Correlations between earthquake recurrence and paleolake changes in Surprise Valley, CA

Brian Marion

Master’s Thesis Proposal
**Introduction and Purpose**

Evaluating seismic hazard and fault activity in a region with a low strain rate is challenging, largely because the earthquake recurrence interval exceeds historical seismicity records. The northwestern Basin and Range (NWBR) (Figs. 1 & 2) is one such region. Surprise Valley in the NWBR (Fig. 3) is bound by the Surprise Valley fault (SVF), an active normal fault with at least five earthquakes of M 6.8-7.3 since 35 ka and an irregular recurrence interval (Personius et al., 2009). Surprise Valley also hosted a pluvial lake (Fig. 2) that reached its highstand ~15 ka (Ibarra et al., 2014); additional dated paleoshorelines constrain the lake level history over the last 25 ky. These two datasets, in combination with high resolution topography, allow us to ask the following questions:

- How are earthquakes and slip distributed along the SVF?
- How do earthquakes and slip change over time?
- What role, if any, has pluvial Lake Surprise played on the spatial and temporal variations of slip along the SVF?

Both the filling of reservoirs (Bell and Nur, 1978; Gupta, 2002) and removal of pluvial lakes (Oldow and Singleton, 2008; Weldon, 2009) have been shown to induce earthquakes. In the Summer Lake basin (Fig. 2), an earthquake cluster correlates with rapid removal of Lake Chewaucan (Weldon, 2009), and seismogenic landslides were facilitated by the heightened water table associated with the lake (Badger and Watters, 2004). It is this rapid change in water volume, both an increase and decrease that can alter the stress environment, through a combination of the change in stress state, change in pore fluid pressure in saturated rocks, raising of the water table, and lubrication of the faults, to induce seismicity. During Lake Surprise’s highstand, it had a volume of 218 km$^3$, which equates to an increased load on the bedrock and
underlying faults (Ibarra et al., 2014). The irregular earthquake recurrence interval determined by Personius et al. (2009) may be explained with the equally variable changes in lake level for Lake Surprise during the Pleistocene. Overlaying the information provided in Personius et al. (2009) with Ibarra et al. (2014)’s lake level history suggests a potential correlation: a cluster of earthquakes occurs at the same time as a rapid decrease in lake level (Figs. 4 & 5).

Additional research is needed to substantiate and quantify this initial correlation. In order to further explore this correlation and address my research questions, I will

1. Document offset of paleoshorelines across the SVF through lidar-based mapping;
2. Correlate lake level history with earthquakes;
3. Obtain radiocarbon dates on paleoshoreline tufas;
4. Determine how offset and slip rate vary along strike of the SVF.

Background and Significance

Tectonic Setting

The Basin and Range extensional province (Fig. 1) contains hundreds of north-trending ranges and adjacent basins formed primarily by normal faulting in the late Tertiary and Quaternary (Wallace, 1984). It is bordered on the west by the Sierra Nevada and on the east by the Wasatch Fault zone and the Colorado Plateau (Fig. 1). The northwestern portion of the province spans the borders of California, Nevada, and Oregon (Figs. 1 & 2); normal faults in this region have been active since at least 12 Ma (Colgan et al., 2006; Henry and Perkins, 2001; Lerch et al., 2008). It is a low-strain region (Kreemer et al., 2012) that has accommodated only about 15% extension since 15 Ma (Egger and Miller, 2011), yet it has been shown to be capable of producing large earthquakes, along the SVF specifically, over the last 35 ka (Personius et al., 2009).
The NWBR also hosted numerous pluvial lakes over the last 2 my (Fig. 2) and valleys have recorded the most recent pluvial lake formation from the Last Glacial Maximum (Fig. 2); the majority of lake highstands in this region occurred between 15 and 18 ka (Ibarra et al., 2014; Mifflin and Wheat, 1979; Reheis, 1999). The shorelines formed during ancient lake-level stillstands and exhibit both erosional and depositional geomorphic features (Reheis, 1999). Wave-cut terraces are the most prevalent and are exposed discontinuously around the basins. These shorelines are then cut by faults and provide a record of the complex interaction between fault displacement and lake-level changes.

**Surprise Valley**

Surprise Valley is a N-S trending valley (Fig. 3) formed as a result of extension since the mid-Miocene. It is bounded by normal faults along the range fronts of the Warner Range to the west and the smaller Hays Canyon Range to the east; the SVF and the Hays Canyon fault (HCF) respectively (Egger, 2014; Egger and Miller, 2011). Playas in the upper, middle and lower sub-basins (Fig. 3) occupy the valley floor, which is estimated to be filled with 1-2 km of Tertiary and Quaternary basin sediments (Lerch et al., 2010). Numerous fault scarps line the western side of the valley (Fig. 3). These were initially mapped by Hedel (1980); Bryant (1990) reevaluated this initial effort and removed several features determined to be paleoshoreline features. More recently, Egger (2014) made use of high-resolution LiDAR (1 point per 0.5 m²) data to produce a more detailed map of scarps and Quaternary deposits along the SVF. Scarps along 64 km of the SVF demonstrate that surface offset of measured scarps ranges from 0.8-22.2 m (Egger, 2014). At least 38 scarps preserve geomorphic evidence for multiple events, with apparent surface offsets limited to 0.6-4.9 m per event. Estimates of the magnitude of the most recent event documented in the scarps is 7.0-7.3 (Egger, 2014). Paleoseismic trenching along the SVF reveals
at least 5 earthquakes M 6.8–7.3 have occurred in the last 35 ka (Figs. 4 & 5), with a recurrence interval of 4.2 ± 4.7 ka (Personius et al., 2009). The late Holocene slip rate has been calculated as 0.6 ± 0.1 mm/yr (Personius et al. 2009).

Along the eastern side of Surprise Valley, shoreline features (Fig. 6) are eroded into bedrock that consists of mid to late Cenozoic rhyolite, basalt, and tuff units (Carmichael et al., 2006; Egger and Miller, 2011). Laminated shoreline tufa on exposed bedrock is abundant on several shorelines between 1420 and 1450 m of elevation (Ibarra et al., 2014). Ibarra et al. (2014) determined a paleolake history by collecting surficial deposits of organic carbonates, or tufas along specific shorelines, and dated them using accelerator mass spectrometer (AMS) radiocarbon ($^{14}$C) geochronology. These dates demonstrate a range of the oldest at ~22 ka with the lake highstand at ~15 ka, and a steady, rapid decline of lake level to roughly ~5 ka (Fig. 5) (Ibarra et al., 2014). These new data of paleoshoreline ages offer an opportunity to refine the estimate of Holocene (and perhaps Quaternary) slip rate along the SVF. Figure 5 suggests that the uncertainty in earthquake recurrence interval is a reflection of the highly irregular time in between the last five major earthquake events, and the fact that three are clustered near the rapid removal of the lake, is similar to the study along the Ana River fault by Weldon (2009).

Fault Segmentation

Surprise Valley has apparent fault segmentation along the SVF. Evidence for this segmentation exists from the fact that the last major earthquake recorded along the SVF ruptured ~42 km of the 95 km long fault and I expect this to be characteristic of the faults rupture behavior. In addition, the fault scarps along the western side of the valley have a tendency to extend out into the basin, before jumping to the north-west to the next set of fault scarps (Fig. 4).
This step-over behavior could be defining structural boundaries that could define fault segmentations.

Fault segmentation is commonly used to estimate the potential earthquake size. Segment boundaries play an important role in arresting earthquake ruptures from event to event (Zhang et al., 1999). In the Basin and Range Province, earthquake rupture terminations are commonly associated with structural discontinuities, but not all-structural discontinuities have the capability to terminate an earthquake rupture. Multiple fault ruptures have had their geometric pattern studied after a major historic earthquake such as 1915 Pleasant Valley (Fig. 7), 1872 Owens Valley, 1954 Fairview Peak and Dixie Valley earthquakes (Zhang et al., 1999). These studies have suggested three important relationships between rupture termination and size of structural discontinuities (Zhang et al., 1999):

- Terminations of normal faulting earthquakes are often associated with structural discontinuities.
- The sizes of structural discontinuities at the end of earthquake rupture zones are generally the largest among the structural discontinuities within the rupture zone.
- There appears to be a trend that larger earthquake ruptures are stopped by larger structural discontinuities.

Along the SVF, the last major earthquake ruptured only ~42 km of the 95 km long fault, based on interpretations of the smallest offsets that are preserved in active alluvial fans (Egger, 2014). If this event is characteristic of typical earthquakes that occur along the SVF, the fault may contain structural boundaries that I can infer in this study based on my findings of how earthquakes and slip vary along strike of the SVF.
Connections between Earthquakes and Lakes

Caskey and Ramelli (2004) examined shoreline features formed by the late Pleistocene pluvial Lake Dixie in Dixie Valley, central Nevada, that record crustal deformation resulting from isostatic rebound of the Lake Lahontan basin and from Holocene and historic surface faulting. Constructional beach bars on the east side of Dixie Valley show eastward tilt of 0.16 m/km, indicating that lithospheric flexure due to isostatic rebound is symmetrical with the west side of the Lahontan basin (Caskey and Ramelli, 2004). Pleistocene Lake Bonneville records crustal deformation as a result of isostatic rebound as first noted by Gilbert, (1890) and refined and built upon by Crittenden Jr. (1963) and Nakiboglu and Lambeck (1983). This idea doesn’t fit well with smaller Pleistocene lakes like Lake Surprise, Alvord, and Chewaucan as the weight of the water that filled these basins is significantly less than the weight of Bonneville and Lahontan basins.

The triggering of earthquakes by filling of artificial reservoirs has been known about for over seven decades (Gupta, 2002). Bell and Nur (1978) identify the main effects of reservoir loading relevant to triggering of earthquakes:

- Elastic stress increase that follows the filling of the reservoir.
- Increase in pore fluid pressure in saturated rocks, due to decrease in pore volume caused by compaction, in response to elastic stress increase.
- In areas where the water table is low prior to impoundment of the reservoir, the flow of water from the reservoir into unsaturated strata and thereby raising the groundwater table.
- Viscous fluids can lubricate a fault zone to reduce the frictional stress during an earthquake by as much as 50% relative to dry rock friction (Brodsky and Kanamori, 2001).
Less research has addressed the effect of the removal of pluvial lakes on seismicity. Pluvial lakes fill and recede on relatively short timescales (on the order of $10^4$ yrs) in comparison with the tectonic environments around them, which can operate on the order of $10^6$ yrs—the Basin and Range specifically has been actively faulting for 18-16 Ma (Dilek and Moores, 1999); potentially affecting seismicity through changes in stress regime, pore pressure, water tables, and fault lubrication.

In the NWBR, paleoseismic data on the Ana River fault in Summer Lake Basin (Fig. 2) document a cluster of three ~M7.0 earthquakes in the past 7-13 ka, three times the number expected from the average recurrence interval over the previous ~70 ka when the fault was under the lake (Weldon, 2009). In addition, gigantic landslides (Fig. 8) cubic kilometers in volume scallop the southwestern part of the escarpment, and the deposits run out several kilometers, characteristic of rock avalanches (Badger and Watters, 2004). Geotechnical rock-mass characterization and slope-stability analyses confirm observations that these landslides were initiated within the weak tuffaceous sedimentary rocks along shallow, east-dipping, planar failure surfaces (Fig.8), are insensitive to groundwater fluctuations, and are stable under static conditions; while pseudostatic analyses revealed that strong shaking was required to trigger these events (Badger and Watters, 2004).

In the Alvord Basin, active normal faults disrupt flights of three and five shorelines of pluvial Lake Alvord that formed during at least two periods of lake-level highstand in the Pleistocene (Oldow and Singleton, 2008). Oldow and Singleton (2008) used Terrestrial Laser Scanning georeferenced with GPS, allowed detailed analysis of shoreline altitudes where they are crosscut by fault (Fig. 9). Variation in shoreline elevation measured across faults and on opposing sides of the basin indicates that fault slip occurred during and following periods of
lake-level recession (Oldow and Singleton, 2008). During the late Pleistocene and Holocene, 26 periods of fault slip occurred on at least eight faults during and after water levels decreased (Oldow and Singleton, 2008). Deformation rates varied with time, and displacement was heterogeneously distributed on structures across the extensional basin (Oldow and Singleton, 2008).

This phenomenon is explained by Hampel & Hetzel (2006) with their results showing that the duration of the seismically quiet period during loading and the intensity of the slip rate increase during unloading are primarily controlled by the magnitude of the load. The time lag between the changes in loading and the reaction of the fault is mainly determined by the viscosity of the asthenosphere. Parameters that play only a minor role for the fault’s response include the rate of load removal, fault strength, and the thickness of the lithosphere (Fig. 10) (Hampel & Hetzel, 2006).

The last major earthquake along the SVF only rupturing 42 of the 95 km length of the fault and my own preliminary results that demonstrate a variable slip rate along strike of the SVF shows promising results for how earthquakes and slip vary along strike of the SVF. The presence of an earthquake cluster (Fig. 5) between 4 and 13 ka and the highly irregular recurrence interval provide solid indication of how earthquakes and slip has changed over time. And lastly, the first order correlation of the earthquake cluster during the period of lake-level recession (Fig. 5), is a good start on answering the question of how Lake Surprise has impacted the temporal variations of earthquakes and slip along the SVF.
Methods

In order to address those questions further, I will use the following methods to achieve four objectives:

Objective 1: Document offset of paleoshorelines across the SVF through lidar-based mapping. Along the western side of the valley, shoreline features have been offset by fault scarps (Fig. 11). I will use the lidar data acquired by the National Center for Airborne Laser Mapping (NCALM) with funding from a grant to Glen, Egger, and Ippolito from NASA’s UAS-Enabled Earth Science Program to map paleoshorelines along the eastern, western and northern reaches of the valley. This will provide the basemap I will use to measure offsets of the paleoshorelines. A slopes map of the area makes these shoreline features very apparent (Fig. 11).

I will correlate the shorelines on all sides of the valley by looking for patterns in elevation difference. The shorelines along the eastern side (Fig. 6) have not been altered by faulting, and by using their relative spacing in elevation, they represent a control group. I will compare them to the paleoshorelines along the western side to measure the changes in elevation spacing that can be explained by offset along the SVF, as has been documented by Personius et al. (2009). If groups of paleoshorelines are homogeneously offset vertically from their counterparts across the valley, then it’s reasonable to associate that offset with a single event or with multiple events that occurred after the lake depleted; while on the other hand, if individual paleoshorelines are offset apart from each other relative to their eastern counterparts, then a series of multiple events occurred during the depletion of the lake, and by knowing all of the ages of the shorelines and large earthquake events, I can attempt to tie this all together.

Objective 2: Correlate lake level history with earthquakes. The paleoshorelines along the eastern side of the valley have been extensively dated in Ibarra et al. (2014). I have used that data
with dated earthquake events provided by Personius et al. (2009) to correlate the lake level changes with clustering of earthquakes in Figure 5. With the paleoshoreline data provided, I am able to look at multiple offsets across several time frames to define a potentially variable slip rate that specifically relates the earthquake clustering to a particular rate of lake level change. Like what Weldon (2009) recorded in the Summer Lake basin, the main clustering of earthquakes appear to be correlated with the rapid removal of lake water between 15 and 5 ka (Fig. 5).

Another thing to note is that the last 4 major earthquakes documented (Egger, 2014; Personius et al., 2009) have all taken place after the youngest paleoshoreline was carved. This narrows down the possibilities of mapping the offset of paleoshoreline groups to get at a slip rate. The paleoshorelines, according to this relationship, will all be offset as a single group from their counterparts across the valley.

**Objective 3: Obtain radiocarbon dates on paleoshoreline tufas.** Over 2 weeks of field work, I will, if possible, locate and collect samples of paleoshoreline tufas along the western side of the valley, and in other undated regions of the valley (see Fig. 3 for locations of dated samples). Up to eight tufa samples will be radiometrically dated using $^{14}$C AMS analysis at varying shoreline levels to match with dated shorelines across the valley from Ibarra et al. (2014). These dates will then be used as markers for measuring offset and calculating slip rate.

**Objective 4: Determine how offset and slip rate vary along strike of the SVF.** Using the LiDAR data, along with the measurements taken from the paleoshorelines, mapping the distribution of slip along strike is more accessible. There are three specific sections along the western side of the valley that contain dated paleoshorelines (Fig 3). By acquiring three individual offsets between these groups and their corresponding eastern paleoshorelines, they can be compared and contrasted with each other along the length of the fault. Offset and slip rate are
expected to change along the length of the SVF with the idea of fault segmentation. If the majority of earthquakes are not going to rupture along the entire length of the fault, the offset of paleoshorelines in the upper basin, which is structurally different to the middle and lower sections of the valley, could be used to determine the existence of fault segmentation along the SVF. The middle and lower lake sections are bounded by normal faults on both sides while the upper lake section is not bounded by the HCF in the east and the valley changes from a full graben structure in the middle and lower lake sections to a half-graben in the upper lake (Fig. 3). This major structural change could play a significant role in the assertion that the SVF is structurally segmented.

**Preliminary Results**

My preliminary results obtained from measuring offset paleoshorelines using lidar-derived elevations suggest that slip rate varies along strike of the SVF. I measured vertical offsets along the western side of the upper, middle and lower lake segments of paleoshoreline elevations that I correlated together with the paleoshorelines along the eastern side (Fig. 6). Paleoshorelines in the upper lake basin displayed an offset of 4.74 m over the last 19.44 ± 1.46 ka. The middle lake measured an offset of 14.38 m over the last 16.48 ± 0.87 ka. And the lower lake measured an offset of 11.5 m over the last 20.85 ± 1.84 ka. Using the measured offsets and the ages provided by Ibarra et al. (2014), I calculated the average slip rate over those periods of time. I have based these slip rates on three differing fault orientations: 60° to represent standard normal fault mechanics, 67° from a local fault exposure (Personius et al., 2009), and 35° from a seismic imaging 30 km (Lerch et al., 2010).
Table 1

<table>
<thead>
<tr>
<th>Lake Section</th>
<th>Fault Dip (°)</th>
<th>Slip (m)</th>
<th>Time period (ka)</th>
<th>Slip rate (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper lake</td>
<td>60</td>
<td>5.47</td>
<td>19.5</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>5.16</td>
<td>19.5</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>8.26</td>
<td>19.5</td>
<td>0.42</td>
</tr>
<tr>
<td>Middle lake</td>
<td>60</td>
<td>16.6</td>
<td>16.5</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>15.5</td>
<td>16.5</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>25.07</td>
<td>16.5</td>
<td>1.52</td>
</tr>
<tr>
<td>Lower lake</td>
<td>60</td>
<td>13.28</td>
<td>21</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>12.4</td>
<td>21</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>20.05</td>
<td>21</td>
<td>0.96</td>
</tr>
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</table>

These calculations provide a rough estimate of the varying slip rate along the fault. Additional field work to acquire exact ages of shorelines along the western side would confine these slip rate calculations further. Along the strike of the SVF, the amount of measured slip and the slip rate is characteristic of earthquake rupturing patterns (Dawers and Anders, 1995). The center segments of the SVF have the highest slip and greatest slip rate while the slip and slip rate die out towards the edges of the fault. Even with my limited number of measured slip rate along strike of the SVF, the data fits to the characteristic bell curve shape (Dawers and Anders, 1995).

The clustering of earthquakes during the time of rapid lake depletion suggests that the Pleistocene lake has played a role temporally in the evolution of SVF’s history (Fig. 5). This look into the past was only accessible with the presence of paleoshorelines that have been offset by the SVF. This is just the beginning of a very promising look into the complete history of the Surprise Valley.
### Budget

<table>
<thead>
<tr>
<th>Budget Item</th>
<th>Amount Budgeted</th>
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<tr>
<td>SUV rental</td>
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<td>Gas</td>
<td>$150</td>
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<tr>
<td>Lodging</td>
<td>$210</td>
</tr>
<tr>
<td>Per diem</td>
<td>$700</td>
</tr>
<tr>
<td>DirectAMS sampling</td>
<td>$1,632</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$3,198</strong></td>
</tr>
</tbody>
</table>

### Budget Justification

**Enterprise Rental SUV:** 2 weeks at $253 per week. SUV with 4WD is required to carry field equipment and reach remote mountain field sites.

**Gas:** 492 miles from Ellensburg WA to Cedarville, CA (x2). 516 miles of commuting around field area. Rental SUV has an average of 22-23 mpg, gas prices set to $2.00 a gallon.

1500 miles/22 mpg = 68.2 gallons of gas, at $2.00 a gallon = ~$150.00.

**Lodging/Per diem:** 2 weeks of tent camping at Sunrise Motel, charges $15 a night ($15 * 14 days = $210). $25 per day for food expenses per person, for myself and a field assistant for 2 weeks ($25 * 2 people * 14 days = $700).

**DirectAMS sampling fees:** DirectAMS radiocarbon dating service charges $204 per carbonate sample. For up to 8 samples comes out to $1632.
Figures

**Figure 1** – Hillshaded digital elevation model (DEM) of the Basin and Range province in western United States. The earthquakes are locations where M6.0 and greater earthquakes took place over the last 100 years (provided by USGS). The Basin and Range province in bounded in the west by the Sierra Nevada and to the east by the Colorado Plateau and the Wasatch fault zone in Central Utah.
**Figure 2** – Hillshaded DEM of the NW extent of the Basin and Range province. Blue regions denote the highstand (marked in m above sea level) of the many Pleistocene pluvial lakes that filled the fault controlled valleys (Ibarra et al., 2014; Reheis, 1999). The purple circles are locations of earthquakes over the last 10 years with a M3.0> in size (Provided by USGS). The largest purple circle denotes the region currently undergoing a seismic swarm that started in July, 2014. Lake Surprise, much like Lake Chewaucan and Lake Alvord keeps a robust record of paleoshorelines with direct proximity to a major fault, the SVF that is useful for accessing paleoseismic information that is more easily obtained than through trench work.
Figure 3 – Hillshaded DEM of Surprise Valley. The tan regions denote the three main lake playas. The green boxes are areas where Ibarra et al. (2014) gathered tufa samples for dating of the paleoshorelines. Blue boxes are the regions where Personius et al. (2009) did their paleoseismic studies along the SVF. The grey outline is the extent of the high resolution lidar data acquired by NCALM in 2013. The black rectangles are areas along the SVF where paleoshoreline features are expressed, and their corresponding areas with paleoshorelines along the eastern side of the valley to measure relative offset from. Along the SVF, there are
Quaternary fault scarps that extend out into the lake basin (best example is just north of the northern-most paleoseismic study site from Personius et al, 2009) and then jump to the northwest to meet back up with the Warner Range periodically along strike. These step-overs could represent apparent fault segmentation along the SVF.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Surprise Valley Chronology</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Historic constraint (1850 AD ± 5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SV-R03 (1,350 ± 45 14C yr B.P.; 1,170 ± 350 cal yr B.P.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earthquake P1 (1,200 ± 100 yr)</td>
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</tr>
</tbody>
</table>

### Phase (buried soil on P2 colluvial wedge)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Age (14C yr B.P.; 1,000 cal yr B.P.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW-R05</td>
<td>1,240 ± 140 yr B.P.; 900 ± 1,410 cal yr B.P.</td>
</tr>
<tr>
<td>SVSC-R01</td>
<td>1,300 ± 35 yr B.P.; 1,170 ± 1,300 cal yr B.P.</td>
</tr>
<tr>
<td>SV-01</td>
<td>1,110 ± 630 yr; 1,5 ± 0,3 ka</td>
</tr>
<tr>
<td>SV-R04</td>
<td>1,960 ± 180 yr B.P.; 1,520 ± 2,350 cal yr B.P.</td>
</tr>
<tr>
<td>SV-03</td>
<td>4,870 ± 400 yr; 4,8 ± 0,4 ka</td>
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### Earthquake P2 (5,800 ± 1,500 yr)

<table>
<thead>
<tr>
<th>Sample</th>
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<tbody>
<tr>
<td>SV-04</td>
<td>8,260 ± 2,850 yr; 6,9 ± 1,1 ka</td>
</tr>
<tr>
<td>Mazama ash (7,930 ± 150 cal yr B.P.)</td>
<td></td>
</tr>
<tr>
<td>SV-R02</td>
<td>7,050 ± 55 yr B.P.; 7,740 ± 980 cal yr B.P.</td>
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</table>

### Earthquake P3 (8.5 ± 0.5 ka*)

### Earthquake P4? (10,960 ± 3,200 yr)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Age (14C yr B.P.; 1,000 cal yr B.P.)</th>
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<tbody>
<tr>
<td>SV-08</td>
<td>13,380 ± 2,840 yr; 13,4 ± 2,2 ka</td>
</tr>
<tr>
<td>Lahontan highstand (13,060 ± 200 14C yr B.P.; 14,800 ± 1,100 cal yr B.P.)</td>
<td></td>
</tr>
<tr>
<td>SV-05</td>
<td>17,690 ± 4,640 yr; 16,8 ± 2,1 ka</td>
</tr>
</tbody>
</table>

### Earthquake PX (18,200 ± 2,600 yr)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Age (14C yr B.P.; 1,000 cal yr B.P.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SV-08</td>
<td>18,400 ± 3,170 yr; 19,6 ± 2,5 ka</td>
</tr>
<tr>
<td>SV-07</td>
<td>28,080 ± 4,440 yr; 23,8 ± 4,9 ka</td>
</tr>
</tbody>
</table>

**Figure 4** - OxCal model (version 4.1) [Bronk-Ramsey, 1995, 2001, 2008] of timing constraints on prehistoric surface-rupturing earthquakes on the Surprise Valley fault. All ages from Cooks Canyon trench except SVSC-R01, which is from Steamboat Canyon exposure. Ages are listed in a sequence (in stratigraphic order with no depth constraints) and one phase (stratigraphic order
unknown). Historic constraint is lack of surface-rupturing earthquakes since European settlement of Surprise Valley at about 1850 AD [Hedel, 1980]. Light gray areas are prior probability distribution functions (PDFs) of calibrated radiocarbon (SV-R## samples), luminescence (SV-L## samples), tephra, and lacustrine highstand ages. The dark gray areas are posterior PDFs resulting from Bayesian analysis of timing constraints. Black areas are modeled PDFs of individual earthquakes. Earthquake P3 (marked with an asterisk) is estimated age (see text); all other earthquakes are calculated with OxCal. Reported luminescence ages listed in years; OxCal model ages rounded to nearest 100 years and listed in ka. Reported radiocarbon ages listed in 14C years B.P.; OxCal-calibrated ages listed in cal year B.P. White dots are weighted means; brackets are 2s uncertainties. (Personius et al., 2009). Specific layers (Mazama ash, and Lahontan highstand) are used as timing benchmarks and are used to constrain ages of individual earthquake events. We now have data provided by the dated paleoshorelines that provide even stronger constraints to the ages of these earthquake events.
Figure 5 – (A) Lake Surprise shoreline elevation change graph from Ibarra et al. (2014). The gray error envelope bounds all sample ages with elevations <1531 m; the gray line relies of radiocarbon ages only. Dashed lines are tentative correlations. (B) Timing constraints on prehistoric surface-rupturing earthquakes on the Surprise Valley fault from Personius et al. (2009). All ages are from the Cooks Canyon trench. The extent of the paleoseismic data extends back to 35 ka, the earliest earthquake event (PX) however, doesn’t happen until 17-20 ka (Personius et al., 2009). Take note that the main clustering of earthquakes (P2, P3, and P4) appear to take place during the relatively quick period of drainage of Lake Surprise.
Figure 6 - View looking eastward of the layered paleoshorelines of California's Lake Surprise. The shorelines are much more pronounced along the eastern side of the valley, as shown here. Photo by Anne Egger.
Figure 7 - Surface rupture associated with the 1915 Pleasant Valley earthquake. Data are from Wallace (1984). (Zhang et al., 1999).

Figure 8 - A cross section shows the interpreted stratigraphy and the pre- and postfailure conditions of the depletion zone. The late Pleistocene (16.8 ka) highstand is locally preserved on or near the Winter Ridge fault scarp. Qls3 deposits are derived from Qls2 but have been deformed most recently during the Holocene, probably by secondary landsliding. (Badger and Watters, 2004).
Figure 9 - Hillshade and slope maps of 30 m digital elevation model (DEM) (southeastern Alvord Point) used to isolate shoreline features and fault scarp geometry. (A) Hillshade of 0.30 m resolution DEM. (B) Slope analysis of 0.30 surface with slope angle increasing from blue to red. (C) Slope analysis sample at 2.0 m pixel dimension to suppress noise from sagebrush and surface debris to better isolate maximum curvature of riser crest. (D) Interpreted position of riser-crest lines (black) and fault scarps (red). (Oldow and Singleton, 2008).
Figure 10 – State of stress before, during and after glacial loading and flexure in a region of active extension, where the maximum principal stress $\sigma_1$ is vertical. (a) Before loading, the Mohr circle for stress, which represents the stress state at a point P, touches the line representing the Mohr-Coulomb failure criterion; that is, normal faulting occurs (see text for a detailed description of the Mohr diagram and the Mohr-Coulomb failure criterion). (b) Application of a load to Earth’s surface increases $\sigma_1$. Flexure of the lithosphere, however, affects the horizontal
stress, leading to an increase in $s_3$ in the upper part of the lithosphere and a decrease in $s_3$ in its lower part. At point P the overall effect is a reduction of the differential stress $s_1 - s_3$; that is, the diameter of the Mohr circle decreases. In other words, upon loading, the Mohr circle becomes smaller and is shifted to the right with the result that normal faulting stops. (c) In the course of unloading and elastic rebound the Mohr circle is shifted to the left, and its diameter increases again such that it touches the line of the Mohr-Coulomb failure criterion; that is, normal faulting starts again. Note that the thickness of the ice sheet is exaggerated with respect to the lithospheric thickness (Hampel & Hetzel, 2006).
Figure 11 – Slope map draped over hillshade, both derived from lidar-based DEM. The blue colors are steeper areas while the green colors are shallow areas. Take note that along the eastern edge of the figure, there are paleoshorelines that have been offset by a Quaternary fault scarp. This areas along the paleoshorelines would be a places I would examine for tufa samples for radiometric $^{14}$C AMS analysis.
References


Hedel, C. W., 1980, Late Quaternary faulting in western Surprise Valley, Modoc County, California [M.S. Master's]: San Jose State University, 142 p.


