 5 deposits at the channel deposit (Unit 4bc). Unit 4 is a general on-lap sequence in the trench view, thickening to the northwest (0.3 to 1.4 m in thickness). Unit 4b shows evidence of strong shaking and liquefaction, including the northwest margin of the channel deposit, that had a liquefied upper tip near station 24. The channel was deeper and was shifted to the southeast relative to the channel encountered in Trench 5C. The uniqueness of the channel in the trench gave a very high degree of confidence that the channel was the same one encountered in both Trenches 5C and 5D; the channel deposits are a pebbly sand in parallel and cross laminated beds that is coarser than most surrounding deposits. The unconformity and relatively undisturbed overlying deposits (Unit 4a) are best observed in Trench 5D, especially between stations 15 and 25. In Trench 5D, Unit 4a appears to be part of a broad cross section of a channel that ran across the surface shortly after PE3.

Unit 3 shows a relatively constant thickness throughout the exposure (30 to 50 cm thick); this is the thicker down-thrown side following PE2 as indicated in Trenches 5B and 5E. This is shown even more dramatically in Unit 2, which has several very diatomaceous zones in this position; the maximum thickness of Unit 2 is 1.1 m. The youngest channel crossing the fault (Unit 1a) was also best preserved in Trench 5D. Unit 1 blankets the trench exposure with a thin deposit (20 to 40 cm thick) with some variations in thickness related to coppice dunes.

No tectonic structures were observed in Trench 5D.

Two episodes of severe liquefaction can be observed in Trench 5D, similar to T5C. The oldest episode is the liquefaction of Unit 5c (PE4), overlain by an unconformity and Unit 5a sands, especially in the southeastern part of the trench. This liquefaction consists of contorted bedding, likely related to lateral spreading (is this why Unit 5c is missing southwest of station 14?), and some intrusion structures. The second episode is from PE3 and liquefied Units 4b and 5a; these deposits are also overlain by an unconformity and relatively undisturbed deposits (Unit 4a). In this position (the down-thrown side), liquefaction of Unit 4b is severe and ubiquitous with wild contortions (e.g., folds, overturned folds), injected beds, and isolated pods of deposits. The angular unconformity on the Unit 5c liquefied deposits, overlain by channel deposits (Unit 4bc) separates these two liquefaction events.

Trench 5E

Trench 5E was excavated to confirm that the channel was relatively straight across the fault, and successfully did so. This 3-m-deep trench was dug just northwest of the channel exposed in Trench 5D and through the central part of the channel exposed in Trench 5C. There was a quick extension of Trench 5E, the sketch log portion that was dug immediately prior to filling, that explored whether the channel was offset by “Fault F2” found in Trenches 5A and 5B. Trench 5E was initially about 6.3 m long, the approximate width of the “box” within the Trench 5 complex, and was oriented N33°E, crossing the fault at nearly 90°. The trench was expanded to a total length of 18.9 m during the second excavation and a quick sketch log made southwest of Trench 5C. Only the area within the “box” was logged in detail. The log of Trench 5E is shown in Plate 5.

Older deposits in the trench consist of green and brown clayey deposits (Unit 7) faulted against probable Lake Lahontan deposits northeast of the main fault and in the bottom of the southwestward extension of the trench. Only 30 cm of these older deposits exposed on the bottom of the trench. The probable Lake Lahontan deposits (Unit 5c?) northeast of the fault has contorted bedding near Fault F1, and a fault strand within Unit 5c? is truncated and capped by Unit 4c; this deformation is consistent with faulting during PE4.

The older deposits are overlain by the channel pebbly coarse sands (Unit 4bc) southwest of the main fault and brownish sandy deposits of Unit 4c northeast of the fault. Unit 4b, made up of alternating sandy and silty deposits, overlies Unit 4c deposits, and has moderate to severe soft-sediment deformation (liquefaction). Unit 4b has an unconformity on top of it, which is overlain by a 20-cm-thick deposit of Unit 4a sands and silts; the unconformity and Unit 4a are mapped with uncertainty west of the fault. Some erosion of Unit 4b from the up-thrown side of the fault is possible, but lateral juxtaposition of the two sides across the fault makes any relationship apparent until explored in the third dimension (right-lateral offset of ~2.5 m indicated by the channel offset). In Trench 5E Unit 4b is generally about 30 cm thick southwest of the fault and about 50 cm thick northeast of the fault. However, Unit 4b is also 30 cm thick over the channel maximum thickness in Trench 5D, which would most closely correspond to the Trench 5E exposure, so no significant erosion is required to match the sides.

The channel deposit (Unit 4bc) was thick on the southwestern side and truncated at the fault. Only a thin layer corresponding to the channel was mapped on the opposite side of the fault, and no where in Trench 5E were the thick channel deposits found on the northeastern side of the fault confirming the channel was offset by the fault and did not have an apparent offset because of a complication, such as a bend in the channel. The channel offset is tightly constrained and could only be bending over a 3-m reach in a way that increases the offset.

Unit 3 was distinguished in the box part of the trench, where it thickens on the relatively down-dropped side across the fault. The lower part of the deposit (Unit 3, ~30 cm thick) appears to be deformed by the fault, and it is overlain by a 40-cm-thick colluvial deposit (Unit 3a) that filled in against a fault scarp (PE2); this is similar as in Trench 5B that the PE2 event horizon is within Unit 3. Unit 2 thickens similar to Unit 3 across the fault (from ~40 cm to 50+ cm). The brown sandy silts of Unit 1 are about 20 to 50 cm thick and blanket the site with only local variations in thickness.

The main fault in Trench 5E is a reverse-right oblique-slip fault (F1). It is a discrete fault zone that splays into an asymmetric flower structure within Unit 4. The strike of the fault is N50°W, which trends a little more northerly than the overall fault indicating a left-stepping pattern. The apparent reverse offset of the base of Unit 4a is about 40 to 50 cm, which is accommodated by both discrete faulting and warping near the fault. Juxtaposition of units across the fault is consistent with a significant component of right-lateral strike-slip. The splay faults bound the zone and there is a splay through the central portion of the deforming wedge. The splay, which is slightly back-tilted near the top, actually has an apparent normal dip-slip offset, and probably most of the strike-slip displacement occurred along it, based on having the most mismatch of layers across it. Some injection of silts seems to have come out of this back-tilted fault splay and gone into Unit 4b in the hanging wall; this may be liquefaction venting through Fault F1 during PE3. Total lateral displacement of the fault near the base of the trench is probably 4 to 6 m (events PE4, PE3, and PE2), whereas the channel offset (Unit 4b-c deposits) is about 2.5 m right-lateral. PE1 dose not appear to have ruptured the surface at Trench 5E. The base of Unit 4bc is unfaulted across the projection of Fault F2 in the extension of Trench 5E, thus the channel offset during PE2 and PE3 was located along Fault F1.

Liquefaction of Unit 4b is evident in Trench 5E, including contorted bedding and injection features. Liquefaction is most severe near Fault F1 in Unit 4b, and was severe within the down-thrown side with contorted bedding and layer thickness variations. This liquefaction was caused by PE3. There is some older deformation in Unit 5c? near Fault F1 at the base of the trench, but it is uncertain whether this deformation is from faulting or contortion from liquefaction.

Trench 7

Trench 7 was excavated to expose the northeastern toe of the push-up mound Trench 1 (dePolo and Ramelli, 2004) was in and to look for additional evidence of PE1 and PE3; PE1 has small offsets and is difficult to locally define (e.g., PE1 was not distinctly identified in the Trench 5 complex), and PE3 occurred during a time of erosion (possibly earthquake induced) represented by an unconformity in most trench exposures. Only a short trench (11.8 m long) was dug across the main fault zone. Trench 7 had a maximum depth of 2.5 m and was oriented N22°E, perpendicular to the local fault, which strikes N65°W. At the Trench 7 site there is a sharp fault scarp at the edge of the push-up mound and a small flat on the buttressing side (down-thrown side). The log of Trench 7 is shown in Plate 6.

Older sediments of Unit 7 were exposed in the uplifted core southwest of the fault and on the down-dropped side. In the uplifted core the muds and sands were highly contorted, folded, and faulted; most of this deformation was pre-PE4 because Lake Lahontan sediments cover the core and have little deformation. A bulk of the structure and bedding in the uplifted core is tilted to the southwest. Unit 5b, the massive lacustrine deposit that blanketed the area following PE4, appears to have blanketed the uplift core at Trench 7 as well and filled a wedge on the back of this core, which was tilted by PE4 (maximum exposed thickness of Unit 5b is 60 cm). It is possible that some earlier lacustrine sediments were previously deposited on this core but have laterally spread off the titled block during PE4, as was observed in Trench 1. On the down-thrown side, Unit 5a was directly deposited on Unit 7, and subsequently eroded, deformed by faulting, and buried. These well-sorted sands with laminated bedding appear to thicken towards the fault (>90 cm thick), as in Trench 1, possibly filling a depression created in the northeast side of the fault from PE4.

Unit 4a appears to be a buttress deposit that covers a slight angular unconformity and thins towards the fault, probably against a relic fault scarp. This indicates that PE3 created a small fault scarp that Unit 4a was deposited against. Unit 4a is as much as 35 cm thick.

Greenish, clay rich Unit 3 also tapers to the southwest towards the fault as if it is buttressing a higher area and was not found over the push-up mound; Unit 3 is as much as 35 cm thick. A small wedge of sheared Unit 3 is caught up within the fault zone, faulted and sheared by PE2 and PE1.

A colluvial wedge (Unit 2b) was formed against the fault scarp created during PE2 (maximum thickness ~40 cm), which has subsequently been sheared by PE1. The entire trench site was blanketed by laminated silts, fine sands, and diatomaceous deposits of Unit 2, which are distinctly thicker on the northern side of the fault (as much as 60 cm thick). This in turn was blanketed by 10 to 40 cm of brown sandy silts of Unit 1.

Only the main fault zone (F1) was exposed in the trench, although deformation from other structures is likely in the uplifted core. The main fault is complex at Trench 7 because shearing is accompanied by thrusting. Faulting is distributed, with several faults in the zone, and the highest levels of discrete faulting is not aligned with the most recent fault traces near the bottom of the trench. The faulted colluvial wedge (Unit 2b) and the sheared wedge of Unit 3 are along secondary faults that show both apparent thrusting (Unit 7 thrust over Unit 5a), and apparent normal dip-slip (Unit 2b down-dropped against Unit 5a), likely caused by lateral juxtaposition. This part of the fault is connected to the deeper main fault by a vertical and slightly back-tilted fault trace, but may also be connected to faults in the uplifted core that are more directly aligned. Adjacent to the main fault within the core is a small anticline, that may be caused by drag folding from reverse dip-slip displacement. There is significant deformation within Unit 5a next to the main fault; the base of the unit is tectonically deformed, there are internal conjugate(?) shears aligned with faults, the edge of the unit is completely faulted against another deposit (i.e., completely truncated by faulting), and the unit is warped upwards next to the fault. This deformation would be from PE1, PE2, and PE3. During the last few earthquakes the ground was shifted laterally at Trench 7 and shortened with some thrusting. In this case the thrusting is caused by the irregularity in the fault zone that is creating the push-up mound at T1 and T7; the fault is crossing more westerly than its general trend and the push-up mound is overriding the adjacent ground a little. PE1 has good evidence in this trench; faults offset the colluvial wedge associated with PE2, similar to Trench 1.

The small fault scarp at Trench 7 is shifted slightly to the down-thrown side of the fault. The fault scarp was a broad feature to begin with, the dominant motion being lateral displacement. Simple blanketing of fault scarps by Units 1 and 2, combined with some minor surface micro-hydrological activity, probably explains the current location of this fault scarp. The fault scarp height (~30 cm) is diminished from the offset below indicated by Unit 2a (~60 cm scarp height) mostly due to burial by Units 1 and 2.

Summary of Fault Features

The trenches offer some insight into the surficial manifestation of a major strike-slip fault. Near surface fault traces are either vertical or dip to the southwest with a small reverse component, and commonly have well-developed, symmetric and asymmetric flower structure within their upper meter. Complete juxtaposition of older units across the main fault is commonly observed in the trenches. In younger faulted deposits some similar layers can be seen, but the thicknesses of units is commonly dissimilar. Surface expression of earthquake ruptures include small fault scarps as much as 60 cm high (created by both reverse and normal movement), open fissures, mole-tracks, and warps. Faulting both breached land forms or remained shallowly buried. The main fault zone is commonly about 1 m wide. There are some secondary faults, but most of these are in the hanging wall or over a tight left-stepping pattern with faults striking 6° to 11° more northerly than the local overall fault strike.

The result of the box trench was a relatively precise right-lateral offset measurement of a distinct, buried channel, clearly demonstrating the right-lateral component of the WSVFS, and giving an estimate of the size of single-event displacements at the Mid-Valley site. The channel was definitely the same one encountered in Trench 5C and Trench 5D based on a distinguishing grain size. The projection of the channel from these trenches into a vertical plane at the fault is shown in Figure 3. The channel spreads out a little on the down-thrown side, but a match between the central parts of the channel can be made. Some possible offset measurements are also shown in Figure 3. Based on the projection of the channel across the trenches (using both sides of the trench) and projecting to the fault in the field the best estimate of 2.5 ± 0.5 m right-lateral displacement was made. Trench 5E was excavated to test whether there were any bends in the channel that would diminish the offset, and no such bends were found. The vertical offset is ~1 ± 0.25 m, down-to-the-northeast displacement based on Figure 3. Net displacement at the site is therefore ~ 2.7 ± 0.5 m. This offset was created during PE2 and PE3. Thus, 2.7 ± 0.5 m divided by two gives the single-event displacement, 1.35 ± 0.5 m. This value is for the southern reach of the WSVFS, and may be a minimum.

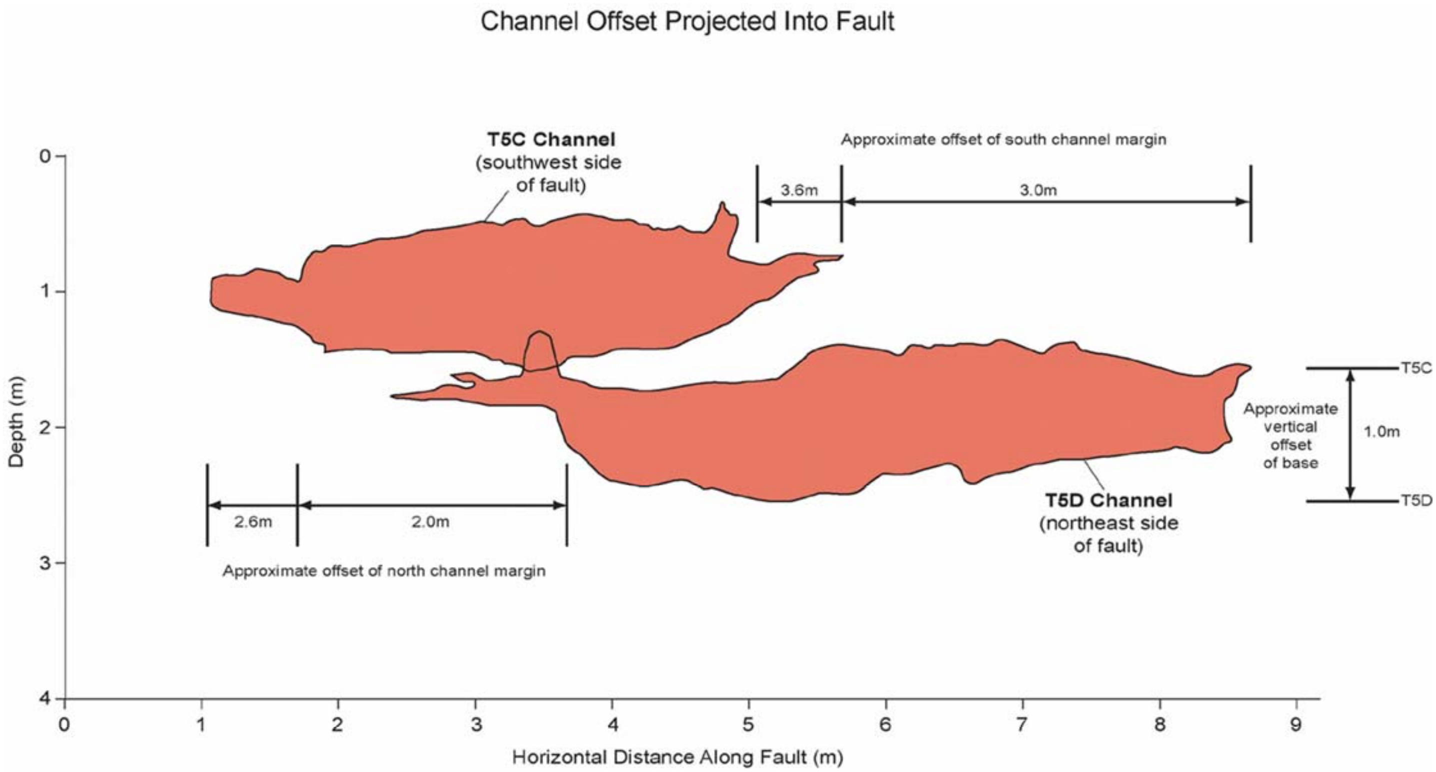


Figure 3. Offset stream channel cross-sections projected into a vertical view at the fault (view to the northeast, across the fault). The fault strike (plane of the paper) is N65°W. Cross-fault distance between the channel exposures is 5.7m. Right-lateral and vertical displacement is indicated by the difference in location of the channel on either side of the fault. Some offset measurement possibilities are indicated; the best estimate of the offset is 2.5±0.5m based on projections of the channel margins into the fault. Vertical offset is 1±0.25m based on this figure.

Overall, the trench exposures indicate the surficial features are undergoing some secondary contraction, coincident with the dominant right-lateral strike-slip motion. This is supported by reverse offsets along major faults, push-up mounds, and local entrenchment of stream channels (local uplift), and tilting of push-up blocks. There is significant warping on the hanging wall side of the fault that is contributing to the total offset of units. A general lack of secondary faults encountered in the trenches also indicate a slightly contracting surficial setting (e.g., lack of antithetic faults at the trench level). At and near the surface, the vertical principal stress direction approaches 0, and local thrusting at the surface trace is favored even with dominant strike-slip motion. So the contraction can be a local phenomenon, around the lip of the surface rupture (breaking up into push-up features), related to local fault interactions, or related to a deeper secondary component. Linear ridges and features are intermittent along the WSVFS, which could support more local fault effects are responsible for the contraction.

The fault traces encountered in the Trench 5 complex all had strikes that were more northerly than the overall fault trace by 6° to 11° indicating the fault traces are left-stepping echelon traces that are confined to the 6 m width of the "box" (no faults were encountered in Trenches 5C and 5D). This is consistent with the right-lateral strike-slip motion documented along the WSVFS.

Small fault scarps are found in all possible positions relative to the causative fault, on top or coincident with it (Trench 2 - not described in this study, see dePolo and Ramelli, 2004), in front of the fault (Trench 5B), or in the hanging behind the fault (Trench 5A). The main controlling factors were burial and coppice dune formation. Steady burial on both of the fault tends to build the scarp out into the footwall, whereas relatively rapid burial of the footwall, high relative deposition on the hanging wall, and/or coppice dune formation on the hanging wall all can cause the scarp to retreat into the hanging wall. In all cases, the fault was within approximately 1 m of the fault scarp.

A strategy employed in the general excavation at the Mid-Valley site is to trench push-up features with the hope that earlier fault activity would be exposed. This was most successful at Trench 1 (see dePolo and Ramelli, 2004), where the recent last five events were exposed on the faulted front of the mound, and three additional events were discovered in the uplifted core of the mound. The strategy in this study was to use the micro-geomorphology to approximate where paleo-stream channels were located, and this was successful. By understanding the history of the push-up features gained from trenching, a relatively tight, buried offset target was defined.

Paleoearthquakes along the Southern WSVFS

Paleoearthquake PE1

Evidence for PE1 includes shearing, small offsets, and possible warping of Unit 2 deposits, in particular involving a colluvial deposit related to PE2 (Trenches 1, 2, 7). PE1 is not evident in all trenches. It had a small, discontinuous surface rupture, and earlier, similar small events may not be recognized as distinct events. Offsets from PE1 in Trench 2 (not shown in this report) are in very young deposits that are among the highest in the section (Unit 1), lack soil development, may be related to a young fault scarp, and are likely late Holocene, perhaps within the last two thousand years. Maximum offsets measured were as much as 20 cm apparent vertical (normal?).

Paleoearthquake PE2

Faulting from PE2 created 20- to 60-cm-thick colluvial wedge deposits, indicating fault scarps of similar or larger heights were created. PE2 is evident in all trenches and lateral offset during it is attributed to half of the total right-lateral offset of the stream channel exposed in the box trench, approximately 1.25 m. There appeared to be tilting and warping of the push-up blocks from PE2, consistent with the large apparent vertical offsets. Vertical offsets from PE2 are apparent normal and apparent reverse indicating local control on these apparent vertical offsets. The colluvial deposits and the event appear to have occurred in early Holocene, because the event horizon is either near the top of Unit 3, or near the bottom of Unit 2 and includes eroded chunks of Unit 3. The lower part of Unit 3 is bulk radiocarbon dated at 10 ky to 13 ky cal bp (2 sigma, dendro-corrected range).

Tectonic depressions created by PE2 were wet areas and were filled with Unit 3. Where there was uplift and a scarp at Trenches 1, 5A and 7, colluvial deposits of Unit 2b or Unit 3 were formed.

Paleoearthquake PE3

The evidence for PE3 is entirely indirect or secondary; this is partly because the area was one of erosion, or erosion was induced at the site from an event. The event horizon is usually an unconformity (commonly an angular unconformity). The most visible evidence for PE3 is liquefaction which gets more contorted and with higher fold amplitudes adjacent to the fault in Trenches 5A, 5B, and 5E. In Trench 5E there is a silty injection area in the immediate hanging wall that indicates the main fault acted as a conduit for liquefaction. The next most distinct evidence is the angular unconformity on liquefied Unit 4b and overlain by Unit 4a in Trenches 5B and 5D.   In Trench 7 there appears to be a tilted angular unconformity on Unit 5a, which likely was tilted by PE3 (Unit 5a is post-PE4).   Unit 4a and Unit 3 appear to form tapering, buttress contacts as if they were filling against a fault scarp created by PE3. PE3 occurred between the high stand of Lake Lahontan and the early Holocene deposition of the green, clay-rich deposits of Unit 3, and appears to be latest Pleistocene (post ~ 15 ky bp).

Paleoearthquake PE4   (highstand event)

PE4 occurred during the highstand of latest Pleistocene Lake Lahontan, when the site was under about 30 m of water. This is supported by severe liquefaction, lateral spreading, and dating of lacustrine deposits. A fissure was created at the fault in Trench 1 and filled with massive lacustrine sand that blanketed the site and filled the tectonic fissure. Severe liquefaction from PE4 has been identified in Trenches 1 5C, and 5D.

The liquefied sand was dated using photo-stimulated luminescence (PSL) dating at 15.3 ± 4 kybp (2 sigma) which is consistent with other dating constraints of the highstand. Adams and Wesnousky (1998) have bracketed the highstand of Lake Lahontan with radiocarbon dates between 15,798 and 15,117 cal ybp (2 sigma).

Paleoearthquake PE5

A large fissure fill in Trench 1, subsequently fissured by PE4, is the primary evidence for PE5. Other evidence includes truncated faults and down-dropped blocks. This event appears to have occurred prior to the high stand of Lake Lahontan, and included small pieces of an Av horizon formed on an adjacent uplifted block at that time.

Paleoearthquake PE6

PE6 is recognized on a fault splay west of the main fault (Trench 1; dePolo and Ramelli, 2004), in the uplifted core of the push-up mound. Subaerial sands are faulted and caught up in a wedge. Subsequent erosion of a fault scarp created by PE6 created a colluvial/tectonic depression-fill deposit with interfingers of coarser material that eroded from the top of the fault scarp. These deposits are all older than, and are fissured by, PE5. Apparent reverse displacements during PE6 are 1.5 m.

Paleoearthquake PE7

A second truncated fault splay in the uplifted block of Trench 1 is capped by deposits that are faulted by PE6, and thus represents an older event. This event caused 1 to 2 m of apparent reverse displacement and well as assumed strike-slip motion. PE7 is younger than Unit 7, which is dated at about 21 ky bp.

Paleoearthquake PE8(?)

PE8(?) is the most unconstrained event, with an uncertain capping deposit that is faulted by PE7 in Trench 1. The uncertainty comes from both faults involved in PE7 and PE8? possibly moving during the same event, but this does not seem likely because the apparent offsets are large and of opposite apparent motion. The fault that PE8? occurred along has nearly 1.5 m of apparent normal dip-slip displacement, whereas offsets during PE7 include about the same amount of apparent reverse movement. An earthquake surface rupture that involved both of these faults would slide along one fault in contraction then switch to a second fault splay, change dip-slip motion, and relatively down-drop the geology which does not seem likely. With such large apparent offsets this double-splay earthquake would have been the largest observed with large lateral offsets. Even though the faulted capping deposit over the fault with PE8? along it is uncertain, it is probable and favored; this indicates two separate events, PE7 and PE8. PE8? is younger than Unit 7, which is dated at about 21 ky old.

Summary of Paleoearthquakes, Slip Rates, and Average Earthquake Recurrence Intervals

Along the southern portion of the WSVFS earthquakes have had variable interseismic intervals, which have recently increased in time. Another way of viewing this is to say we had a cluster of earthquakes in latest Pleistocene and only two events in Holocene (fig. 4). Slip rates are difficult to define at the Mid-Valley site, but a post-Lake Lahontan to earliest Holocene rate based on the offset buried channel is about 0.26 to 0.59 m/ky. This is a quarter to a half the apparent long-term rate of the WSVFS (~1 m/ky). The Holocene rate is even more dramatic: with an estimated 0.5 m offset during PE1 and an accumulation period of ~8 ky, a rate of 0.06 m/ky or 1/17 the long-term rate is calculated. With relatively high rates of geodetic strain and local paleoseismic events in the western Great Basin, it is unlikely the fault system has slowed down. It is more likely that a large earthquake or series of earthquakes along the WSVFS is geologically imminent.

This variation in earthquake occurrence can be illustrated by viewing the latest Pleistocene and Holocene periods. The bounding date ranges are 18 ky to 25 ky for the entire paleoseismic record, and 10 ky to 13 ky for the green clay-rich unit in the middle of the record, or approximately bounding the Holocene. Using the maximums and minimums of the dates, the oldest time period (~21 ky to ~ 12 ky bp) could be between 5 ky and 15 ky in duration. Five to six earthquakes occurred in the oldest time period and one to two occurred during the youngest time period (~12 ky bp to present). The youngest time period could be 10 ky to 13 ky in duration. In the youngest period two events could be placed such that they divide the 10 ky duration into thirds (~3 ky), or one event can be open ended. Using these data:

Time Period	~21 ky to ~12 ky bp	~12 ky bp to present
Average Earthquake Recurrence Interval	1.5 ky (0.8 - 3 ky)	6 ky (3 ky - >13 ky bp)

Paleoearthquake History of the Warm Springs Valley Fault System at the Mid-Valley Site

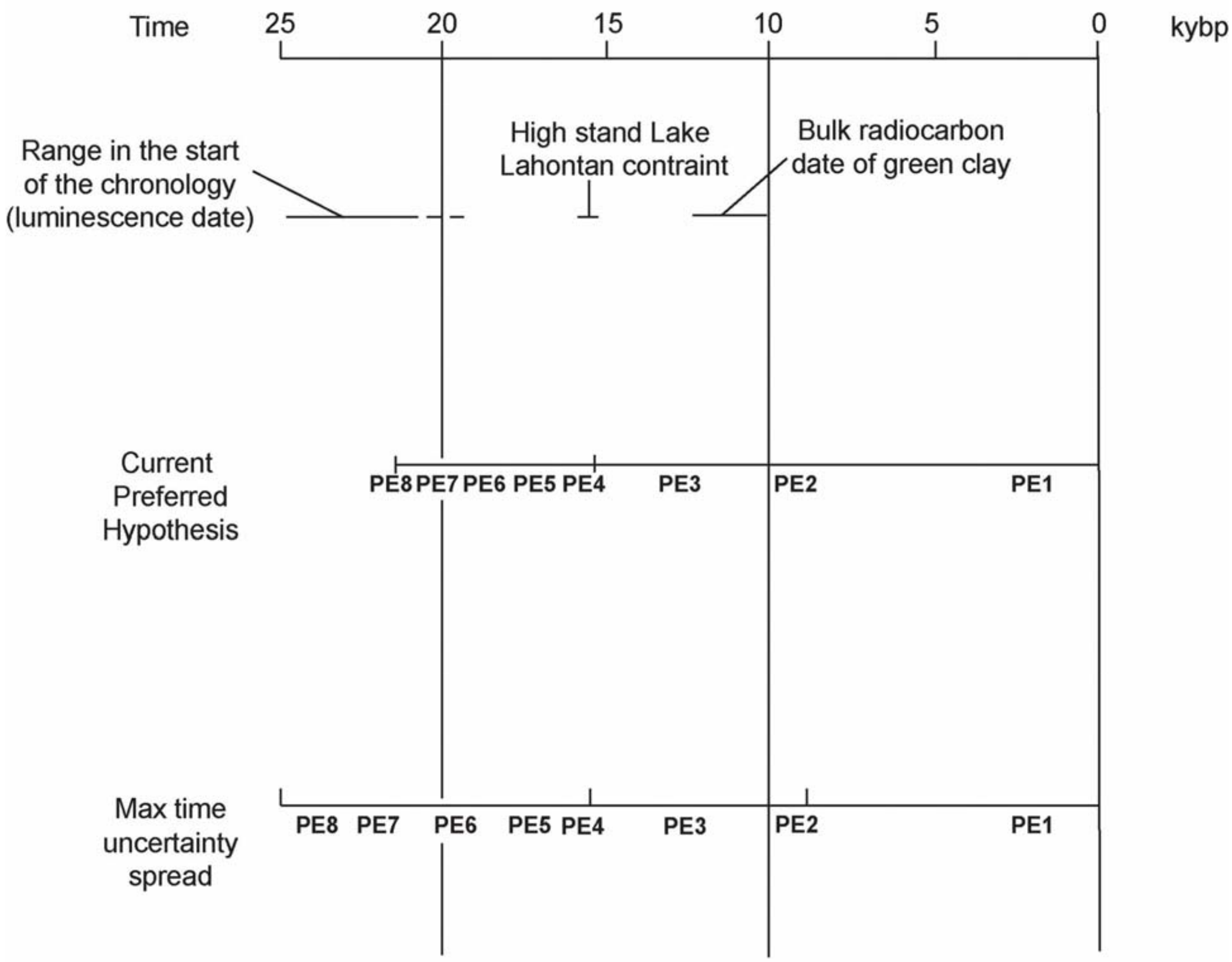


Figure 4. Two examples of the possible paleoearthquake history of the WSVFS at the Mid-Valley site. PE4 occurs during the high stand of Lake Lahontan and is an important constraint. A cluster of earthquakes occrred in latest Pleistocene, whereas a relatively low level of activity occurred in the Holocene.

Table 1 Paleoearthquake History at the Mid-Valley Site if the Warm Springs Valley Fault System

Paleo-earthquakes and Age	Event Horizon	Evidence for Paleoearthquake(vert., RL)	Estimated Displacement Estimate	Basis for Displace.	Style of Deform.
PE1 latest Holocene	unconf. on Unit 1b (T2)	sm. colluv. wedge, upward term. flts. (T2) shrd. deposits	av. - 20 cm	T2 - offsets meas. from log on F1	RL SS (?)
PE2 early Holocene	upper part Unit 3, lower part Unit 2 (T1, T5A, T5B)	colluv. wedge, flted. Unit 3, offset stream chan.	av. - 60 cm (T2); RL - ~1.25 m (T5 complex)	est. scarp height; est. stream chan. offset	NRL OS
PE3 < 15 ka & > 9 ka	unconf. on Unit 3b (T5B&D)	liquefaction, ang. unconf.; buttress depo. on scarp; fault silt ejecta.	RL - ~1.25 m	est. stream chan. offset	NRL OS
PE4 ~ 15 ka (high stand)	unconf. on Unit 5C, fissure fill (T1)	liquefaction, ang. unconf., fissure fill, tilted block	av. - ~ 50 cm	offset deposits	NRL OS
PE5 < 21 ka & > 15 ka	fissure fill (T1)	fissure fill	???	???	RL SS(?)
PE6 < 21 ka & > 15 ka	buried fault scarp, unconf. within Unit 6 (T1)	offset & shrd. deps., colluv. deposits, upward term. flts	av. - ~1.5 m	min. vert. offset of deposits	RRL OS
PE7 < 21 ka & > 15 ka (T1)	unconf. on faulted wedge with Unit 8	upward term. flt	av. - ~1 to 2 (?) m	~ offset deposits	RRL OS (?)
PE8 (?) < 21 ka & > 15 ka	unconf. on top(?) of Unit 7 (T1)	offset deposit, buttressed Unit 6(?) sm. wedge	av. - 1.5 m	offset deposits	NRL OS

The geomorphology of the push-up mound that Trenches 1 and 7 are in has some micro-surface in it that consistent with two to three earthquakes (although the mound has be active at least since PE4). The detailed topographic map of the site (fig. 2) shows two distinct surfaces on the mound, a northwestern half that is 20 to 25 cm higher than the surrounding area and the other half that is about 10 to 15 cm higher than that. Because PE1 had limited offset, the lower surface was probably isolated by PE2 and the higher surface by PE3.

Fault Slip Rate Studies

The north-central portion of the WSVFS was explored for evidence of Holocene offsets, offsets of the high shoreline of Lake Lahontan, and estimates of fault slip rates. The main trace of the WSVFS at the southern margin of Honey Lake Valley was explored using aerial reconnaissance and examination of aerial photography. At this southern margin there is a potential (but equivocal) offset of the highstand shoreline, an offset alluvial fan, and prominent geomorphic expression of strike-slip faulting. Several field reconnaissance trips were made resulting in these preliminary observations. They are preliminary because no detailed maps or detailed descriptions of deposits were made, and no specific dates collected.

Holocene offsets

At least two sites were found with probable evidence of Holocene offset. These are along the set of offset hills along the fault immediately south of Honey Lake Valley. One site is on the eastern side of the two southern hills (there are three hills total). At this site there is a sidehill fault scarp with an offset of about ½ m high along the side of the hill that appears as a relatively unvegetated scar. This offset is caused by movement along a secondary fault splaying from the main fault trace. The freshness of the scar indicates it is late Holocene.

The second site is immediately north of the northernmost hill. Here the main fault forms a small graben and there are two small fault scarps in a row, each about ½ m high. The freshness of the scarps and youthfulness of the materials they are formed in indicates a Holocene age. There are some other small scarps along this reach of the fault that are likely Holocene as well, but they are not as definitively so.

Possible offset of shoreline from the highstand of Lake Lahontan

Only in one site along the main fault is there a possible offset of the high shore line (~15 ka). This is where the fault enters from the south into Honey Lake Valley (see fig. 5 where the fault intersects the high shoreline). Unfortunately this offset is equivocal. A shoreline scarp can be seen at a small reentrant where the fault projects down a gully in a latest Pleistocene deposit. This shoreline scarp may be offset as much as 3 m right-laterally, but the offset is not definitive and alternatively could be an irregularity in the shoreline scarp. The site is an opportunity for further study, however. To prove this offset the shoreline scarp and outboard lacustrine deposits could be trenched to look for faults that would cause the offset. A box trench would be useful to measure the offset of the shoreline angle, but the materials are bouldery. Prior to trenching, the site should be surveyed in detail, because the trenching would wipe out the small scarp.

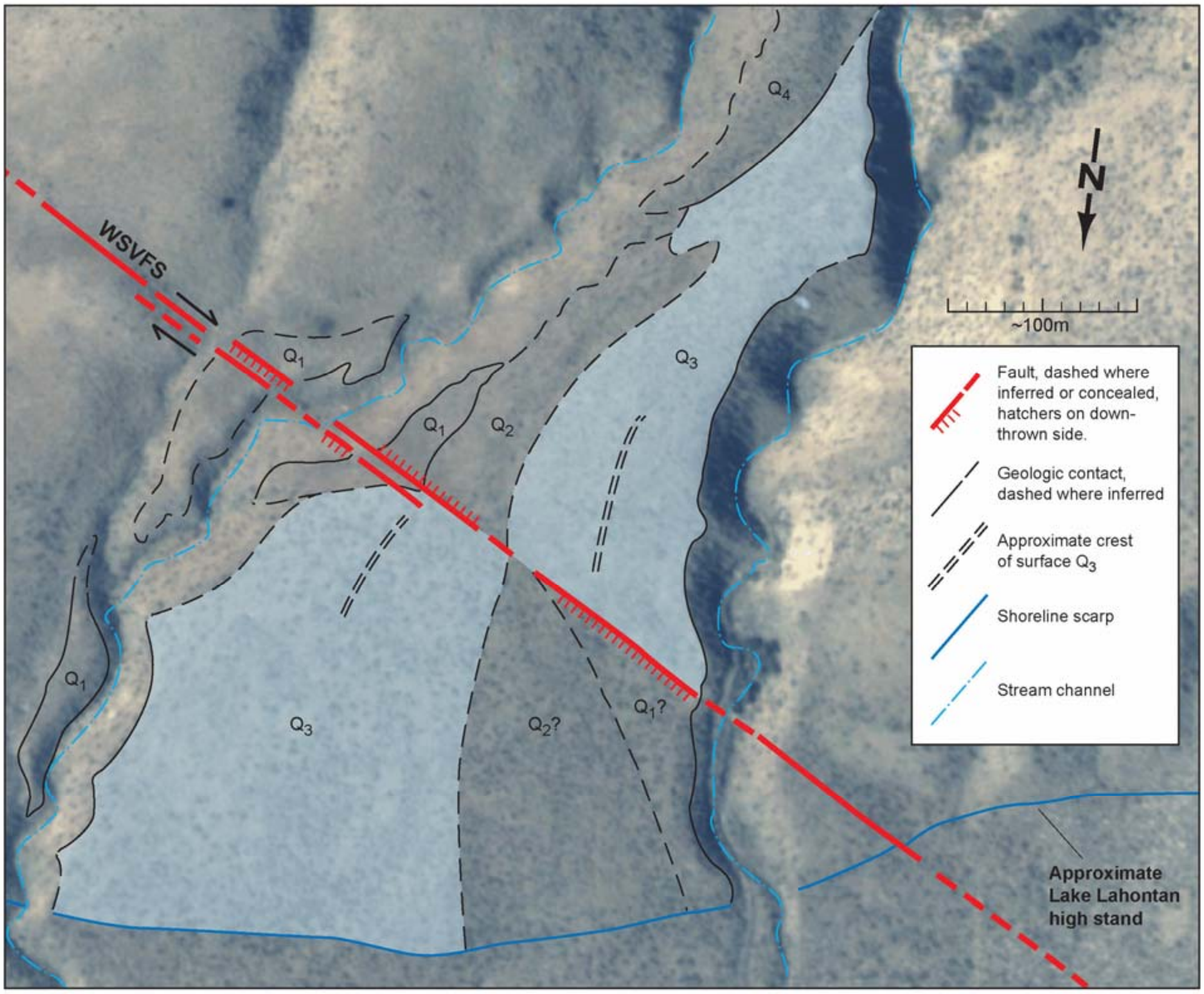
Fault Slip Rates (offset alluvial fan surface)

A debris flow-dominated fan immediately south of Honey Lake Valley (40^o 3.839' N Lat., 119^o 59.535' W Long.) is clearly offset right-laterally, and examination of the entire portion of the WSVFS in Nevada indicates it is the best case of an offset fan. The older part of the fan, which makes up most of the fan, is the surface examined. The right-lateral offset is indicated by an offset crest and margins of the surface, and alternating relative down-thrown sides of scarps across the fan that are consistent with the offset of the fan deposit (fig. 5). In Figure 5 three groups of deposits/surfaces were defined based on aerial photographic mapping and a reconnaissance field visit. The crest of unit Q3 was identified in the field.

The measurement of the offset was made using the approximate crest of the surface and a 50-m measuring tape along the fault. Offsets of the margins of the deposit yield similar results, but have been eroded and had more uncertainty. The crest of the surface is preserved and could be approximated within several meters. The measured offset is 95 m right-laterally with an estimated uncertainty of +15 m and -11 m. Thus, the preferred right-lateral offset is 95 m, the maximum offset is 110 m, and the minimum offset is 84 m. Although these measurements were made carefully, they should be considered preliminary. More exploration of this offset alluvial fan are warranted, mapping the fan more carefully, constructing a micro-topographic surface of the fan to reconstruct fault offsets, and dating different parts of the fan. A small complication for future research is that half of the fan and fault is on multiple private-land owners property. Some evidence was collected on this fan that might support progressive offset of younger surfaces but these observations and data need more work to be understood and reported.

The approximate age of the deposit is estimated based on the surface morphology of the deposit, its relative position, the depositional style, and preliminary observations of the soil formed on the deposit. Many boulders are scattered on the surface with some filling between them of eolian silt and reworked fines. Only crude, relict bar forms may remain with most of the original bar-and-swale topography totally smoothed. Some surface boulders are slightly wind scalloped, but most are relatively uneroded. The deposit is the highest on the fan, and has younger terraces cut into or buttressed into it. The deposit appears to be dominated by coarse debris flows, commonly formed during interglacial periods. Parts of the soil formed in the deposit were observed in stream cuts near the apex of the fan. This is not an optimum place to observe a soil for judging time because the A horizon is cumulate in nature and is expanding the soil horizon with time. Well-drained grusy deposits also may allow precipitation to move further down in the deposit than usual complicating the calcic horizon formation. Also the site is near the aridisol and

Figure 5. Sketch map of a fan offset along the north-central Warm Springs Valley Fault System



mollisol boundary, so soils aren’t as distinct. Here the deposit is dominated by granitic rocks. There is a brown, loose silty sand cap as much as 50 cm thick (probably largely eolian). This overlies a colored B horizon in grusy material with small to medium granular structure, with weak, discontinuous clay films covering some of the clasts and some clay bridges between clasts. The colored B horizon is approximately 30 to 40 cm thick where observed. Below this was only slightly altered grusy material (~C horizon). Taken together, it seems likely the deposit is Sangamon in age or about 80 to 130 ky. The maximum age estimate for this surface is about 300 ky, and the minimum age estimate is 50 ky.

The preferred right-lateral fault slip rate of the WSVFS based on the offset of the older surface is 0.7 to 1.2 m/ky, the minimum fault slip rate is 0.3 m/ky, and the maximum fault slip rate is 2.2 m/ky. An independent long term rate for the WSVFS can be estimated by using a 10 to 15 km right-lateral offset of a Miocene stream channel (Faulds and others, 2005) and a 3.6 to 6 My time frame for the offset (Henry and others, 2002). This yields a long term, right-lateral rate of 1.7 to 4.2 m/ky. The younger rates estimated here are significantly lower than the long term rates, but the maximum younger rate is within the long term range. The long term geologic rate measures across the entire system, so other, unmeasured parallel fault strands could also make up some of this difference. In a more extreme possibility, the crest correlation could be wrong and more Q3 deposit has been eroded away by the eastern stream, thus, offsets and slip rates would be larger. The fault may have also slowed down some or become more inefficient. Nevertheless, the younger rates (0.7 to 1.2 m/ky) are relatively large and make the WSVFS one of the five most active faults in western Nevada.

Earthquake Potential along the WSVFS

The sizes of potential earthquakes along the WSVFS are estimated using fault length, fault area, and single-event fault displacement. Earthquake magnitude versus fault length or fault area are traditional correlations used in estimating the potential sizes of earthquakes that can occur along a fault. In the case of the WSVFS, earthquake segments that can be used in these correlations have been hard to define because of structural connectivity and a lack of spatially distributed paleoseismic data. There are sections of the fault with different geomorphic expressions, but this is primarily due to the different environments the system crosses (e.g., basin floor, alluvial fan, bedrock). There is a large pull-apart basin in the Virginia Mountains (5-6 km long) and a bend in the mid part of the system that can be considered as potential segment boundaries. Things are further complicated by having a poorly defined northern section of the system. The total length of the WSVFS is 96 km, and a half length is 48 km. Using the major pull-apart basin in the central part of the system, the northern segment would be 50 to 57 km long (fig. 6). Additionally considering the bend in the system the southern segment would be 38 to 46 km long (38 km is the distance from the southern end to the bend and 46 km is the distance from the southern end to the pull-apart basin). These potential earthquake segments are shown in Figure 6. The bend in the system is slight (~6^{o}) and, for ruptures propagating up from the south, would be dynamically contractional and might tend to transfer a rupture through the bend (King and Nabelek, 1985).

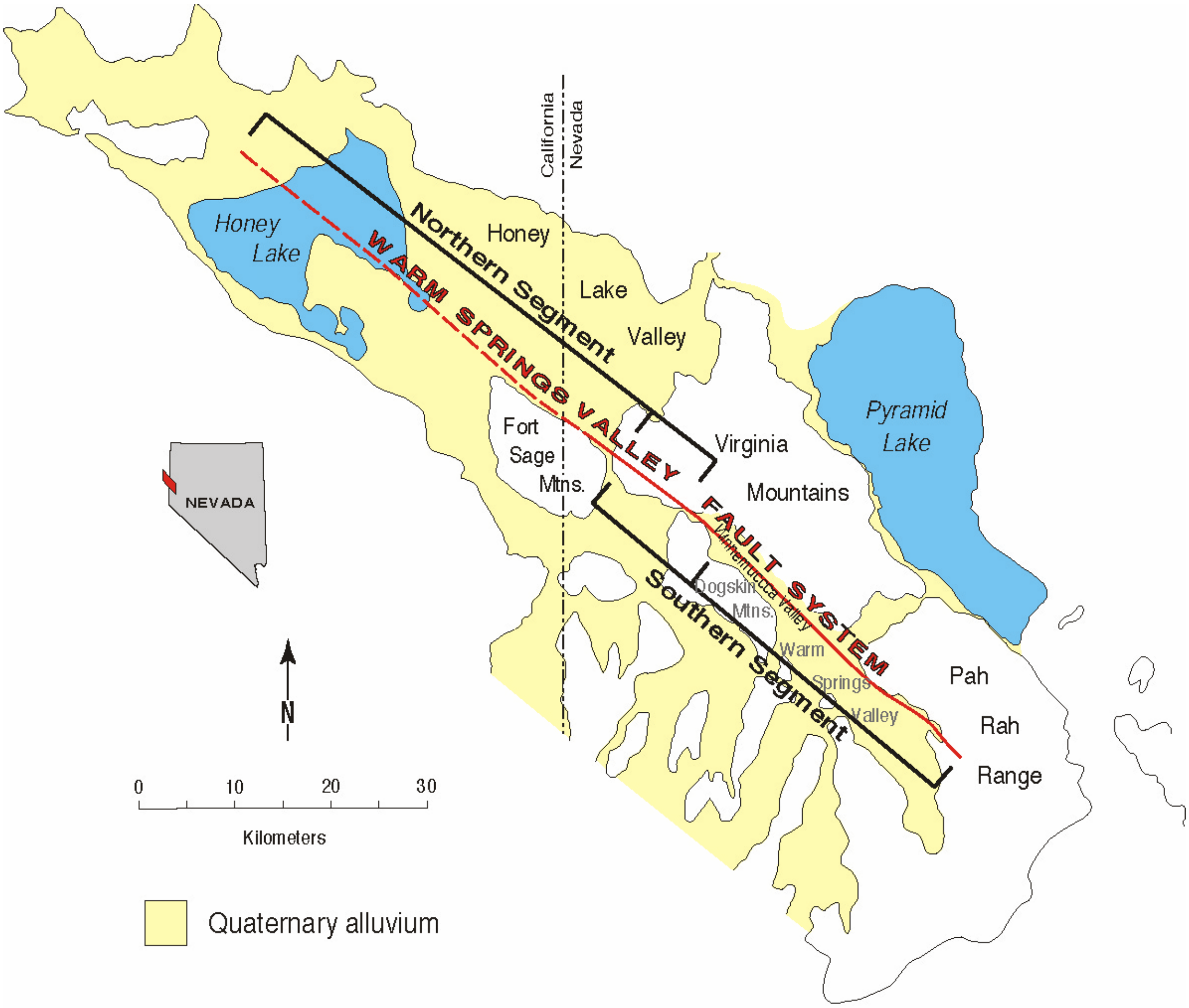


Figure 6. Possible earthquake segmentation model for the WSVFS. The main segmentation boundary is the Virginia Mountains pull-apart basin.

Thus, the bend is less likely to be a earthquake segment barrier if the rupture propagates from the south.

An earthquake can nucleate at the bend, however, and propagate to the south (38 km). Although it is not thought likely that the entire system would rupture during a single earthquake, at this point, there is nothing indicating it couldn't. The pull-apart basin that is used for a segment boundary does have faults that bypass it. The total fault system rupture serves mostly as an end member or bounding event on a distribution of possibilities that exist for the WSVFS.

Moment magnitudes are estimated using relationships from Wells and Coppersmith (1994) and Hanks and Bakun (2002), and are shown in Table 2. The reference number indicates in Table 3 which relationship is used.

Fault area is used as a check for the potential bi-linear relationship in magnitude versus rupture length (Hanks and Bakun, 2002). There is a concern that the commonly used Wells and Coppersmith (1994) relationship for magnitude versus length underestimates the magnitudes for long strike-slip faults (Hanks and Bakun, 2002). The total length and half length of the system were used as a test of whether this consideration is important for the WSVFS. Fault area was calculated using an assumed seismogenic depth of 15 km. These areas were used with Hanks and Bakun's (2002) relationship to estimate a moment magnitude. The values (Table 3) are comparable to those obtained for the same input length values using the Wells and Coppersmith (1994) relationship, therefore this concern is not important for the WSVFS.

There are some single-event displacements derived from the box trench that can be used to scale potential earthquake size. The estimate of single-event displacement from PE2 and PE3 is 1.35 ± 0.5 m (0.85 m to 1.85 m). Estimates based on these displacements are limited to the southern WSVFS, and may be minimums because it is not known how representative they are, or whether there might be additional, undiscovered displacement on buried parallel fault traces.

The WSVFS can have large earthquakes (M6.9 to 7.3), although the last three events along the southern part of the system may have been on the low side of this range. Other paleoearthquakes appear to have been larger, however, and the Mid-Valley site may not represent possible larger displacements to the north, leading to potential underestimations of magnitude. More research and paleoseismic data are needed to understand the earthquake segmentation of the WSVFS. For now, the Virginia Mountains pull-apart basin is the most important feature along the system for consideration as a potential segment boundary. The magnitudes estimated for the southern segment (M7.0) and the northern segment (M7.1) are considered the best estimates of the maximum earthquake for the WSVFS. The most recent earthquake at the Mid-Valley site (PE1) was the smallest event identified, in terms of observed displacement and continuity of offset. The event was likely a mid-magnitude 6 event, around or just above the threshold of surface faulting (~M6.5 - dePolo, 1994). It is important to note that although PE1 is the only small event in the Holocene, additional small events could occur in latest Pleistocene and escape detection because of overprinting by subsequent, larger earthquakes. The largest earthquake that might be considered for the WSVFS is a M7.3, and the distribution of events ranges down to M6.5

(approximate magnitude of PE1?). It is not clear how "characteristic" the WSVFS is, but there are some event-to-event similarities for groups of events.

Potential displacements along the WSVFS are ≥1.35 m right-lateral displacement for the southern segment and probably even larger values for the longer northern segment. Reverse dip-slip displacements of 0.5 to 1 m have been observed; these reverse displacements occur locally, near push-up features. Specific trenching is needed to determine local dip-slip potential.

Table 2
Relationships Used for Estimating Potential Earthquake Magnitudes (strike-slip faults)

Ref. #	Reference	Scaling Relationship
1.	Wells and Coppersmith (1994)	Mw = 5.08 + 1.16 log L
2.	Wells and Coppersmith (1994)	Mw = 6.69 + 0.79 log D
3.	Hanks and Bakun (2002)	Mw = 4/3 log A + 3.07 ± 0.04, A > 537 km^2

Table 3
Estimated Earthquake Magnitudes for the WSVFS

Fault Length

Fault Length	Relation Ref. #	Estimated Magnitude
96 km total length	1	M7.3
48 km half length	1	M7.0
38-46 km S. section	1	M6.9-7.0
50-57 km N. section	1	M7.1

Fault Area

Fault Area	Relation Ref. #	Estimated Magnitude
720 km^2 (48 km)	3	M6.9
1,440 km^2 (96 km)	3	M7.3

Single-Event Displacement

Fault Displacement	Relation Ref. #	Estimated Magnitude
1.35 m (PE2 & PE3)	2	M6.8
1.85 m (max. value)	2	M6.9
0.85 m (min. value)	2	M6.6

Conclusions

This project successfully explored a buried, right-laterally offset channel and a right-laterally offset alluvial fan surface along the WSVFS. The offset channel was exposed with a box trench and found to have 2.5 ± 0.5 m right-lateral displacement, attributable to two or three paleoearthquakes; only two of these earthquakes has coseismic evidence at the Trench 5 complex and offsets per event are assumed to be 2.5 divided by 2, or 1¼ m per event. The youngest event (PE1) is the smallest observed and is documented at other trenches (1, 2, and 7).

Eight probable paleoseismic events are identified at the Mid-Valley site, all since a luminescence date of 21 ± 4 kyr (2 sigma). Only two of these eight events are since a radiocarbon date of 9,950 - 12,942 ^{14}C cal bp (2 sigma), whereas, five to six events occurred between ~21 and ~10 ky bp. Thus, earthquake activity has been significantly less in the Holocene than in the latest Pleistocene. This brings up the question, did earthquake activity (potential) recently dramatically decrease along the WSVFS to 25% of what it was, or is the system ripe for an earthquake?

At the Fort Sage Mountain site an alluvial deposit with an estimated age of Sangamon (80 to 130 ka) is offset about 95 m right laterally (+15 m, - 11 m). Preliminary observations on an alluvial fan indicate a preferred right-lateral strike-slip rate of 0.7 to 1.2 m/ky, or about 1 m/ky. The estimated minimum rate is 0.3 m/ky and the maximum rate is 2.2 m/ky. All of these rates are minimums for the WSVFS because they are developed along only one strand of the system, albeit it is the main strand. Other strands and faults need to be examined before the total slip rate of the system is known. Whether the lateral offset of the Lake Lahontan high shoreline exists is equivocal, but if it is displaced, it could be offset as much as ~3 m right-laterally based on visual ground inspection.

Potential earthquake magnitudes along the WSVFS range from M6.5 to M7.3 (moment magnitudes), and the most likely maximum earthquake along the system is M6.9 to M7.1. The preferred, recent average earthquake recurrence interval is 6 ky, with maximum and minimum intervals of >13 ky to 3 ky, but we are likely much closer to the next earthquake along the southern WSVFS than these values would imply. This is because geomorphic expression indicates a long-term, relatively high slip rate, and geodetic measurements show there are local high levels of lateral strain.

Further research is needed to successfully define earthquake segments along the WSVFS. A late Holocene offset occurs at both the Mid-Valley site and the Fort Sage Mountains site, and there could be a correlative early Holocene event as well. Correlation of any of the older events is totally unknown and paleoseismic trenching is needed at the Fort Sage Mountains to explore the probability of continuity during earthquakes. Research into the paleoseismology of the Honey Lake Valley section of the WSVFS is also needed. For now, an unconstrained spectrum of earthquake segmentation models exists for the WSVFS. An unsegmented earthquake along the entire fault is possible, but a two or three segment model seems more likely to jibe with the ≥1.35 m single-event, right-lateral oblique displacement.
The WSVFS could have a major earthquake today or tomorrow, it would be no scientific

surprise. That the fault has had a cluster of events is not unusual. But several lines of reasoning indicate the WSVFS is a robust, active fault system, but through most of Holocene no large events have occurred (only a small event within the last few thousand years). If the slip rate of the WSVFS is 1 m/ky for the WSVFS, then we are "overdue" for an event (over the last ~10 ky, PE2=1.25 m + PE1=0.5? m = 1.75 m versus an accumulated displacement potential of 10 m). Did the WSVFS slow down? Or are we overdue for an earthquake?

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