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Seismic Source Characterization of Faults in the Portland and Tualatin Basins and a
Paleoseismic Study of the Gales Creek Fault, OR

by

Alison Elizabeth Horst

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
in
Geology

Thesis Committee:
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Portland State University
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ABSTRACT

Portland, OR lies within the tectonically active forearc of the Cascadia subduction zone. Several, potentially hazardous, northwest striking faults in and around the Portland Basin are classified as Quaternary active by the USGS, but little is known about their Holocene activity. Geologic and geodetic studies in the Pacific Northwest (PNW) document ongoing clockwise rotation of the region since at least 16 Ma. Models for crustal deformation in the PNW suggest northwest trending faults accommodate dextral shear inferred from increasing clockwise rotation rates west of Portland. I compiled structural information to improve the seismic source characterization of these faults, and using empirical scaling relationships for fault length and earthquake magnitude, I find that many of the faults in the region are capable of generating earthquakes of magnitude 6 to 7.

The focus of this study is the Gales Creek fault (GCF) which is the longest northwest-trending fault in the study area with prominent geomorphic expression, located 35 km west of Portland. In addition to a seismogenic source characterization, I investigated the GCF through paleoseismic trenching to document the style and timing of surface deforming earthquakes. I interpret three surface rupturing earthquakes from stratigraphic and structural relationships in the trench. Radiocarbon samples from offset stratigraphy constrain these earthquakes to have occurred ~1,000, ~4,200 and ~8,800 calibrated years before present. The penultimate earthquake backtilted a buried soil into the hillslope creating accommodation space that was infilled by a colluvial deposit. The most recent earthquake faulted and formed a fissure within the penultimate colluvial deposit. My results suggest the GCF is active, and has experienced at least three surface-

deforming earthquakes in the Holocene. New earthquake timing constraints presented here, combined with ongoing research on the central GCF will better constrain the lateral extent of prehistoric surface rupturing earthquakes, and can be used to refine magnitude estimates for the GCF.

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1. Introduction

Off the coast of the Pacific Northwest (PNW), the Cascadia subduction zone extends from Northern California to Vancouver Island, British Columbia. Here, the Juan de Fuca plate subducts beneath North America along the Cascadia megathrust. In the forearc, the Puget-Willamette lowland is home to several of the largest cities in the PNW including: Vancouver, B.C. (V), Seattle (Se), Olympia (O), Portland (P), Salem (Sa), and Eugene (E) (Figure 1) (Blakely et al., 2000). Seismic hazards in subduction zones include megathrust earthquakes and associated tsunamis, deep intraplate earthquakes, as well as distributed inland crustal deformation. Oblique convergence from the Cascadia subduction zone has led to arc-parallel migration of the forearc (McCaffrey, 1994; Wells et al., 1998) and evidence from GPS, geologic deformation, and paleomagnetic data reveal clockwise rotation of the crust, relative to stable North America (Wells et al., 1998). With deformation distributed across a network of crustal faults, slip rates are low and it is likely many of these faults have not been active in the historical time period.

Geophysical and geologic observations indicate the Portland Basin has experienced folding and faulting since the middle Miocene (Beeson et al., 1985; Blakely et al., 1995). Several northwest-striking faults in and around the Portland Basin (Figure 1) are classified as Quaternary active in the Quaternary Fault and Fold Database (QFFD) (U.S. Geological Survey, 2006), though little is known about their recent activity. The PNW is mountainous and densely forested, which makes identification of fault scarps in the field problematic. Surface expression on these faults has recently been revealed by high-resolution topographic maps, derived from Light Detection and Ranging (lidar). If rotation observed with GPS is accommodated as north-south compression and translation

Figure 1. Regional map of Quaternary active faults and microseismicity in the Portland and Tualatin Basins on a lidar-derived hillshade overlain on a transparent elevation map. Locations for all faults except Gales Creek and Sherwood are from Quaternary Fold and Fault Database; Gales Creek and Sherwood faults mapped by Wells and others (2018). Faults labeled: GC: Gales Creek (shown in red), BV: Beaverton, SH: Sherwood, MA: Mount Angel, CM: Canby-Molalla, BT: Bolton, OF: Oatfield, EB, East Bank, PH: Portland Hills, LL: Lackamas Lake, and DTC: Damascus-Tickle Creek (DTC shown on map but not included in seismic source characterization due to lack of data on the fault). (Inset) Tectonic setting of Pacific Northwest United States showing GPS surface velocity vectors (pink arrows) relative to a stable North America (McCaffrey et al., 2013, 2016). Cascadia Subduction zone labeled CSZ; rates of motion on the Juan de Fuca (JdF) and Pacific (PAC) plates are indicated by black arrows, modified from Carlson and others (2017). Black box shows area of Figure 1.

along northwest trending fault zones in the Puget-Willamette lowland (Wells and McCaffrey, 2013), then northwest trending faults in the Portland and Tualatin Basins are likely active and accommodating dextral slip.

The primary objective of this research is to evaluate faults in the Portland and Tualatin Basins and investigate whether they are active and accommodating regional stresses. In order to understand how crustal block rotation and northward translation is affecting faults around Portland, I present a catalog of fault characteristics from faults in the Portland and Tualatin Basins compiled using existing literature on fault parameters such as strike, dip, length, and sense of movement. The Gales Creek fault (GCF) is the longest northwest-trending fault in the study area with prominent geomorphic expression, located 35 km west of Portland. In addition to a seismogenic source characterization, I investigated the GCF through paleoseismic trenching to document the style and timing of surface deforming earthquakes. My results indicate the GCF is Holocene active and has experienced at least three surface-deforming earthquakes in the Holocene.

Over two million people live in the greater Portland metropolitan area, a region with mapped bedrock faults, and no paleoseismic studies to document prehistoric earthquakes. In 1993, the Scotts Mills earthquake occurred just south of Portland and caused approximately 30 million dollars in damage (Liberty et al., 2003). A similar rupture today closer to the populated city center would be devastating. Considering that the Gales Creek fault is Holocene active (results herein) due to regional north-south compressive stress, it is likely other, similarly oriented bedrock faults in the region are also active.

2. Geologic Setting

2.1 Pacific Northwest Tectonics

Strain accumulating in the forearc of the Cascadia subduction zone occurs from northeast-directed subduction as well as the northward migration of the Oregon forearc block (McCaffrey et al., 2013; Morell et al., 2017). Geologic studies along the Oregon Coast Range and Cascade Volcanic Arc have noted clockwise rotation from paleomagnetic north for at least the past 16 million years (Wells and McCaffrey, 2013; Wells and Simpson, 2001). Western Oregon has rotated 1.19 ± 0.1 degrees/m.y. about a vertical axis through most of the Cenozoic (Wells and McCaffrey, 2013). Block models have been developed to explain on-going rotation and translation of the Oregon coast and forearc (Wells et al., 1998; Wells and Simpson, 2001; Wells and McCaffrey, 2013). Deformation from rotation is expressed as extension in the Basin and Range, shortening in the northern Cascade Arc and across the Yakima fold and thrust belt. In the Oregon Coast Range and Puget-Willamette lowland, these models show that rotation is associated with translation along crustal faults. Observations of active high-angle crustal faults oriented in the northwest direction within the forearc of Cascadia suggest regional transpression (Morell et al., 2017). If the block models are correct, northwest trending faults accommodate Quaternary dextral displacement. Block models suggest the northern Oregon and Washington forearc are accommodating approximately 7-9 mm/yr. of shortening (Wells et al., 1998). Wells and others (1998) estimate the Oregon forearc block accounts for 4-7 mm/yr. of this slip. Accordingly, faults at the latitude of the Portland Metropolitan area (Table 1 and Appendix A) have an estimated distributed slip of

approximately 5 mm/yr., extending into the backarc (Wells et al., 1998; Wong et al., 2001).

The Portland region has had few historical earthquakes to inform seismic hazard characterization. There are about a dozen mapped faults in the Quaternary Fault and Fold Database (QFFD) (U.S. Geological Survey, 2006), and sparse paleoseismic data for the region. The Scotts Mills earthquake was one of the most notable historic earthquakes in the region. This $M_w = 5.7$ earthquake occurred on March 25, 1993, on a restraining bend of the Mount Angel fault just south of Portland (Blakely et al., 1995; Thomas et al., 1996). Focal mechanisms from this earthquake revealed reverse and right-lateral motion (Thomas et al., 1996). This is consistent with north-south compressive stress along the northwest trending Gales Creek-Mount Angel fault zone (Blakely et al., 2000). A similar rupture closer to the urban corridor would pose significant risk to infrastructure in the Portland metropolitan area (Wong et al., 2000; Tesfamariam and Wang, 2011).

2.2 Northwest Oregon Regional Seismic Sources

The seismic source characterization is a compilation of fault length, strike, dip, sense of movement, slip rate, most recent activity, displacement, and other fault parameters compiled from published literature and a review of earthquake focal mechanisms. The historic earthquake record is a very small portion of the entire fault record, and faults have likely not produced the greatest magnitude earthquake they are capable of in this time period (Burbank and Anderson, 2011).

There are twelve faults in the Portland and Tualatin Basins in the QFFD (U.S. Geological Survey, 2006), and numerous bedrock faults are mapped in the region (Wells et al., 2018). A fault is considered to be sufficiently active if it has ruptured in the

Holocene, since approximately 11 ka (Bryant, 2010). All of the faults in the Portland and Tualatin Basins included in the QFFD are classified as late Quaternary (<130,000 years) or older, besides the Mount Angel fault (latest Quaternary: <15,000 years) (U.S. Geological Survey, 2006) (Table 1). The Portland Basin has a long geologic history of deposition and erosion (Liberty et al., 2003) in a region that receives large amounts of precipitation. Therefore, any surface expression on these faults is likely indicative of geologically youthful features.

Wells and Coppersmith (1994) compiled a global catalog of surface rupturing earthquakes and earthquake parameters including fault type, rupture length, and magnitude earthquake produced, and developed an empirical scaling relationship for fault rupture length and earthquake magnitude. Using this relationship, I estimate the maximum magnitude earthquake that could be generated on the faults in the Portland area. I use Hanks and Bakun (2002) to estimate maximum earthquake magnitude based on fault rupture area, with maximum depth to the base of seismogenic crust in the PNW estimated between 20 and 25 km (Hyndman et al., 2003). I also used the relationship between displacement and rupture length from Wells and Coppersmith (1994) and calculated average displacement that could occur on each of these fault lengths. Primary characteristics of these seismic sources are shown in Table 1, and a more comprehensive database can be found in Appendix A. Information on maximum magnitude earthquake and average displacement can be found in Table 2.

2.2.1 Faults

The steeply dipping Portland Hills-Clackamas River fault zone and Sandy River-Frontal fault zones (also referred to as the Lackamas Lake fault), bounding the Portland

Basin, are interpreted to be right-stepping, right-lateral zones of a pull-apart basin (Yelin and Patton, 1991, Evarts et al., 2009; McPhee et al., 2014). McPhee and others (2014) interpret gravity data to suggest fold and thrust geometry resulting from Neogene compression has been superimposed on ancestral pull-apart basins. Major northwest-trending structures in the greater Portland Metropolitan region include the Portland Hills-Clackamas River, Gales Creek-Mount Angel, and Canby-Molalla fault systems (Figure 1).

The Portland Hills fault zone (PHFZ) includes the Portland Hills, East Bank, and Oatfield faults (Wong et al., 2001) (Figure 1). Previous studies report variable dips ranging from 70°-90°, and all structures in the PHFZ have dip-slip displacements (Blakely et al., 1995; Beeson et al., 1989; Yelin, 1992; Wong et al., 2000). Focal mechanisms for earthquakes between July-October 1991 along the PHFZ had right-lateral and reverse sense of strain (Blakely et al., 1995). The Portland Hills fault is widely interpreted to be steeply dipping to the northeast (Beeson et al., 1989; Pratt et al., 2001; Schlicker et al., 1964; Balsille and Benson, 1971). However, recent gravity data inverted for the region reveals a sub-vertical Portland Hills fault and steeply southwest dipping East Bank fault (McPhee et al., 2014). McPhee and others (2014) show normal, southwest-side-down, displacement of Columbia River Gorge Basalt (CRB) and Paleogene and Early Miocene sedimentary units across the East Bank fault. Aeromagnetic data show the Oatfield fault to have a significant reverse component, with 15 Ma CRB structurally above 1 Ma Boring Lava (Walsh et al., 2011; Fleck et al., 2014).

2.2.2 *Seismicity*

Focal mechanisms from historical seismicity demonstrate the Portland Basin has had elements of shortening, extension, and dextral slip on faults (Evarts et al., 2009). As previously mentioned, the Mw 5.7 Scotts Mills earthquake had reverse and right-lateral focal mechanisms. Conversely, on November 6, 1962, a Mw 5.2 earthquake occurred in the Portland Basin on a right-lateral fault and had a component of normal slip near Vancouver, WA (Yelin and Patton, 1991). A series of reverse-right lateral earthquakes $M \leq 2.8$ occurred along the northern end of the Portland Hills in 1982-1985 (Blakely et al., 1995; Yelin and Patton, 1991). During July-October 1991 there was another swarm of reverse-right lateral earthquakes at the north end of the Portland Hills with magnitudes ≤ 3.5 . The largest of the 1991 earthquakes showed reverse and dextral-slip mechanisms (Yelin and Patton, 1991; Yelin, 1992). Diverse earthquake focal mechanisms observed on faults indicate the Portland Basin has had a complicated history of deformation.

Table 1. Fault metrics for seismic source characterization. Ages from US Geological Survey (2006); references for other characteristics can be found in Appendix A.

Fault	Dip Direction	Dip Angle	Sense of Movement	Length (km)	Age (QFFD)
Beaverton	South	70°	Reverse	15	Middle and late Quaternary
Bolton	West	70°	Reverse & right-lateral strike slip	9	Class B (Various age)
Canby-Molalla	Northeast	70°	Right-lateral	51	Late Quaternary
East Bank	Northeast	70°-90°	Reverse & right-lateral strike slip	55	Middle and late Quaternary
Gales Creek	West	70°-90°	Reverse & right-lateral strike slip	73	Undifferentiated Quaternary
Helvetia	West	70°	Reverse & right-lateral strike slip	10	Undifferentiated Quaternary
Lackamas Lake	Southwest	70°	Normal & right-lateral strike slip	44	Middle and late Quaternary
Mount Angel	Northeast	60°-70°	Reverse & right-lateral strike slip	32	Latest Quaternary
Newberg	Southwest	70°	Reverse	8	Undifferentiated Quaternary
Oatfield	Northeast	70°	Reverse & right-lateral strike slip	40	Undifferentiated Quaternary
Portland Hills	Southwest	70°	Reverse & right-lateral strike slip	62	Undifferentiated Quaternary
Sherwood	South	50°	Reverse	14.5	N/A (from bedrock faults)

Table 2. Maximum earthquake magnitude and average displacement calculations for seismic sources. Regressions for maximum earthquake magnitude for strike-slip, normal, and reverse faults and average displacement from Wells and Coppersmith (1994). Regression for strike-slip faults using rupture area from Hanks and Bakun (2002).												
							Average Displacement (AD) (in m)	Maximum Magnitude Earthquake (M)				
							Strike-Slip	Strike-Slip	Normal	Reverse	Strike-Slip	
	SRL	Max	Min	Max	Min		$\log(AD) = -1.7 + 1.04 * \log(SRL)$	$M = (4/3) * \log(A) + 3.07 \pm 0.04$	$M=4.86+1.32*\log(SRL)$	$M = 5 + 1.22 * \log(SRL)$	$M = 5.16 + 1.12 * \log(SRL)$	
Fault	Length (km)	Depth (km)	Depth (km)	Area (km3)	Area (km3)			Max	Min			
Sherwood	14.5	25	20	362.5	290	0.3		6.5	6.4	6.4	6.5	
Portland Hills	62	25	20	1550	1240	1.5		7.3	7.2	7.2	7.2	
Oatfield	40	25	20	1000	800	0.9		7.1	6.9	7.0	7.0	
Newberg	8	25	20	200	160	0.2		6.1	6.0	6.1	6.2	
Mount Angel	32	25	20	800	640	0.7		6.9	6.8	6.8	6.8	
Lackamas Lake	44	25	20	1100	880	1.0		7.1	7.0		7.0	
Helvetia	10	25	20	250	200	0.2		6.3	6.1	6.2	6.3	
Gales Creek	73	25	20	1825	1460	1.7		7.4	7.3	7.3	7.2	
East Bank	55	25	20	1375	1100	1.3		7.3	7.1	7.1	7.1	
Canby-Molalla	51	25	20	1275	1020	1.2		7.2	7.1	7.1	7.1	
Bolton	9	25	20	225	180	0.2		6.2	6.1	6.2	6.2	
Beaverton	15	25	20	375	300	0.3		6.5	6.4	6.4	6.5	

2.3 *Gales Creek Fault*

The northwest trending Gales Creek fault forms the boundary between the Coast Range uplift and the Northern Willamette Valley (Figures 1 and 2a) (Blakely et al., 2000). The fault has significant surface expression, and a strong gravity gradient on the order of 110 mGal exists along at least 50 km of the fault (Wells et al., 2009). Magnetic data show 10-15 km of dextral offset in Eocene basement (Blakely et al., 2000; Wells et al., 2009; McPhee et al., 2014). Subhorizontal slickensides and drag folding are consistent with dextral slip on the fault (Wells et al., 2009; 2018). To the south and on trend with the GCF, the Mount Angel fault generated a 5.7 Mw earthquake in 1993. It is possible that the GCF connects with the similarly northwest trending Mount Angel fault in the subsurface (Blakely et al., 2000) (Figure 1).

If a fault has generated a large surface-rupturing earthquake in the late Holocene, surface expression should be apparent in local topography. Lidar and aerial imagery along the 73-km long GCF trace reveal strong surface expression in rugged, steep, forested mountainous terrain. Previous mapping identified uphill-facing scarps, offset streams, and shutter ridges along the western end of the GCF (Wells et al., 2009). Along the northern most part of the GCF, I analyzed the mapped fault trace and main stream channels using ESRI basemaps in ArcGIS and Google Earth. I mapped four dextrally deflected drainages in the study area of Clear Creek site (Figure 2b). Offsets were measured by projecting trends of both the upstream and downstream sections to the fault traces. Lateral displacement measured for all deflected drainages that crossed the GCF range from ~700 to 2,000 meters (Figure 2b, Table 3). The upstream channel of Iler Creek doesn't continue far past the fault trace; however, I include this drainage because

elevation profiles across the creek indicate a steep channel of up to 100 feet deep that continues to the northwest.

In 2016, the Bureau of Reclamation excavated two paleoseismic trenches on the GCF at Scoggins Dam (Figure 1). Reclamation trenches revealed faulted charcoal-bearing flood plain deposits, ^{14}C ages reveal the most recent event was Holocene in age (Redwine et al., 2017). Here, I present results from a new trench on the GCF near Clear Creek, north of the Scoggins Dam sites (Figure 1). Results from this study can be used to correlate evidence of surface rupturing earthquakes and earthquake timing along fault strike between sites, to geologically constrain minimum fault rupture lengths. The Holocene history of large paleoearthquakes on the GCF constrains GCF recurrence (earthquake frequency), its proportion of the regional slip rate budget, and past earthquake magnitudes for regional seismic hazard assessments.

Figure 2. (a) Topography along the Gales Creek fault, fault trace from Wells and others (2018) on a hillshade produced from a filtered DEM derived from lidar data. Arrows show relative sense of movement on the fault. (b) Northern section of the GCF with deflected drainages shown in blue and the GCF red. White solid lines show measured offset along drainage. Black box shows area of Figure 3a.

Table 3. Measurements of deflected drainages along the northern Gales Creek fault.

Stream Name	Channel Offset	Offset Measurement
Gales Creek	a – a'	753 m
Bateman Creek	b – b'	1,966 m
Iler Creek	c – c'	1,615 m
	c – c''	2,064 m
Parson's Creek	d – d'	1,459 m

3. Clear Creek Site

The Gales Creek fault is geomorphically expressed as well-defined linear breaks in slope along northeast-facing hillslopes in the area of the Clear Creek site. The Clear Creek site is located at the north end of the GCF (Figure 3). Local fault traces were previously mapped at a scale of 1:24,000 (Wells et al., 2018). I mapped small-scale (~1 m relief) tectonic and geomorphic features in the Clear Creek study area with lidar derivatives generated from 3-foot bare earth DEMs. Lidar was collected by the Oregon Lidar Consortium.

The Clear Creek trench site on the GCF is about 200 meters east of Clear Creek (Figure 3); it is flanked by a northeast-facing hillslope mapped as Eocene intrusive rocks of the Coast Range (Figure 3a) (Wells et al., in press). At the Clear Creek site, the GCF is mapped at the inflection point of the hillslope on the southwest edge of the side-hill bench, and on the northeast margin of the flat side-hill bench, where the slope of the ground surface rapidly increases to 30° (Figure 4). A sag pond is mapped ~30 m north of the site along the side-hill bench (Figure 3b). South of the site, I observe two side-hill benches, see elevation profile b-b' (Figure 5). A hand auger transect across the fault prior to trenching revealed abundant organic material for ¹⁴C dating and correlative stratigraphy vertically offset across a fault (Figure 4). The trench was positioned along a ~10-meter-wide, flat-lying, side-hill bench (Figure 3b).

Landslides are mapped in the region around Clear Creek trench as Holocene and Pliocene Landslide deposits (Wells et al., 2018) (Figure 3a). I find no evidence of such a disturbance upslope of the Clear Creek trench, and no evidence of hummocky topography for these types of deposits downslope or adjacent to the trench site (Figure 3b).

Figure 3. (a) Geological map of northern Gales Creek fault, Washington County, OR. (b) Slope map with contours showing the Gales Creek fault (red), a marsh along the fault, and locations of Figures 4 and 5 elevation profiles. Arrows show relative sense of motion (dextral) along the GCF.

Figure 4. (a) Photograph of the Clear Creek trench site before excavation, photo looking northwest along the Gales Creek fault. The break in slope along the hillside, indicated by a red line, is where the Gales Creek fault forms a sidehill bench in the topography. Person for scale on the northeast side of the photo. (b) Lidar-derived elevation profile taken in ArcGIS perpendicular to the Gales Creek fault trace, showing the trench outline in blue and v-trench outline in green (not to scale because of oblique angle to profile). Fault traces observed in trenches shown in red, and GCF inferred as dotted black line at depth.

Figure 5. Lidar-derived elevation profile taken perpendicular to the Gales Creek fault trace, highlighting two side-hill benches along a high ridge located approximately 100 m southwest of the Clear Creek site. See Figure 3b for location of elevation profile.

4. Methodology

We excavated a fault-perpendicular trench across the GCF near Clear Creek road, Gales Creek, Washington County, OR. The primary trench was approximately 12 meters long and 1½ meters deep and oriented N69°E. The trench was dug by hand and then deepened post fire season with a backhoe. Downslope, the backhoe also excavated a 7-meter long v-trench extension oriented N96°E, on the southeast end of the trench (Figure 3b). I collected differential GPS locations for the trench outline with a Trimble GeoXH and post processed points with GPS Pathfinder Software. We scraped trench walls to remove shovel marks and backhoe smear, and expose micro-stratigraphy. The trench exposure was gridded with a 1 m x 0.5 m nail grid as reference points for photomosaicing trench logs and taking measurements. High resolution orthomosaics were generated using Agisoft Photoscan software (Reitman et al., 2015). Stratigraphic units and structural relationships were documented and described on the photo logs, charcoal and OSL sample locations and bulk soil samples were also documented on these logs.

Sedimentological units were distinguished primarily based on soil type, color, moisture condition, and clast/grain size component percentages. I used detrital charcoal samples of key stratigraphic units to constrain the ages of the deposits using ¹⁴C dating. I collected a total of 300 detrital charcoal samples from all units, and selected 27 samples from 9 stratigraphic units for Accelerated Mass Spectrometry (AMS) ¹⁴C dating. I densely sampled stratigraphic units that closely bracket paleoearthquake horizons, and also selected samples from sequence stratigraphy between the key stratigraphic units for AMS dating (Table 4). Prior to lab submission, I cleaned the samples with DI water and removed excess material and modern rootlets. After samples were cleaned I sent them to

Lawrence Livermore National Lab Center for AMS (LLNL CAMS) for ^{14}C dating, ^{13}C splits were also measured. I used OxCal v4.3.2 (Bronk-Ramsey, 2009) to construct a calibrated age model for stratigraphic units and earthquakes identified at the Clear Creek site.

5. Results

5.1 Clear Creek Trench Stratigraphy

The Clear Creek trench exposed a buried organic soil horizon, slope-derived colluvium, and fissure deposits. I identify five primary stratigraphic units northeast of the fault zone, and four additional units southwest of the fault zone (Figures 6 and 7).

Figure 6. Stratigraphic columns and descriptions of deposits on a photomosaic base separated on either side of the GCF fault zone. The photomosaic is overlain with linework, black lines are unit contacts, and red lines are interpreted earthquake horizons (E1 and E2). Unit numbers are arbitrarily designated and displayed above soil type to the side of photomosaic.

5.1.1 Units Northeast of Fault Zone

The deepest and oldest stratigraphic unit, 90, is a massive, brown sandy silt, with 15-25 cm thick siltstone clastic interbeds. The clastic interbeds comprise approximately

<10% percent of the unit, the remaining >90% of the unit is massive sandy silt with pockets of gray clay. Unit 90 is located ~0.25 m to 2 m below the ground surface between meters H7 and H12 (in which H and V are trench wall grid coordinates and correspond with the trench logs, Figure 7). Unit 90 siltstone clastic interbeds consist of 1-7 cm sub-rounded to sub-prismoidal clasts that are oxidized brown, reddish yellow, dusky red, and white and contain redoximorphic mottles. The thin clastic interbeds dip 20-30° to the southwest. Unit 90 is an interbedded colluvium sourced by angular shale clasts of the Eocene Yamhill Formation (Wells et al., in press).

Unit 80 is a massive yellowish-brown silt, with 1% small, 1 cm to 3 cm sub-rounded tan, pink, and light orange weathered siltstone pebbles. Unit 80 has weak, blocky pedogenic structure, orange mottles and common charcoal fragments. Unit 80 is laterally continuous between meters H5 and H11, and dips ~20° to the southwest (Figure 7). Unit 80 unconformably overlies unit 90; the base of unit 80 is eroded and diffuse over a few centimeters.

Unit 40 is a dark grayish-brown silt, with 1% small, 1 cm to 3 cm sub-rounded tan, pink, and light orange weathered siltstone pebbles and abundant charcoal. The upper horizon of unit 40 dips ~10° to the southwest. (Figure 7). Unit 40 has a wavy basal contact that is gradational over 3 cm. Unit 40 ranges from a few centimeters thick at the northeast (Figure 7, H7) increasing in thickness to 0.5 m at the southwest (Figure 7, H3 – H5). We did not excavate to the base of this unit at the southwest (Figure 7, H3 – H5) where it is thickest. On the southeast wall meters H2 – H5 the stratigraphy darkened in color with depth from brown to dark grayish-brown, below this a second weaker medium grayish brown planar surface was observed. I interpret these changes in sediment

Figure 7. Photomosaics, linework, and interpreted trench logs for the northwest and southeast walls of the Clear Creek trench site. Radiocarbon sample locations are indicated by black solid boxes, calibrated and modeled age ranges are displayed in years before present. Southeast wall is reflected.

Figure 7. continued.

grading from top to bottom, lighter to darker, between H3 – H5, to represent two periods of soil development with a pulse of sedimentation separating the two soil horizons.

Unit 30 is a dark yellowish brown silty clay (80%) with boulders (20%). Boulders are matrix supported, and fine upward, primarily resting on the basal contact with underlying units 40 and 80. Boulders are sub-rounded to sub-angular diabase ranging from ~2 cm to ~0.5 m in diameter. The rest of the unit is made up of silty clay with iron-rich pebbles. Unit 30 is located between meters H2 – H8, and is ~0.25 m to 1 m below the ground surface (Figure 7). Unit 30 has a sharp basal contact, and unconformably overlies units 40 and 80. Unit 30 is interpreted to be slope-derived colluvium. Diabase boulders are sourced by the outcrops of ‘Intrusive rocks of the Coast Range,’ map unit Tis, as mapped by Wells et al. (2018), immediately upslope of the Clear Creek trench site (Figure 3). Sub-rounded to sub-angular diabase boulders reflect spheroidal weathering by exfoliation, rather than rounding as a function of transport (Wells et al., 2018)

Unit 10 is a dark brown, massive, silt with sparse angular pebbles. Unit 10 silt has granular pedogenic structure, abundant charcoal and roots, and is heavily bioturbated in places. It is the highest stratigraphic unit continuously exposed along the length of the trench. (Figure 7). The base of unit 10 is wavy and irregular; the basal contact is diffuse over 3-5 cm between meters H0 and H2, discontinuous and eroded between meters H2 – H4, and sharp between meters H4 and H12. Unit 10 is interpreted to be the modern soil A horizon.

5.1.2 Units Southwest of Fault Zone

Units 20, 50, 60, and 70 are mapped southwest of the fault zone, from meters H0 – H2 (Figure 7). These stratigraphic units do not visually correlate with the units mapped

northeast of the fault zone. Contacts between these units are diffuse, and distinguished primarily based on texture and component percentages of weathered pebbles, decreasing stratigraphically downward.

The deepest and oldest stratigraphic unit on the southwest side of the trench is unit 70, a massive dark brown silty clay. Unit 70 silty clay contains 1% small, 1 cm to 3 cm sub-rounded and sub-prismoidal weathered light orange, tan, and pink siltstone pebbles, decreasing stratigraphically downward. Unit 70 is 1.5 – 2 m below the ground surface, and the base of the unit is not exposed.

Unit 60 is a massive dark yellowish brown silty clay overlying unit 70, with a diffuse basal contact over 5-10 cm. Unit 60 contains ~7% sub-rounded and sub-prismoidal weathered light orange, tan, and pink siltstone pebbles, ranging in size from 1 cm to 3 cm. Unit 60 is ~1 m – 1.5 m below the ground surface on the southwest side of the trench.

Unit 50 is a massive dark yellowish brown sandy silt, with a diffuse basal contact over 5-10 cm. Unit 50 contains ~10% sub-rounded and sub-prismoidal weathered light orange, tan, and pink siltstone pebbles, ranging in size from 1 cm to 3 cm. Unit 50 is ~0.5 m – 1 m below the ground surface on the southwest side of the trench, and has a coarse, granular texture.

Unit 20 is a yellowish-brown silt, containing abundant charcoal and ~15% sub-rounded and sub-angular weathered light orange, tan, and pink siltstone pebbles, ranging in size from 1 cm to 3 cm. The basal contact of unit 20 is irregular and diffuse over 1 cm to 3 cm. The unit is granular with massive to single-grain structure, and is 0.25 m to 0.5 m below the ground surface.

5.2 Clear Creek Trench Structure

The Clear Creek trench exposed a 1-1.5 m-wide fault zone between meters H2 and H4 (Figure 7). The fault zone consists of 6 to 8 sub-vertical fault strands (Figure 7). The fault zone juxtaposes colluvium of unit 30 (northeast of meter H4) with units 50, 60, and 70 (southwest of meter H2). Vertical faults and shears extend upward in units 40 and 80, meters H5 – H8 (Figure 7). The fault that truncates unit 40 has a 24° strike and vertical dip (Figure 7). This strike is 73° oblique to the 311° striking primary fault trace mapped with lidar. The base of unit 40 is offset ~20 cm to 0.5 m across vertical faults between meters H5 and H6 (Figure 7). Units southwest of the fault zone are sheared between meter H1, V1 – 1.5 (Figure 7).

5.3 Deposit Age Estimates and Sedimentation Rates

Abundant organic matter in the stratigraphic units at the Clear Creek site provides the framework for my OxCal stratigraphic age model. The oldest unit, 90, is constrained with one sample and is between 14,262-13,900 calendar years before present (cal B.P.) Unit 80 is 10,377-8,823 cal B.P., and unit 40 is 8,940-6,852 cal B.P. On the southwest end of the trench, units 70, 60, and 50, fall between 5,904-5740, 5,586-5,331, and 1,698-1,544 cal B.P., respectively. Unit 30 is 1,293-1,063 cal B.P.; unit 20 is 280-64 cal B.P., and unit 10 is 960-0 cal B.P. (Figure 8, Table 4, Appendix G). Appendix G contains ages of samples not included in the OxCal models because they were stratigraphically inconsistent (i.e. stratigraphically higher samples were older and vice versa).

Figure 8. Summary of age results from stratigraphic ordering using OxCal Version 4.3 (Ramsey, 2017), showing probability density functions (pdf) for radiocarbon samples, with 2σ uncertainty shown by the solid bar below the pdf. Prior pdfs are light gray (e.g. sample GCF-T1-B-89) and represent the pdf calibrated ages; posterior pdf's are shaded dark gray, these pdf's are trimmed with stratigraphic ordering information in OxCal. Modeled paleoearthquake Pdf's are highlighted by pink bars.

Table 4. Radiocarbon results for detrital charcoal samples from the Clear Creek trench site. Samples listed in italic font were stratigraphically inconsistent and were not used in the Oxcal Model.

Sample Number	LLNL ID Number	Unit	$\delta^{13}\text{C}^*$	AMS Radiocarbon Age (yr B.P.) †	Calibrated Radiocarbon Age (cal. B.P.) ‡
GCF-T1-A-273	N121963	10	-25	190 ± 30	302-0
GCF-T1-B-184	N121022		-24.0	995 ± 25	960-799
GCF-T1-B-185	N121021		-27.8	145 ± 25	282-3
<i>GCF-T1-B-261</i>	N121964	20	-25	105 ± 30	280-64
<i>GCF-T1-B-207</i>	<i>N121023</i>	30	-25	<i>4445 ± 35</i>	<i>5284-4881</i>
GCF-T1-B-71	N121025		-29.0	1210 ± 25	1236-1063
GCF-T1-B-72	N121024		-25	1305 ± 30	1293-1181
<i>GCF-T1-A-17</i>	<i>N121026</i>		-29.5	<i>2080 ± 25</i>	<i>2125-1990</i>
<i>GCF-T1-A-167</i>	<i>N121029</i>		-25.2	<i>6400 ± 25</i>	<i>7415-7269</i>
<i>GCF-T1-A-204</i>	<i>N121028</i>		-24.2	<i>6000 ± 25</i>	<i>6911-6751</i>
GCF-T1-B-77	N121034	40	-22.4	6855 ± 30	7755-7615
GCF-T1-B-78	N121033		-25	6880 ± 60	7844-7601
GCF-T1-A-189	N121031		-23.4	7135 ± 25	8010-7883
GCF-T1-A-205	N121030		-25	6420 ± 220	7735-6852
GCF-T3-B-453	N121965		-25	7565 ± 30	8414-8344
GCF-T3-B-454	N121966		-25	8075 ± 35	8940-8771
GCF-T1-A-214	N121967	50	-25	1700 ± 30	1698-1544
GCF-T1-A-216	N121968	60	-25	4750 ± 30	5586-5331
GCF-T1-B-227	N121969	70	-25	5065 ± 30	5904-5740
GCF-T1-B-89	N121970	80	-25	7940 ± 30	8989-8823
GCF-T1-B-246	N121036		-24.6	9130 ± 25	10377-10227
GCF-T1-B-117	N121971	90	-25	12230 ± 40	14262-13900
LLNL, Lawrence Livermore National Laboratory; AMS, Accelerated Mass Spectrometry					
†The quoted age is in radiocarbon years using the Libby half-life of 5568 years and following the conventions of Stuiver and Polach (1977).					
‡Radiocarbon ages calibrated using OxCal v.4.2.4 software (Bronk Ramsey, 2008, 2009), using the IntCal13 atmospheric CO ₂ calibration curve (Reimer et al., 2013) and reported with 2σ error					
* $\delta^{13}\text{C}$ values are assumed values according to Stuiver and Polach (1977, p.355), without decimals. Values measured for the material itself are given with a single decimal place					

I calculated the sedimentation from an age-depth plot of ^{14}C samples collected from the Clear Creek trench (Figure 8) by separating the data into the two groups on either side of the fault zone. Units southwest of the fault zone (20, 50, 60, and 70) were grouped and a linear regression fit to the ^{14}C data yields a rate of 0.1 mm/yr., with a R^2 value of 0.91. Samples northeast of the fault zone in units 10, 30, 40, and sample 89 in unit 80 were grouped and yielded a sedimentation rate of 0.1 mm/yr., with a R^2 value of 0.41. Samples 246 (unit 80) and 117 (unit 90) were excluded, as they are out of stratigraphic order based on their age in comparison to the rest of samples in the dataset. I calculated a sedimentation rate for samples in unit 40, and a linear regression yielded a rate of 0.5 mm/yr. with a R^2 value of 0.84.

Figure 9. Scatter plot of calibrated radiocarbon ages versus stratigraphic depth below the ground surface. Sedimentation rates are calculated for samples southwest of the fault zone, northeast of the fault zone, and for unit 40. Open circles represent the two oldest samples excluded from the sedimentation rate calculation because tilting of the ground surface has made them stratigraphically higher than equivalent units just a few meters away.

5.4 Earthquake Evidence

I find stratigraphic and structural evidence for three surface-rupturing earthquakes at the Clear Creek site (E1-E3). We also find weak evidence for one younger large magnitude earthquake, and weak evidence for older surface deformation.

5.4.1 Event E1

Evidence for E1 is expressed as two primary vertical fault strands that extend upward and truncate unit 30, between meters H2 and H4 (Figure 7). These faults displace units 30 and 40 and form a roughly 1 m long and 0.5 m deep fissure within unit 30. The fissure fill contains intact soil clasts of unit 30 (Figure 7). Units 50, 60, and 70 are truncated by the southwestern most fault and juxtaposed in vertical fault contact against units 30 and 40. On the northwest wall in the hand-dug trench, cobbles in colluvial unit 30 are vertically aligned between fault traces at the southwest margin of the fissure (Figure 10, H2.7, V1).

5.4.2 Event E2

Unit 40, a well-developed soil, dips $\sim 10^\circ$ to the southwest and into the hillslope, vertically offset by ~ 0.5 m. This unit is truncated on the northeast end of the trench and in sub-vertical fault contact with unit 70 (Figure 7, H6 – H8). Numerous faults and fractures extend upward into units 40 and 80, terminating within or at the top of unit 40 (Figure 7).

Figure 10. Photomosaic of meters H2 – H4 exposed in the hand-dug trench, northwest wall. Three aligned cobbles are located between fault strands at meter ~H2.6.

5.4.3 Event E3

Unit 40 thickens considerably from the northeast where it is ~0.25 m thick to ~>0.5 m thickness at the southwest (Figure 7, H2 – H7). A gradational color change is observed in unit 40 on the southeast wall (Figure 7, H2-5). Detrital charcoal age samples from this unit indicate rapid sedimentation (Figure 9).

5.4.4 Weak Evidence of Younger Surface Deformation

A structural depression within unit 10, the modern A horizon, is observed on both trench walls between meters H3 and H4 (Figure 7). This <0.2 m trough like depression aligns with and is nestled within the fissure associated with E1. The small trough is not clearly associated with any shears or faults, it may be an area of root throw or bioturbation. Angular diabase cobbles are mapped in place within unit 10 and exposed at the ground surface at the inflection in the hillslope, these are located on the northwest wall, meters H2 – H3 (Figure 10) and southeast wall, meters H2 – H3 (Figure 7). We list this as event E0 in Appendix F.

5.4.5 Possible Earlier Deformation

We map a reverse fault in the northeast extension V-Trench where unit 90 is stratigraphically thrust above stratigraphically younger diabase colluvium (Appendix E). It is stratigraphically unclear how displacement on this reverse fault relates to faulted stratigraphy within the primary fault zone from trench meters H2 – H8 (Figure 7).

6. Discussion

6.1 Earthquake History

6.1.1 Event Interpretations

Trench stratigraphy at the Clear Creek site reveals evidence for at least two Holocene surface deforming earthquakes, and weaker evidence for a third. Earthquake E2 occurred when unit 40, a well-developed soil, was at the ground surface (Figure 11a). E2 dropped unit 40 downward 1 m at meter H2 (Figure 7), and backtilted unit 40 $\sim 15^\circ$ to the southwest into the hillslope (Figure 11b). Accommodation space was created where unit 40 was down-dropped and back-tilted was in-filled by rocky colluvial unit 30. Diabase boulders are abundant along the base of the unit and are flat-lying on the contact with underlying unit 40 (meters H2.5 – H8.5) (Figure 7 and 10c). The size range and abundance of these diabase boulders is unique to colluvial unit 30, other units are finer-grained and generally contain siltstone clasts. I interpret a change in deposition, and infer these boulders to be a gravity driven deposit from steep hillslopes above the fault-bound, side-hill bench, that were loosened and transported by strong ground motions from E2.

E1, which occurred after E2, faulted the rocky colluvial unit 30, and opened an upward-terminating fissure within the colluvial deposit (meters H2 – H4) (Figure 7 and 10d). Subvertical fault splays activated by this large earthquake extend upward into unit 30. Vertically aligned cobbles on the margin of the fissure (meters H2 – H3, Figure 10) (meters H3 – H4, Figure 7) were moved laterally and tilted into this upright position during E2.

There is weaker evidence for a third earthquake, E3, within unit 40 that is older than E2. Unit 40 is a soil developed on unit 80 from meters H5 – H7, and it is ~ 0.25 m

thick (Figure 7). Unit 40 is interpreted as a marsh soil from meters H2 – H5, and is > 0.5 m thick. When this soil was at the surface, it likely looked similar to the marsh mapped a few meters north of Clear Creek trench site (Figure 3b). On the southeast wall, the gradational coloring in unit 40 from light brown at the top to darker gray at the bottom suggests two soil horizons (Figure 7, meters H5 – H7), which is representative of a stable surface with moderate soil development and subsequent deposition followed by further soil development. ^{14}C ages from the unit reveal relatively rapid sedimentation within unit 40 of 0.5 mm/yr. (Figure 9). Rock uplift and erosion rates do vary systematically across the Coast Range (Kobor and Roering, 2004). However, the uplift rate of the central Coast Range mountains is 0.1-0.3 mm/yr. (Personius et al., 1995), which coincides with the 0.1 mm/yr. sedimentation rate calculated for all other samples in the Clear Creek trench (Figure 9). The observed higher sedimentation rate for unit 40 supports the existence of E3, in which deformation down-dropped the ground surface and created accommodation space which was slowly infilled by fine-grained marsh deposits of unit 40. The creation of accommodation space in the same region was also observed for E2, though this deformation was infilled by a colluvial deposit. A deeper, benched trench could reveal the base of unit 40 and its stratigraphic relationship with unit 80 at depth.

6.1.2 Earthquake Timing

Earthquake ages were estimated with ^{14}C data from detrital charcoal samples within each stratigraphic unit. With detrital charcoal, the youngest dates from a given unit generally best reflect the maximum age of that deposit. Charcoal samples were large, abundant, and angular, suggesting minimal erosion and rounding from transport and a local ^{14}C source. I infer samples are not re-worked and are sourced from local fire events.

Samples are likely older than the deposit, though given the sample abundances, size and angularity they likely have minimal inherited age due to long residence time in the landscape prior to deposition.

To evaluate earthquake timing, I created a probabilistic model using OxCal Bayesian analysis (v.4.3.2; Bronk-Ramsey, 2017). OxCal models the timing of events by weighing the ^{14}C ages in stratigraphic order (Bronk Ramsey, 2008; Leinkemper and Bronk Ramsey, 2009) and yields earthquake timing probability density functions (PDFs). I initially included all 27 samples from Clear Creek site in the OxCal model, but in evaluating the results I eliminated outliers that did not fit within the model stratigraphically. See Appendix G for sample ^{14}C ages not included in the preferred OxCal model (Figure 8).

My preferred earthquake OxCal model for the Clear Creek site constrains E1 between units 10 and 30 (1,169-854 cal. B.P.), E2 between units 30 and 40 (7,095-1,273 cal. B.P.), and E3 between units 40 and 80 (8,963-8,796 cal B.P.) with 2σ uncertainty (Figure 8). This preferred model excludes units 50, 60, and 70, because there is no structural evidence for earthquakes between these units and stratigraphy does not clearly correlate with deposits northeast of the fault zone (Figure 7, Figure 8). The calibrated and modeled radiocarbon ages of ^{14}C samples demonstrate a gradual increase in age from unit 10 to unit 90 with larger time gaps between units 50 and 60, and units 80 and 90 (Table 4, Figure 8). Units 50, 60, and 70, southwest of the fault zone, correlates in age with unit 30, northeast of the faults. Unit 30 was deposited immediately after E2 and all ^{14}C age distributions collected from this unit should be closely spaced in time. However, charcoal ^{14}C ages had a wide range from this unit (Table 4) suggesting either some amount of

residence time in the landscape prior to deposition or that charcoal may be from a long-lived tree species and could have a large in-built ^{14}C age if the sample was sourced deep within the tree (e.g. Gavin, 2001). As a result of this, I only include the youngest samples from the unit, charcoal samples 71 and 72, see Appendix G for a stratigraphic sequence OxCal model with no earthquakes for all ^{14}C samples analyzed for the site, including those excluded from our preferred and alternate earthquake models because they were out of stratigraphic order. Appendix H is an alternate earthquake OxCal model with event E2 placed between units 50 and 60. We correlate stratigraphy on the southwest (unit 50, 60 & 70) and northeast (units 30 & 40) sides of the fault zone based solely on unit ages unit 50 is very close in age to unit 30, and units 60, and 70 are substantially older than unit 30, the event horizon for E2. This alternate model places E2 between units 50 and 60 because there is a large time hiatus between units 50 and 60, suggestive of an unconformity (non-deposition or erosion), disrupting steady sedimentation.

Figure 11. Schematic reconstruction of vertical deformation from earthquakes E1 and E2 created by incrementally retro-deforming the northwest trench log. In a and b of the sequence, units southwest of the fault zone are younger than units 40 and 80, so trench wall outline is left in gray for reference. Unit lines become un-dashed after E1 occurs. This reconstruction does not address lateral slip, only the vertical component of deformation.

6.1.3 Evidence of Younger Deformation (E0)

I find weak evidence for surface disturbance after E1, based on a small depression ~30 cm wide and ~15 cm deep within unit 10, observed on both trench walls (Figure 7, H3 – H3.5). I also observe large, angular diabase cobbles buried just below the surface at the hillslope inflection (Figure 7, H2 – H3). There are no younger deposits above this depression, and soil above the cobbles is heavily bioturbated (Figure 7, H3 – H3.5). Boulders at the site are all diabase, and are sourced upslope of the trench from Intrusive rocks of the Coast Range (geologic unit Tis) (Figure 3a). I interpret the presence of boulders and cobbles in the deposits to be related to destabilization from ground acceleration from an earthquake, or from other non-tectonic rockfall processes. Because I only see boulders and cobbles in one older deposit (unit 30), associated with E2, it is likely the cobbles within unit 10 are evidence of ground acceleration.

I consider the depression and presence of diabase cobbles weak evidence of a younger surface deforming event. However, it is also possible that deposition of large cobbles could have resulted from a large magnitude earthquake along the GCF at another location, where widespread ground motions were also felt at Clear Creek site, but little to no surface deformation occurred. Land use changes such as logging could have uprooted boulders in this area. I also consider the possibility that the Tillamook Burn of 1933 and also 1939 and 1945 in the northern Oregon Coast Range (Neiland, 1958) could have caused trees to come down and root throw could result in such a depression.

6.1.4 Evidence of Older Deformation (EE)

I find evidence for reverse faulting on the GCF within stratigraphy of the V-trench; unit 90 is found stratigraphically above diabase colluvium (Appendix C). Diabase

is also present in unit 30 as gravity-driven colluvium, as a result of E2. It is likely the diabase found stratigraphically below the reverse fault in the V-trench is there as a result of a surface-rupturing earthquake. There was not abundant charcoal found in the walls of the V-trench, so there is no way to constrain the timing of this event.

Interbeds of the Yamhill Fm. colluvium, unit 90, are tilted $\sim 20\text{-}30^\circ$ to the southwest (Figure 7). After retrodeformation, unit 90 remains tilted $\sim 10^\circ$ to the southeast (Figure 11). Earlier surface-deforming earthquakes on the GCF likely caused the southwest tilt of this stratigraphic unit. E1 and E2 caused a $\sim 10^\circ$ tilt in units 40, 80, and 90, after retrodeforming the $\sim 10^\circ$ tilt from E1 and E2, I find that the unit is still tilted $10\text{-}20^\circ$ to the southwest (Figure 11). Assuming each earthquake tilted the ground surface the same amount, roughly 5° to the southwest, this indicates there were at least two additional earlier surface deforming earthquakes that tilted unit 90. Unit 90 lacked abundant organic material and stratigraphic resolution to evaluate the timing of earlier events.

6.2 Paleoearthquake Magnitude, Rupture Length, and Displacement Estimates

Using empirical scaling relationships from Wells and Coppersmith (1994), I calculate the maximum earthquake magnitude the GCF could produce. If the entire 73 km length of the fault were to rupture, the result would be a Mw 7.2 earthquake, based on the regression for a strike-slip fault (Table 2). Using regressions from Hanks and Bakun (2002) I used fault rupture area to calculate another magnitude estimate for a strike slip fault; for a 20-km fault depth, the resulting earthquake would be a Mw 7.3, and for a 25-km fault depth, a Mw 7.4. Though this is much larger than historic crustal earthquakes in the region which have been <6 Mw (Thomas et al., 1996), it is consistent with estimates

of crustal earthquake potential along the St. Helens seismic zone in Washington State (Weaver, 1983). Though considerable attention has been given to risk associated with subduction zone earthquakes in the PNW (e.g. Raghunandan et al., 2015; Petersen et al., 2002), my results highlight that $>M_w$ 7 crustal earthquakes also pose significant risk for the Portland Metropolitan area and should be taken into account by regulators and developers.

The GCF is primarily a right-lateral strike-slip fault (Wells et al., 2009) and relationships between surface rupture length and lateral displacement reveal that for a 73-km strike-slip rupture, average displacement is 1.7 m (Table 2) (Wells and Coppersmith, 1994). However, evidence for reverse faulting on nearby structures, and my observation of a reverse fault in the V-trench (Appendix C) indicate paleoearthquakes on the GCF also have a component of vertical motion. I observe 0.5 m of vertical offset in E2, measured from across the top of unit 40 from the northeast-most end to where that plane intersects the fissure. With empirical scaling relationships, I calculate a lateral to vertical slip ratio by dividing average lateral displacement of 1.7 m (Table 2) (Wells and Coppersmith, 1994), by vertical displacement, 0.5 m from E2; yielding a lateral to vertical ratio of 3.4 to 1.

My results indicate the intervals between large earthquakes at the Clear Creek site are 3,173 years between E1 and E2, and 4,695 years between E2 and E3. The average recurrence interval between paleoearthquakes that ruptured the surface at the Clear Creek site is 3,934 years during the past 10 ka. The minimum age constraints on E1, E2, and E3, gives recurrence between earthquakes of 419 years and 7,523 years. Using the maximum age constraints, the intervals are 5,926 and 1,868 years. Preliminary estimates of long-

term slip rates on the GCF are 0.24 mm/yr. since 50 Ma and 0.6 mm/yr. since 15 Ma (Wong et al., 2000; R.E. Wells, personal comm.). In these estimates, the GCF is considered an independent fault segment that failed in repeats of the same size earthquake and released all built up strain. I compare the average recurrence interval (3,934 years) to the expected recurrence for the GCF, calculated by dividing the expected lateral slip per event, 1.7 m (Wells and Coppersmith, 1994) by the fault slip rate, 0.6 mm/yr., which gives a lower, but comparable recurrence of 2,833 years.

Using the 0.6 mm/yr. slip rate, I calculate the amount of slip that built up between events, and was likely released in a large earthquake. Between E2 and E3 there is an average interval of 4,695 years, which would result in 2.8 m of expected lateral displacement. Between E1 and E2 there is an interval of 3,173 years, which results in and expected 1.9 m of lateral slip.

6.2.1 Right-laterally deflected drainages

Along the northern GCF (Figure 2b, Table 3) Gales Creek is offset 753m, Bateman Creek 1,966m, Iler Creek (minimum) 1,615m, and Parson's Creek 1,459m. Based on 0.6 mm/yr. slip rate, the time it took for these streams to deform is 1.3 m.y., 3.3 m.y., 2.7 m.y., and 2.5 m.y., respectively. This suggests that Coast Range topography has existed and the GCF has been active since at least 3.3 Ma. It also indicates the streams are likely much younger than the Coast Range itself, which likely emerged as a continuous subaerial topographic feature sometime in the early to mid-Miocene based on a transition from marine to marginal-marine and continental sedimentary rocks in the Astoria Basin (Niem et al., 1992; Armentrout, 1983). Stream offsets become progressively shorter to the north, which suggests the fault is younger to the north or it

has repeatedly greater displacements on the southern end. It could also indicate that the age of streams decreases to the north.

6.3 Regional Fault Implications

My results indicate the GCF is a northwest-trending, Holocene active fault. The other northwest-trending bedrock faults mapped in the region such as the Portland Hills, Oatfield, East Bank, Lackamas Lake, Bolton, and Canby-Molalla faults are experiencing the same regional stresses, due to the clockwise rotation of the PNW relative to stable North America (Wells and McCaffrey, 2013; Brocher et al., 2017). It is likely that other northwest-trending faults in the Portland region have also produced surface rupturing earthquakes in the Holocene, based on sense of motion of these faults and regional principal stresses. The Portland Hills, Oatfield, and East Bank faults are analogous to the GCF, but run through downtown Portland, Oregon. A surface-rupturing earthquake on one of these faults could be catastrophic for millions of people living in the Portland metropolitan area (Tesfamariam and Wang, 2011; Raghunandan et al., 2015).

7. Conclusions

I present a seismic source characterization that highlights northwest trending strike-slip faults with a reverse component in the forearc of Cascadia in northwest Oregon. The Gales Creek fault is the largest of these northwest-trending strike-slip crustal faults, and it is accommodating clockwise rotation and northward migration of the Oregon coast block resulting from oblique subduction of the Juan de Fuca plate.

Paleoseismic results from the Clear Creek trench site reveal the GCF has produced at least three surface-rupturing earthquakes in the Holocene. E1 occurred between 1,169 and 854 years B.P. and E2 between 7,095 and 1,273 years B.P., and E3 between 8,963 and 8,796 years B.P. with 2σ uncertainty. Older colluvial stratigraphy suggests stratigraphic evidence for additional events. My results suggest the recurrence interval between large magnitude earthquakes is approximately 3,934 years at the Clear Creek site. The GCF is 73-km long, and using empirical scaling relationships, if the full length of the fault were to rupture, the result would be a Mw 7.2 earthquake, which could cause significant damage to structures in the Portland metropolitan area.

Low slip rates over the broad mountainous PNW result in low slip accumulation on individual structures. Subdued geomorphic expression that is quickly eroded or obscured in this region by heavy rainfall and thick vegetation makes it difficult to identify active structures. Holocene activity on the GCF documented in this study provides an analog for other bedrock faults in the forearc of Cascadia and suggests that they too represent active seismic sources.

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Appendix A. Portland Metropolitan Fault Database

Beaverton Fault			
	Data	Type of Data	References
Location	Fault extends at least 7 km north of the Farmington Hills	Well water logs correlating with a magnetic boundary	Popowski, 1996
	Fault continues >3 km east of Cooper Mountain, with down to the north	Water well data	Madin, 1990
Length	15 km	QFFD	Personius, 2002a
Strike	East-West	Aeromagnetics	Blakely et al., 2000
	N86°E	QFFD	Personius, 2002a
Dip	North-verging	Inversion of gravity data	McPhee et al., 2014
	South	Regional stress field	Blakely et al., 2000; McPhee et al., 2014; Wells and McCaffrey, 2013
	70° South	Focal Mechanisms from microseismicity	University of Washington, 1963
	Down to the north	Water wells	Madin, 1990
Sense of Movement	Thrust/reverse, responding to north-south maximum horizontal compressive stress of the region	Inversion of gravity data	McPhee et al., 2014
	The Beaverton fault and other contractional structures in the region such as the Cooper Mountain anticline and Parrett Mountain uplift are interpreted to be a left compressional step between the right-lateral Canby-Molalla fault and the Gales Creek fault zone.	Aeromagnetic data	Blakely et al., 2000
Slip Rate	<0.2 mm/yr	QFFD	Personius, 2002a
Displacement	Top of CRBG offset	Water well logs	Madin, 1990
	CRBG offset ~350 m down to the north	Seismic reflection data	Popowski, 1996
	Fault offsets Eocene basement >1km	Inversion of gravity data	McPhee et al., 2014
Age	Late Miocene to Pleistocene. Water well goes into 292 m of Grande Ronde basalt, indicative of a topographic low in early to middle Miocene.	Cooper Mountain well	Popowski, 1996

	Fault growth likely occurred during deposition of lower Miocene to Pliocene sediments, suggested by the lower portion of sedimentary sequence being thickened closest to the fault.	Seismic reflection data	Popowski, 1996
Other	Beaverton fault offsets Eocene Basement, displacing it >1km down to the north; and also displaces the overlying CRBG by ~200 m.	3D gravity inversion of the Tualatin Basin	McPhee et al., 2014

Bolton Fault			
	Data	Type of Data	References
Location	Exposed south of Lake Oswego	Low-altitude aeromagnetic data	Blakely et al., 1995
Length	9 km	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
Strike	Northwest	Aeromagnetic data	Blakely et al., 1995
	N53°W	QFFD	Personius, 2002b
Dip	70° North	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
	Southwest	Geologic mapping	Beeson et al., 1989
	West	Based on geologic mapping and regional stress field	Wells et al., 2018; Wells and McCaffrey, 2013
Slip Rate	<0.2 mm/yr	QFFD	Personius, 2002b
Sense of Movement	Reverse, right lateral	Geologic mapping	Beeson et al., 1989

Canby-Molalla Fault			
	Data	Type of Data	References
Length	51 km	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
	50 km	QFFD	Personius, 2002c
Strike	N34°W	QFFD	Personius, 2002c
Dip	70° Northeast	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
	67° Northeast	Focal Mechanisms from microseismicity	University of Washington, 1963
	75° Northeast	Focal Mechanisms from microseismicity	University of Washington, 1963
Slip Rate	<0.2 mm/yr.	QFFD	Personius, 2002c
	Poor geomorphic expression (based on offsets from Blakely et al., 2000) suggests low slip rates in late Quaternary.	QFFD	Personius, 2002c
Displacement	4km right-lateral separation of underlying Eocene bedrock, and minimum of 150 m of vertical offset in CRBG	Aeromagnetic data	Blakely et al., 2000
Sense of Movement	Right-lateral	Aeromagnetic data	Blakely et al., 2000
	Right-lateral, reverse	QFFD	Personius, 2002c

East Bank Fault			
	Data	Type of Data	Reference
Location	Parallel Portland Hills Fault, 2-3 km to the east.	QFFD	Personius, 2002d
Length	29 km	QFFD	Personius, 2002d
	55 km	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
Strike	N46°W	QFFD	Personius, 2002d
	N42°W	Low-altitude aeromagnetic data	Blakely et al., 1995
Dip	Southwest	QFFD	Personius, 2002d
	Northeast	Low-altitude aeromagnetic data	Blakely et al., 1995
	70-90° Northeast	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
	65°	Focal Mechanisms from microseismicity	University of Washington, 1963
Sense of Movement	Reverse	QFFD	Personius, 2002d
	High angle normal fault	Geologic mapping	Madin, 1990; Beeson et al., 1991
	Reverse slip	Low-altitude aeromagnetic data	Blakely et al., 1995
Slip Rate	< 0.2 mm/yr	QFFD	Personius, 2002d
	Estimated rates 0.05-0.4 mm/yr	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
Offset	60-120 m of down to the west vertical displacement of Miocene CRBG volcanic rocks and 60-90 m of vertical displacement of Miocene-Pliocene Troutdale Formation across the fault.	Cross-sections and geologic mapping	Beeson et al., 1991
Most Recent Activity	Late Pleistocene or Holocene vertical displacement, observed in seismic reflectors.	Shallow seismic reflection	Pratt et al., 2001

Gales Creek Fault			
	Data	Type of Data	References
Location	Fault forms the southwest margin of the Tualatin Basin	Geologic mapping	Popowski, 1996
	Bounding Coast Range uplift	Aeromagnetic data	Blakely et al., 2000
Length	31 km	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
	73 km	QFFD	Personius and Haller, 2017a
Strike	N41°W	QFFD	Personius and Haller, 2017a
Dip	Steeply dipping to the west	Structural and geologic mapping	Wells terroir map 2018
	70° Northeast	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
Sense of Movement	Reverse and right-lateral	QFFD	Personius and Haller, 2017a
	Dextral	Geologic mapping and gravity data	Wells, 2009
	Dextral strike-slip and vertical separation apparent along fault zone	Seismic design mapping	Geomatrix Consultants Inc., 1995
	Dextral slip indicated by: subhorizontal slickensides, vertical offsets varying along strike, dextral separation of Coast Range fold axes, and 6km dextral separation of CRBG beds between Dundee Hills and Parrett Mountain.	Aeromagnetic data	Blakely et al., 2000
Slip Rate	0.1-0.4 mm/yr	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
	<0.2 mm/yr	QFFD	Personius and Haller, 2017a
	0.24 mm/yr since 50 Ma and 0.6 mm/yr since 15 Ma	Structural and geologic mapping	Ray Wells, 1997 (personal comm. With Wong, 2000)
Other	If part of the larger Gales Creek-Mount Angel fault zone, the vertical separation may have reverse sense of displacement	Seismic design mapping	Geomatrix consultants Inc., 1995

Helvetia Fault			
	Data	Type of Data	References
Location	Extends from the McKay Creek valley SE to Orenco	Water well logs	Popowski, 1996
Length	10 km	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
	7 km	QFFD	Personius, 2002e
Strike	N25°W	Water well logs	Popowski, 1996
	N26°W	QFFD	Personius, 2002e
Dip	70° W	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
Slip Rate	<0.2 mm/yr	QFFD	Personius, 2002e
Sense of Movement	Right-lateral, reverse	QFFD	Personius, 2002e
Displacement	100 m CRBG is much thicker to the west	Well logs	Popowski, 1996
Most Recent Activity	Fault displacement likely occurred in late Miocene to Pliocene.	Seismic reflection shows erosion and folding of basalt, but no vertical deformation in overlying sediments	Popowski, 1996

Lackamas Lake (Sandy River/Frontal) fault			
	Data	Type of Data	References
Location	Northern end of Lackamas Lake	Based on topography and evidence of fault gouge	Yelin and Patton, 1991
	Forms northeast boundary of Portland Basin.	Aeromagnetic data	Blakely et al., 1995
	Parallel Portland Hills fault, north of the Columbia River in Washington	Topography and focal mechanisms from microseismicity	Yelin and Patton, 1991
Length	7 km southeast from northern end of Lackamas lake.	Topography	Yelin and Patton, 1991
	44 km	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
Strike	Northwest	Topography	Yelin and Patton, 1991
	N30°W	Zone of earthquakes along eastern margin of Portland Basin striking in this orientation.	Yelin and Patton, 1991
	Northwest	Aeromagnetic data	Blakely et al., 1995; 2000
Dip	Fault is displaced down to the west	Inference based on topography	Mundorff, 1964
	70° Southwest	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
	36° Southwest	Focal Mechanisms from microseismicity	University of Washington, 1963
	45° Southwest	Focal Mechanisms from microseismicity	University of Washington, 1963
Sense of Movement	Normal	Inference based on topography.	Mundorff, 1964
	Dextral strike-slip with component of normal faulting	Gravity data	Yelin and Patton, 1991
Depths	15-20 km	Focal Mechanisms from earthquakes.	Yelin and Patton, 1991
Most Recent Activity	Mw 5.2 EQ in 1962 occurred between Frontal and Portland Hills faults	Location of earthquake epicenter	Yelin and Patton, 1991
Age	Age unknown, but fault displaces rock of late Oligocene age	Groundwater investigation	Mundorff, 1964
Other	Frontal fault and Portland Hills fault are right-stepping, right-lateral fault zones	Focal Mechanisms from microseismicity	Yelin and Patton, 1991

Mount Angel Fault			
	Data	Type of Data	References
Length	30 km	QFFD	Personius, et al., 2014
	>55 km, interpreted to connect with the geologically mapped GCF to the northwest.	Aeromagnetic data	Blakely et al., 2000
Strike	N43°E	QFFD	Personius, et al., 2014
	N24°W	Earthquake main shock focal mechanisms	Blakely et al., 2000; Thomas et al., 1996
	Defined plane in West-Northwest direction	Aftershocks from 1993 Scotts Mills EQ	Yeats et al., 1996
	Northwest	Earthquake focal mechanisms (1993 Scotts Mills EQ)	Thomas et al., 1996
Dip	60° Northeast	Earthquake focal mechanisms (1993 Scotts Mills EQ)	Thomas et al., 1996
	58° Northeast	Earthquake main shock focal mechanisms	Blakely et al., 2000; Thomas et al., 1996
	60-70° Northeast	Seismic reflection and aeromagnetic data	Werner, 1990; 1992; Yeats et al., 1996
	80°	Focal Mechanisms from microseismicity	University of Washington, 1963
Sense of Movement	Reverse, right-lateral	QFFD	Personius, et al., 2014
	Subequal reverse and right-lateral strike-slip	Earthquake focal mechanisms (1993 Scotts Mills EQ)	Thomas et al., 1996
	Dip-slip and right-lateral strike-slip	Geologically mapped	Beeson et al., 1989
	High angle reverse-oblique	Boreholes	Werner, 1990
Slip Rate	<0.2 mm/yr	QFFD	Personius, et al., 2014
	0.23 mm/yr (for the past 30 Ka)	SH-wave refraction and reflection methods	Wang and Madin, 2001
Displacement	200 m offset in CRBG	Seismic and Aeromagnetic data	Liberty et al., 1999
Most Recent Activity	Mw 5.6 Scott Mills Earthquake (1993)	Aeromagnetic data; Focal mechanisms	Blakely et al., 2000; Yeats et al., 1996
Other	May connect with the Gales Creek fault 25 km to the northwest	Aeromagnetic data	Blakely et al., 2000

Newberg Fault			
	Data	Type of Data	References
Location	Part of Gales Creek-Mount Angel northwest-striking structural zone	QFFD	Personius, 2002g
Length	8 km	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
	5 km	QFFD	
Strike	N42°W	QFFD	Personius, 2002g
Dip	70° Southwest	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
Slip Rate	<0.2 mm/yr	QFFD	Personius, 2002g
Sense of Movement	Reverse, if connected to Gales Creek / Mt. Angel fault zone	Geologic and structural mapping	Wells et al., 2018
Other	This structure may link the Mount Angel and Gales Creek faults	Magnetic expression	Blakely et al., 2000

Oatfield (Sylvan-Oatfield) Fault			
	Data	Type of Data	Reference
Location	Along western flank of the Portland Hills.	Gravity	Blakely et al., 2000
Length	29 km	QFFD	Personius, 2002h
	40 km	Gravity	Blakely et al., 2000
	40 km	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
Strike	N41°W	QFFD	Personius, 2002h
Dip	Northeast	QFFD	Personius, 2002h
	70° East	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
	Southwest	Geologically mapped	Beeson et al., 1989
	East-dipping	Exposures from boreholes drilled for metropolitan light-rail tunnel through the Portland Hills.	Blakely et al., 1997
	Steeply; Northeast	Aeromagnetic data	Blakely et al., 1995
Displacement	West Sylvan Fault: 7-20 m Central Sylvan Fault: 76-100 m	Excavation across Tualatin Mountains for construction of light-rail tunnel	Walsh et al., 2011
Sense of Movement	Reverse and right-lateral	QFFD	Personius, 2002h
	High-angle reverse fault	Geologically mapped	Beeson et al., 1989
	Reverse and strike slip	Microseismicity	Yelin, 1992
	Thrust	Aeromagnetic data	Blakely et al., 1995
	Reverse (vertical) and dextral	Exposures from boreholes drilled for metropolitan light-rail tunnel through the Portland Hills.	Blakely et al., 1997
Slip Rate	<0.2 mm/yr	QFFD	Personius, 2002h
	Estimate of 0.05-0.4 mm/yr	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
(vertical)	West Sylvan Fault: 0.01-0.02 mm/yr. Central Sylvan Fault: 0.07-0.08 mm/yr.	Excavation across Tualatin Mountains for construction of light-rail tunnel	Walsh et al., 2011
Offset	100 m offset of 1 Ma Boring Lava	Exposures from boreholes drilled for metropolitan light-	Blakely et al., 1997

		rail tunnel through the Portland Hills.	
Other	The fault forms linear magnetic anomalies and southwest-facing escarpments in volcanic rocks of the Miocene CRBG in Tualatin Mtns, and northern Willamette Valley.	Geologically mapped	Beeson et al., 1989; 1991
	150 m of Mio-Pleistocene age sediments are stratigraphically above CRBG	Water wells	Popowski, 1996; Madin, 1990
	Boring lava vents along the length of the fault suggest it acted as a conduit for emplacement of Boring lava	Water wells and geologically mapping	Popowski, 1996
	The Sylvan fault is interpreted as a subsurface continuation of the Oatfield fault.	Gravity data	Blakely et al., 2000

Portland Hills Fault			
	Data	Type of Data	References
Location	Part of Portland Hills-Clackamas River structural zone, SE Portland?	Geochemical analysis of Frenchman Springs Member of the CRBG	Beeson et al., 1985
	Forms NE margin of Tualatin Mountains and SW margin of Portland Basin	QFFD	Personius and Haller, 2017b
Length	49 km	QFFD	Personius and Haller, 2017b
	Active zone of deformation is 400 m wide	Seismic reflection, GPR, magnetic methods, trench excavation @ North Clackamas Park and Rowe Middle school	Liberty et al., 2003
	62 km	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
Strike	N37°W	QFFD	Personius and Haller, 2017b
	Northwest	Geologically mapped	Beeson et al., 1989
Dip	Southwest	QFFD	Personius and Haller, 2017b
	Steeply Southwest	Geologic Mapping	Schlicker and Finlayson, 1979
	Southwest	Aerial and field reconnaissance	Unruh et al, 1994
	Northeast	Geologic mapping	Beeson et al., 1989
	70° Northeast	Seismic design mapping	Geomatrix Consultants, Inc., 1995
	Northeast side up displacement	Shallow seismic reflection data	Pratt et al., 2001
	Southwest	Aeromagnetic data	Blakely et al., 1995
	70-90° Southwest	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
Sense of Movement	Reverse, right-lateral	QFFD	Personius and Haller, 2017b
	Right-lateral	Geologic mapping	Schlicker and Finlayson, 1979
	Right-lateral strike slip	Geologic mapping	Beeson et al., 1985
	Reverse to vertical	Earthquake scenario and probabilistic ground shaking maps	Wong et al., 2000
	Normal	Geologic mapping, based on CRBG and November 1962 earthquake	Schlicker et al., 1964; Balsille and Benson, 1971

	Right-oblique strike-slip	Geologic mapping	Beeson et al., 1989
	Asymmetrical folding above SW dipping blind thrust	Based on topography of Portland Hills escarpment	Unruh et al., 1994
	Near vertical dip slip	Geologic mapping	Beeson et al., 1989
	Reverse or reverse oblique	Seismic design mapping	Geomatrix consultants, Inc., 1995
	Transpressional	Aeromagnetic data	Blakely et al., 1995
	Strike-slip with minor dip slip component.	Seismic reflection, GPR, magnetic methods, trench excavation at North Clackamas Park and Rowe Middle school, Clackamas.	Liberty et al, 2003
	Strike-slip or dip slip	Seismic profiling	Pratt et al., 2001
	Reverse is primary mode of deformation.	Seismic reflection data	Wong et al., 2001
	Right-stepping, right-lateral fault zone.	Microseismicity	Yelin and Patton, 1991
	Reverse displacement, with component of right-lateral strike slip.	Tectonic setting and geologic mapping	Beeson et al., 1989; Blakely et al., 2000
	Reverse	Aeromagnetic data	Blakely et al., 1995
Slip Rate	<0.2 mm/yr	QFFD	Personius and Haller, 2017b
Depth	5-20 km	Microseismicity	Wong et al., 2001; Yelin and Patton, 1991
Other	Fault defines western margin of pull-apart basin.	Geologic mapping	Beeson et al., 1989
	Faulted anticline of Miocene CRBG.	Geologic mapping and subsurface data	Evarts et al., 2009
	Fault trace corresponds with low gravity values (-28 mGal), so likely dense basement rocks are not major part of Portland Hills uplift.	Gravity inversion	McPhee et al., 2014

Sherwood Fault			
	Data	Type of Data	References
Location	Separates northeast dipping Chehalem Mountain beds from SE dipping Parrett Mountains	Water well logs	Hart and Newcomb, 1965
	Possibly continues along northern end of Amity Hills.	Seismic profiles	Yeats et al., 1996
	Appears as southwest continuation of northern margin of Columbia trans-arc lowland through which CRBG traversed the Cascade Range.	Geochemistry and geologic mapping of the CRBG	Beeson et al., 1989a
	Bounds the southeastern margin of the Tualatin Basin and northern margin of the northern Willamette basin	A broad northeast-trending gravity high	McPhee et al., 2014
Length	14.5 km	Geologic mapping of bedrock faults.	Wells et al., 2019
Strike	Northeast	Aeromagnetic data	Blakely et al., 2000
Dip	50° South	Focal Mechanisms from microseismicity	University of Washington, 1963
Displacement	Basement to northwest of the fault is offset vertically ~300 m lower than to the south	Aeromagnetic data	McPhee et al., 2014
Other	Originated as normal fault in the Eocene.	Aeromagnetic data	McPhee et al., 2014
	On strike and possibly related to Lake Oswego fault.	Geologic mapping	Popowski, 1996; Beeson et al., 1989

Appendix B. Fault data from focal mechanisms (University of Washington, 1963). Distance from fault measured from ArcGIS; Length of fault measured using Pythagorean theorem with depth of earthquake and distance from fault.

Beaverton Fault					
<i>Focal Mechanism Information</i>					
Strike	Dip	Magnitude EQ	Depth of EQ (km)	Distance from fault (km)	Length of fault at Depth
60°	70°	2.6	26.1	0.659	26.1

Canby Molalla Fault					
<i>Focal Mechanism Information</i>					
Strike	Dip	Magnitude EQ	Depth of EQ (km)	Distance from fault (km)	Length of fault at Depth
315°	75°	2.4	21.2	4.8	21.7
319°	67°	2.1	22.2	3.46	22.4

East Bank Fault					
<i>Focal Mechanism Information</i>					
Strike	Dip	Magnitude EQ	Depth of EQ (km)	Distance from fault (km)	Length of fault at Depth
320°	65°	2.8	15.2	0.34	15.2

Lackamas Lake Fault					
<i>Focal Mechanism Information</i>					
Strike	Dip	Magnitude EQ	Depth of EQ (km)	Distance from fault (km)	Length of fault at Depth
104°	36°	2.5	5.6	4.06	6.9
125°	45°	2.5	15	7.13	16.6

Mount Angel Fault					
<i>Focal Mechanism Information</i>					
Strike	Dip	Magnitude EQ	Depth of EQ (km)	Distance from fault (km)	Length of fault at Depth
340°	80°	2.4	25.2	8.89	26.7

Sherwood Fault					
<i>Focal Mechanism Information</i>					
Strike	Dip	Magnitude EQ	Depth of EQ (km)	Distance from fault (km)	Length of fault at Depth
95°	50°	2	20.7	2.77	20.9

Appendix C. Clear Creek Trench Detailed Unit Descriptions						
Basal Contact	Consistency	Moisture Condition	Color	Depth	Soil Type	Unit
Base of unit not exposed	Medium-stiff	Dry	7.5 YR 5/4 Brown (with smaller amounts of 5YR 6/8 Reddish Yellow; and even less of 7.5 YR 3/3 Dusky Red; and 10YR 8/1, White)	~1/4m-2+m below ground	Sandy Silt	90
Base of unit not exposed meters H5-H7; Eroded and wavy and diffuse over a few centimeters meters H7-11	Medium-stiff below unit 10; Very soft below unit 40	Dry below unit 10; Moist under unit 40	10YR 5/4 Yellowish Brown	~1/4m-2+m below ground	Silt	80
Base of unit not exposed meters H2-H5; Sharp basal contact meters H5-H7	Soft	Damp to Moist	10YR 4/2 Dark Grayish Brown	~1/2m-2+m below ground	Silt	40
Basal contact diffuse with pockets of coarse sand and pebbles at base meters H2-H4; Sharp basal contact meters H4-H7	Medium-stiff	Damp	10YR 4/4 Dark yellowish brown	~1/4m-1m below ground	Silty Clay	30
Wavy and irregular; Diffuse over 3-5 cm meters H0-H2, Discontinuous and eroded meters H2-H4; Wavy and sharp meters H4-12	Medium-stiff to stiff	Dry	10YR 3/3 Dark Brown	~0m-1/4m below ground	Silt	10

Appendix C. continued.					
Other	Clast Characteristics	Component Percentages	Rounding/Size	Unit	Soil Structure
Mottled redoximorphic features; Slight soil development; Clay film visible in pedogenic structure	Matrix-supported siltstone clastic interbeds 15-25 cm thick, dipping ~30-40° to the southwest; interbedded with sandy silt and clay pockets	In most places 2-3%, but can get up to 10% within clastic interbeds	Sub-rounded and spherical to sub-prismatic weathered pebbles ranging in size from 1-7 cm	90	Massive
Red-orange mottles	White, tan, orange, light pink weathered siltstone pebbles	<1%	Sub-rounded pebbles ranging in size from 1-3 cm	80	Massive
Dried pedogenic structure and organic soil	White, tan, orange, light pink weathered siltstone pebbles	<1%	Sub-rounded pebbles ranging in size from 1-3 cm	40	Massive
	Iron-rich, matrix-supported weathered siltstone pebbles and diabase cobbles and boulders	15-20%	Poorly sorted sub-angular and sub-rounded pebbles, cobbles, and boulders ranging in size from ~2 cm to ~0.5 m diameter	30	Massive
Pedogenic structure, organic material	N/A	N/A	N/A	10	Granular, massive structure

Appendix C. continued.	
Geologic Interpretation	
Interbedded colluvium of the Yamhill Formation	
B Horizon or wind-blown silt/loess	
Buried A Horizon	
Colluvium made up of weathered diabase parent material;	
Modern A Horizon	

Appendix C. continued.						
Basal Contact	Consistency	Moisture Condition	Color	Depth	Soil Type	Unit
Base of unit not exposed	Soft	Moist	10YR 3/3 Dark Brown (with red specks mixed in)	~1 1/2m-2m below ground	Silty Clay	70
Diffuse basal contact over 5-10 cm	Soft to Medium-stiff	Damp	10YR 3/4 Dark Yellowish Brown	~1m-1 1/2m below ground	Silty Clay	60
Diffuse basal contact over 5-10 cm	Medium-stiff	Damp	10YR 4/6 & 3/6 Dark Yellowish Brown	~1/2m-1m below ground	Sandy Silt	50
Irregular and diffuse over 1-3 cm	Stuff	Dry	10YR 5/4 Yellowish Brown	~1/4m-1/2m below ground	Silt	20

Appendix C. continued.						
Other	Clast Characteristics	Component Percentages	Rounding/Size	Unit	Soil Structure	
High plasticity	Weathered orange and pink siltstone pebbles decreasing stratigraphically downward	<1%	Sub-rounded and sub-prismoidal weathered pebbles ranging in size from 1-3 cm	70	Massive	
High plasticity	Weathered orange and pink siltstone pebbles	~7%	Sub-rounded and sub-prismoidal weathered pebbles ranging in size from 1-3 cm	60	Massive	
High plasticity, coarse grains, granular texture	Weathered orange and pink siltstone pebbles	~10%	Sub-rounded and sub-prismoidal weathered pebbles ranging in size from 1-3 cm	50	Massive	
Charcoal-dense unit; weathered pebbles are sub-angular/sub-rounded	Weathered orange and pink siltstone pebbles	~15%	Sub-rounded and sub-angular weathered pebbles ranging in size from 1-3 cm	20	Granular with massive to single-grain structure	

Appendix C. continued.	
Geologic Interpretation	
Southwest unit – moved laterally by GCF to be next to primary units	
Southwest unit – moved laterally by GCF to be next to primary units	
Southwest unit – moved laterally by GCF to be next to primary units	
Southwest unit – moved laterally by GCF to be next to primary units	

Appendix D. Photomosaic and interpreted trench log for northwest and southeast walls of hand-dug trench

Appendix D. continued

Appendix E. Photomosaic and interpreted trench log for north and south walls of V-trench

V-Trench North Wall

N96°E

V-Trench South Wall

Appendix F. Summary of Earthquake Evidence

Earthquake	Trench	Location in Trench	Earthquake Evidence	Earthquake Horizon	Earthquake Qualifier	Rank
E1	Primary	NW & SE m 2-4	Sub vertical fault splays extend upward into unit 30. Units 50, 60, and 70 are truncated on the southwest by the faults. Units 30 and 40 are truncated to the northeast.	Unit 30	Very Likely	5
E1	Primary	NW & SE m 2-4	Upward terminating fissure within colluvial unit 30	Unit 30	Very Likely	5
E1	Primary	NW m 3-4	Plucked cobbles of unit 30 are upright and aligned at faults	Unit 30	Very Likely	5
E1	Hand-dug	(hand dug) NW m 2-3	Cobbles of unit 30 are upright and aligned at faults	Unit 30	Very Likely	5
E2	Primary	NW m 4-8; SE m 4-7	Upward fault terminations within unit 40	Unit 40	Very Likely	5
E2	Primary	NW m 5-6; SE m 5-6	Offset in base of unit	Unit 40	Very Likely	5
E2	Primary	NW m 7-8; SE m 6-7	Unit 40 is in vertical contact with unit 80	Unit 40	Very Likely	5
E2	Primary	NW m 2-8; SE m 2-7	Buried soil backtilted dipping into the hillslope and vertically offset ~0.5 m	Unit 40	Likely	4
E2	Primary	NW m 2-8; SE m 2-7	Soil overlain by colluvium with flat-lying boulders	Unit 40	Likely	4
E2	Primary	NW m 3-8; SE m 3-7	Growth strata observed from unit 30 thickening to the SW	Unit 40	Likely	4
E3	Primary	SE m 2-7; NW m 2-8	Gradual thickening in unit 40 to the southwest	Unit 40	Probable	3
E3	Primary	SE m 2-7; NW m 2-8	Greater sedimentation rate in unit 40 ¹⁴ C samples compared to all samples	Unit 40	Probable	3

E3	Primary	SE m 2-5 (vertical m 1.8)	Gradational color change in unit 40 with apparent contact (over ~1-2 cm). Unit 40 is lighter above vertical meter ~1.8.	Unit 40	Likely	4
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Weak Evidence of Additional Earthquakes						
Earthquake	Trench	Location in Trench	Earthquake Evidence	Earthquake Horizon	Earthquake Qualifier	Rank
E0	Hand- dug	NW m 2- 3; SE m 2-3	Large, angular boulders and cobbles in place at hillslope inflection point	Unit 10	Probable	3
E0	Primary	SE m 2-3	Large, angular boulders and cobbles in place at hillslope inflection point	Unit 10	Probable	3
E0	Primary	NW m 3- 4; SE m 3-4	Depression / fissure within unit 10	Unit 10	Probable	3
EE	Primary	NW m 7- 12; SE m 7-11	Tilt of interbedded unit 90 to the SW after retrodeformation	Unit 90	Probable	3
EE	V- trench	N m 12- 14; S m 11-13	Reverse fault stratigraphically offsets unit 90	Unit 90	Probable	3
EE	V- trench	N m 13- 16; S m 12-16	Diabase colluvium stratigraphically below reverse fault	Unit 90	Probable	3

Earthquake	Sum of Rank	Average Rank
E0	9	3
E1	20	5
E2	27	4.5
E3	10	3.3
EE	9	3

Appendix G. OxCal Model without earthquakes for samples not included in Figure 8 and Table of ^{14}C data with 2σ uncertainty.

Name	Unmodelled (BP)			Modelled (BP)				
	from	to	%	from	to	%	A	C
R_Date GCF-T1-B-273	302	...	95.4	223	-2	95.4	100.5	98.2
R_Date GCF-T1-B-185	282	5	95.4	230	-2	95.4	97.7	99.4
Phase Unit10								
R_Date GCF-T1-B-261	269	13	95.4	280	64	95.4	96.5	99.4
Phase Unit20								
R_Date GCF-T1-B-207	5284	4880	95.5	5284	4881	95.3	99.5	98.9
R_Date GCF-T1-B-71	1234	1061	95.4	1235	1061	95.4	99.5	98.8
R_Date GCF-T1-B-72	1293	1181	95.4	1294	1181	95.4	99.2	99
R_Date GCF-T1-B-17	2125	1990	95.4	2125	1990	95.4	100.1	98.5
R_Date GCF-T1-B-167	7418	7271	95.4	7415	7269	95.4	100	99.1
R_Date GCF-T1-B-204	6910	6750	95.4	6911	6751	95.4	99.6	99.1
Phase Unit30								
R_Date GCF-T1-B-77	7756	7615	95.4	7755	7615	95.4	99	99.1
R_Date GCF-T1-B-78	7844	7597	95.4	7844	7601	95.4	100	98.6
R_Date GCF-T1-A-189	8010	7883	95.4	8010	7883	95.4	99.8	98.9
R_Date GCF-T1-A-205	7691	6794	95.4	7732	7284	95.4	104.5	96.5
R_Date GCF-T1-B-453	8414	8344	95.4	8414	8345	95.4	99.5	99
R_Date GCF-T1-B-454	9123	8785	95.4	8940	8771	95.4	11.8	98.3
Phase Unit40								
R_Date GCF-T1-B-89	8979	8642	95.4	8989	8823	95.4	89.5	99.6
R_Date GCF-T1-B-246	10378	10227	95.4	10376	10227	95.4	100	98.7
Phase Unit80								
R_Date GCF-T1-B-117	14276	13991	95.4	14262	13989	95.4	100.7	96.8
Phase Unit90								
Boundary base				14954	14145	95.4		98.6
Sequence GCF_ClearCk_2018								

Appendix H. Alternate OxCal Model with E2 between units 50 and 60, and Table of ^{14}C data with 2σ uncertainty.

Name	Unmodelled (BP)			Modelled (BP)			A	C
	from	to	%	from	to	%		
R_Date GCF-T1-A-273	301	...	95.4	301	-2	95.5	99.2	99.2
R_Date GCF-T1-B-185	282	5	95.4	282	3	95.3	98.5	99.6
R_Date GCF-T1-B-184	963	800	95.3	960	799	95.4	92.7	99.4
Phase Unit10								
E1				1170	852	95.4		99.7
R_Date GCF-T1-B-71	1234	1061	95.4	1236	1063	95.4	97.6	99.5
R_Date GCF-T1-B-72	1293	1181	95.4	1293	1181	95.4	99.2	99.4
Phase Unit30								
R_Date GCF-T1-A-214	1697	1544	95.4	1697	1544	95.4	99.8	99.4
Phase Unit50								
E2				5457	1674	95.5		96.7
R_Date GCF-T1-A-216	5586	5331	95.4	5586	5331	95.4	99.7	99.5
Phase Unit60								
R_Date GCF-T1-B-227	5905	5741	95.4	5904	5741	95.4	99.7	99.5
Phase Unit70								
R_Date GCF-T1-B-77	7756	7615	95.4	7755	7615	95.4	99.7	99.6
R_Date GCF-T1-B-78	7844	7597	95.4	7844	7601	95.4	100	99.1
R_Date GCF-T1-A-189	8010	7883	95.4	8010	7883	95.4	99.6	99.2
R_Date GCF-T1-A-205	7691	6794	95.4	7700	6792	95.4	99.8	97.1
R_Date GCF-T1-B-453	8414	8344	95.4	8414	8344	95.4	99.9	99.5
R_Date GCF-T1-B-454	9123	8785	95.4	8916	8770	95.4	12.1	99.5
Phase Unit40								
E3				8964	8795	95.4		99.8
R_Date GCF-T1-B-89	8979	8642	95.4	8990	8837	95.4	88.2	99.8
R_Date GCF-T1-B-246	10378	10227	95.4	10376	10227	95.4	99.6	99.5
Phase Unit80								
R_Date GCF-T1-B-117	14276	13991	95.4	14261	13990	95.4	101.1	99.1
Phase Unit90								
Boundary base				14954	14147	95.4		99.3
Sequence GCF_ClearCk_2018								

Appendix I. Links for publically accessible data sources used in this study

Data Type	Source	URL
OxCal	ORAU – OxCal online	https://c14.arch.ox.ac.uk/ oxcal/OxCal.html
Lidar	DOGAMI lidar viewer	https://gis.dogami.oregon.gov/ maps/lidarviewer/