Documenting the Earthquake History of the Thousand Springs Fault in Summer Lake Basin, Oregon, USA

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DOCUMENTING THE EARTHQUAKE HISTORY OF THE THOUSAND SPRINGS
FAULT IN SUMMER LAKE BASIN, OREGON, USA.

A Thesis
Presented to
The Graduate Faculty
Central Washington University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Geology

by
Elizabeth Rose Curtiss
June 2020
We hereby approve the thesis of

Elizabeth Rose Curtiss

Candidate for the degree of Master of Science

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Dr. Walter Szelia

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Dean of Graduate Studies
ABSTRACT

DOCUMENTING THE EARTHQUAKE HISTORY OF THE THOUSAND SPRINGS FAULT IN SUMMER LAKE BASIN, OREGON, USA.

by

Elizabeth Rose Curtiss

June 2020

Defining seismic hazards in low-strain-rate regions such as the northwestern Basin and Range can be difficult due to the infrequency of earthquakes. Revealing the earthquake records of low-strain-rate regions can refine our understanding of the variability of earthquake sizes and recurrence intervals, however, which can ultimately improve hazard analysis.

Four active normal faults form the Summer Lake basin, in the northwestern Basin and Range: The Thousand Springs (TSF), Ana River (ARF), Slide Mountain, and Winter Ridge faults. Other than the TSF, the faults in the Summer Lake basin have documented histories that include surface-rupturing (>M6) earthquakes. Scarps along the TSF were only recently mapped and its earthquake history has not been previously documented. The TSF cuts through an area with relatively low sedimentation rates and numerous tephras from the past ~250,000 years and thus earthquakes on this fault are preserved and dateable through trenching.

We dug two trenches across the TSF in 2019, exposing multiple episodes of offset bracketed by deep to shallow-water lake sediments, a sand dune, and tephras which were identified based on correlations of their physical characteristics, stratigraphic sequence, glass chemistry, and radiocarbon dates from the lake sediments: Tephra 2 (Ice Quarry tephra), Pumice Castle tephra, Mount St Helens Cy tephra, Wono tephra, Trego Hot Springs tephra, Mount St Helens Mp, and a black tephra. These tephras, and a sand dune most likely containing reworked Mazama ash and lacustrine sediments, are offset by a
fault zone that spans a minimum of four meters with at least five fault strands. The only unit that was able to be correlated across the fault zone, MSH Cy tephra, had a total offset amount of 2.4 m. The next youngest tephra, Wono, is offset by 2.0 m and THS is offset by 1.8 m, which were both determined by extrapolating missing sections. Based on offset of individual tephras and the comparison between the two trenches, we have identified at least five surface-rupturing earthquakes. The events in chronological order are as follows: The oldest event (event 5) occurred 54.1 – 71 ka, event 4 occurred 30.5 – 45.6 ka, event 3 occurred 24.8 – 29.1 ka, event 2, which was a folding event at our sites, occurred 7.6 – 12.7 ka, and the most recent event (event 1) occurred after 7.6 ka.

These results suggest that the TSF is just as active as the nearby Ana River Fault, which has had at least 8 earthquakes in the past ~80 ka compared to the TSF’s 5 earthquakes. Comparing the TSF’s activity to lake level changes in the basin during the Quaternary suggests that the crust could be responding to the changes of the lake level, causing variability in the earthquake recurrence intervals. These insights are applicable to the forecasting of earthquakes in the northwestern Basin and Range and other low-strain-rate regions.
ACKNOWLEDGMENTS

I would like to thank the College of the Sciences and the Graduate School of Research at Central Washington University for funding my field work both during Spring Break and Summer 2019, without which this project would not have been possible. I also would like to acknowledge the use of facilities, plus the scientific and technical assistance of the instrument staff at the M.J. Murdock Charitable Trust Multidisciplinary Research Laboratory, Central Washington University, USA, a facility partially funded by the M.J. Murdock Charitable Trust.

I also am extremely grateful for my thesis committee chair, Dr. Anne Egger, who has shaped me into a strong researcher and provided constant guidance, support, and timely, invaluable feedback on my work. I am most grateful for her trust in me and my abilities throughout my time at Central. I would also like to thank my committee member, Dr. Ray Weldon, for his constructive feedback and providing equipment for the field including the University of Oregon undergraduate “volunteers” whose hard labor was most helpful: Allie Thompson, Megan Wyatt, Belyn Grant, Noel Blackwell, Ulises Beltran, Phil Catanzaro, Joey Olson, and Karen Silva. Ray’s trenching expertise was crucial to my study’s success and I can’t thank him enough, especially for donating funds to help cover field work costs from the “Weldon Foundation” and gifting me his clay scraper. I also want to thank Dr. Walter Szeliga, my other committee member, for his positivity, expertise, and for not judging me when I would cry from laughing during our seismology Friday labs.

I owe a big thanks to my hard-working field assistants, Amy Gilliland and John Neer. Amy was beyond flexible and helped me on all my test flights when learning how to operate the UAVs at Central. She then again was invaluable during Spring Break when we traveled down to Summer Lake to hike all over the basin scoping out optimal trench sites. I am also very grateful for John without who, logging my trenches would not have
been possible. I am most appreciative for his dedication to detailed notetaking and for his company in the field.

I need to acknowledge two people, without who, I would not be in graduate school: my parents, Tim and Stephenie Curtiss. Their interest, support, and love, through verbal, financial, and physical ways, have be a backbone to this project. A huge thanks to my father for lending his truck, trailer, and his own physical labor to the trench operation of set-up and take-down. His positive attitude and witty jokes made field work a lot more fun and I can’t thank him enough. I also owe a huge thanks to my mother, a ray of sunshine, who helped run errands, make meals for me and my field team, and helped with tasks for trenching. Her positive attitude and stylish outfits were a wonderful addition to have in the field. I also can’t thank her enough for all she did for me and my team.

I am grateful for the community of Summer Lake who welcomed me into their town as one of their own and provided me with any help and equipment I needed. I would like to especially thank Dale Chiono, who owns the Summer Lake general store. He loaned me equipment whenever I came asking and was always such a pleasant conversationalist. A big thanks also to Det Kirkendal who dug our trenches and filled them back in for us and to Ethan at the fishery for lending his pump. I also want to thank Jay and Connie who run the Ana Reservoir RV Park for their hospitality and kindness.

I want to acknowledge and thank my lovely friends, David Bruce and Valerie Strasser, whose help, support, and friendship carried me through hard times during these past years. Their willingness to help edit, motivate, and make me laugh means more to me than they know, and I can’t thank them enough for all that they’ve done for me.

I would also like to thank Dr. Angela Halfpenny who runs the Murdock Lab at Central for her expertise, companionship, and willingness to tackle and establish a technique that had yet to be done in the Murdock lab. I also owe a big thanks to Dr. Craig Scriver, whose technical expertise came to the rescue uncountable amount of times. And lastly, I want to thank the entire Geology faculty and staff for their support and aid.
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### Plate

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CHAPTER I

INTRODUCTION

Understanding low-strain-rate regions can be difficult due to the infrequency of earthquakes. Since large events (> 6 M and surface-rupturing) are rare, there is little urgency to study and quantify the seismic hazards of these regions. Even though these low-strain-rate tectonic settings are relatively low in hazards, some can have high risk, and thus it is important to develop a complete seismic hazard assessment of such areas. Another benefit to revealing earthquake records of low-strain-rate regions is refining the understanding of the variability of earthquake sizes and recurrences which can ultimately improve earthquake forecasting.

The Northwestern Basin and Range (NWBR) is a low-strain-rate region (Kreemer et al., 2012) within the Basin and Range (Figure 1) in North America. The range-bounding faults mainly trend north-south and are predominantly extensional, with little to no lateral movement (Pezzopane, 1993; Pezzopane and Weldon, 1993; Egger et al., 2018). This region has had no historical surface-rupturing events though geologic evidence shows the faults have been active throughout the Quaternary (Pezzopane and Weldon, 1993; Langridge, 1998; Personius et al., 2003, 2017; Egger et al., 2018). Paleoseismic investigations are required to fully expose the activity of this region to understand the seismic hazards (Personius et al., 2017).

To understand and characterize both the variability of earthquakes and the seismic hazards in regions like the NWBR, we must take the entire picture into account. Every active fault contributes to the seismic hazards and thus it is crucial to examine all active faults not just the largest ones to gather a complete picture.
Figure 1: Map of the northwestern Basin and Range (NWBR), extent is in orange. Modern lakes extents are shown in blue. Shaded relief DEM is from USGS 1-arc second database from 2013. Faults with previous paleoseismic trenches (pink) are shown in black. CITGF – Crack-in-the-Ground fault. VPF – Viewpoint fault. ARF – Ana River fault. SMF – Slide Mountain fault. SVF – Surprise Valley fault. BRF – Black Rock fault.
Summer Lake

Summer Lake basin is a normal-fault-bound basin in the NWBR, in south-central Oregon (Figures 1, 2). Its west side is bound by the north-trending, east-dipping Winter Ridge fault (WRF), which forms the Winter Rim escarpment, and the Ana River fault (ARF) (Figure 2). The southern margin is bound by the arcuate, east-west-trending, north-dipping Slide Mountain fault (SMF) (Figure 2). Evidence from trenches on the SMF and ARF (Pezzopane, 1993; Langridge, 1998) and large seismogenic landslides along the western and southern margins (Badger and Watters, 2004) indicate that the WRF, ARF, and SMF have produced multiple earthquakes ~M7 in the last 20 ky. Historically, there have not been any surface-rupturing earthquakes, only events with magnitudes less than 2.0 (Egger et al., 2018).

The Summer Lake basin hosted Summer Lake and pluvial Lake Chewaucan, which transgressed and regressed multiple times during the Quaternary, documented by paleoshorelines and sediment accumulation in the basin. These sediments also contain a well-documented sequence of tephras derived from the nearby Cascade volcanoes (Kuehn and Negrini, 2010) that are key to constraining the timing of slip along faults where they are exposed by trenching.

This extensive, well-documented tephrochronology of the basin, combined with a continuous but low sedimentation rate of the northern portion of the basin and the fact that the faulting is predominately dip-slip, makes Summer Lake and ideal setting for a paleoseismological investigation. These factors allow for a long record of preserved, datable earthquakes.
Figure 2. Map of Summer Lake basin. Faults (red) are mapped scarps, not full fault traces. Shaded relief DEM is from USGS 1-arc second database from 2013. Pluvial lake level is shown in light blue layered on top of land-ownership plots. Roads are from USGS – National Geospatial Technical Operations Center. Land-ownership data is from BLM Geospatial Publication Center.
Thousand Springs Fault

On the eastern side of the basin, the Thousand Springs fault (TSF), whose fault scarps have been recognized throughout the past decades, was recently mapped as an active north-trending, west-dipping normal fault about 8 km long (Niewendorp et al., 2013; Egger et al., 2018). The earthquake history of the TSF is unknown, but given its orientation, it could be accommodating as much (or more) slip as the east-dipping faults as the deformation of Summer Lake basin continues to form. Extension in the northern portion of Summer Lake is predominantly ENE – WNW, which is nearly perpendicular to the TSF, a favorable orientation for the TSF to accommodate strain (Crider, 2001; Treerotchananon, 2009).

This study’s goal is to document the previously unknown earthquake history of the TSF. The earthquake history of the TSF will add significant insight to the overall earthquake activity of the basin. By adding more to the story of the earthquake history of Summer Lake and thus understanding the tectonic activity across the entire basin, we can apply that understanding to the bigger picture of the NWBR and other low-strain-rate regions where earthquake records aren’t preserved, or field work isn’t feasible. The extensive earthquake record of the basin can also help improve the understanding of the when earthquakes occur and how big they are which will help improve forecasting models by exposing those patterns, if they exist.
CHAPTER II

BACKGROUND

Northwestern Basin and Range

The Basin and Range is an extensional tectonic region in western North America (Inset of Figure 1; Personius et al., 2017; Egger et al., 2018). The Northwestern Basin and Range (NWBR), which spans northeastern California, southern Oregon, and northwestern Nevada (Figure 1), has been a region of active extension for the past ~12 Ma (Egger et al., 2018). The extension occurs mostly through dip-slip motion along several normal faults which have proven capable of producing surface-rupturing earthquakes (>M6) (Pezzopane and Weldon, 1993; Personius et al., 2017; Egger et al., 2018).

Extension in the NWBR is predominantly E–W accommodated by mainly north-south trending normal faults with average slip rates ranging from ~0.1 – 0.8 mm/yr (Personius et al., 2017). There have been multiple paleoseismic investigations on faults in the NWBR. In the Fort Rock basin, paleoseismic investigations on the Crack-In-The-Ground and Viewpoint faults (Figure 1) exposed at least 2 large (>M6) earthquakes on both faults during 11 – 14.5 ka (Pezzopane, 1993; Egger et al., 2018). Surprise Valley fault’s paleoseismic investigations exposed five large earthquakes in the last 20 ky (Personius et al., 2009). The Steens fault zone, located in the Lake Alvord basin (Figure 1), has had three large earthquakes in the last ~12 ky (Personius et al., 2007). The Black Rock fault, located in Nevada, north of Pyramid Lake (Figure 1) has had three large earthquakes in the last ~18 ky (Personius et al., 2017).

Paleoseismology of Summer Lake Basin

Summer Lake basin was formed by a set of related normal faults: the Winter Ridge Fault (WRF), the Slide Mountain Fault (SMF), the Ana River Fault (ARF), which
may be a splay of the WRF (Langridge, 1998), and the Thousand Springs Fault (TSF) (Figure 2). The WRF is the largest fault with the most significant offset (Figure 2), but documenting its earthquake history has proven difficult due to the massive landslides that occur along it (Badger and Watters, 2004). The SMF has been trenched and exposed at least two faulting events in the last ~18 ka, but it is difficult to gather age constraints on the events due to the large amount of sediment, mainly from landslides (Pezzopane, 1993). Mainly lake sediments and colluvium were exposed in the trench, whose contacts and cross-cutting relations were used as evidence for earthquake events. Charcoal from a non-offset alluvial fan that overlies the scarp provided a minimum age constraint for the events of 2130 ± 90 yrs B.P and deep-lake sediments, which most likely are from the last high-stand of Lake Chewaucan, provide a maximum age constraint of 12 – 18 ka (Pezzopane, 1993).

In contrast to these two faults that form the most significant topographic features, the ARF (Figure 3) is in a region of the basin with a very low sedimentation rate (~0.07 mm of sediment per year); it has been trenched several times and has a well-documented earthquake history of 11 events in the last 167 ± 10 ka (Figure 4) (Langridge, 1998; Egger et al., 2018).

**Tephrochronology of Summer Lake**

The other factor that has allowed the elucidation of the long earthquake record on the ARF is the tephra-rich stratigraphic record in the basin that spans the last 250 ky, collected from natural exposures and trenching on the ARF, and sediment coring in the basin (Davis, 1985; Mullineaux, 1986; Negrini and Davis, 1992; Cohen et al., 2000; Kuehn and Negrini, 2010). Volcanic eruptions produce tephra layers with unique physical and chemical properties; these properties allow dispersed tephras to be correlated. Summer Lake hosts such an extensive tephra record because it is located
downwind of the Cascade volcanoes, which have had extensive work done characterizing eruption histories and chemical signatures (Bacon and Lanphere, 2006; Myers and Driedger, 2008; Clynne et al., 2009). Most tephra in the record have been identified through physical and chemical characteristics and their depositional ages were determined with different geochronological techniques and correlations. A key concept of
Figure 4: Composite stratigraphic column from the ARF exposures and trenches. The section is not to scale. Earthquake events are indicated by stars. Sources of the ages of tephras are discussed in the text and their geochronological method used to date them are in parentheses next to the age: $^{14}$C – radiocarbon, A/D – Age-vs-depth Model, pm – paleomagnetism correlation, tl – thermoluminescence, K-Ar – Potassium-Argon dating. Revised from Egger et al., 2018.
correlating tephras is matching the sequence of the tephras in relation to each other; Matching the physical properties of each tephra: color, grain size, thickness, and other properties, and the order they fall in.

The well-documented tephrostratigraphy of Summer Lake is a useful geochronologic tool. The Summer Lake basin contains at least 88 tephra beds that date back 250 ky (Kuehn and Negrini, 2010). This study makes use of tephras from the last 80 ky (Figure 4).

The oldest tephra for the purpose of this study is the Ice Quarry (tephra 2), a 3 – 4 cm thick, gray-pink-white tephra with thin layers (~2 mm) (Kuehn and Negrini, 2010), dated by thermoluminescence at 67.3 ± 7.5 ka (Berger, 1992). On the basis of an age-depth model that was created with the ages of many tephra in Summer Lake basin, however, the preferred age for tephra 2 is ~74 ka, at the older end of the uncertainty for the thermoluminescence age (Langridge, 1998).

Above tephra 2 is the Pumice Castle tephra (Figure 4), a set of tephras from closely spaced eruptions of Mt. Mazama (Davis, 1985; Bacon and Lanphere, 2006). This tephra is commonly very resistant, made up of coarse sand-sized pumice grains, dark gray to a pinkish-white, ~10 cm thick, and has a ~6 cm thick reworking of ash and sand above it (Langridge, 1998; Kuehn and Negrini, 2010). The tephra’s chemistry has been correlated to a dacite flow found on the east flank of the volcano and to other tephra deposits near Crater Lake, OR, and in California (Rieck et al., 1992). Its depositional age of 71 ± 6 ka comes from K-Ar dating of the dacite flow found on the vent (Bacon and Lanphere, 2006) and provides stratigraphic constraint for the preferred age of tephra 2.

Tephra H (Figure 4) is a gray to white tephra that ranges in thickness from 0.1 – 0.6 cm in different areas of the Summer Lake basin (Davis, 1985; Langridge, 1998; Kuehn and Negrini, 2010). It has not yet been correlated to a source and its depositional age was determined through age-depth models: 57 ka (Langridge, 1998) and 54.1 ± 5 ka.
54.1 ± 5 ka is my preferred depositional age for tephra H.

Mt. St. Helens Cy tephra (Figure 4) is a member of the set C tephras, the oldest stage of dated Mt. St. Helens eruptions (Mullineaux, 1986; Clynne et al., 2009). The ~10 cm-thick tephra grades from gray to white, and is darker at the base where the proportion of biotite is higher (Kuehn and Negrini, 2010), along with cummingtonite and orthopyroxene (Langridge, 1998). Approximately 5 cm of reworked ash and silt commonly lie directly above the tephra (Langridge, 1998; Kuehn and Negrini, 2010).

Berger and Busacca (1995) used thermoluminescence to determine a depositional age of 46.3 ± 4.8 ka for Cy. Zic et al. (2002) used paleomagnetic correlation to determine an age of 45.6 ka. Clynne et al. (2009) used radiocarbon but could only determine an upper age value of 47.43 ± 0.6 ka. The preferred age is the most recent and tightly constrained age of 45.6 ka, since Clynne et al. could only provide an upper age constraint.

Wono tephra (Figure 4) is a white, ~2–6 cm thick layer commonly found overlying a tufa bed (Langridge, 1998; Cohen et al., 2000; Negrini et al., 2000; Kuehn and Negrini, 2010). Langridge (1998) reported orthopyroxene and some hornblende. Davis (1985) used radiocarbon to constrain the deposition age and reported it as 24.8 ka, which is uncalibrated but was reported without error thus I cannot calibrate it. Benson et al. (1997) reported it as 27.3 ± 0.3 ka which is uncalibrated and uncorrected for reservoir effect which Zic et al. (2002) corrected to 29.1 ± 0.9 ka. This same value was used by Kuehn and Negrini (2010). The preferred age is 29.1 ± 0.9 ka.

The Trego Hot Springs (THS) tephra (Figure 4) has been correlated across the NWBR and is easily identified in the field because of its distinct physical properties. THS is white, ~3–5 cm thick, with hornblende and orthopyroxene (Langridge, 1998). Many sources also document a ~3–5 cm thick, cross-bedded sandy-silt and ash layer directly
above the tephra in the Summer Lake basin (Davis, 1985; Negrini and Davis, 1992; Langridge, 1998; Cohen et al., 2000; Kuehn and Negrini, 2010). The THS tephra was sourced from Crater Lake (Mt. Mazama), OR (Davis, 1983, 1985). Rieck et al. (1992) reported the tephra’s age as 23.4. ka by combining paleomagnetic data with previously published tephrochronology data from Davis (1985). Berger (1992) used thermoluminescence to determine an age and compared it to previously published radiocarbon dates to produce an age of 24.3 ± 2.7 ka. Benson et al. (1997) used radiocarbon and reported a deposition of 23.2 ± 0.3 14C years B.P. Kuehn and Negrini (2010) averaged Berger's (1992) thermoluminescence age of 23.5 ± 2.5 ka and Zic et al.’s (2002) radiocarbon age of 25.0 ± 1.1 ka to 24.8 ± 1.0 ka. The preferred age is the most recently revised age of 24.8 ± 1.0 ka.

Tephra Mp (Figure 4) is a tephra from eruption set M from Mt. St. Helens during the Cougar stage (Mullineaux, 1986; Clynne et al., 2009). Davis (1985) reported the depositional age of Mp as 22.23 – 24.27 ka1. Mullineaux (1986) reported it between 21.01 – 22.38 ka2, Langridge (1998) reported it as 21.72 ± 0.73 ka3, and ~22.9 ka reported by Clynne et al. (2009) and Kuehn and Negrini (2010). The preferred depositional age for Mp is 22.9 ka.

Black tephra is one of the few mafic tephras in the upper portion of the Summer Lake basin’s stratigraphy (Figure 4). Its depositional age was determined through an age vs. depth model where other independent geochronometer ages are plotted against stratigraphic depth and a fitted trend is applied to determine the depositional ages of beds that didn’t have another method of being dated (Kuehn and Negrini, 2010). This method

1 Originally reported as 18,650 ± 550 – 20,350 ± 500 years B.P. and was calibrated in this study.
2 Originally reported as 19,200 – 20,400 years B.P. and was calibrated in this study.
3 Originally reported as 19,800 ± 600 years and was calibrated in this study.
was needed for this tephra because of its young age and a lack of datable material. There have been contradicting analytical results published correlating the tephra to different possible known mafic tephras: Negrini and Davis (1992) determined a depositional age of 18.24 ka, Langridge (1998) modeled an age of 14 – 17.5 ka, and Kuehn and Negrini (2010) modeled this tephra’s depositional age to 20.4 ka. All three ages were determined using age vs. depth models. In this study, the preferred depositional age for the black tephra is 20.4 ka.

**Pluvial Lake Levels and Earthquakes**

Throughout the Quaternary, lakes in the Northwestern Basin and Range grew during glacial periods and receded during interglacial periods (Cohen et al., 2000; Negrini et al., 2000). Today, Summer Lake is a very shallow (<2 m deep) (Figure 5), closed basin lake (Cohen et al., 2000). Summer Lake, Lake Abert, and XY Lake are sub-basins of a larger basin that hosted pluvial Lake Chewaucan (Figure 1; Allison, 1945, 1982; Cohen et al., 2000). Stratigraphy and dating of paleoshorelines have been used to reconstruct lake levels of Lake Chewaucan throughout the last ~250,000 years (Allison, 1982; Davis, 1985; Negrini and Davis, 1992; Freidel, 1993; Cohen et al., 2000; Negrini et al., 2000; Licciardi, 2001; Zic et al., 2002; Egger et al., 2018). For the purpose of this study, I will only focus on the last ~80,000 years, comparing the lake level changes to the timing of earthquakes in the Summer Lake basin.

Summer Lake’s history is poorly constrained prior to ~45 ka. Using the hydrograph for the past 45 ky, I estimate shallow water sediments to indicate a shoreline elevation at ~1300 m, deep water sediments indicate a shoreline elevation at ~1350 m, and very deep water sediments indicate a shoreline elevation of ~1400 m. Based on sedimentary deposits, the lake was deep from 65 – 60 ka followed by a period of shallow water (Figure 5). From 45 – 25 ka, the lake was very deep (Figure 5), and the three sub-
Figure 5. Combined Hydrograph and Earthquake Record of Summer Lake and the Ana River fault (ARF), Winter Ridge fault (WRF), Slide Mountain fault (SMF), and Thousand Springs fault (TSF). Earthquakes age constraints from the Ana River fault are from Langridge (1998) and Egger et al. (2018); age constraints from the Winter Ridge and Slide Mountain faults are from Pezzopane (1993). The gap in deposition is from Cohen et al. (2000), Negrini et al. (2000), and Negrini and Davis (1992). Exposure of Paisley fan unconformity is from Jenkins et al. (2012) and Allison (1982). Ages of tephra deposits are discussed in text. Revised from Egger et al., 2018.
basins were connected: Summer Lake, XY lake, and Lake Abert (Figure 1). From 25 – 13 ka, the lake fluctuated but stayed relatively deep (Figure 5). For the past ~13 ky the lake has been close to modern levels with a slight increase in elevation ranging 1280 – 1290 m during 3 – 7 ka (Figure 5) (Allison, 1982; Pezzopane, 1993).

Timing of earthquakes on the faults in the Summer Lake basin are variable throughout the Pleistocene and Holocene (Egger et al., 2018). Some studies have suggested that faults can rupture in clusters or swarms in response to lakes growing and receding causing a change in stress, pore pressure, and fluid paths within the crust (Gupta, 2002). Models suggest that the rate of loading or unloading of a body of water has a significant effect to the resistance of failure along faults (Bell and Nur, 1978). For example, the quick removal of Summer Lake would cause weakening in the crust due to the pore pressure decreasing at a much slower rate than the removal of the lake thus causing failure along the faults that lie beneath the lake (Bell and Nur, 1978). Pluvial lakes in the Basin and Range had rapid transgressions, some lakes dropping up to 80 m in 1 ky (Benson et al., 1990; Egger et al., 2018). The rapid removal of Summer Lake could have played a role in when the faults rupture by causing a change in the state of stress in the crust.
CHAPTER III

METHODS

Trenching

Potential trench locations were sought along the TSF with scarp heights ≤ 2 m on Bureau of Land Management (BLM) land that was accessible by existing roads (Figure 2). We excavated two trenches across the TSF using a backhoe (Figure 6). The southern trench was 40 m long and 0.5–2 m deep (Figure 6). The northern trench was initially 40 m long and 0.5–2 m deep, but due to the height of the water table, we only focused on the westernmost 12 m (Figure 6). We also excavated a 3 m-square bench at meter 6 of the south wall, both for safety and a 3D exposure of the fault zone (Figure 6).

We scraped the trench walls smooth to remove backhoe markings and roots, gridded the walls with a 1 by 0.5 m string grid, marked unit and fault contacts with colored nails, collected samples for tephrochronology and radiocarbon dating, and photographed the gridded, marked walls. I created orthomosaics of the photographs using Agisoft Metashape and logged the stratigraphy, faults, and sample locations on the mosaics in the field. For the southern trench, I logged a total of 28 m (Figure 6; Plate 1) and for the northern trench, I only logged a total of 12 m (Figure 6; Plate 2). I made the decision to not map the entire trenches dug due to a couple of reasons; First, the eastern sides of both trenches exposed the footwall stratigraphy, which was mostly horizontal and undeformed and didn’t provide new information thus I chose to only log 10 m of the footwall in the southern trench and 5 m of the footwall in the northern trench (Figure 6). Second, for the northern trench, I chose to only log the 12 m that spanned the fault zone due to a very high (near surface) water table that had to be continuously pumped while we logged.
Figure 6. Thousand Springs Summer 2019 Trenches. Full extents of trenches shown in pink. Extent logged on trench logs in light orange. TSF trace in red. Shaded relief DEM is derived from DOGAMI database (Niewendorp et al., 2013).
Radiocarbon Dating of Carbonate Samples

I collected eight carbonate sediment samples from the lake sediment units (Table 1, Appendix A12). Two samples were sent to Direct AMS in Bothell, WA, for radiocarbon dating, where they were processed as pre-treated carbonate sediment (Brock et al., 2010). Sample TS19EC34, which is a carbonate-rich sediment sample, came from the southern trench north wall (Plate 1). Sample TS19EC29, which is from a thin caliche horizon, came from the northern trench south wall east bench (Plate 2).

Tephrochronology

I collected 35 tephra samples from 12 tephra layers, most of them easily correlated with known tephras based on appearance (Table 2, Appendix A). Eight of the tephras were preliminarily identified in the field based on their physical characteristics and stratigraphic sequences through comparison to the published tephra record of the basin. All but two tephra samples were collected from the exposed section. The two additional samples were collected from the hanging walls at depth with an electric auger: TS19EC22 from the northern trench and TS19EC23 from the southern trench. This was done to attempt to correlate tephra units across the fault zone.

Of the 35 tephra samples, 16 were chosen for glass grain chemical analyses using the Scanning Electron Microscope (SEM) based on which samples will best provide an age constraint to different faulting events and the locations of where the samples were collected from. The samples were prepped using the standard operating procedures for creating resin mounts using the Struers CitoVac in CWU’s Murdock Lab (Appendix B).

For each sample, 30 glass grains were analyzed using the energy dispersive spectroscopy (EDS) method (Hafner, 2017) through the Aztec software (Oxford Instruments, 2011) (Appendix C). The chemistry spectra were normalized using an Aztec calibration file (Appendix B) I created specifically for standardizing volcanic glass
chemistry using known obsidian standards from the United States Geological Survey (USGS), National Institute of Science and Technology (NIST), and Max Planck Institute (MPI) (Froogatt, 1992). Each standard grain had 10 chemistry spectra collected spread across the grain to collect an accurate average of the glass’s chemical composition. Each composition collected was compared to the known compositions sent with the standards and a correction factor was determined for all elements to match the known compositions. These correction factors per element were used to create an Aztec standardization file.

By applying the standardization file to my collected data, I re-quantified and normalized the chemistry for seven of my 16 samples. The re-quantified chemistry of each tephra was then input into an excel model that ran a similarity algorithm which matched my data to the published data and output the best matched correlation for each of my samples along with a similarity coefficient on how accurately they match (Appendix D).

Using the combination of physical characteristics, stratigraphic order, corrected glass chemistry, and carbonate chronology, I correlated the tephras exposed in the TSF trenches to the published record to constrain the depositional age of each tephra layer.
CHAPTER IV

RESULTS

We dug two trenches perpendicular to the Thousand Springs fault (Figures 3 and 6). The fault scarp height at the northern trench is 2.1 m with a slope of 8.8° and at the southern trench is 1.8 m with a slope of 8.2°. The trenches exposed a 4-m wide fault zone with a total offset of 1.6 – 2.4 m and a stratigraphic section with twelve tephra units contained within ten mostly lacustrine sedimentary units (Figure 7).

Units Exposed

The units exposed in the trench walls are Holocene to Late Pleistocene and are divided into two groups: sedimentary units (Table 1) and tephra units (Table 2). The tephra group has eight recognizable tephras based on their distinctive physical characteristics and stratigraphic order and four thin, discontinuous tephras: thin-gray tephra, coarse-gray tephra, Tephra G, and Tephra E (Table 2). The well-defined eight tephras are referred to by their published names and occur in stratigraphic order from oldest to youngest: Tephra 2, Pumice Castle (PC), Tephra H, Mount St. Helens Cy (Cy), Wono, Trego Hot Springs (THS), Mount St. Helens Mp (Mp), and the Black Tephra. Further confirmation of the initial identification was achieved through glass grain chemistry and collected radiocarbon dates.

The stratigraphically deepest exposed tephra (Plates 1 and 2; Table 2) has physical properties (Table 2; Appendix A1) that correlate to the Ice Quarry tephra (Tephra 2). The glass chemistry of Tephra 2 (Table 3) furthers this correlation by matching with Tephra 2 (Ice Quarry) with a similarity coefficient of 0.969 (Table 4) and thus has a depositional age of 67.3 ± 7.5 ka.
Figure 7. Composite stratigraphic column from the Thousand Springs fault trench exposures. Colors indicate tephra layers with their identification and ages on the right. Radiocarbon dates (#34 and #29) are from this study. Furthest left column states lake level based on sedimentary units. Earthquake events are identified by stars and are placed in the relative position within the ages of the stratigraphy in which they occurred.

PC (Appendix A2) is exposed in both trenches (Plates 1 and 2: Table 2) with physical properties (Table 2) matching those of the Pumice Castle tephra from the ARF sites which has a published age of 71 ± 6 ka. The glass chemistry of the PC sample (Table 3) correlates to the Pumice Castle tephra, matching with a similarity coefficient of 0.96 (Table 4). This was the 8th best match where the top seven matches for my sample
Table 1. Sediment units exposed in both TSF Summer 2019 trenches. The Sand Dune unit states it “possibly contains Mazama ash” which is referring to the 7.6 ka eruption and is based on similar dunes reported to contain Mazama ash.

<table>
<thead>
<tr>
<th>Unit Descriptions - Sedimentary</th>
<th>Color and physical properties</th>
<th>Grain Size</th>
<th>Thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand Dune</td>
<td>Gray. Medium ripple cross beds (hard to see due to all same color). Dune shape with topography. Discontinuous. Possibly contains Mazama ash.</td>
<td>Sand</td>
<td>30 - 40</td>
</tr>
<tr>
<td>Colluvial Wedge</td>
<td>Gray. No bedding or other structures. Some broken tephra pieces present. Very cohesive and tough chunks.</td>
<td>Silt and clay</td>
<td>~95 (minimum, no base contact)</td>
</tr>
<tr>
<td>A (11,7,8)</td>
<td>Brown and tan color with ripple laminations. Well sorted. Contains Mp and black tephra.</td>
<td>Silt to fine sand</td>
<td>120</td>
</tr>
<tr>
<td>B (9)</td>
<td>Upper 8 - 14 cm dominately brown clay with tephra lenses and chunks. Rest of unit is dominately silt/fine sand with ripple laminations.</td>
<td>Clay to fine sand</td>
<td>24 - 34</td>
</tr>
<tr>
<td>C (10)</td>
<td>Brown with thin black ripple laminations. Well sorted. Pebble-rich thin layer within fairly continuous ~2 cm below wono</td>
<td>Silty clay to fine sand</td>
<td>23 - 25</td>
</tr>
<tr>
<td>D (1)</td>
<td>Tan color. Hardpan/caliche pebble layer discontinuous along base. Few roots present at base contact, gradational contact with Cy tephra below</td>
<td>Silt and sand interbedded</td>
<td>5 - 8</td>
</tr>
<tr>
<td>E (2)</td>
<td>Gray (slight tanish). Well sorted. Very small thin roots present throughout layer. Sharp contact with tephra H below (slight gradational with reworked silt/ash)</td>
<td>Silt to fine sand intermixed</td>
<td>6 - 8</td>
</tr>
<tr>
<td>Caliche layer (3)</td>
<td>White/gray color with black and dark colored pebbles. Consistently found under tephra H. Sharp erosional contact with Unit F.</td>
<td>Fine sand with ~5mm pebbles.</td>
<td>3 - 4</td>
</tr>
<tr>
<td>F (4)</td>
<td>Brown/gray color. Thin (2-3mm) carbonate lenses throughout. 0.25m section of dominately clay/silt with no carbonates about 10 cm above Pumice Castle. Soft and crumbly towards the top. Holds moisture well. TGT lenses present ~30 cm from top of unit</td>
<td>Fine sand intermixed with silt and clay (fines downwards)</td>
<td>~100</td>
</tr>
<tr>
<td>G (5&amp;6)</td>
<td>Brown and light tan (some thin black) laminations with ripple crossbedding. Carbonate lenses present throughout. Tephra 2 deposited within unit.</td>
<td>Silt and very fine sand interbedded</td>
<td>22 - 24</td>
</tr>
</tbody>
</table>
Table 2. Tephra units exposed in both TSF Summer 2019 trenches. Tephra names are from the References column.

<table>
<thead>
<tr>
<th>Unit Descriptions - Tephras</th>
<th>Unit name</th>
<th>Present in trenches</th>
<th>Color and physical properties</th>
<th>Grain Size</th>
<th>Thickness (cm)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black tephra</td>
<td>NT (only east wall), ST (both walls)</td>
<td>Black. Mostly continuous. Thinly ripple crossbeds of silt (brown, white/tan, and some black) above and below. 6.15 cm above Mp.</td>
<td>Silt</td>
<td>0.3 cm</td>
<td>Langridge, 1998; Kuehn and Negrini, 2010</td>
<td></td>
</tr>
<tr>
<td>MSH Mp</td>
<td>NT (only east wall), ST (both walls)</td>
<td>White to light gray. Biotite present at base. Continuous lenses. 21.05 cm above THS</td>
<td>Silty clay fines upwards</td>
<td>0.5 cm</td>
<td>Langridge, 1998; Kuehn and Negrini, 2010</td>
<td></td>
</tr>
<tr>
<td>Tego Hot Springs</td>
<td>NT (both walls), ST (both walls)</td>
<td>Tan/light gray to white. Thinly cross-bedded top 3 cm. Continuous in some sections, other parts very broken up</td>
<td>Silt to fine sand size fines upwards</td>
<td>6 cm</td>
<td>Langridge, 1998; Kuehn and Negrini, 2010</td>
<td></td>
</tr>
<tr>
<td>Thin White Tephra - below THS (Tephra E)</td>
<td>NT (north wall)</td>
<td>White. Discontinuous</td>
<td>Silt</td>
<td>0.25 - 0.5 cm</td>
<td>Langridge, 1998; Kuehn and Negrini, 2010</td>
<td></td>
</tr>
<tr>
<td>Wono</td>
<td>NT (both walls), ST (both walls)</td>
<td>Light gray to white. Pumice sand grains? Thin ripple crossbeds. Very broken up where exposed. Pebble layer consistently below</td>
<td>Sand to fine sand. Lenses of silty clay</td>
<td>4 cm</td>
<td>Langridge, 1998; Kuehn and Negrini, 2010</td>
<td></td>
</tr>
<tr>
<td>Thin White Tephra - below Wono (Tephra G)</td>
<td>NT (both walls)</td>
<td>White. Discontinuous</td>
<td>Silt</td>
<td>0.25 cm</td>
<td>Langridge, 1998; Kuehn and Negrini, 2010</td>
<td></td>
</tr>
<tr>
<td>Coarse Gray Tephra - unknown tephra</td>
<td>NT (both walls)</td>
<td>Gray, light gray intermixed. No clear bedding. Discontinuous lenses and pockets</td>
<td>Sand, well-sorted (no grading)</td>
<td>~10 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSH Cy</td>
<td>ST (both walls)</td>
<td>Light blue-gray while wet and white when dry. Dense amount of biotite present at base. Thinly cross-bedded top 5 cm. Continuous</td>
<td>Silt to sand size, fines upwards</td>
<td>12 - 14 cm</td>
<td>Langridge, 1998; Kuehn and Negrini, 2010</td>
<td></td>
</tr>
<tr>
<td>Tephra H</td>
<td>ST (both walls)</td>
<td>Light blue-gray while wet and white when dry. Some biotite present at base. Thinly cross-bedded top of pure tephra 0.5 cm and above is 2 cm of reworked gray silt and ash. Continuous. Caliche/hardpan pebble-rich layer consistently directly below.</td>
<td>Silt to fine sand size fines upwards</td>
<td>2 - 3 cm</td>
<td>Langridge, 1998; Kuehn and Negrini, 2010</td>
<td></td>
</tr>
<tr>
<td>Thin Gray Tephra - below H</td>
<td>NT (both walls), ST (both walls)</td>
<td>Gray. No bedding. Discontinuous lenses. Often carbonate lenses found ~ 2 cm above</td>
<td>Silt</td>
<td>0.2 - 0.4 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pumice Castle</td>
<td>NT (both walls), ST (both walls)</td>
<td>Dark brown/black with tan-white pumice sand-sized grains. Ripple cross-bedded throughout entire unit. Above unit is ~7 cm of reworked tephra and silty clay in ripple cross beds. Continuous</td>
<td>Coarse sand to sand sized fines upwards</td>
<td>10 - 12 cm</td>
<td>Langridge, 1998; Kuehn and Negrini, 2010</td>
<td></td>
</tr>
<tr>
<td>Tephra 2</td>
<td>NT (both walls), ST (both walls)</td>
<td>White and tan color. Thinly interbedded of silty and sand sized gray beds. clay tan/white</td>
<td>Fine sand to silt size</td>
<td>3 cm</td>
<td>Langridge, 1998; Kuehn and Negrini, 2010</td>
<td></td>
</tr>
</tbody>
</table>
The Cy tephra (Appendix A4) is exposed in both trenches but was only logged on the southern trench logs (Plate 1; Table 2). Its physical properties (Table 2) match those of the MSH Cy tephra exposed at the ARF sites, whose known depositional age is 45.6 ka. The glass chemistry of the Cy sample (Table 3) correlated to a Mount Saint Helens Set C tephra’s chemistry with a similarity coefficient of 0.904 (Table 4).

The Wono tephra (Appendix A5) is exposed in both trenches on both walls (Plates 1 and 2; Table 2). Its physical properties (Table 2) and stratigraphic order (Figure 7) correlate strongly to the ARF Wono tephra that has a depositional age of 29.1 ± 0.9 ka. Its glass chemistry (Table 3) matches to the glass chemistry of the Wono tephra with a similarity coefficient of 0.703 (Table 4). The similarity coefficient is the lowest for this sample because its top 50 matches were different samples of Tephra G, which is another tephra from Mt. Mazama. Tephra G dates ~30.5 ka and based on the physical properties of Wono and Tephra G, I chose the best matched Wono sample.

THS (Appendix A6) is exposed in both trenches on both walls but becomes eroded away on the west side of the northern trench (Plates 1 and 2). THS’s physical properties (Table 2) match well with the published physical properties of the THS tephra exposed at the ARF sites that has a well-published age of 24.8 ± 1.0 ka. Its glass chemistry (Table 3) also correlates to the Trego Hot Springs tephra with a similarity coefficient of 0.914 (Table 4). The similarity coefficient is also somewhat low for this sample because its top 50 matches were different samples of Wono, though many samples were listed as “Similar to Wono but younger,” which both Wono and THS are sourced from Mt. Mazama and are close in age. Based on the physical properties of THS and Wono, I chose the best matched sample that included THS.

Mp tephra (Appendix A7) is exposed on both walls in the southern trench (Plate 1; Table 2) and only in the eastern wall of the bench in the northern trench (Plate 2). Its physical properties (Table 2) and stratigraphic order (Figure 7) correlate strongly to the
Table 3. Normalized glass chemistry of 11 tephra samples in oxide weight %.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Field ID</th>
<th>SiO2</th>
<th>TiO2</th>
<th>Al2O3</th>
<th>FeO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na2O</th>
<th>K2O</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS19EC04</td>
<td>Thin Gray Tephra</td>
<td>66.89</td>
<td>0.89</td>
<td>15.07</td>
<td>5.11</td>
<td>1.42</td>
<td>4.04</td>
<td>4.47</td>
<td>2.10</td>
</tr>
<tr>
<td>TS19EC05</td>
<td>MSH Cy</td>
<td>78.24</td>
<td>0.00</td>
<td>13.28</td>
<td>0.95</td>
<td>0.23</td>
<td>1.46</td>
<td>3.61</td>
<td>2.24</td>
</tr>
<tr>
<td>TS19EC06</td>
<td>Pumice Castle</td>
<td>71.32</td>
<td>0.60</td>
<td>14.94</td>
<td>3.02</td>
<td>0.78</td>
<td>2.57</td>
<td>4.17</td>
<td>2.60</td>
</tr>
<tr>
<td>TS19EC07</td>
<td>Tephra 2</td>
<td>74.31</td>
<td>0.33</td>
<td>14.14</td>
<td>2.25</td>
<td>0.25</td>
<td>1.08</td>
<td>4.37</td>
<td>3.27</td>
</tr>
<tr>
<td>TS19EC08</td>
<td>Trego Hot Springs</td>
<td>75.75</td>
<td>0.29</td>
<td>13.71</td>
<td>1.80</td>
<td>0.31</td>
<td>1.36</td>
<td>3.95</td>
<td>2.84</td>
</tr>
<tr>
<td>TS19EC09</td>
<td>MSH Mp</td>
<td>77.46</td>
<td>1.57</td>
<td>12.60</td>
<td>1.11</td>
<td>0.28</td>
<td>1.38</td>
<td>3.45</td>
<td>2.15</td>
</tr>
<tr>
<td>TS19EC15</td>
<td>Wono</td>
<td>75.12</td>
<td>0.29</td>
<td>13.82</td>
<td>2.01</td>
<td>0.34</td>
<td>1.35</td>
<td>4.17</td>
<td>2.90</td>
</tr>
<tr>
<td>TS19EC19</td>
<td>Unknown CGT</td>
<td>77.82</td>
<td>0.00</td>
<td>13.45</td>
<td>0.95</td>
<td>0.25</td>
<td>1.49</td>
<td>3.71</td>
<td>2.33</td>
</tr>
<tr>
<td>TS19EC22</td>
<td>Cy - augured</td>
<td>77.82</td>
<td>0.00</td>
<td>13.45</td>
<td>0.95</td>
<td>0.25</td>
<td>1.49</td>
<td>3.71</td>
<td>2.33</td>
</tr>
<tr>
<td>TS19EC25</td>
<td>Tephra E</td>
<td>77.55</td>
<td>0.13</td>
<td>13.55</td>
<td>0.97</td>
<td>0.26</td>
<td>1.52</td>
<td>3.69</td>
<td>2.33</td>
</tr>
<tr>
<td>TS19EC26</td>
<td>Tephra G</td>
<td>77.69</td>
<td>0.11</td>
<td>13.65</td>
<td>0.95</td>
<td>0.04</td>
<td>1.51</td>
<td>3.76</td>
<td>2.29</td>
</tr>
</tbody>
</table>

Table 4. Correlated results of 11 tephra samples. Samples were matched using a weighted mean algorithm excel model provided by Stephen Kuehn. The model matched sample names are from a compiled database of tephra samples. *Not the number 1 match, discussed in text.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Field ID</th>
<th>Model Match</th>
<th>Similarity Coefficient (Weighted Mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS19EC09</td>
<td>MSH Mp</td>
<td>MSH M/18560-20350 (18.1-20.8 ka)*</td>
<td>0.883</td>
</tr>
<tr>
<td>TS19EC08</td>
<td>Trego Hot Springs</td>
<td>Similar to Wono and Trego*</td>
<td>0.914</td>
</tr>
<tr>
<td>TS19EC25</td>
<td>Tephra E</td>
<td>MSH Set C</td>
<td>0.967</td>
</tr>
<tr>
<td>TS19EC15</td>
<td>Wono</td>
<td>Wono*</td>
<td>0.703</td>
</tr>
<tr>
<td>TS19EC26</td>
<td>Tephra G</td>
<td>Strong similarity to MSH set C, could be Tephra OO of Davis (1985)</td>
<td>0.914</td>
</tr>
<tr>
<td>TS19EC19</td>
<td>Coarse-Grained-Gray</td>
<td>Wono Tephra</td>
<td>0.968</td>
</tr>
<tr>
<td>TS19EC05</td>
<td>MSH Cy</td>
<td>MSH set C</td>
<td>0.904</td>
</tr>
<tr>
<td>TS19EC22</td>
<td>MSH Cy (augured)</td>
<td>MSH Set C</td>
<td>0.901</td>
</tr>
<tr>
<td>TS19EC04</td>
<td>Thin-Gray-Tephra (below Tephra H)</td>
<td>MSH Set C</td>
<td>0.938</td>
</tr>
<tr>
<td>TS19EC06</td>
<td>Pumice Castle</td>
<td>Tephra 8 (Pumice Castle 1)*</td>
<td>0.960</td>
</tr>
<tr>
<td>TS19EC07</td>
<td>Tephra 2</td>
<td>Tephra 2</td>
<td>0.968</td>
</tr>
</tbody>
</table>
ARF Mp tephra that has a depositional age of 22.9 ka. The model also matched its glass chemistry (Table 3) to the Mt. St. Helens Set M tephra with a similarity coefficient of 0.883 (Table 4). This was the 7th best match where the top six matches for my sample were different samples of MSH Sets S or J. MSH So tephra (top match) dates 12.9 ka and MSH Jy (2nd match) dates 12 ka. Based on the stratigraphic position of my Mp tephra compared to THS and my carbonate sample TS19EC34, I chose the next best matched tephra which was MSH M.

The black tephra (Appendix A8) is also exposed on both walls in the southern trench (Plate 1; Table 2) and in the eastern wall of the bench in the northern trench (Plate 2). Its physical properties (Table 2) corelate with a couple black tephras but its stratigraphic order both in relation to the other tephras and the lake sediments correlate it strongly to a mafic tephra with a depositional age of 20.4 ka.

The four thin, discontinuous tephras, also in stratigraphic order, are thin, white tephra lenses ~3 cm below THS (Tephra E), thin white tephra lenses ~7 cm below Wono (Tephra G), coarse-grained, gray tephra lenses ~25 cm below Wono, and thin gray tephra lenses ~20 cm below tephra H.

There are 10 sedimentary units exposed in the trenches and 8 of them describe a cyclic transition from deep water to shallow water lake sediments and subaerial exposure (Table 1). The youngest unit are the colluvial wedges, seen in both trenches (Plates 1 and 2). The next youngest unit is a sand dune, only present in the northern trench on both walls (Plate 2 and Appendix A). Davis (1985), Langridge (1998), and Kuehn and Negrini (2010), found ash from the Mazama eruption in the sand dunes; therefore, we assume the sand dune exposed in our trench dates to ~7.6 ka. The rest of the sedimentary units are all lacustrine and are labeled A – G (Table 1).

Some of the lake sediments contained carbonate lenses, suggesting near-surface water depths (Appendix A). Sample TS19EC34, from the upper portion of unit A, has an
age of 12,998 – 12,735 cal B.P. (Plate 1, Table 5). Because TS19EC34 is laminar carbonate-rich sediment, its age represents depositional age and thus provides an age of the upper portion of unit A. Sample TS19EC29, from the upper portion of unit C, has an age of 29,773 – 29,127 cal B.P (Plate 2, Table 5). This sample’s age represents the caliche horizon’s depositional age.

Table 5. Radiocarbon results from Direct AMS, calibrated using OxCal’s INTCAL 13 calibration curve.

<table>
<thead>
<tr>
<th>ID</th>
<th>Sample Type</th>
<th>Amount Analyzed (g)</th>
<th>Radiocarbon Age</th>
<th>1σ</th>
<th>Calibrated years BP</th>
<th>% Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS19EC34</td>
<td>carbonate sediment</td>
<td>4.92</td>
<td>11002</td>
<td>44</td>
<td>12998 - 12735</td>
<td>95.4</td>
</tr>
<tr>
<td>TS19EC29</td>
<td>caliche piece</td>
<td>21.06</td>
<td>25383</td>
<td>98</td>
<td>29773 - 29127</td>
<td>95.4</td>
</tr>
</tbody>
</table>

**Sedimentation Rates**

No tephra units were exposed on either side of the fault zone this is why we decided to auger on the hanging wall to reach the next tephra below Wono, which allowed me to correlate the Cy tephra across the fault zone. To correlate other tephra units and calculate offset and slip rates, I developed a sedimentation rate model to estimate the thickness of the unexposed portion of the section between Cy and Wono on the footwall (Figure 7). I divided the thickness of sediments between Cy and tephra H (8 cm) by their age difference (8.5 ka), which produces a sedimentation rate of 0.9 cm/ka (0.009 mm/yr). Projecting this rate between Cy and Wono, which differ in age by 16.5 ky, gives a thickness of 15.5 cm, compared to the 75 cm between them on the hanging wall. I also used this rate to determine the thickness of the sediments between Wono and THS in the footwall which resulted in a thickness of 4.0 cm.

The assumption of a steady sedimentation rate suggested by Davis (1985) has since been revised due to the discovery of multiple unconformities and a more refined tephrochronology. Langridge (1998) discusses the variations in sedimentation rates seen
along the Ana River fault, which are similar to the variations we see in the TSF trench exposures (Figure 8). The lowest rates occur between tephra H and Cy (0.9 cm/ka (0.009 mm/yr)) (Figure 8). The average rate for the entire exposed section is ~5 cm/ka (0.05 mm/yr), but taking the unconformities into account suggests a sedimentation rate of ~12 cm/ka (0.12 mm/yr) below tephra H, <5 cm/ka (<0.05 mm/yr) from tephra H to Tephra G, and ~9 cm/ka (0.09 mm/yr) from Tephra G to the top of the section (unconformity below the dune) (Figure 8).

Fault Zones

The fault zone has a minimum width of 4 m with five strands (Plates 1 and 2). In the southern trench, the main strand is at meter 19, marked by a colluvial wedge to the W, offset of PC and tephra 2, and shearing of tephra H across a 0.3 m-wide zone (Plate 1, m 19 and Appendix E). In the northern trench, the zone is 8.5 m wide with 14 fault strands with the main strand at meters 5 – 6 (Plate 2 and Figure 9). On the eastern side of the main strand, PC and tephra 2 are present, and THS and Wono are on the western side (Plate 2 and Appendix F).

The fault strands dip steeply to the west (60 – 80°) (Plates 1 and 2). Some of the exposed units are more deformed: tephra 2 has boudinage present (Plate 2 box A) and PC has compaction deformation above the boudins in tephra 2 (Plate 2 box A). Tephra H is drag-folded over the main fault strand in the southern trench (Figure 10) only present on the north wall.

Event Evidence

From stratigraphic and structural evidence in the two trenches, I have interpreted at least five significant earthquakes to have occurred on the TSF in the northeastern
Figure 8. Age-vs-Depth Model for the stratigraphy exposed from the TSF 2019 trenches. Each tephra’s geochronological method is stated in the parentheses. Unconformity shifts are estimated based on sedimentation rates below them and uses the assumption that the higher sedimentation rate below the unconformity and how thick the unconformity layer is, the more time is missing. The grey error envelope is determined by the errors on the geochronometers. This simplified error envelope could be refined by incorporating error from depths of tephras and deposition time. Stars represent earthquake events and are plotted in the middle of their age constraints (except for Event 5 which is plotted closer to its older age constraint).
portion of the Summer Lake basin. This interpretation is my preferred number of events but also, is the minimum number of earthquakes exposed in the trenches based on the following evidence for each event.

**Most Recent Event (Event 1)**

There has been at least one event in the last 7.6 ky (Plate 2). The strongest evidence for the youngest event is seen in the northern trench, where a sand dune is truncated by a colluvial wedge (Figure 9). On the north wall, at meters 5 – 5.5, the contact between the sand dune and the sandy topsoil unit is gradual and sloping with the topography thus could be inferred as either a depositional contact or a fault contact.
Due to the fact that sand dunes across the basin have been documented to contain ash from the Mt. Mazama eruption at 7.6 ka (Davis, 1985; Langridge, 1998; Kuehn and Negrini, 2010), we make the assumption that the dune at our trench site formed \( \leq 7.6 \) ka. This event thus can be constrained to have occurred in the last 7.6 ky.

In the southern trench, the evidence for this event is seen by the youngest tephras: black tephra, Mp, and THS, all cut by fault strands (Figure 10). Assuming a constant sedimentation rate (0.9 cm/ka), which is a simplification, THS is offset by a total of 1.6 m (Table 6). The average offset for faulting in the Basin and Range is \( \sim 1 \) m (Wells and Coppersmith, 1994; Hemphill-Haley and Weldon, 1999) thus this 1.6 m of offset could be recording one or more than one event. With no evidence to distinguish an older event than the one that truncates the dune, we infer that there was one large event that happened in the last 7.6 ka (Figures 7 and 10). In the southern trench, the youngest dated offset material is lacustrine deposits (containing carbonates) above black tephra that we collected a radiocarbon age of 13.0 – 12.7 ka.

Event 2

The next event occurred between 7.6 and 12.7 ka (Figure 7). The primary evidence for this event is folding of black tephra, Mp, THS, Wono, and lacustrine deposits above and between the tephras, best seen in the southern trench (Figure 10), although folding is present in the northern trench as well (Plate 2). The dune is deposited on top of the folded sediments in the northern trench (Plate 4) which is the younger age constraint for the event. Other evidence includes small offsets (\( \sim 25 \) cm) of PC and tephra 2 and tephra H drag-folded over those offsets (Figure 10). The evidence suggests that at our trench sites, this event caused folding (Figures 11 and 12), though it is possible to have ruptured through the surface farther south on the fault where the scarp height is greater (Figure 3).
Events 3 and 4

Events 1 and 2 are based on observed differential offsets of Wono and Cy. Using a sedimentation rate of 0.9 cm/ka (0.009 mm/yr) calculated from the sediment thickness between Cy and tephra H (Figure 8), I projected the thickness between Cy to Wono on the footwall. For simplification, I projected the tephras as undeformed to measure total offset, which allowed me to determine a total offset of 2.4 m for Cy and 2.0 m for Wono. By reconstructing the stratigraphy and aligning THS (1.6 m), Wono is still offset by 40 cm and Cy by 80 cm (Table 6; Figures 11 and 12). This difference in total offset suggests that the Wono tephra experienced an event that THS didn’t, and that Cy experienced an event that Wono didn’t, thus requiring at least two earthquakes: events 3 and 4 that both were offset by ~0.4 m (Table 6).

Table 6. Calculated offsets per earthquake event on the TSF. The right column states the explanation how I estimated the total offset of the MSH Cy tephra (Cy), Wono tephra, and Trego Hot Springs tephra (THS). PC – Pumice Castle tephra. For event 5, I used the minimum and maximum sedimentation rates from the section to determine a range of offsets since the section between Cy and PC in the hanging wall was unexposed.

<table>
<thead>
<tr>
<th>Event</th>
<th>Offset</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.6 m</td>
<td>I used 0.9 cm/ky to project upwards on the footwall from Cy to Wono and THS</td>
</tr>
<tr>
<td>2</td>
<td>folding</td>
<td>I measured from the top of THS (projected on the footwall) to the top of THS in the hanging wall</td>
</tr>
<tr>
<td></td>
<td>~2 m</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.4 m</td>
<td>I used 0.9 cm/ky to project upwards on the footwall from Cy to Wono and THS</td>
</tr>
<tr>
<td>4</td>
<td>0.4 m</td>
<td>I used 0.9 cm/ky to project upwards on the footwall from Cy to Wono and THS</td>
</tr>
<tr>
<td>5</td>
<td>0.2 - 1.5 m</td>
<td>I used 0.9 cm/ky and 11 cm/ky to project downwards on the hanging wall from Cy to PC</td>
</tr>
</tbody>
</table>
Figure 11 Northern Trench South Wall Reconstruction of events. Scale is 1:1. From 9 – 12 m, the log is 3 m south compared to 0 – 6 m and the east wall of the bench is not shown. Colors indicate tephra layers and match figure 7’s colors. Modern Day shows the exposed tephras with Tephra H and Cy projected above the surface on the footwall using the known thickness between Pumice Castle, Tephra H, and Cy from further east exposures in the trench that were not logged. Cy is projected below Wono 75 cm on the hanging wall whose depth came from auguring. ~7,000 yrs ago shows the most recent event (MRE) removed and Trego Hot Springs (THS) realigned by shifting it up 1.6 m. Wono and THS were projected up from Cy on the footwall by using the sedimentation rate from between Tephra H and Cy (0.009 mm/yr) which was how the total offset of THS was determined. ~28,000 yrs ago shows event 2 and 3 removed and Wono realigned (which was offset a total of 2 m). ~45,000 yrs ago shows event 4 removed and Cy realigned (which was offset a total of 2.4 m). ~70,000 yrs ago shows Pumice Castle and Tephra 2 realigned and soft-sediment deformation removed.
Figure 12. Southern Trench North Wall Reconstruction of events. Scale is 1:1. Colors indicate tephra layers and match figure 7’s colors. Modern Day shows the exposed tephras with Wono and THS projected above the surface on the footwall using the sedimentation rate from between Tephra H and Cy (0.009 mm/yr) which was how the total offset of THS was determined. Cy is projected below Wono 75 cm on the hanging wall whose depth came from auguring. The folded tephras on both the hanging wall and footwall were projected assuming a simple folding (no other deformation) with constant thickness of sediment between the tephras. ~7,000 yrs ago shows the most recent event (MRE) and colluvial wedges removed and Trego Hot Springs (THS) realigned by shifting it up 1.6 m. ~13,000 yrs ago shows event 2 removed by unfolding the layers and realigning the small offset (25 cm) of PC. ~28,000 yrs ago shows event 3 removed and Wono realigned (which was offset a total of 2 m). ~45,000 yrs ago shows event 4 removed and Cy realigned (which was offset a total of 2.4 m).
**Event 5**

Evidence for this event is seen in both trenches. In the northern trench, both walls show Pumice Castle and tephra 2 more deformed than younger overlying tephras. Both PC and tephra 2 are folded with soft-sediment deformation between meters 1 – 4 (Figure 13). PC shows compaction deformation and tephra 2 is boudinaged beneath PC and pinches out at the fault zone (Figure 13). Sediments become more resistant to deformation as their shear strength increases (Collinson and Thompson, 1982). Shear strength is a function of grain cohesion, normal and shear pressure, excess pore-fluid pressure, and the angle of internal friction (Collinson and Thompson, 1982). This relationship indicates that if sediment is too deeply buried, the normal stress would be too high to allow soft-sediment deformation to occur. This relationship is our evidence to infer that the deformation we see in Pumice Castle and tephra 2 happened when the tephras were very close to the surface.

Figure 13. Box B from Plate 2: Northern Trench South Wall, 2 – 4 m, showing evidence of soft-sediment deformation of Pumice Castle and Tephra 2.

Because soft-sediment deformation occurs at saturated sediment depths of 1-2 m, and evidence suggests that lake level was high from ~70 – 60 ka (Figure 5), PC and
tephra 2 would have been at relatively shallow sedimentary depths (0 – 2 m) at this time (Collinson and Thompson, 1982). Thus, the oldest event can be constrained to 54.1 – 71 ka, likely closer to the older age constraint of 71 ka, when lake level was high and Pumice Castle was very close to the surface, if not at the surface.
CHAPTER V

DISCUSSION

Timing of Earthquakes in the Summer Lake Basin

In the past ~70 ka, there have been at least five significant earthquakes on the TSF (Figures 11 and 12). The five earthquakes occurred after ~7.6 ka, between 7.6 – 13 ka, between 24.8 – 29.1 ka, between 30.4 – 45.6 ka, and between 54.1 – 71 ka (Figures 5 and 7). The frequency and number of events is similar to that seen on the Ana River fault, suggesting that the TSF is just as active as the ARF (Figure 5). For both of these faults, the recent number of earthquakes could mean that they are experiencing a high faulting activity or that the geologic record is preserving them better than older events.

Comparing the earthquake timing on the TSF to the range-bounding WRF and SMF is more difficult because of the lack of documented earthquake histories of those faults. The WRF is the largest fault with the greatest offset, though there is only one documented earthquake that occurred 3.5 – 10 ka (Pezzopane, 1993). The SMF’s earthquake history is also difficult to constrain, though there have been at least two surface-rupturing events in the last ~18 ka (Pezzopane, 1993). Based on the amount of offset on these faults, they have to have had more earthquakes in the past compared to the ARF and TSF.

Comparing the timing of earthquakes on the TSF and ARF indicates that the faults in the basin are still active today. There has been at least one large (~ M7) earthquake in the last ~15 ka on both faults (Figure 5). Before ~15 ka, there was a period from 15 – 22 ka where none of the faults in the basin hosted earthquakes. Prior to 22 ka, the timing of earthquakes is poorly constrained, and it is more difficult to see patterns (Figure 5).
Based on the timing of earthquakes, the faults’ failures seem to be influenced by the same factors. The primary factor is the extension occurring in the crust which loads strain on the faults. Lake level changes could be a factor influencing the timing of earthquakes on the faults based on the clumped patterns we see in the Summer Lake basin occurring during periods following drastic lake level changes (Figure 5).

Stratigraphy

The tephrostratigraphy of the basin is well-documented and thus provides age constraints to the timing of earthquakes on the TSF (Davis, 1985; Negrini and Davis, 1992; Langridge, 1998; Kuehn and Negrini, 2010; Egger et al., 2018). The younger well-defined and documented tephras of the basin are evident in the exposed sections along the TSF, however four other tephras that are not well-documented or very distinctive because of their size/quantity: a thin-gray tephra below Tephra H, a coarse-gray tephra, a thin-white tephra below Wono, and a thin-white tephra below THS. Comparison to the ARF’s exposed stratigraphy from previous trenching studies show that we see the same well-documented, distinctive eight tephras seen in the TSF exposures and the four less-distinctive tephras. The tephras’ physical characteristics are very similar, mainly thickness varies slightly on either side of the basin. One tephra whose thickness is significantly different is tephra H. At the ARF trench sites, tephra H is thin (4 – 5 mm) and discontinuous (Langridge, 1998; Kuehn and Negrini, 2010). In the TSF exposed sections, tephra H is ~4 cm thick and continuous.

Half of the less-distinct tephras have been mentioned in previous studies (Davis, 1985; Langridge, 1998; Negrini et al., 2000; Kuehn and Negrini, 2010; Egger et al., 2018) but further works to more precisely determine depositional ages for the tephras and to correlate glass chemistry to a source could still be completed.
The oldest less-distinct tephra exposed in the TSF stratigraphy is a thin gray tephra below tephra H. This tephra is possibly the same as tephra H0.2 from Kuehn and Negrini (2010) where tephra H was commonly seen in other locations in the basin to have small tephra lenses ~20 cm below it (Kuehn 2019 personal communication). Its glass chemistry (Table 4) best matched with Tephra H with a similarity coefficient of 0.983 (Table 4).

One of the unknown tephras exposed in the TSF section – the coarse-grained, gray tephra below Wono is only exposed in the northern trench (Figure 14) and is not mentioned in previous studies. It is exposed in the TSF section in lenses up to 30 cm wide and 10 cm thick (Appendix A9). It is unclear whether this tephra is a new (not previously documented) tephra or a reworked lens from an older tephra. Its glass chemistry (Table 3) matched best with the Wono tephra for its top 15 matches with the top match having a similarity coefficient of 0.968 (Table 4).

The other two less-distinct exposed tephras – thin, white tephras below Wono and THS – have been documented in previous studies (Langridge, 1998; Kuehn and Negrini, 2010; Egger et al., 2018). The older of the two (one below Wono) is most likely tephra G,
described as a white, thin (0.3 – 1.5 cm), silt–very-fine-sand grained, discontinuous tephra (Langridge, 1998; Negrini et al., 2000; Kuehn and Negrini, 2010). In the TSF exposures, this tephra matches those physical descriptions and stratigraphic location thus correlates strongly. Tephra G has published depositional age of 30.5 ± 0.4 ka from Langridge (1998) and an age vs. depth modeled age of 30.4 ka from Kuehn and Negrini (2010). This tephra’s glass chemistry (Table 3) matched best with MSH set C tephra with a similarity coefficient of 0.914 (Table 4) or Tephra OO with a similarity coefficient of 0.908.

The youngest of the less-distinct tephra is likely the same tephra as tephra E also documented in previous studies (Langridge, 1998; Kuehn and Negrini, 2010; Egger et al., 2018). Tephra E’s glass chemistry is hard to distinguish from THS’s thus is suggested that tephra E is an earlier event from the same vent that erupted THS – Mount Mazama (Davis, 1983; Langridge, 1998). Langridge (1998) assigned a depositional age of 23.8 ± 0.3 ka for tephra E based on the sedimentation rate between the THS and Wono tephra which is a consistent age based on the chronology of Mount Mazama’s eruptions (Bacon and Lanphere, 2006). This tephra’s glass chemistry (Table 3) matched best with MSH set C tephra with a similarity coefficient of 0.967 (Table 4) or Tephra OO with a similarity coefficient of 0.956.

In addition to the tephrochronology, radiocarbon dating of carbonate-rich sediments has further provided age constraints on the exposed section that previously was unconstrained. While radiocarbon dating of carbonates can sometimes be unreliable due to a discrepancy between the external and the center of the carbonates – carbonate cores are the first to precipitate and thus are older than the precipitate layers that grow over the core (Hajdas et al., 2004), it can be reliable when (1) the samples are leached to remove any younger surface contamination and precipitants and (2) when carbonates are younger than 20 ka which will also help to avoid the difference in ages of the external precipitants
and the core of the carbonates (Hajdas et al., 2004). Sample TS19EC34 is younger than 20 ka and resulted in a radiocarbon age (12,998 – 12,735 cal B.P.) that fits the tephrostratigraphy well (Figure 7; Table 5). The sample is a laminar carbonate in Unit A which provides a depositional age of the upper portion of the unit. Though the other sample (TS19EC29) is not younger than 20 ka, its radiocarbon age (29,773 – 29127 cal B.P.) still agrees well with the tephrostratigraphy that we have independently identified (Figure 7; Table 5). Sample TS19EC29 is from a caliche layer directly below Wono and provides the depositional age of that layer.

The calculated sedimentation rates at the Ana River sections is similar to the calculated rates at the Thousand Springs section, as would be expected based on the proximity of these two section. Langridge (1998) determined a sedimentation rate on the hanging wall of the ARF between THS and Wono to be 0.085 mm/yr (35 cm over 4100 years) compared to what I calculated for that same section on the TSF to be 0.067 mm/yr (29 cm over 4300 years) (Figures 7 and 4). The slight difference between the two rates is likely due to the proximately of the ARF site being closer to the steep edges of the northwestern portion of the basin and the input from the Ana River while the TSF’s location is more in the center of the basin thus further from the basin’s edge with no river to input sediment. On average, the sedimentation rate at the ARF site is ~1.3 times higher than at the TSF site (Figures 7 and 4) thus the rates across the northern part of the basin are similar.

Overall, the stratigraphy exposed in the TSF trenches is very similar to the stratigraphy exposed along the ARF. Minor variations are likely due to the elevation of the two sites where the ARF runs through a slightly lower elevation of the basin than the TSF (Figure 3). The exposed stratigraphy in the TSF trenches expands the knowledge of tephras extent within the basin since no published work has been done on the northeastern portion of the Summer Lake basin.
Earthquake Timing Compared to Lake Level History

There is a possible correlation between timing of when lake level drops rapidly and the faults rupturing (Figure 5), as has been proposed previously by Bell and Nur (1978), Benson et al. (1990), Scarberry et al. (2010), and Egger et al. (2018). The last high stand of Lake Chewaucan was around ~15 ka. The most recent earthquakes on the TSF occurred after ~15 ka: EQ1 after 7.6 ka and EQ2 between 7.6 – 13 ka (Figure 5). The timing of the most recent earthquakes on the TSF is similar to the ARF and the only documented earthquakes on the WRF and the SMF (Figure 5). The WRF and SMF earthquake history before ~15 ka is unknown thus makes correlating their earthquakes to lake level changes difficult. The lake level data of Summer Lake spans the past 250 ky (Negrini et al., 2000; Zic et al., 2002; Egger et al., 2018) though Figure 5 only shows the past 80,000 years and lake levels before 45 ka are less precise.

The older events on the TSF are harder to interpret due to their poor timing constraints but EQ3 does occur around the time Summer Lake regressed from its maximum high stand for the last ~80 ka which was around 24 – 27 ka (Figure 5). We also could be seeing a possible correlation between the growth of Summer Lake 35 – 50 ka and the timing of EQ4 on the TSF and Event 6 on the ARF (Figure 5) where the loading of the lake could have led to failure on both the faults.

Seismic Hazards of Low-Strain-Rate Regions

The seismic hazard of Summer Lake is low due to the low frequency of large (~M7) earthquakes and the risk is low due to the small population in the valley. Previously, the understanding of the seismic hazards of the basin came from the western margin, where the documented earthquakes are minimal in amount for a large portion of the basin area – most of the well-documented earthquakes are from the ARF in the northwestern
part of the basin. This study has provided more insight about the extent of seismic hazards in the Summer Lake basin as a whole. The TSF, which runs through the northeastern margin of the basin (Figure 2), has the potential to rupture based on our findings where previously was unknown. This could suggest that the northern portion of the basin, containing the ARF and TSF, has a slightly higher seismic hazard than the southern portion, thus increases the risk of the town of Summer Lake or that the lack of documented earthquakes from the southern portion is hiding a bigger part of the seismic hazard story.

Based on my findings of the timing of earthquakes on the TSF, low-strain-rate regions, like the NWBR, are most likely accommodating extension along both range-front margins and more towards the centers of the basins. The timing of earthquakes of all the faults could suggest that low-strain-rate region faults accommodate strain as a system, instead of independent of each other, due to the same factors influencing their failures. Another benefit of revealing the earthquake record of the TSF is providing data to see the variability of earthquake both timing and sizes across the faults of the basin. The timing of earthquakes on the TSF is variable with some events separated by short periods of no activity and some events separated by longer periods (Figure 5). Earthquakes on the ARF on average caused 1 m offsets (Pezzopane, 1993; Langridge, 1998) where for the TSF, the offset on average are 0.5 m (Table 6). The larger offsets for the TSF events, as discussed previously, could be recording one or more than one event.
A paleoseismic investigation on the Thousand Springs fault has exposed a minimum of five significant earthquake events in the past 80 ky which indicates a recurrence interval of ~14 ka (Figure 7): EQ1 occurred after 7.6 ka, EQ2 occurred between 7.6 and 13.0 ka, EQ3 occurred between 24.8 and 29.1 ka, EQ4 occurred between 30.5 and 45.6 ka, and EQ5 occurred between 54.1 and 71 ka. The offset per event ranges from 0.4 – 1.6 m (Table 6). The history of the TSF was unknown before this study, and this new record shows that it is as active as other major faults in the region. For low-strain-rate regions, 5 large events in 80 ky is considered highly active and thus the TSF plays a significant role in extension and deformation of the Summer Lake basin.

In addition to documenting the earthquake history of the TSF, this study provided more data to support the hypothesis that the rapid regression of Summer Lake and Lake Chewaucan has the potential to influence rupture on the faults in the basin (Figure 5).

Low-strain-rate regions, like the NWBR, are low in hazard but have the potential to be high in risk; Thus, to fully understand the seismic hazards of low-strain-rate regions like the NWBR, one must examine all active faults in the region. The TSF whose surface expression is minor compared to other faults in the Summer Lake basin, proved to be just as active as the other faults. The faults in these regions could also be influenced by factors such as changes in lake-level. This understanding could be applied to similar low-strain-rate regions where environmental influences may not have been considered before but now could provide insight into different factors influencing the timing of large magnitude earthquakes (> M6).
REFERENCES


Freidel, D.E., 1993, Chronology and Climatic Controls of Late Quaternary Lake Level Fluctuations in Chewaucan, Fort Rock, and Alkali Basins, South Central OR: University of Oregon, 244 p.


Hafner, B., 2017, Energy Dispersive Spectroscopy on the SEM:


Myers, B., and Driedger, C., 2008, Eruptions in the Cascade Range during the past 4,000 years:


Negrini, R.M., Erbes, D.B., Faber, K., Herrera, A.M., Roberts, A.P., Cohen, A.S.,


APPENDICES

APPENDIX A

TEPHRA AND CARBONATE SAMPLE PHOTOS

Figure A1: Tephra 2 (Ice Quarry Tephra)
Figure A2 A and B: Pumice Castle Tephra
Figure A3: Tephra H
Figure A4: Mt. St. Helens Cy Tephra (above Tephra H)

Figure A5: Wono Tephra
Figure A6: Trego Hot Springs Tephra
Figure A7 A and B: Mt. St. Helens Mp Tephra
Figure A8: Black Tephra
Figure A9 A and B: Coarse Gray Tephra Below Wono

Figure A10: Thin White Tephra Below THS
Figure A11: Thin Gray Tephra Below Tephra H

Figure A12 A and B: Carbonate Sediment
1. Switch machine **On** using button on right hand side back corner
2. If there is no **Tap Tube** or the one is has been used it will need to be replaced. The tap tubes are a **Single** use consumable. They are stored in a brown cardboard box in the cupboard under the Accutum 100.
3. Insert the new **Tap Tube** into the hole on the **Side** of the Citovac and make sure it is pushed all the way in. Place the tube through the **Pipe Section** on **Rotate** the **Black Knob** to close the tube off.
4. Check that the **Base Plate** which rotates is covered in **Aluminium Foil**, if foil is damaged/overly dirty replace foil. The replacement foil is stored in the drawer labelled Citovac.
5. Place **Samples** onto the **Kapton Tape** in the **Fixiform Moulds** and insert the **Sample Collar**.
6. Place **Samples** around the **Edge** of the **Rotating Base Plate** inside the Citovac chamber. **Rotate** the **Plate** and check that the **Center** of all the **Samples** sit under the **Tap** and to confirm they can be filled with resin.
7. Press the top center button and **Choose Method A** from the menu, push down the lid and press **Start**. The chamber will pump down the samples. Check the end of the tap tube to feel that it is not sucking air; if it is turn the black knob until air is no longer being sucked into the chamber through the tube.
8. Now mix the **Struers Epofix Resin** in the plastic cup using the ratio of **25g of Resin** to **3g of Hardener**.
9. **Note**: to create 12 samples of 10mm high mix 75g resin with 9g hardener.
10. Then **Stir** the resin/hardener mix by hand for at least 3 **minutes**, use the stop clock to time.
11. The resin then needs to **Rest** for 5 **minutes** to let the bubbles dissipate before filling the Fixiform moulds.
12. Place the **Cup of Resin** into the **Holder** on the Citovac and **Place** the **End** of the **Tap Tube** into the **Resin mix**.
13. Position the **First Sample mould** **Under** the **Tap** and **Rotate** the **Black Knob** to **Fill** the mould until the **Sample Collar** is completely **Covered** so the resin block will be approximately 10mm in height. This height ensures it will fit into the Tegramin 30 polisher and various analytical machines.
14. Once all **Sample Moulds** are **Full** release the vacuum by pressing the red stop button twice, the first press will only pause the program, second press cancels the program. Release the Vacuum but before the vacuum is completely gone Press the Green **Start button** again to Pump the chamber back to Vacuum. Repeat this Pumping Cycle a few times and then leave the samples under vacuum for the full Method A.
15. **Note**: If you notice a large number of bubbles in the resin release the vacuum and gently stir the resin. Then repeat Step 14.
16. Unless another user needs the Citovac, leave the samples in the chamber for 24 hours whilst the resin cures.
17. After 24 hours remove the samples from the Fixiform moulds using the Wupty tool stored in the Citovac drawer. The samples are now ready for polishing.
Cressington 208C Evaporative Coater
Standard Operating Procedures (SOP)


1. Instrument is kept under vacuum. Switch off power, remove bell jar and check that the desired stage is fitted. If not fit required stage.

2. **Remove Carbon Rods and Prepare**: one with a flat surface (using sandpaper) and one with the correct spigot - using the Pelco sharpening tool. Load the “flat” carbon rod in the right static holder with the end aligned just under half way over the circle in the backplate, tighten the allen bolt. Place the sharpened rod in the left holder, ensure the spring is retracted fully and the carbon rod is in contact with the other rod before tightening the allen bolt.

3. Wipe or Blow off any loose carbon flakes off the inside of the lid and chamber.

4. Load samples into chamber on the appropriate stage and in the correct position: (a) tilted at 30-35° for stubs (b) 0° for polished flat samples and place a small piece of filter paper partially under the sample(s). Replace bell jar. Rotate stage (speed 1) to check that none of the samples will hit the thickness monitor or cable.

5. Close the lid, hold it down and switch the coater **On** with the red power button (will light up).
6. Turn the thickness monitor on and press **Reset** to zero the monitor, confirm density of 1.0.
7. Wait until chamber pressure is lower than **10⁴ mbar**. This will take 5-10 minutes.
8. For stubs, start the stage rotating at the desired speed (4 or 5 is recommended).
9. **Outgas the rods:** select **Manual** and **Co** (up/down arrows swap mode), turn the voltage to zero press **Start/Stop** and rotate the manual control **Voltage** knob until the rods glow (100-125 A).
10. Switch to **Auto** (6s voltage 3.7) and press **START/STOP** to coat sample. Or use **Manual** and **Pu**, set voltage knob at **3.7** then hold **START/STOP** and adjust knob to ensure voltage stays around **150 A**. Check thickness and repeat until the desired thickness builds up (EDS 10-20 nm).
11. Stop the stage rotating. Turn off coater. Once vented, remove samples, loosen the carbon rod allen bolts using screwdriver, separate rods. Turn off thickness monitor. Switch coater back on.
SEM: Energy Dispersive Spectroscopy (EDS)
Standard Operating Procedures (SOP)

Instrument Lab room number: 310, Instrument Lab phone: 509-963-2704

Important: You can perform EDS with the CBS detector in place. EDS data can be collected from individual spots or on a raster grid to create a single Map or Large Area Mapping (LAM) – multiple maps stitched together.

Note: For Quantitative EDS the Electron Beam must be Calibrated on the Cobalt 99.999% pure Standard before EDS data collection.

Note: Data is collected using a USB thumb drive or external HDD by plugging it into the computer labelled Oxford. Data is stored on the D drive.

Suggested Operating Conditions
Accelerating Voltage (kV): 20
Spot Size: 5 or 6
Current (nA): 2.7 or 13 (see FEI beam current table)
Working Distance (WD): 10 mm

Sample Orientation

Sample Loading & SEM Setup
1. Follow instruction as for imaging for placing the sample(s) into the SEM and bringing the SEM to operating conditions.
2. Once a location(s) for analysis have been identified and focused then EDS analysis can begin.

Aztec Software Setup
1. Double Click on the Aztec icon on the desktop of the bottom left monitor.
2. The software will open to the Welcome to Aztec screen. Choose between creating a New Project or Open Project. For new samples not analysed before, click on New Project which will open a new screen called Create a New Project. Give the project a suitable Name and next to Location click Browse and navigate to the D drive and then open your own folder or create one naming it
YourSurnameFirstInitial. Choose the General Profile, unless you have created your own. Then click OK.

3. The AZtec software main screen will now be displayed.

4. In the Top-Left Corner check the software is in EDS-SEM operation not EBSD. Next select either Point & ID (individual spectra collection) or Map mode from the drop down menu. On the left hand side, Right Click on “Specimen 1” to Rename the sample.
5. Click on the **First Arrow** at the top labelled **Describe Specimen**, there are 4 tabs: Summary, Specimen Geometry, Pre-defined Elements and Image Registration. On the **Summary** tab, you can add notes about the project, specimen and site. At the bottom of the screen under **Specimen Coating Information**, check the box if the sample is coated and then ensure that the coating element is correct (normally carbon or gold or platinum) and enter the coating thickness in nanometers (nm).

6. On the **Specimen Geometry** tab, ensure that “**Use Pretitled Specimen Holder**” is **Not Checked**. The other information will be “grabbed” from the SEM.
7. On the **Pre-defined Elements** tab ensure that “**Perform AutoID During Acquisition**” is **Checked**, then the software will automatically identify and label the EDS spectrum peaks with elements. Or you can choose which elements the software should label by clicking on the periodic table, but it will only then label the elements chosen.

8. **Image Registration** tab can be used if an image collected from a source other than the SEM will be used for navigation. Click on **Browse** to select the image to load.
Quantitative Energy Dispersive Spectroscopy (EDS)

1. **Note:** Quantitative EDS can only be performed when the beam can be Calibrated on the Cobalt (Co) standard and it is in the SEM chamber at the same time as the samples i.e. the electron beam is not switched off between beam calibration and sample data collection.

2. On **Arrow 1, Describe Specimen**, on the left hand side, Right Click on “Specimen 1” to Rename the sample to **Cobalt Standard**. At the bottom of the screen under **Specimen Coating Information**, Uncheck the box next to “Specimen is Coated”, as the Cobalt Standard is not coated.

3. In the **Top-Left Corner** check that **EDS-SEM** is selected and choose **Optimize** from the drop down list. The screen will change to the **Optimize** window.
4. Ensure that the **Calibrate** tab is selected at the top of the screen. Next to **Routine** select **Beam Measurement** and check that the **Element** selected is **Cobalt**. Ensure that the entire field of view on the SEM is the Cobalt standard. Then click on **Start**.

5. Aztec will collect a beam measurement and the highlighted box represents where the characteristic X-Ray peak should be for the element chosen. If there is no peak in the highlighted box, then either the wrong element is selected or the SEM is at the wrong operating conditions for EDS or the sample is at the wrong working distance. Double check all of these items and run the beam measurement again.
6. Once AZtec has completed the beam measurement a message will appear stating ?click Yes. Then click Start again, to perform a second beam measurement. This time when the message appears it should be within X % of the previous beam measurement. If not, collect another beam measurement until it is.

7. Now the instrument is ready to collect quantitative data.

Spot Energy Dispersive Spectroscopy (EDS)

1. In the Top-Left Corner check that EDS-SEM and Point & ID are selected.
2. Click on the Second Arrow labelled Scan Image. Then click on Settings to choose the Input Signal from the SEM. Choose SE for secondary electron images or BSE for either backscattered or cathodoluminescence images. Then Define the Image Collection Parameters. For a quick image use a scan size of 1024 and a dwell time of 5µs, for a good quality image use 1024 and a dwell time of 35µs. To close the settings window just click on the screen outside of the settings window. Click on Start to collect a quick image. Check the image, if the brightness and contrast are not correct adjust the brightness and contrast in the SEM software and recollect the image by clicking Start.
3. **Note:** the **Input Signal** is captured from the **Top Left Quad** on the SEM screen, so the signal you would like to collect in the AZtec software needs to be located there.

4. Click on the **Third Arrow** across labelled **Acquire Spectra**. Then click on **Settings** to **Define the Collection** and **Display Parameters** for the EDS analysis. The maximum the **Energy Range** (keV) can be set as the **Accelerating Voltage** being used on the SEM (normally 20 keV for EDS), but due to **Overvoltage** each characteristic X-ray line needs 2.7 times the energy stated for full activation which means that emissions around 8 keV will be fully excited at 20 keV, so setting the energy range to 10 is a more practical
use of space. Use the number of channel at **2048**. The **Process Time** for Spot analysis should be **6**. Acquisition mode should be **Counts** and **500000** provides quality data. **Pulse Pile Up Correction** should always be **Checked**. Left click on the image at each location an EDS analysis should be collected. The spot in yellow is actively being measured, spots labelled in blue have not been analysed yet and spots labelled in white have already been collected. On the top right under **Data View**, on the **Data Tree** tab all of the collected spectra are shown and the actively being collected data shows a green bar which increases to show how close the data is to finish being collected.

5. **Note**: You can click on the previously collected spectra under the **Data Tree** to view them whilst the system is actively collecting the next spectra.

6. When all of the EDS spot analyses have been collected you have a few options: (A) move to a new location and repeat steps 2-4 or (B) collect a map at the current
location (C) move to the forth arrow labelled Confirm Elements (data processing) or (D) Finished with data collection.

7. **Note:** arrows 4 and 5, **Confirm Elements** and **Calculate Composition** (can only be done if a beam calibration was performed before data collection is begun) are both data processing and should be performed offline using **Post-processing PC1** in room 303.

8. **Option A:** Navigate the SEM to the next area where EDS spectra will be collected. If this is still on the same sample in the Aztec software return to Arrow Two, **Scan Image** and then click on **New Site**. The settings will still be as you set them earlier, so click on **Start** to collect an **Image** of the new area. Then move to Arrow Three, **Acquire Spectra** and select spots for analysis. If moving to a new sample return to Arrow 1, **Describe Specimen** and click on the + New Specimen button. A second specimen will appear **Right Click** and **Rename** and then repeat steps 2-4.

9. **Option B:** please follow the instructions under either **Single Map** or **Large Area Mapping (LAM).**

10. **Option C:** please follow instructions under **Post-processing Spot Data.**

11. **Option D:** go to **File-Save Project** and close AZtec by clicking on the **Red Cross** in the top right corner.

**Post-processing Spot Data**

1. Go to arrow four, **Confirm Elements.**
2. Highlight the **Spectra** under the **Data Tree** you wish to **Analyse.**

   The spectra will now be shown with the element ID’s the software has automatically assigned.
3. Double Left-click on a Peak on the Spectra and under Candidate Elements all possible matches to that peak will be shown. This list can then be evaluated to decide which element fits the peak(s) best. Then the element can be included or excluded from the Confirmed Elements list.

4. Repeat until all Peaks have been correctly Identified. Confirm this by looking at the Fitted Spectrum and checking for areas where it does not match the peaks. If the fitted spectrum matches the peaks well, then all elements have been correctly identified.

5. Note: if you have peaks that you still cannot identify turn on No Pulse Pile Up correction. If the peaks you cannot match are under an area with a lot of pile then the peak(s) are probably not real and are left over pile up peaks that have not been fully corrected for.
6. Save the project by going to File – Save Project.

Comparing Multiple Spectra
1. Click on Compare Spectra.
2. Go to the Data Tree tab and Highlight all of the spectra you would like to compare by holding down Control and Clicking on each Spectra. Once they are all highlighted click Add Selected Spectra.

3. All of the Selected Spectra will now be displayed on one graph for comparison.
4. The colour of each spectra can be changed by Clicking on the down arrow next to the colour square and number and choosing a new colour from the list.

5. The graph can be exported by Right-click within the graph and choosing Export - Save As or choose Export – Settings to define how the graph will be saved and then choose Save As.

Single Map Energy Dispersive Spectroscopy (EDS)

1. In the Top-Left Corner check that EDS-SEM and Map are selected. On Arrow 1, Describe Specimen, on the left hand side, Right Click on “Specimen 1” to Rename the sample.

2. Click on the Second Arrow labelled Scan Image. Then click on Settings to choose the Input Signal from the SEM. Choose SE for secondary electron images or BSE for either backscattered or cathodoluminescence images. Then Define the Image Collection Parameters. When mapping collect a good quality image, use 1024 and a dwell time of 35µs or higher. To close the settings window just click on the screen outside of the settings window. Click on Start to collect an image. Check the image, if the brightness and contrast are not correct adjust the brightness and contrast in the SEM software and recollect the image by clicking Start.
3. **Note:** the **Input Signal** is captured from the **Top Left Quad** on the SEM screen.

4. Click on the **Third Arrow** across labelled **Acquire Map Data**. Click on **Settings** to Define the **Collection Parameters** for the EDS analysis.

5. Choose **Resolution** of **1024** and use a **Fixed Duration**. The maximum the **Energy Range** (keV) can be set as the **Accelerating Voltage** being used on the SEM but due to **Overvoltage** each characteristic X-ray line needs 2.7 times the energy stated for full activation which means that emissions around 8 keV will be fully excited at 20 keV, so setting the energy range to 10 is a more practical. Use the number of channels at **2048** and a process time of at least **4**. The **Frame Count** and **Pixel Dwell Time (µs)**, will vary based on how much time can be spent collecting a single map. Then click **Start**.

6. Once an EDS map has been started you will see the screen fill up with colours representing the relative concentrations of each element.
7. **Note**: The colour of the map will keep changing as the software rebalances the colours to track the relative concentrations of the elements being identified.

8. Go to **File–Save Project** to ensure all map data has been saved.

9. When the EDS map has been collected you have a few options: (A) click on **TruMap** or **QuantMap** (can only be done if beam measurement was performed on Cobalt standard) to reprocess the map or (B) collect a **Large Area Map (LAM)** (C) move to a new location, create a **New Site** and repeat steps 2-8 to collect a single map (D) move to the forth arrow labelled **Construct Maps** (data processing) or (E) **Finished** with data collection.

10. **Note**: arrows 4 and 5, **Construct Maps** and **Analyze Phases** are both data processing and should be performed offline using **Post-processing PC1** in room 303.

11. **Option A**: Click on **TruMap** or **QuantMap** (can only be done if beam measurement was performed on Cobalt standard). The software will **Reprocess** the map using a mathematical algorithm to correct for artefacts, element overlaps and false variations due to X-ray background.

12. **Option B**: Follow the instructions under **Large Area Mapping (LAM)**.

13. **Option C**: **Navigate** the **SEM** to the next area where a map will be collected. If this is still on the same sample in the Aztec software return to **Arrow Two, Scan Image** and then click on **New Site**. The settings will still be as you set them earlier, so click on **Start** to collect an **Image** of the new area. Then move to **Arrow Three, Acquire Map Data** and click **Start**. If moving to a new sample return to **Arrow 1, Describe Specimen** and click on the + **New Specimen button**. A second specimen will appear **Right Click** and **Rename** and then repeat steps 2-8.

14. **Option D**: please follow instructions under **Post-processing Map Data**.
15. **Option E:** go to **File-Save Project** and close **AZtec** by clicking on the **Red Cross** in the top right corner.

**Large Area Mapping (LAM) Energy Dispersive Spectroscopy (EDS)**

1. In the **Top-Left Corner** check that **EDS-SEM** and **Map** are selected. On **Arrow 1, Describe Specimen**, on the left hand side, **Right Click** on “Specimen 1” to **Rename** the sample.

2. Click on the **Second Arrow** labelled **Scan Image**. Then click on **Settings** to choose the **Input Signal** from the SEM. Choose **SE** for secondary electron images or **BSE** for either backscattered or cathodoluminescence images. Then **Define the Image Collection Parameters**. When mapping collect a good quality image, use **1024** and a dwell time of **35µs** or higher. To close the settings window just click on the screen outside of the settings window. Click on **Start** to collect an image. Check the image, if the brightness and contrast are not correct adjust the brightness and contrast in the SEM software and recollect the image by clicking **Start**.

3. **Note**: the **Input Signal** is captured from the **Top Left Quad** on the SEM screen.

4. Click on **Automate**, this will open a new window. Choose **Rectangle** if just a collect a single line of maps is required or **Quadrilateral** for an area of maps and click **Next**.
5. On the SEM, **Navigate** to the **Top Left** corner of where the LAM should start and **Focus** the sample, ensuring the **WD** is **10mm**. **Unlink Z height** and then in Aztec click **Accept**. **Point 1** in the table will now be populated with numbers. **Navigate** to the **Top Right** corner and **Repeat** the process until all four corners have been defined, then click **Next**. Check that the X and Y numbers are in pairs, to ensure that the map has 90° corners.
6. Check how many **Fields** it will take to cover the area. Insert the number of fields into the **LAM Time Calculator** excel file to get an estimate of how long the LAM will take. Adjust the **Size** of the area to be mapped or **Magnification** to control the time it will take to perform the LAM. Once the area size and number of fields has been defined, Adjust the **Magnification** to ensure the highest magnification is used (that does not increase the number of fields), click **Finish**.

7. On the top right corner of the screen under **Data View** on the **Automation** tab there should now be an **Area** listed. Under the area there should be a line corresponding to the number of **Fields** (confirms the number of fields required to cover the area) and a second line stating **Electron Image** (confirms the LAM will collect images).

8. Click on the **Third Arrow** across labelled **Acquire Map Data**. Click on **Settings** to **Define** the **Collection Parameters** for the EDS analysis.
9. Choose **Resolution** of **1024** and use a **Fixed Duration**. The maximum the **Energy Range** (keV) can be set as the **Accelerating Voltage** being used on the SEM. Use the number of channels at **2048** and a process time of at least of between **2** to **4**. The **Frame Count** and **Pixel Dwell Time (µs)**, will vary based on how much time can be spent collecting a single map. Then click **Start**. Once happy with the collection conditions click on Automate and choose Existing Area and then click Finish. Now on the top right corner of the screen under **Data View** on the **Automation** tab there should be line for EDS in the list.

10. Then check the settings for the automation and ensure Turn Beam off at End is selected and so is align images using BSE.

11. **Note:** **NEVER EVER SELECT TURN FILAMENT OFF! THIS WILL BREAK THE SEM!!!!!!!**

12. Click on Run and the stage will move to the location of the first map, collect the **Image** and then collect the EDS map.

13. **Note:** The colour of the map will keep changing as the software rebalances the colours to track the relative concentrations of the elements being identified.

14. Go to **File-Save Project** to ensure all map data has been saved.

15. When the Automated run has finished click on the Monateg button and then have the BSE image selected and click Align and then Montage. This will stick all of the individual images together into one large one that will then appear in the data tree. The data can now be analysed offline.

16. **Note:** arrows **4 and 5**, **Construct Maps** and **Analyze Phases** are both data processing and should be performed offline using **Post-processing PC1** in room **303**.
17. **Option A**: Click on **QuantMap** (should only be used if a beam measurement was performed on the Cobalt standard at the start). The software will **Reprocess** the map using a mathematical algorithm to correct for artefacts, element overlaps and false variations due to X-ray background.

18. **Option B**: **Navigate** the SEM to the next area where a LAM will be collected. If this is still on the same sample in the Aztec software return to **Arrow Two, Scan Image** and then click on **New Site**. The settings will still be as you set them earlier, so click on **Start** to collect an **Image** of the new area. Then move to **Arrow Three, Acquire Map Data** and click **Start**. If moving to a new sample return to **Arrow 1, Describe Specimen** and click on the **+ New Specimen button**. A second specimen will appear **Right Click** and **Rename** and then repeat steps 2-8.

19. **Option C**: please follow instructions under **Post-processing Map Data**.

20. **Option D**: go to **File-Save Project** and close **AZtec** by clicking on the **Red Cross** in the top right corner.
APPENDIX C

SPECTRA MAPS OF CHEMISTRY SPECTRA COLLECTION LOCATIONS

TS19EC05 - 5X Magnification

C1: Spectra Map of Chemistry Spectra Collection Locations of Sample TS19EC05 – MSH Cy Tephra.
TS19EC09 - 5X Magnification

Top

A Spectra #s 1-10
B Spectra #s 11-20
C Spectra #s 21-30

E.Curtiss

TS19EC15 - 5X Magnification

C7: Spectra Map of Chemistry Spectra Collection Locations of Sample TS19EC22 – MSH Cy Tephra (augured sample).
APPENDIX D

EXCEL FILE OF TEPHRA CHEMISTRY MODEL INPUTS AND THE TOP 15 MATCHES

File is attached as an excel file located under supplemental documents.
APPENDIX E

SOUTHERN SOUTH WALL LOG RECONSTRUCTION OF EARTHQUAKE EVENTS

[Diagram showing geological layers and events over time]

- Modern Day
- ~7,000 yrs ago
  - Removed MRE
  - THS shifted up 1.6 m
- ~12 ka - folding event
Appendix E. Southern Trench South Wall Reconstruction of events. Scale is 1:1. Colors indicate tephra layers and match figure 7’s colors. Modern Day shows the exposed tephras with Wono and THS projected above the surface on the footwall using the sedimentation rate from between Tephra H and Cy (0.009 mm/yr) which was how the total offset of THS was determined. Cy is projected below Wono 75 cm on the hanging wall whose depth came from auguring. The folded tephras on both the hanging wall and footwall were projected assuming a simple folding (no other deformation) with constant thickness of sediment between the tephras. ~7,000 yrs ago shows the most recent event (MRE) and colluvial wedges removed and Trego Hot Springs (THS) realigned by shifting it up 1.6 m. ~13,000 yrs ago shows event 2 removed by unfolding the layers and realigning the small offset (25 cm) of PC. ~28,000 yrs ago shows event 3 removed and Wono realigned (which was offset a total of 2 m). ~45,000 yrs ago shows event 4 removed and Cy realigned (which was offset a total of 2.4 m).
APPENDIX F

NORTHERN NORTH WALL LOG RECONSTRUCTION OF EARTHQUAKE EVENTS

Northern Trench: North Wall

<table>
<thead>
<tr>
<th>Dates</th>
<th>Modern Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>~7,000 yrs ago</td>
<td>Removed MRE</td>
</tr>
<tr>
<td></td>
<td>THS shifted up 1.6 m</td>
</tr>
</tbody>
</table>

Known depth from augering

Trench Floor
Northern Trench: North Wall

Dates

~28,000 yrs ago

~45,000 yrs ago

~65,000 yrs ago
Appendix F. Northern Trench North Wall Reconstruction of events. Scale is 1:1. Colors indicate tephra layers and match figure 7’s colors. Modern Day shows the exposed tephras with Tephra H and Cy projected above the surface on the footwall using the known thickness between Pumice Castle, Tephra H, and Cy from further east exposures in the trench that were not logged. Cy is projected below Wono 75 cm on the hanging wall whose depth came from auguring. ~7,000 yrs ago shows the most recent event (MRE) removed and Trego Hot Springs (THS) realigned by shifting it up 1.6 m. Wono and THS were projected up from Cy on the footwall by using the sedimentation rate from between Tephra H and Cy (0.009 mm/yr) which was how the total offset of THS was determined. ~28,000 yrs ago shows event 2 and 3 removed and Wono realigned (which was offset a total of 2 m). ~45,000 yrs ago shows event 4 removed and Cy realigned (which was offset a total of 2.4 m). ~70,000 yrs ago shows Pumice Castle and Tephra 2 realigned and soft-sediment deformation removed.