Jump to Navigation

Quaternary Fault and Fold Database of the United States

As of January 12, 2017, the USGS maintains a limited number of metadata fields that characterize the Quaternary faults and folds of the United States. For the most up-to-date information, please refer to the interactive fault map.

Seattle fault zone (Class A) No. 570

Last Review Date: 2016-11-25

citation for this record: Johnson, S.Y., Blakely, R.J., Brocher, T.M., Haller, K.M., Barnett, E.A., Bucknam, R.C., Haeussler, P.J., Pratt, T.L., Nelson, A.R., Sherrod, B.L., Wells, R.E., Lidke, D.J., Harding, D.J., and Kelsey, H.M., compilers, 2016, Fault number 570, Seattle fault zone, in Quaternary fault and fold database of the United States: U.S. Geological Survey website, https://earthquakes.usgs.gov/hazards/qfaults, accessed 12/14/2020 03:03 PM.

Synopsis	The Seattle fault zone is a 4- to 7-km-wide east-trending fault zone that extends from the Cascade Range foothills on the east across the Puget Lowland to Hood Canal, crossing Lake Sammamish, Lake Washington, Puget Sound, Bainbridge Island, and the Kitsap Peninsula. Various strands of the fault zone lie largely concealed beneath the major population centers of Seattle, Bellevue, and Bremerton. It forms the northern boundary of a belt of bedrock exposures that cross much of the Puget Lowland. The depth to bedrock north of the fault zone is as much as 1 km (Yount and others, 1985 #4746; Johnson and others, 1999 #4729). The fault zone has been imaged on seismic-reflection profiles collected in Puget Sound and adjacent waterways (Yount and Gower, 1991 #4744; Johnson and others, 1994 #4730; Pratt and others, 1997 #4737; Johnson and others, 1999 #4729), correlates with large gravity and magnetic

	anomalies (Danes and nine others, 1965 #4723; Blakely and others, 2002 #4716), and is represented by a prominent velocity anomaly on tomographic models (Brocher and others, 2001 #4718; Calvert and others, 2001 #4722). These data indicate the zone consists of three or more south-dipping thrust faults that form the structural boundary between the Seattle uplift on the south and the Seattle basin on the north. Blakely and others (2002 #4716) have named three of these structures the frontal fault, the Blakely Harbor fault, and the Orchard Point fault. Nelson and others (2003 #5868) termed the "frontal fault" the "Seattle fault." The Seattle fault zone also includes north-dipping reverse or thrust faults, such as the Toe Jam Hill fault (Nelson and others, 2000 #4733; 2002 #4736; 2003 #5868), which forms a complex scarp in densely forested terrain on Bainbridge Island. Slip on both south- and north-dipping faults within the zone probably is associated with offset on a south-dipping master fault (*e.g.*, Pratt and others, 1997 #4737) at depth. Surface-deforming earthquakes have occurred on the Seattle fault zone in the latest Holocene, most recently about 1040–910 cal yr BP, (A.D. 900–930) as summarized by Nelson and others (2014 #7675).
Name comments	Danes and others (1965 #4723) first suggested the presence of a major east-trending fault in the Puget Lowland near Seattle on the basis of gravity and magnetic anomalies and drill-hole data. Rogers (1970 #4738) also noted the large geophysical anomalies in the same location and suggested the name "Seattle-Bremerton fault." Gower and others (1985 #4725) briefly outlined geologic and geophysical relationships across this feature, which they designated "inferred structure I." Yount and Holmes (1992 #4745) introduced the name "Seattle fault" for this feature, which they considered a south-dipping thrust or reverse fault. Recognition that the structure includes multiple parallel faults and other structures led to the use of the name "Seattle fault zone" (Johnson and others, 1999 #4729; Brocher and others, 2001 #4718; Nelson and others, 2003 #5868).
County(s) and State(s)	KING COUNTY, WASHINGTON KITSAP COUNTY, WASHINGTON
Physiographic province(s)	PACIFIC BORDER
Reliability of location	Good Compiled at 1:24,000 and 1:100,000 scale. *Comments:* Strands of the Seattle fault zone are generally concealed beneath a cover of water, dense vegetation and thick Pleistocene glacial and interglacial deposits. Inferred locations of south-dipping faults in the Seattle fault zone are based on high-resolution seismic-reflection profiles

	(Johnson and others, 1999 #4729; Brocher and others, 2001 #4718; Liberty and Pape, 2007 #7654; Liberty and Pratt, 2008 #7619; Liberty 2009 #7620; Lamb and others, 2012 #7673), high-resolution aeromagnetic surveys (Blakely and others, 2002 #4716), geologic mapping (*e.g.*, Haeussler and Clark, 2000 #4726; Dragovich and others, 2007 #7594), and interpretation of LiDAR (Bucknam and others, 1999 #4721; Harding and Berghoff, 2000 #4728; Harding and others, 2002 #7671; Haugerud and others, 2001 #4735; 2003 #6211; Yoko and others, 2006 #7680; Muller and Harding, 2007 #7674). Location of fault from GER_Seismogenic_WGS84 (http://www.dnr.wa.gov/publications/ger_portal_seismogenic_features.zip, downloaded 05/23/2016) attributed to Haugerud (2005 #7605), Dragovich and others (2007 #7594), Liberty and Pratt (2008 #7619), and Liberty (2009 #7620).
Geologic setting	The east-trending thrust faults of the Seattle fault zone accommodate north-south compression due to the northward-migrating forearc of the Cascadia convergent margin (Wells and others, 1998 #4742; McCaffrey and others, 2000 #4731; Miller and others, 2001 #4732). Geodetic studies (*e.g.*, Khazaradze and others, 1999 #4734) indicate about 4–5 mm/yr of north/south crustal shortening in western Washington, some of which is accommodated by slip on the Seattle fault zone (Wells and Johnson, 2000 #4743). The fault zone forms the boundary between uplifted Tertiary rocks of the Seattle uplift on the south and thick Tertiary to Quaternary strata of the Seattle basin on the north. Gravity and seismic studies (*e.g.*, Brocher and others, 2001 #4718, 2004 #7631) indicate that Eocene volcanic rocks exposed at the surface in the Seattle uplift are buried by as much as 9–10 km of younger sediments in the Seattle basin. Long-term contraction rates across the Seattle uplift determined through analysis of fold geometry suggest between 0.25 and 1.0 mm/yr for the past few hundreds of thousands of yeas, which accounts for about 10 percent of the total shortening of the western Washington crust (Booth and others, 2004 #7670).
Length (km)	69 km.
Average strike	N85°W
Sense of movement	Thrust *Comments:* The Seattle fault zone is a complex zone that accommodates north-south shortening (Yount and Holmes, 1992 #4745; Johnson and others, 1994 #4730; Pratt and others, 1997 #4737; Johnson and others, 1999 #4729; Brocher and others, 2001 #4718; Blakely and others, 2002 #4716; Brocher and others, 2004 #7631). Dominant slip is south side up

	on south-dipping faults, producing the Seattle uplift. The zone also includes north-dipping reverse faults, such as the Toe Jam Hill fault and Waterman Point fault (Nelson and others, 2000 #4733; Haugerud and others, 2001 #4735; Nelson and others, 2002 #4736; Nelson and others, 2003 #5868; Haugerud and others, 2003 #6211; 2003 #6250).
Dip	25°–80° S. *Comments:* Dip proposed by various investigators spans a broad range. Using industry seismic-reflection data, Johnson and others (1994 #4730) inferred a mean dip of 45–60° S. to a depth of ~ 6 km for the northern fault in the Seattle fault zone (Frontal fault of Blakely and others, 2002 #4716), and suggest the dip of the zone shallows with depth. Using a different industry seismic-reflection database, Pratt and others (1997 #4737) inferred a dip of about 45° S. for the Frontal fault in the upper 6 km and presented a model showing a dip of about 20–25° S. at depths of 6–16 km. Johnson and others (1999 #4729) used high-resolution seismic-reflection data to infer that the dip of the Frontal fault in the upper 1 km varies along strike from 44–65° S. Haeussler and others (2000 #4727) used outcrop structural data in central Kitsap County to infer that the Frontal fault dips 65–70° S. near the surface but shallows to roughly 30° at depths of 5–6 km beneath Gold Mountain, west of Bremerton. Based on microseismicity, Brocher and others (2001 #4718) favor a model in which the Seattle fault zone dips steeply from the surface to a depth of about 25 km. Nelson and others (2014 #7675) summarize the on going debate regarding the subsurface geometry of the Seattle fault zone and presents the various models in figure 3.
Paleoseismology studies	Paleoseismologic investigations of shoreline deposits and trenching studies have been conducted along and near fault strands of the Seattle fault zone. Detailed investigations of shoreline deposits of Puget Sound and sediments and submerged forests of Lake Washington are described in some of the sites listed below. These off-fault investigations document evidence for late Holocene land-level changes, tsunamis, and (or) landslides that are interpreted to be effects of large earthquakes and faulting in this region. The evidence from many of these off-fault sites can be confidently correlated with a Holocene earthquake on the Seattle fault zone. Nelson and others (2014 #7675) compile calibrated radiocarbon ages that closely limit the times of surface deformation near the Seattle, Tacoma [581], and Saddle Mountain [575] faults. Evidence from some other off-fault sites, however, cannot be confidently related to a specific fault or zone of faults. The off-fault sites discussed below are included herein with the Seattle fault zone based on existing reports and

interpretations as well as in part based on their proximity to the Seattle fault zone. Some other coastal study sites nearby in the Puget Lowland, such as the Shine, Winslow, and Hansville sites (*e.g.*, Bucknam and others, 1992 #602; Sherrod, 2001 #4740), have been reported to show little or no evidence of late Holocene land-level changes, tsunami deposits, and other possible earthquake-related features. In addition to the paleoseismology sites listed below, Schuster and others (1992 #600) reported rock avalanches and limiting radiocarbon ages from the southeastern Olympic Mountains. They concluded that these avalanches probably were triggered by seismic shaking related to earthquakes in the last few thousand years, and suggested that the Seattle fault zone was one of a few obvious candidates for the earthquakes that might have triggered these avalanches. These rock avalanche study sites are discussed in more detail in the paleoseismology studies of the Saddle Mountain faults [575], which are located along the southeastern flank of the Olympic Mountains directly southeast of the rock avalanches studied by Schuster and others (1992 #600).

Restoration Point (570-1) and Alki Point (570-2). Bucknam and others (1992 #602) documented several meters of abrupt late Holocene uplift at these two coastal sites in the Seattle fault zone. Based on isotopic age dating and other information, they concluded that this uplift probably reflected land-level changes related to a major earthquake along the Seattle fault zone about 1000–1100 years ago. Other studies and more precise age dating (*e.g.*, Atwater and Moore, 1992 #597; Atwater, 1999 #4715), suggest that uplift at these sites probably is related to subsidence at the West Point site (570-3) and imply that the earthquake responsible for these land-level changes can be more tightly constrained to about 1050–1020 cal yr BP (A.D. 900–930). Sherrod and others (2000 #4741) expanded on this earlier study with a core transect across a nearby marsh. The stratigraphy beneath the marsh concurs that the area experienced abrupt 7 m uplift that shifted the tide flat to a freshwater environment around 1000 cal yr BP.

West Point (570-3) and Cultus Bay (570-4). The West Point site is located in tidal flat sediments at West Point along west edge of Seattle and east coast of Puget Sound. Based on tidal marsh stratigraphy and radiocarbon ages from this site, Atwater and Moore (1992 #597) documented evidence for subsidence and a tsunami generated in the Puget Sound about 1100–1000 years ago. The evidence suggests that a large earthquake on the Seattle fault zone generated the tsunami by causing abrupt uplift south of the fault (*e.g.*, at Restoration Point, 570-1, and Alki Point, 570-2) and complimentary subsidence to the north at West Point. Atwater and Moore (1992 #597) also correlated tsunami deposits of similar age at Cultus Bay on southern Whidbey Island with this event, but reported that there is no evidence of related land-level changes at Cultus Bay. Atwater (1999 #4715) later reported high-precision radiocarbon ages from a Douglas Fir log at the West Point site, which constrain the age of this earthquake to between 1050–1020 cal yr BP (A.D. 900–930, Atwater, 1999 #4715).

Lake Washington sites (570-5). The eastern part of the Seattle fault zone crosses Lake Washington. At several sites in and along the lake, submarine landslides, turbidites, and submerged forests on submarine landslides provide evidence of prehistoric earthquakes along the Seattle fault zone and (or) along faults elsewhere in Cascadia (*e.g.*, Karlin and Abella, 1992 #598; Jacoby and others, 1992 #599; Prunier and others, 1997 #6712; Karlin and others, 2004 #6713). Jacoby and others (1992 #599) dated submerged trees on landslide deposits in the lake and reported that the most recent landslides in three separate localities may have occurred simultaneously, about 1000 years ago. Based on tree-ring pattern matching with a dated log from the West Point site (570-3), they concluded that bark-year trees from the Lake Washington sites all died in the same year and same season as did the tree from the West Point site that later yielded a high-precision radiocarbon age of A.D. 900–930 (see Atwater and Moore, 1992 #597; Atwater, 1999 #4715). They noted that these results suggest that these landslides probably were triggered by the same seismic events that produced subsidence and tsunami deposits at West Point. More recently Karlin and others (2004 #6713) reported results of high-resolution seismic reflection, sidescan sonar swath, and sediment coring investigations in Lake Washington; these investigations also obtained magnetic susceptibility profiles and radiocarbon ages from terrigenous sediments in cores. Results of these studies provide detailed information on the distribution, geometry, age, and causes of submarine landslides in Lake Washington, and identify numerous large blockslides, sediment slumps, and debris flows. They also identified probable seismically induced turbidite (seismite) layers in their core samples. They noted that massive submarine block slides and retrogressive submarine slope failures probably were triggered by large earthquakes on the Seattle fault zone and (or) large to great temblors elsewhere in Cascadia. They further noted that magnetic profiling and radiocarbon ages from cores of probable seismites imply seven sedimentary disturbances in the lake in the last 3500 years. They correlated one of the turbidites with the A.D. 1700 Cascadia subduction zone earthquake, and correlated another with the A.D. 900–930 earthquake along the Seattle fault zone. They suggested that the other turbidite layers probably are also seismites caused by landslides during earthquakes; and they concluded that, collectively these deposits appear to provide a record of strong ground motion in this region that has occurred about every 300–500 yr during the past 3500 yr.

Toe Jam Hill site, trenches 570-6 to 570-10. Nelson and others (2000 #4733; 2002 #4736; 2003 #5868) presented the results of a trenching investigation that included five trench sites along the scarp of the Toe Jam Hill fault, a north-dipping backthrust in the Seattle fault zone. From east to west, the names assigned to these trench sites (Nelson and others, 2000 #4733; 2002 #4736; 2003 #5868) and the corresponding site numbers assigned herein are, Crane Lake (570-6), Blacktail (570-7), Mossy Lane (570-8), Saddle (570-9), and Bear's Lair (570-10). Four of these sites are located within about 200 m of an adjacent trench. Results from these trenching investigations indicate three or possibly four surface-rupturing earthquakes between about 2500 and 1000 yr BP.

Snohomish River delta sites (570-11). The Snohmomish River delta is located directly north of Everett, Washington, along Puget Sound. Based on detailed study of channel-bank stratigraphy at numerous sites along the delta and radiocarbon ages, Bourgeois and Johnson (2001 #4720) reported evidence for at least three episodes of liquefaction, at least one event of abrupt subsidence, and at least one tsunami since about A.D. 800. They report radiocarbon ages, which combined with stratigraphic relations, indicate that a prominent event of strong shaking produced liquefaction, abrupt subsidence, and a tsunami between A.D. 800–980. Bourgeois and Johnson (2001 #4720) concluded that these features probably resulted from the earthquake on the Seattle fault zone 1050–1020 cal yr BP (A.D. 900–930).

Two sites at Vasa Park, RipRap (570-12) and Blackberry (570-13) were located along an eastern strand of the Seattle fault zone near the west shore of Lake Sammamish, about 16 km east of Seattle. The trenches exposed a west to north northwest-striking fault zone. At the Rip Rap site, glacial till and Miocene bedrock are in fault contact across subvertical dip-slip faults that appear to accommodate bedding-plane slip in the steeply dipping till. Based on detailed study of an excavation across the main strand of the fault zone at this locality, Sherrod and others (2001 #4739) and Sherrod (2002 #7677) reported a fault, within a complex zone of faults, that places weathered Miocene volcaniclastic sediments on the southwest over Pleistocene glacial deposits to the northeast. They noted that these relations show clear evidence of Pleistocene or younger faulting, but also noted that any Holocene history is unknown, because post-glacial soils and colluvial deposits were previously removed from this site. Radiocarbon ages suggest that the last event occurred between 11,550±40 yr BP and 4,500 yr BP. Sherrod and others (2001 #4739) and Sherrod (2002 #7677) also reported that a ravine, about 4 km east of this site at Factoria, exposes proglacial lake sediments thrust over younger outwash and till.

Waterman Point trenches 570-14 to 570-16. Nelson and others (2003 #6250) presented data from a trenching investigation that included three trench sites along the scarp of the Waterman Point fault; the trenches exposed north-dipping backthrust faults that juxtapose Oligocene bedrock over a late Holocene forest soil. From east to west, the names assigned to the trenches and the corresponding trench-site numbers assigned herein are Nettle Grove (570-14), Madrone Ridge (570-15), and Snowberry (570-16); the latter two about 200 m apart. All three trenches showed evidence of a large earthquake about 1100–900 yr BP. Stratigraphy in the Madrone Ridge trench suggests a second, younger undated surface-rupturing earthquake producing vertical displacement of less than 2.4 m of the total scarp height of 4.3 m (Nelson and others, 2014 #7675). In addition, later analysis of radiocarbon ages may provide evidence for a second surface-rupturing earthquake in the Snowberry trench (Nelson and others, 2014 #7675).

Kelsey and others (2008 #7672) surveyed the Seattle fault zone uplifted shore platforms initially documented by Bucknam and others (1992 #602) at two locations to determine whether uplift was uniform throughout the Seattle fault zone, indicating a single regional uplift A.D. 900–930 (Atwater, 1999 #4715) event since 7.0 ka (Sherrod and others, 2000 #4741), or if shoreline uplift elevations locally vary where the platforms intersect the north-side-up reverse faults mapped by Nelson and others (2003 #5868) that possibly independently ruptured the Seattle fault zone at least three times in the past 3 k.y. Kelsey and others (2008 #7672) mapped two uplifted platforms north of the Point Glover (site 570-17) fault where only one platform extends along the shoreline south of the fault. They infer that north-side-up reverse offset along the Point Glover fault locally uplifted the upper platform once and then regional uplift during the Seattle fault zone A.D. 900–930 earthquake resulted in the uplift of the lower platform. Cumulative offset of the upper platform is about 12.7 m with approximately 3.5–4 m attributed to the earthquake on the Point Glover fault and 9 m attributed to the regional uplift associated with the A.D. 900–930 earthquake on the Seattle fault zone. At a location on the west coast of Bainbridge Island where the Toe Jam Hill fault (mapped in trenches by Nelson and others (2003 #5868) intersects the shoreline (site 570-18), surveys across the uplifted platforms indicate that two earthquakes deformed the shoreline: the regional Seattle fault zone A.D. 900–930 event and an earlier, local event that uplifted the hanging wall of the Toe Jam Hill fault 3–3.5 m (Kelsey and others, 2008 #7672).

Gorst Creek (site 570-19). Arcos (2012 #7669) mapped tsunami and overlying debris flow deposits in core stratigraphy and outcrop exposures near the terminus of Gorst Creek where it empties in the wetlands

	surrounding Sinclair Inlet. Deposits beneath the modern wetland record a former wetland that was abruptly uplifted at least 3 m and then inundated by a sandy tsunami deposit from offshore, which in turn was covered by a sandy debris flow that surged down Gorst Creek. Based on soft-sediment deformation within the top of the tsunami deposit and lack of vegetation on its surface, Arcos (2012 #7669) infers that the debris flow occurred soon after the tsunami. This suggests that the earthquake triggered not only the tsunami but also might have caused slope instability soon after. Uplift is constrained to A.D. 690–990 by a maximum age of radiocarbon-dated leaves beneath the debris flow deposit and a minimum age from a hemlock cone above the sand deposits. Arcos (2012 #7669) correlates the uplift to the A.D. 900–930 Seattle fault rupture. Because this site is located between the Seattle and Tacoma faults, which might have ruptured simultaneously. Arcos (2012 #7669) modeled tsunamis generated by each fault and determined that the Seattle fault zone was the more likely source of the tsunami deposits. Following the debris flow, the uplifted, forested area began to subside back to intertidal conditions between A.D. 1520–1880, based on the radiocarbon-dating of an in-situ hemlock snag now consumed by the salt marsh, first mapped in 1880. Study locations are generalized as one location; individual sites are shown on figure 3A of Arcos (2012 #7669) Spotted Frog trench (site 570-20) across the Island Wood scarp, southwestern Bainbridge Island, exposed till in fault contact with Miocene volcaniclastic deposits (Nelson and others, 2014 #7675). The trench exposed evidence of two surface-deforming events; the first with less than 1.7 m of slip and the second with more than 0.9 m. Radiocarbon ages suggest deformation occurred during the same time frame as other studies in the region.
Geomorphic expression	Late Holocene uplift in the Seattle fault zone produced a terrace commonly 5 to 7 m high along shores of Puget Sound (Bucknam and others, 1992 #602). This belt of uplift extends 5–10 km southward from the Frontal fault and 30 km eastward from Dyes Inlet to the Duwamish River. Faulted glacial deposits near Bellevue (Sherrod and others, 2001 #4739) show that late Quaternary faulting continues eastward across Lake Washington. Late Holocene backthrusting within the Seattle fault zone produced short (1- to 2-km-long), 3- to 7-m-high scarps along the Toe Jam Hill fault (Bucknam and others, 1999 #4721; Nelson and others, 2000 #4733; 2002 #4736; 2003 #5868), and Waterman Point fault (Haugerud and others, 2001 #4735; Haugerud and others, 2003 #6211; Nelson and others, 2003 #6250). Additional tectonic landforms have undoubtedly been buried or eroded during Pleistocene glaciation. The Puget Lowland was occupied at least five times during the Pleistocene by a lobe of the

	continental ice sheet, with the most recent ice retreat occurring about 16 ka (Porter and Swanson, 1998 #6237). Much of the present landscape reflects this glacial history (Booth, 1994 #4719). The tops of bedrock hills on the Seattle uplift stand as much as 300–400 m higher than the tops of drumlins comprised of glacial drift to the north in the Seattle basin.
Age of faulted surficial deposits	The Seattle fault (frontal fault of Blakely and others, 2002 #4716) is largely concealed beneath young glacial deposits and vegetation. Interpretations of seismic-reflection data suggest it juxtaposes Tertiary bedrock and Quaternary glacial and interglacial deposits at shallow depth (Johnson and others, 1994 #4730; Pratt and others, 1997 #4737; Johnson and others, 1999 #4729). Sherrod and others (2001 #4739) describe a possible exposure of the Seattle fault near the west shore of Lake Sammamish, juxtaposing Miocene bedrock and undated Quaternary glacial deposits. Recent LIDAR topographic imagery suggests the Seattle fault may be a blind structure since deglaciation (about 15,000 yr BP) along much of its trace. In this scenario, upper Quaternary deposits are folded above the buried fault tip, but not ruptured at the surface. The Blakely Harbor fault is also concealed, but geologic and geophysical data suggest it juxtaposes Miocene nonmarine deposits and Eocene-Oligocene marine deposits at shallow depth across much of the central Puget Lowland. The Port Orchard fault is similarly concealed, however, geologic and geophysical data indicate that at shallow depth it forms a contact between Eocene-Oligocene marine deposits and Eocene volcanic rocks (Johnson and others, 1994 #4730; 1999 #4729; Blakely and others, 2002 #4716). Trenches across the scarps of north-dipping faults show displacement of Pleistocene to late Holocene deposits. The Toe Jam Hill fault cuts Miocene bedrock, Pleistocene glacial deposits, and postglacial (latest Pleistocene to Holocene) deposits. The faulted strata are as young as 1100–900 yr BP (Nelson and others, 2000 #4733; 2002 #4736; 2003 #5868). The fault along the Waterman Point scarp cuts Eocene-Oligocene bedrock and glacial and postglacial Pleistocene and late Holocene deposits (Nelson and others, 2003 #6250).
Historic earthquake	
Most recent prehistoric deformation	latest Quaternary (<15 ka) *Comments:* Nelson and others (2014 #7675) summarize an OxCal analysis of ten of the most closely limiting radiocarbon ages from fault trenches and cores at eight sites that restrict the age a large earthquake on the central Seattle fault zone to 1040–910 cal yr BP (2σ), which overlaps the most precise age for the earthquake's tsunami (1050–1020 cal yr BP) in eastern Puget Sound. In addition, the central Seattle fault zone may slip

	during moderate to large earthquakes as frequently as every few hundred years for periods of 1000–2000 yr, and then not slip for periods of at least several thousands of years.
Recurrence interval	0.2 to 12 k.y. (<16 ka)—Toe Jam Hill fault *Comments:* Detailed paleoseismologic investigations within the Seattle fault zone have been conducted only on Bainbridge Island (Bucknam and others, 1992 #602; Sherrod and others, 2001 #4739; Nelson and others, 2002 #4736; 2003 #5868). One large (M≥ 7) late Holocene earthquake, at 1050–1020 yr BP, was originally inferred on the basis of an uplifted terrace (Sherrod, 1985 #4171; Bucknam and others, 1992 #602; Atwater, 1999 #4715). Numerous studies have documented the regional effects of the 1050–1020 yr BP Seattle fault zone earthquake (Atwater and Moore, 1992 #597; Karlin and Abella, 1992 #598; Jacoby and others, 1992 #599; Schuster and others, 1992 #600; Bucknam and others, 1992 #602; Bourgeois and Johnson, 2001 #4720; Sherrod, 2001 #4740). Five trenches crossing the Toe Jam Hill fault (north-dipping backthrust) on southern Bainbridge Island reveal evidence of 3 or 4 ground-rupturing earthquakes between 2500 and ~1000 yr BP. The youngest of these prehistoric earthquakes overlaps in age with and is inferred to correlate with the 1050–1020 yr BP event. Based on the results of trenching studies, Nelson and others (2003 #5868) report radiocarbon-measured recurrence intervals of ~0.2 to 12 k.y. for post-glacial (since 16 ka) earthquakes along the Toe Jam Hill fault. These post-glacial recurrence intervals range from 12,000 yr between late Pleistocene and late Holocene earthquakes to as little as a century or less for late Holocene earthquakes (Nelson and others, 2003 #5868). Nelson and others (2003 #5868) note that the earthquake history of the Toe Jam Hill fault is at least a partial proxy for the earthquake history of the Seattle fault and other faults in the Seattle fault zone (see also, discussion in "Slip-rate category" below).
Slip-rate category	Between 0.2 and 1.0 mm/yr *Comments:* Preferred rate is about 0.9 mm/yr. Based on analysis of Quaternary structural relief on faults and folds imaged on high-resolution seismic-reflection data in Puget Sound, Johnson and others (1999 #4729) suggested that the Seattle fault (frontal fault of Blakely and others, 2002 #4716) of the Seattle fault zone has a minimum Quaternary slip rate of about 0.5 mm/yr. This estimate assumes that the Frontal fault dips 44°–65° S. in the upper 1 km (see above). Assuming more steep or shallower dips would result in slightly slower and faster slip rates, respectively. Calvert and others (2001 #4722) and ten Brink and others (2002 #6353) suggested a similar slip rate on the Seattle fault in eastern Puget Sound.

	Based on the results of trenching studies, Nelson and others (2003 #5868) reported radiocarbon-measured evidence for post-glacial (since 16 ka) recurrence intervals and vertical-displacement rates along the Toe Jam Hill fault, a backthrust to the Seattle fault. For post-glacial activity along the Toe Jam Hill fault, their results indicate shorter recurrence intervals and higher vertical-displacement rates (~2 mm/yr) during the late Holocene compared to longer recurrence intervals and lower vertical-displacement rates (~0.2 mm/yr) between the late Pleistocene and late Holocene. Nelson and others (2003 #5868) concluded that the higher, late Holocene rates on the Toe Jam Hill fault probably reflect an unusual cluster of earthquakes along this strand of the fault zone rather than a recent increase in the rate of north-south shortening across the entire zone. Cumulative slip rates across the Seattle fault zone probably are a minimum of about 0.7–1.0 mm/yr. However, it is likely that the style, geometry, and perhaps rates of fault-related shortening vary laterally and vary along different strands of the zone as suggested above for the Toe Jam Hill fault. It has also been suggested that slip may diminish at the western end of the fault zone where structural relief also decreases (Brocher and others, 2001 #4718).
Date and Compiler(s)	2016 Samuel Y. Johnson, U.S. Geological Survey Richard J. Blakely, U.S. Geological Survey, Emeritus Thomas M. Brocher, U.S. Geological Survey Kathleen M. Haller, U.S. Geological Survey Elizabeth A. Barnett, Shannon & Wilson, Inc. Robert C. Bucknam, U.S. Geological Survey, Retired Peter J. Haeussler, U.S. Geological Survey Thomas L. Pratt, U.S. Geological Survey Alan R. Nelson, U.S. Geological Survey Brian L. Sherrod, U.S. Geological Survey Ray E. Wells, U.S. Geological Survey David J. Lidke, U.S. Geological Survey David J. Harding, NASA, National Aeronautic and Space Administration, Geodynamics Branch Harvey M. Kelsey, Humboldt State University
References	#7669 Arcos, M.E.M., 2012, The A.D. 900–930 Seattle-fault-zone Earthquake with a wider coseismic rupture patch and postseismic submergence—Inferences from new sedimentary evidence: Bulletin of the Seismological Society of America, v. 102, p. 1079–1098, doi:10.1785/0120110123. #4715 Atwater, B.F., 1999, Radiocarbon dating of a Seattle earthquake to A.D. 900-930 [abs.]: Seismological Research Letters, v. 70, p. 232.

#597 Atwater, B.F., and Moore, A.L., 1992, A tsunami about 1000 years ago in Puget Sound, Washington: Science, v. 258, p. 1614-1617.

#4716 Blakely, R.J., Wells, R.E., Weaver, C.S., and Johnson, S.Y., 2002, Location, structure, and seismicity of the Seattle fault, Washington—Evidence from aeromagnetic anomalies, geologic mapping, and seismic-reflection data: Geological Society of America Bulletin, v. 114, no. 2, p. 169-177.

#4719 Booth, D.B., 1994, Glaciofluvial infilling and scour of the Puget Lowland, Washington, during ice-sheet glaciation: Geology, v. 22, p. 695-698.

#7670 Booth, D.B., Troost, K.G., and Hagstrum, J.T., 2004, Deformation of Quaternary strata and its relationship to crustal folds and faults, south-central Puget Lowland, Washington State: Geology, v. 32, p. 505–508, doi:10.1130/G20355.1.

#4720 Bourgeois, J., and Johnson, S.Y., 2001, Geologic evidence of earthquakes at the Snohomish delta, Washington, *in* the past 1200 years: Geological Society of America Bulletin, v. 113, p. 482-494.

#7631 Brocher, T.M., Blakley, R.J., and Wells, R.E., 2004, Interpretation of the Seattle uplift, Washington, as a passive-roof duplex: Bulletin of the Seismological Society of America, v. 94, p. 1379–1401, doi:10.1785/012003190.

#4718 Brocher, T.M., Parsons, T., Blakely, R.J., Christensen, N.I., Fisher, M.A., Wells, R.E., and SHIPS Working Group, 2001, Upper crustal structure in Puget Lowland, Washington—Results from the 1998 seismic hazards investigation in Puget Sound: Journal of Geophysical Research, v. 106, p. 13,541–13,564.

#4717 Brocher, T.M., Pratt, T.L., Creager, K.C., Crosson, R.S., Steele, W.P., Weaver, C.S., Frankel, A.D., Trehu, A.M., Snelson, C.M., Miller, K.C., Harder, S.H., and ten Brink, U.S., 2000, Urban seismic experiments investigate Seattle fault and basin: Eos, Transactions of the American Geophysical Union, v. 81, p. 551-552.

#602 Bucknam, R.C., Hemphill-Haley, E., and Leopold, E.B., 1992, Abrupt uplift within the past 1700 years at southern Puget Sound, Washington: Science, v. 258, p. 1611-1614.

#4721 Bucknam, R.C., Sherrod, B.L., and Elfendahl, G., 1999, A fault scarp of probable Holocene age in the Seattle fault zone, Bainbridge Island, Washington: Seismological Research Letters, v. 258, p. 1611-1614.

#4722 Calvert, A.J., Fisher, M.A., and SHIPS Working Group, 2001, Imaging the Seattle fault zone with high-resolution seismic tomography: Geophysical Research Letters, v. 28, no. 2337-2340.

#4723 Danes, Z.F., Bonno, M., Brau, E., Gilham, W.D., Hoffman, T.F., Johansen, D., Jones, M,H., Malfait, B., Masten, J., Teague, G.O., 1965, Geophysical investigation of the southern Puget Sound area, Washington: Journal of Geophysical Research, v. 70, p. 5573-5579.

#7594 Dragovich, J. D., Anderson, M. L., Walsh, T. J., Johnson, B. L., and Adams, T. L., 2007, Geologic map of the Fall City 7.5-minute quadrangle, King County, Washington: Washington Division of Geology and Earth Resources, Geologic Map GM-67, scale 1:24,000.

#4725 Gower, H.D., Yount, J.C., and Crosson, R.S., 1985, Seismotectonic map of the Puget Sound region, Washington: U.S. Geological Survey Miscellaneous Investigations Map I-1613, scale 1:250,000.

#4726 Haeussler, P.J., and Clark, K.P., 2000, Preliminary geologic map of the Wildcat Lake 7.5' quadrangle, Kitsap and Mason Counties, Washington: U.S. Geological Survey Open-File Report 00-356, scale 1:24,000.

#4727 Haeussler, P.J., Wells, R.E., Blakely, R.J., Murphy, J., and Wooden, J., L., 2000, Structure and timing of movement on the Seattle fault at Green and Gold Mountains, Kitsap Peninsula, Washington: Geological Society of America Abstracts with Programs, v. 32, no. 6, p. A-16.

#4728 Harding, D.J., and Berghoff, G.S., 2000, Fault scarp detection beneath dense vegetation cover—Airborne laser mapping of the Seattle fault zone, Bainbridge Island, Washington State: Proceedings of the American Society of Photogrammetry and Remote Sensing Annual Conference, Washington, D.C., 9 p.

#7671 Harding, D.J., Johnson, S.Y., and Haugerud, R.A., 2002, Folding and rupture of an uplifted Holocene marine platform in the Seattle fault zone, Washington, revealed by airborne laser swath mapping: Geological Society of America Abstracts with Program, https://gsa.confex.com/gsa/2002CD/finalprogram/abstract_34490.htm

#7605 Haugerud, R., 2005, Preliminary geologic map of Bainbridge Island, Washington: U.S. Geological Survey, Open-File Report OF-2005-1387, scale 1:24,000.

#6211 Haugerud, R.A., Harding, D.J., Johnson, S.Y., Harless, J.L., Weaver, C.S., and Sherrod, B.L., 2003, High-resolution lidar topography of the Puget Lowland, Washington—A bonanza for earth science: Geological Society of America GSA Today, v. 13, no. 6, p. 4-10.

#4735 Haugerud, R.A., Weaver, C.S., and Harless, J., 2001, Finding faults with LIDAR in the Puget Lowland: Seismological Research Letters, v. 72, p. 253.

#599 Jacoby, G.C., Williams, P.L., and Buckley, B.M., 1992, Tree ring correlation between prehistoric landslides and abrupt tectonic events in Seattle, Washington: Science, v. 258, p. 1621-1623.

#4729 Johnson, S.Y., Dadisman, S.V., Childs, J.R., and Stanley, W.D., 1999, Active tectonics of the Seattle fault and central Puget Lowland—Implications for earthquake hazards: Geological Society of America Bulletin, v. 111, p. 1042-1053 and oversize insert.

#4730 Johnson, S.Y., Potter, C.J., and Armentrout, J.M., 1994, Origin and Evolution of the Seattle fault and Seattle basin: Geology, v. 22, p. 71-74 and oversize insert.

#598 Karlin, R.E., and Abella, S.E.B., 1992, Paleoearthquakes in the Puget Sound region recorded in sediments from Lake Washington, U.S.A.: Science, v. 258, p. 1617-1620.

#6713 Karlin, R.E., Holmes, M., Abella, S.E.B., and Sylwester, R., 2004, Holocene landslides and a 3500-year record of Pacific Northwest earthquakes from sediments in Lake Washington: Geological Society of America Bulletin, v. 116, p. 94-108.

#7672 Kelsey, H.M., Sherrod, B.L., Nelson, A.R., and Brocher, T.M., 2008, Earthquakes generated from bedding plane-parallel reverse faults above an active wedge thrust, Seattle fault zone: Geological Society of America Bulletin, v. 120, p. 1581–1597.

#4734 Khazaradze, G.Q., Anthony, and Dragert, H., 1999, Tectonic deformation in western Washington from continuous GPS measurements: Geophysical Research Letters, v. 26, p. 3153-3156.

#7673 Lamb A.P., Liberty L.M., Blakely R.J., Pratt T.L., Sherrod B.L., and van Wijk K., 2012, Western limits of the Seattle fault zone and its interaction with the Olympic Peninsula, Washington: Geosphere v. 8, p. 915–30, doi:10.1130/GES00780.1.

#7620 Liberty, L., 2009, Seismic reflection imaging of the western portions of the Seattle fault: Report to the U.S. Geological Survey under contract number 08HQGR0075, 16 p.

#7654 Liberty, L.M., and Pape, K.M., 2007, Seismic characterization of the Seattle and southern Whidbey Island fault zones in the Snoqualmie River Valley, Washington: Technical report to the U.S. Geological Survey under contract number 06HQGR0111, 17 p., http://earthquake.usgs.gov/research/external/reports/06HQGR0111.pdf

#7619 Liberty, L.M., and Pratt, T.L., 2008, Structure of the eastern Seattle fault zone, Washington State—New insights from seismic reflection data: Bulletin of the Seismological Society of America, v. 98, p. 1681–1695, DOI: 10.1785/0120070145.

#4731 McCaffrey, R., Long, M.D., Goldfinger, C., Zwick, P.C., Nabelek, J.L., Johnson, C.K., and Smith, C., 2000, Rotation and pl. locking along the southern Cascadia subduction zone: Geophysical Research Letters, v. 27, p. 3117-3120.

#4732 Miller, M.M., Miller, D.J., Rubin, C.M., Dragert, H., Wang, Kelin, Qamar, Anthony, and Goldfinger, C., 2001, GPS-determination of along-strike variation in Cascadia margin kinematics—Implications for relative pl. motion, subduction zone coupling, and permanent deformation: Tectonics, v. 20, p. 161-176.

#7674 Muller, J.R., and Harding, D.J., 2007, Using LiDAR surface deformation mapping to constrain earthquake magnitudes on the Seattle fault in Washington State, USA: Urban Remote Sensing Joint Event, Paris, 1-13 April 2007, pp. 1-7, doi: 10.1109/URS.2007.371789.

#6250 Nelson, A.R., Johnson, S.T., Kelsey, H.M., Sherrod, B.L., Wells, R.E., Okumura, K., Bradley, L., Bogar, R., and Personius, S.F., 2003, Field and laboratory data from an earthquake history of the Waterman Point fault, Kitsap County, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-2423, 1 sheet.

#6354 Nelson, A.R., Johnson, S.Y., Kelsey, H.M., Sherrod, B.L., Wells, R.E., Bradley, L., and Okumura, K., 2003, Late Holocene earthquakes on the Waterman Point reverse fault, another ALSM-discovered fault scarp in the Seattle fault zone, Puget Lowland, Washington: Geological Society of America Abstracts with Programs.

#5868 Nelson, A.R., Johnson, S.Y., Kelsey, H.M., Wells, R.E., Sherrod, B.L., Pezzopane, S.K., Bradley, L., and Koehler, R.D., III, 2003, Late Holocene earthquakes on the Toe Jam Hill fault, Seattle fault zone, Bainbridge Island, Washington: Geological Society of America Bulletin, v. 115, no. 11, p. 16.

#4733 Nelson, A.R., Johnson, S.Y., Pezzopane, S.K., Wells, R.E., Kelsey, H.M., Sherrod, B.L., Koehler, R.D., Bradley, L.A., Bucknam, R.C., LaPrade, W.T., Cox, J.W., and Narwold, C.F., 2000, Postglacial and Late Holocene earthquakes on the Toe Jam strand of the Seattle fault, Bainbridge Island, Washington: Geological Society of America Abstracts with Programs, v. 32, p. A-58.

#4736 Nelson, A.R., Johnson, S.Y., Wells, R.E., Pezzopane, S.K., Kelsey, H.M., Sherrod, B.L., Bradley, L.A., Koehler, R.D.I., Bucknam, R.C., Haugerud, R.A., and LaPrade, W.T., 2002, Field and laboratory data from an earthquake history study of the Toe Jam Hill fault, Bainbridge Island, Washington: U.S. Geological Survey Open-File Report 02-0060, 19 p., 2 sheets.

#7675 Nelson, A.R., Personius, S.F., Sherrod, B.L., Kelsey, H.M., Johnson, S.Y., Bradley, L-A., and Wells, R.E., 2014, Diverse rupture modes for surface-deforming upper plate earthquakes in the southern Puget Lowland of Washington State: Geosphere, v. 10, p. 769-796, doi:10.1130/GES00967.1.

#6237 Porter, S.C., and Swanson, T.W., 1998, Radiocarbon age constraints on rates of advance and retreat of the Puget lobe of the Cordilleran ice sheet during the last glaciation: Quaternary Research, v. 50, p. 205-213.

#4737 Pratt, T.L., Johnson, S., Potter, C., Stephenson, W., and Finn, C., 1997, Seismic reflection images beneath Puget Sound, western Washington State—The Puget Lowland thrust sheet hypothesis: Journal of Geophysical Research, v. 102, p. 27,469-27,489.

#7676 Pratt, T.L., Troost, K.G., Odum, J.K., and Stephenson, W.J., 2015, Kinematics of shallow backthrusts in the Seattle fault zone, Washington State: Geosphere, v. 11, p. 1948–1974, doi:10.1130/GES01179.1.

#6712 Prunier, C.F., Karlin, R.E., Holmes, M., Abella, S.E.B., and Pratt, T.L., 1997, Holocene neotectonic deformation and earthquake history in sediments from Lake Washington, Lake Sammamish, and Port Orchard: Eos, Transactions of the American Geophysical Union, v. 78, no. 46, p. 440.

#4738 Rogers, W.P., 1970, A geological and geophysical study of the central Puget Sound Lowland: Seattle, University of Washington, unpublished Ph.D. dissertation, 123 p., 9.

#600 Schuster, R.L., Logan, R.L., and Pringle, P.T., 1992, Prehistoric rock avalanches in the Olympic Mountains, Washington: Science, v. 258, p. 1620-1621.

#7679 Sherrod, B., and Gomberg, J., 2014, Crustal earthquake triggering by pre-historic great earthquakes on subduction zone thrusts: Journal of Geophysical Research, v. 119, p 1273–1294, doi: 10.1002/2013JB010635.

#4740 Sherrod, B.L., 2001, Evidence for earthquake-induced subsidence about 1100 years ago in coastal marshes of southern Puget Sound, Washington: Geological Society of America Bulletin, v. 113, p. 1299-1311.

#7677 Sherrod, B.L., 2002, Late Quaternary surface rupture along the Seattle fault zone near Bellevue, Washington: American Geophysical Union, Fall Meeting 2002, abstract #S21C-12.

#4741 Sherrod, B.L., Bucknam, R.C., and Leopold, E.B., 2000, Holocene relative sea level changes along the Seattle fault at Restoration Point, Washington: Quaternary Research, v. 54, p. 384-393.

#4739 Sherrod, B.L., Haeussler, P.J., Wells, R., Troost, K., and Haugerud, R., 2001, Surface rupture in the Seattle fault zone near Bellevue, Washington: Seismological Research Letters, v. 72, p. 253.

#4171 Sherrod, D.R., 1985, Geologic setting of the Breitenbush-Austin Hot Springs area, Cascade Range, north-central Oregon—Chapter 1, *in* Sherrod, D.R., ed., Geology and geothermal resources of the Breitenbush-Austin Hot Springs area, Clackamas and Marion Counties, Oregon: State of Oregon, Department of Geology and Mineral Industries Open-File Report 0-88-5, p. 1-14.

#6353 ten Brink, U.S., Molzer, P.C., Fisher, M.A., Blakely, R.J., Bucknam, R.C., Parsons, T., Crosson, R.S., and Creagher, K.C., 2002, Subsurface geometry and evolution of the Seattle fault zone and the

Seattle basin, Washington: Bulletin of the Seismological Society of America, v. 92, p. 1737-1753.

#7678 ten Brink, U.S., Song, J., and Bucknam, R.C., 2006, Rupture models for the A.D. 900–930 Seattle fault earthquake from uplifted shorelines: Geology, v. 34, p. p. 585-588, doi: 10.1130/G22173.1.

#4743 Wells, R.E., and Johnson, S.Y., 2000, Neotectonics of western Washington and the Puget Lowland from northward migration of the Cascadia forearc: Geological Society of America Abstracts with Programs, v. 32, p. A-75.

#4742 Wells, R.E., Weaver, C.S., and Blakely, R.J., 1998, Forearc migration in Cascadia and its neotectonic significance: Geology, v. 26, p. 759-762.

#7680 Yoko, O., Satoko, O., Hisashi, S., and Sakae, M., 2006, Late Holocene deformation as deduced from the former shoreline height of marine terraces above the Seattle fault zone, Washington State: Seismological Society of Japan, v. 58, p. 385–399.

#4744 Yount, J.C., and Gower, H.D., 1991, Bedrock geologic map of the Seattle 30' by 60' quadrangle, Washington: U.S. Geological Survey Open-File Report 91-147, 37 p., 4, scale 1:100,000.

#4745 Yount, J.C., and Holmes, M.L., 1992, The Seattle fault—A possible Quaternary reverse fault beneath Seattle Washington: Geological Society of America Abstracts with Programs, v. 24, p. 93.

#4746 Yount, J.C., Dembroff, G.R., and Barats, G.M., 1985, Map showing depth to bedrock in the Seattle 30' by 60' quadrangle, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-1692, scale 1:100,000.