Preliminary Atlas of Active Shallow Tectonic Deformation in the Puget Lowland, Washington

Compiled by

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Abstract

This atlas presents an up-to-date map compilation of the geological and geophysical observations that underpin interpretations of active, surface-deforming faults in the Puget Lowland, Washington. Shallow lowland faults are mapped where observations of deformation from paleoseismic, seismic-reflection, and potential-field investigations converge. Together, results from these studies strengthen the identification and characterization of regional faults and show that as many as a dozen shallow faults have been active during the Holocene. The suite of maps presented in our atlas identifies sites that have evidence of deformation attributed to these shallow faults. For example, the paleoseismic-investigations map shows where coseismic surface rupture and deformation produced geomorphic scarps and deformed shorelines. Other maps compile results of seismic-reflection and potential-field studies that demonstrate evidence of deformation along suspected fault structures in the subsurface. Summary maps show the fault traces derived from, and draped over, the datasets presented in the preceding maps. Overall, the atlas provides map users with a visual overview of the observations and interpretations that support the existence of active, shallow faults beneath the densely populated Puget Lowland.

Introduction

Research during the last quarter century accounts for nearly all of what is known today about the locations, paleoseismic histories, and damage potential of shallow faults that rupture the ground surface in the Puget Lowland, northwest Washington. In 1985, when Gower and others summarized geological and geophysical evidence for the region's shallow faults, only one of these structures, the Saddle Mountain Fault Zone, had demonstrated earthquake activity during the Holocene, or past 10,000 years (Carson, 1973; Wilson and others, 1975, 1979). Today, recent investigations show that there might be as many as a dozen shallow faults that have been active during the Holocene, which together heighten the seismic hazard of the Puget Lowland. These faults, as well as those considered to have been active during at least the Quaternary (the past 1.6 million years), are compiled in the U.S. Geological Survey Quaternary Fault and Fold Database (http://earthquake.usgs.gov/regional/qfaults/), an online database and map resource for fault traces and their source studies.

The primary motive behind producing this atlas is to present in map view both the active, surface-deforming shallow faults in the Puget Lowland and a compilation of the geological field and geophysical observations that underpin their interpretations and locations. By doing so, the atlas updates the Gower and others (1985) map and complements the U.S. Geological Survey Quaternary Fault and Fold Database. Although we include Quaternary faults in this atlas, here we emphasize currently known or suspected faults that have Holocene displacements and present their primary supporting geophysical and geological data evidence. These active and potentially active faults critically impact earthquake hazards in the densely populated metropolitan areas of the Puget Lowland.

The suite of maps is thematically organized, beginning with field evidence for coseismic fault-generated surface deformation and followed by geophysical subsurface observations of potentially related fault structures. In the final summary maps, deformation observations from the preceding maps are compiled and stacked; fault traces are then draped over the observations that support their interpretations. The maps listed below are more thoroughly described in the sections that follow:

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- Map 2 and Inset Map 4: Seismic Surveys and Locations
- Map 5 and Inset Map 6: Thickness of Unconsolidated Quaternary Deposits
- Map 7 and Inset Map 9: Aeromagnetic Anomalies
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- Map 11 and Inset Map 12: Isostatic Residual Gravity Anomalies
- Map 13 and Inset Map 14: Summary of Shallow Fault Deformation Data and Quaternary Faults Traces Draped Over Residual Aeromagnetic Anomalies

The Puget Lowland Geology and Geography and the Atlas Map Area

The Puget Lowland is a north-south-trending structural basin that is flanked by Mesozoic and Tertiary rocks of the Cascade Range on the east and by Eocene rocks of the Olympic Mountains on the west. Quaternary glaciations and subsequent fluvial systems have shaped the basin by leaving behind a thick blanket of sediments (fig. 1) (Tabor and others, 1978, 1993, 2000; Shuster and others, 2005). The Puget Lowland encompasses this formerly glaciated plain, which fringes the surrounding mountains and contains Puget Sound and the eastern part of the Strait of Juan de Fuca. In order to include recent shallow fault studies located outside the lowland (fig. 1), we include in the map area of the atlas the east half of the Olympic Mountains, the west part of the Cascade Range, and the south part of the Georgia Strait. Thus, in the atlas, we define the Puget Lowland as the map area shown in figure 1.

Tectonic Framework of Puget Lowland Shallow Faults

Active shallow faults accommodate regional north-south shortening in the Puget Lowland. Situated near the north end of the Cascadia fore arc, the lowland is subject to tectonic compression as mobile fore-arc blocks migrate northward between the Cascade volcanic arc to the east and the convergent margin of the Cascadia Subduction Zone (CSZ) to the west (fig. 2) (Wells and others, 1998). Oblique subduction of the Juan de Fuca oceanic plate beneath the North America continental plate drives the Oregon Coast fore-arc block northward, compressing western Washington against the relatively stationary backstop of the British Columbia Coast Mountains (fig. 2) (Wells and others, 1998; Wells and Simpson, 2001).

GPS studies show that, between northern Oregon and Canada, the fore-arc blocks are rotating clockwise and translating northward at about 6 to 8 mm/yr (fig. 3) (Wells and others, 1998; Wells and Simpson, 2001; Mazzotti and others, 2002). Within the Puget Lowland, GPS data record north-south shortening rates of from 3.0 to 4.0 mm/yr (red arrows in fig. 3) (Mazzotti and others, 2002, 2003) to 4.4 mm/yr (McCaffrey and others, 2007) after the interseismic loading signal (green and black arrows in fig. 3) of the locked CSZ is removed. The accumulated strain of this shortening is released by large earthquakes on the shallow east-west- to northwest-southeast-trending faults and also accommodated in folds that traverse the Puget Lowland (figs. 4, 5).

Gower and others (1985) delineated some of the Puget Lowland shallow fault zones (fig. 4) on the basis of geophysical and geological field observations that were available in the early 1980’s. Gower and others (1985) noted that, although the majority of recorded earthquakes originate within the North America continental crust at depths less than 35 km, earthquake hypocenters do not correlate well with inferred fault locations (fig. 4). Furthermore, researchers at that time had not yet studied the suspected shallow faults in enough detail to determine whether or not they were currently active.

More recent paleoseismic studies, however, have demonstrated that shallow faults in the Puget Lowland have produced large, surface-deforming Holocene earthquakes (maps 1, 3; table 1). In addition, geophysical investigations have better contrained the locations of these faults in the subsurface (maps 7-12; table 1). Earthquake histories for several of these Puget Lowland faults have emerged from paleoseismic investigations of deformed shorelines, marsh subsidence or uplift, tsunami deposits, liquefaction features, and fault scarps (maps 1, 3; tables 1, 2). Faults for which paleoseismic studies have documented Holocene activity are shown with solid black lines on figure 5 and maps 13, 14 (see fig. 5 and table 1 for references); dashed black lines indicate faults that either have documented earlier Pleistocene deformation or, at most, suspected Holocene activity.

Active Faults Identified by Recent Geophysical and Geological Field Projects

Recent advances documenting Puget Lowland shallow fault activity have resulted from both large, collaborative research initiatives and smaller, independent studies. The USGS Urban Hazards Studies program provides support for aeromagnetic, gravity, and seismic reflection and refraction experiments to map the Puget Lowland subsurface structure and better resolve the location and geometry of underlying faults. Large-scale studies include a high-resolution aeromagnetic survey that extends from Olympia north to the Canadian border and from the Cascade Range foothills west to the east edge of the Olympic Mountains (maps 7-10) (Blakely and others, 1999), as well as a detailed set of seismic reflection and refraction surveys acquired between 1997 and 2002. These seismic experiments, called Seismic Hazards Investigations of Puget Sound (SHIPS), consist of marine surveys within Puget Sound, the Strait of Georgia, and the Strait of Juan de Fuca (map 2) (Brocher and others, 1999; Fisher and others, 1999); an onshore-offshore, 112-km-long two-dimensional seismic refraction/reflection line across the Seattle Basin (Brocher and others, 2000b); a dense passive seismic array that took advantage of the Seattle Kingdome implosion as a seismic source (Brocher, 2002); and two deep-borehole seismic-site-characterization studies in Seattle (Odum and others, 2004).

The large geophysical experiments conducted in the urban area coincided with the acquisition of over 10,000 square kilometers of high-resolution digital topographic data, known as LiDAR (Light Detection And Ranging) (map 1; see summary in Haugerud, 2003; see also, Puget Sound Lidar Consortium, http://pugetsoundlidar.ess.washington.edu/). LiDAR data processing removes the dense forest cover characteristic of the Pacific Northwest, allowing geologists to “see through the trees” and revealing a high-resolution image of the bare-earth ground surface. Subtle surface features such as fault scarps become visible at the centimeter scale of LiDAR imagery.

Pre-LiDAR field investigations documented active crustal faults such as the Saddle Mountain Fault Zone, in the southeastern Olympic Mountains (Wilson and others, 1975, 1979), and the Seattle Fault Zone (fig. 5) (Atwater and Moore, 1992; Bucknam and others, 1992; Jacoby and others, 1992; Karlin and Abella, 1992; Schuster and others, 1992; Sherrod and others, 2001). The arrival of LiDAR imaging, however, greatly facilitated the pinpointing of fault-related surface features such as individual fault scarps. These initial pre-LiDAR findings, in addition to the availability of LiDAR data, prompted several new fault investigations throughout the Puget Lowland (Haugerud, 2003).

Subsequent trench excavations of geomorphic scarps along inferred Holocene faults, some of which were already noted by Gower and others (1985) (fig. 4), and some of which were more recently discovered (fig. 5), have demonstrated that many of these faults have been active in the Holocene (table 2). Results from these Puget Lowland paleoseismic studies, including studies of coastal deformation and paleoecology, extended the currently known active faults from the Canadian border south to Olympia. Puget Lowland faults, summarized on maps 13 and 14 and also table 1, are, from north to south: the Boulder Creek Fault, the Utsalady Point Fault, the Lake Creek-Boundary Creek Fault (also known as the Little River Fault), the Darrington-Devils Mountain Fault, the Southern Whidbey Island Fault Zone (SWIF), the Seattle Fault Zone (SFZ), the Tacoma Fault Zone, the Saddle Mountain Fault Zone, the Frigid Creek Fault, and the Canyon River Fault (Wilson and others, 1979; Atwater and Moore, 1992; Bucknam and others, 1992; Johnson and others, 1996; Sherrod, 1998, 2001; Sherrod and others, 2001, 2002; Haugerud, 2003; Nelson and others, 2003b; Johnson and others, 2004b; Kelsey and others, 2004; Sherrod and others, 2004a; Hughes, 2005; Walsh and others, 2007; Barnett, 2007; Nelson and others, 2007; Sherrod and others, 2008; Blakely and others, 2009; Personius, 2009; Witter and others, 2009; see also, tables 1 and 2 for additional references).

The integration of geophysical and geological field observations of deformation provides a rich dataset that serves to better characterize the locations, geometry, and earthquake histories for shallow faults in the Puget Lowland (table 1). For example, recent studies of the SFZ, the SWIF, the Tacoma Fault Zone, and the Saddle Mountain Fault Zone link subsurface-fault structures mapped from seismic and potential-field surveys to surface-deformation features identified in LiDAR and geological field data (Blakely and others, 2002; Nelson and others, 2003b; Johnson and others, 2004c; Sherrod and others, 2004a, 2008; Blakely and others, 2009).

The Maps

The atlas contains seven 1:600,000-scale maps of the Puget Lowland that depict various types of investigations and fault-generated deformation evidence. In, addition, 1:400,000-scale inset map follows each map. The larger scale maps provide greater detail of the most densely populated region of the Puget Lowland, which also has the greatest seismic risk, the Seattle-Tacoma region. The resolution of all PDF map files is sufficient for onscreen display and printing of finer scale details at larger scales. In order to provide visual and spatial continuity throughout the maps, some features such as fault scarps (orange lines) and trench locations (stars) appear on all maps, as do geographic boundaries and place names. Earthquakes, which have been recorded regionally since 1970, are continual reminders that the Puget Lowland region is seismically active (Pacific Northwest Seismic Network, 2008; *www.pnsn.org*). Shallow (depths less than 35 km) earthquakes larger than magnitude 4 are featured on all maps. (In addition, figure 4 shows epicenters of earthquakes recorded since 1970 as small as, as well as magnitude 2 and focal mechanisms for larger events.) Summary maps 13 and 14 show currently known shallow fault traces draped over residual aeromagnetic anomalies.

It is important to note that, except where faults have ruptured or deformed the ground surface, fault traces drawn on the maps are not pinpoint locations. Instead, many fault traces are based on ongoing projects and only represent inferred and, in some cases, approximate locations of where fault planes either intersect or are thought to project to the ground surface. Thus, the fault traces on these maps should be used only as guides to the general locations of currently identified active fault zones and should not be used for site-specific evaluations of potential earthquake hazards.

Paleoseismic Studies: Map 1 and Inset Map 3

Map 1 and inset map 3 depict fault-related surface deformation features along with the locations of trenches excavated across LiDAR-identified fault scarps. (See table 2 for the trench study names, the sense of fault motion, and the references that describe trench excavations.) Current sources of LiDAR survey data are shown in the maps, as are locations of shoreline studies and directions of observed shoreline subsidence or uplift was observed (Bucknam and others, 1992; Bucknam, 1999; Sherrod, 2001, 2004a). Also shown on inset map 3 are data from a LiDAR-based model of regional marine-terrace uplift during the A.D. 900 SFZ earthquake, which indicates that the region experienced as much as 8.5 m of coseismic uplift near the southern tip of Bainbridge Island (see also, fig. 6) (Bucknam and others, 1992; Muller and Harding, 2005).

Seismic Reflection and Refraction Surveys: Map 2 and Inset Map 4

By imaging the subsurface, seismic reflection profiles can reveal the deeper structure of the Puget Lowland. Although fault planes are not clearly distinguishable in the seismic reflection profiles, imaging of deformed strata can be used to infer the subsurface locations of shallow faults that deform the ground surface (table 1).

Map 2 and inset map 4 depict the locations of both marine seismic surveys and land profiles. Also shown are the projected surface traces of faults that are based on deformed strata observed in the marine seismic reflection profiles (Johnson and others, 1996; Pratt and others, 1997; Johnson and others, 1999, 2001b, 2004c).

Until recently, marine seismic reflection profiles from Puget Sound and the Strait of Juan de Fuca provided the majority of subsurface information on fault structures that cross the Puget Lowland (Pratt and others, 1997; Brocher and others, 1999; Fisher and others, 1999; Johnson and others, 1999; Brocher and others, 2001; Johnson and others, 2004c; Dash and others, 2007; see also, table 1 for additional references). Recent land-based seismic reflection studies of the SFZ and SWIF have extended the marine-survey imaging of the fault zones onto land, as indicated on map 2 and inset map 4 (Brocher and others, 2000b, 2002; Stephenson and others, 2006; Liberty and others, 2008; Sherrod and others, 2008).

Thickness of Unconsolidated Quaternary Deposits: Map 5 and Inset Map 6

The Puget Lowland contains thick Quaternary-age deposits, most of which are derived from the advance and retreat of repeated glacial episodes that covered the region, overprinted by modern fluvial and marine processes. Jones (1996) compiled a point dataset of measured and inferred thicknesses of unconsolidated deposits throughout the Puget Lowland from nearly 4,000 water, oil, coal, and gas well logs and 700 seismic reflection shot sites. Where wells do not reach bedrock, the deepest wells in the area provide a minimum thickness; in addition, Jones (1996) interpolated a regional maximum thickness on the basis of nearby wells that do penetrate bedrock. Deposit thicknesses vary from a thin veneer, on the Puget Lowland margins along the Olympic and Cascade Mountains, to more than 1-km thick, in the Seattle and Everett Basins.

Map 5 and inset map 6 depict contours of deposit thickness and well locations from Jones (1996). Also shown is a generalized bedrock surface derived from the Jones (1996) point data that depicts a simplified image of the Puget Lowland stripped of its thick layer of unconsolidated deposits. Jones' (1996) interpolation accounts for any discrepancies between the point data and the contours and color shading-relief.

Locations where deposits are thin along the northern and southern margins of the Seattle and Everett Basins coincide with the locations of inferred active fault structures (see also, fig. 5 and maps 13 and 14). Subsequent seismic reflection studies indicate that these basins are structurally bounded by faults (Pratt and others, 1997; Brocher and others, 2001; Johnson and others, 2004c). The thick deposits of the Seattle Basin are located at the northern boundary of the SFZ, and the Everett Basin is bounded by the SWIF and the Utsalady Point and Strawberry Point faults (maps 13 and14).

Aeromagnetic Anomalies and Residual Aeromagnetic Anomalies: Maps 7 and 8 and Inset Maps 9 and 10

Potential-field observations provide another means to constrain subsurface fault locations and geometries. Faults that juxtapose rocks that have contrasting magnetic properties produce small magnetic fields near the topographic surface that can be detected with airborne magnetic surveys. Magnetic anomaly maps derived from such surveys provide a way to map faults covered by vegetation, water, or young geologic materials. Maps 7 through 10 show a high-resolution aeromagnetic survey of the Puget Sound region conducted in 1997 (Blakely and others, 1999, 2002). Map 7 and inset map 9 show the original data; map 8 and inset map 10 show the original data reprocessed to emphasize magnetic anomalies originating from shallow magnetic sources by filtering out deeper source anomalies.

Maps 7 and inset map 9 show the location of abrupt magnetization contrasts, informally called "maxspots," as estimated from magnetic anomalies using potential-field geophysical software (Blakely and Simpson, 1986). These maxspots form lineaments, some of which mark the location of shallow faults, as indicated by the spatial association between magnetic lineaments and fault scarps shown on maps 7 and 9.

Isostatic Residual Gravity Anomalies: Map 11 and Inset Map 12

Along with magnetic observations, some gravity anomalies observed in the Puget Lowland indicate possible faults and fault-bounded structural basins. Map 11 and inset map 12 show isostatic residual gravity anomalies that are based on the compilation of Finn and others (1991). Isostatic residual gravity anomalies (Simpson and others, 1986) reflect density of the middle and upper crust. Gravity gradients are present where rocks of contrasting densities are juxtaposed, such as along fault zones; therefore, they are particularly useful for defining sedimentary basins and their bounding faults. The Seattle, Everett, and Tacoma Basins appear in map 11 as broad gravity lows that reflect the relatively low density of basin-filling sedimentary rocks. Also depicted on map 11 and inset map 12 are the locations of sharp density contrasts, also called maxspots, estimated from gravity anomalies (Blakely and Simpson, 1986). For example, a sharp gravity gradient located along the southern margin of the Seattle Basin marks the Seattle Fault.

The spatial density of gravity measurement stations varies throughout the Puget Lowland; accordingly, the data resolution varies. To show this visually, the locations of the gravity stations are depicted on map 11 and inset map 12, and areas of greater station spatial density reflect higher resolution data (Finn and others, 1991). For example, the highest resolution gravity data on these maps cover the region within the Puget Sound between Victoria, B.C., and Tacoma.

Active Shallow Fault Locations: Confluence of Geological and Geophysical Data

Summary of Shallow Crust Deformation Data and Quaternary Fault Traces: Map 13 and Inset Map 14

Shallow faults in the Puget Lowland are mapped where multiple geophysical and geological observations of crustal deformation converge. Together, these observations bolster the identification and characterization of potentially damaging faults and provide a rich database of surface- and subsurface-deformation evidence from geological field surveys (map 1 and inset map 3), seismic reflection profiles (map 2 and inset map 4), structural basin boundaries (map 5 and inset map 6), and potential-field anomaly gradients (maps 7 through 12). In summary maps 13 and 14, deformation observations from maps 1 through 12 have been compiled and stacked; fault traces are then draped over the observations that underpin their characterizations.

For example, figure 7 schematically shows the construction of the summary maps and the array of deformation evidence that constrain the mapping of surface fault traces such as the SFZ. As depicted by data layers in figure 7 and throughout maps 1 through 12, multiple fault-scarp excavations and shoreline-deformation studies quantify surficial Holocene deformation located above sharp magnetic- and gravity-anomaly gradients and above deformed subsurface seismic strata. The SFZ also bounds the edge of the deepest structural basin in the Puget Lowland, the Seattle Basin. North of the Seattle Fault Zone, trench excavations of LiDAR-identified fault scarps, subsurface stratigraphic deformation recognized in seismic reflection profiles, and magnetic-anomaly gradients constrain the location of the SWIF (Sherrod and others, 2008).

These faults and most other Puget Lowland fault traces are differentiated between those that have demonstrated Holocene activity and those for which evidence for Holocene activity is inconclusive but Quaternary activity is suspected (fig. 5; maps 13 and 14). Most Puget Lowland fault traces are from the USGS Quaternary Fault and Fold Database (http://earthquake.usgs.gov/regional/qfaults/), but we have updated several fault traces using work completed since its publication: the South Whidbey Island Fault (SWIF) strands have been mapped farther east across the Puget Sound toward the Cascade Range (Blakely and others, 2004; Sherrod and others, 2005a, 2005b, 2008); the Tacoma Fault also has been extended farther east (Johnson and others, 2004c; Brocher and others, 2001; Sherrod and others, 2004a, 2004b); and the Boulder Creek Fault is a newly recognized fault near the Canadian border (Haugerud, 2005; Barnett, 2007; Barnett and others, 2007; Siedlecki, 2007) (fig. 5; maps 13 and 14; table 1). In addition, the USGS Quaternary Fault and Fold Database does not list the Olympia Fault, but we have included it here as a subject of ongoing research (fig. 5; maps 13 and 14; table 1) (Blakely and others, 1999; Sherrod, 2001).

Recently Identified Active Shallow Faults in Puget Lowland: Paleoseismic and Geophysical Evidence

Southeastern Olympic Peninsula: Saddle Mountain Fault Zone, Canyon River Fault and Frigid Creek Fault

The Saddle Mountain Fault scarps provide the earliest clear indications of fault-related surface deformation in the Puget Lowland (see Tables 1 and 2 for information of specific faults) (Carson, 1973; Wilson and others, 1975, 1979). After identifying fault scarps on aerial photographs of clear cut timberland, Wilson and others (1979) excavated trenches across these scarps and sampled drowned trees from neighboring wetlands for radiocarbon-dating material. Their early work and more recent trenching and wetland studies demonstrate that Holocene reverse faulting created the scarps and submerged an adjacent forest as recently as 1,000 years ago (Wilson and others, 1979; Hughes, 2005; Witter and others, 2009). A ground-magnetic survey supported the presence of east-side-up fault structures beneath the Saddle Mountain Fault Zone that might relate to the observed deformation features (Blakely and others, 2005, 2009).

Other fault scarps that flank the east side of the Olympic Mountains corroborate recent tectonic deformation. Trench excavations across the Canyon River (Walsh and others, 2007), Frigid Creek (Blakely and others, 2009), and Lake Creek-Boundary Creek/Little River Fault scarps (Nelson and others, 2007) confirm Holocene activity along these faults. Blakely and others (2009) suggested that, on the basis of paleoseismic work and aeromagnetic-data analysis, these fault zones form an en echelon chain of active fault segments along the east edge of the Olympic Mountains. Moreover, they might compose the western fault boundary of the SFZ and, thus, be components of the deformation zone that accomodates shortening in the Puget Lowland (Blakely and others, 2009).

Southern and Central Puget Lowland: Seattle, Tacoma, and Olympia Faults

Underlying the urban areas of Seattle and Tacoma, the Seattle Uplift (fig. 4; maps 13, 14) is a wedge of uplifted crust situated between two active fault zones (Gower structures I and K on figs. 4 and 5; see also SFZ and Tacoma Fault Zone on maps 13, 14): the SFZ to the north, interpreted as a south-dipping reverse fault that separates the Seattle Basin from the Seattle Uplift (Yount, 1992; Bucknam and others, 1992; Pratt and others, 1997; Johnson and others, 1999; Blakely and others, 2002; Nelson and others, 2003b; Brocher and others, 2004a); and the north-dipping, reverse Tacoma Fault Zone to the south (Sherrod and others, 2004). Observations, measurements, and radiocarbon dates from earthquake-triggered features demonstrate Holocene deformation along the Seattle and Tacoma Fault Zones include the following: fault scarps on Bainbridge Island (Nelson and others, 2003b), Waterman Point (Nelson and others, 2003a), Vasa Park (Sherrod, 2002), Catfish Lake (Sherrod and others, 2004a, 2004b), Sunset Beach (Nelson and others, 2007), and Saddle Mountain (Hughes and others, 2005; Witter and others, 2009); coastal uplift (maps 1, 3) (Bucknam, 1992; Sherrod, 2001; Sherrod and others, 2002, Sherrod and others, 2004a; Muller and others, 2006; Ota and others, 2006); landslides (Jacoby and others, 1992); and turbidites in Lake Washington (Karlin and Abella, 1992, 1996), and tsunami deposits (Atwater and Moore, 1992).

The most recent uplift event that occurred around 1,100 years ago (A.D. 900-930) probably produced most of the Seattle Uplift deformation features (Atwater and Moore, 1992; Bucknam and others, 1992; Atwater, 1999). A large earthquake, possibly magnitude 7 or greater (Bucknam and others, 1992; Pratt and others, 1997; Muller and Harding, 2005; ten Brink, 2006) uplifted shorelines within the SFZ (Bucknam and others, 1992), caused subsidence of the Seattle Basin north of the fault, and triggered a tsunami in Puget Sound (Atwater and Moore, 1992) (fig. 5; maps 1, 3). On the south edge of the Seattle Uplift, warped shorelines and intertidal marshes that straddle the Tacoma Fault also recorded regional uplift north of the Tacoma Fault and subsidence south of the fault around 1,100 years ago (Bucknam and others, 1992; Sherrod and others, 2002, 2004a, 2004b).

Recent seismic-reflection and aeromagnetic studies helped to constrain subsurface geometry of the Seattle and Tacoma Fault Zones. Seismic reflection profiles image subsurface deformation attributed to the SFZ (maps 2, 4, 13, 14) (Pratt and others, 1997; Johnson and others, 1999; Liberty and Pratt, 2008) and the Tacoma Fault Zone (Pratt and others, 1997; Brocher and others, 2001; Johnson and others, 2004c). Because of large offsets, the fault zones also appear as linear anomalies in gravity (map 11) and aeromagnetic data (map 7) (Gower and others, 1985; Blakely and others, 2002) and as velocity anomalies in seismic-tomography results (Brocher and others, 2001).

Still farther south, a prominent northwest-southeast-trending aeromagnetic anomaly south of Olympia (map 7) and evidence for abrupt submergence of a southern Puget Sound marshland and forest about 1,100 years ago (maps 2, 13) suggest the approximate location of the inferred Olympia Fault (structure labeled “L” in fig. 4) (Blakely and others, 1999; Sherrod, 2001). No fault scarps have been found above this structure, and, other than a broad zone of inferred deformation, the location of the fault trace remains poorly known.

Paleoseismic evidence collected throughout the Puget Lowland indicates that several faults described above may have ruptured during or around the time of the A.D. 900-930 event. Figure 8 shows age ranges of earthquakes on shallow faults throughout the Puget Lowland and the apparent cluster around this event.

South Whidbey Island Fault Zone (SWIF)

North of the SFZ, the SWIF cuts across central and northern Puget Lowland (structure labeled “G’ in fig. 4, 5; map 13) as a possible transpressional fault (Johnson and others, 1996). The SWIF, located by marine seismic-reflection and aeromagnetic data (Johnson and others, 1996), extends from offshore Vancouver Island southeastward nearly 100 km and projects onto land. Blakely and others (2004) and Sherrod and others (2005a, 2005b, 2008; maps 7, 9, 13) mapped the fault strands about another 40 km southeastward toward the Cascade Mountains by modeling aeromagnetic-anomaly data and excavating LiDAR-identified fault scarps. A coastal-uplift study on Whidbey Island (Kelsey and others, 2004) and surface-rupture studies conducted northeast of Seattle (Sherrod and others, 2008) documented at least four earthquakes along the eastern extension of SWIF within the past 16,000 years. Two of the youngest occurred between 3,200 and 2,800 years ago and less than 2,700 years ago (Kelsey and others, 2004; Sherrod and others, 2008).

North Puget Lowland: Darrington-Devils Mountain, Utsalady Point, Strawberry Point, and Boulder Creek Faults

The Darrington-Devils Mountain, Utsalady Point, and Strawberry Point Faults might compose elements of an active oblique-slip transpressional deformation zone between southeastern Vancouver Island and the Cascade Range foothills (structure labeled “A” in figs. 4, 5; Map 13) (Johnson and others, 2001b, 2004b). Trench studies of scarps located along the Darrington-Devils Mountain (Personius and others, 2009) and Utsalady Point Faults indicate that Holocene faulting generated these scarps (map 1). Trench excavations across the Utsalady Point Fault scarps indicate that the fault ruptured at least once, and possibly twice, during the last 2000 years (Johnson and others, 2004b).

Recent paleoseismic work northwest of Mount Baker has shifted the previously mapped, northernmost limit of active shallow faults over 50 km north, from the Darrington-Devils Mountain Fault Zone to just south of the Canadian border. Excavations of LiDAR-identified fault scarps along the mapped trace of the Boulder Creek Fault (map 13) (Misch, 1966), as well as coring of adjacent wetlands, has yielded evidence of three or more Holocene oblique-thrusting events (Haugerud and others, 2005; Barnett, 2007; Barnett and others, 2007). Subsequent trenching (for example, the Smuggler trench) along nearby en echelon fault scarps also has demonstrated faulting (map 1; table 2). Just south of the Boulder Creek fault, Dragovich and others (1997a, 1997b) attribute the 1990 Deming earthquake swarm (Qamar and Zollweg, 1990) (fig. 4) to activity along the Macaulay Creek Thrust Fault (map 13) on the basis of field evidence and earthquake data collected during the swarm. No surface rupture, however, was identified, and so Holocene activity along the thrust fault remains unresolved.

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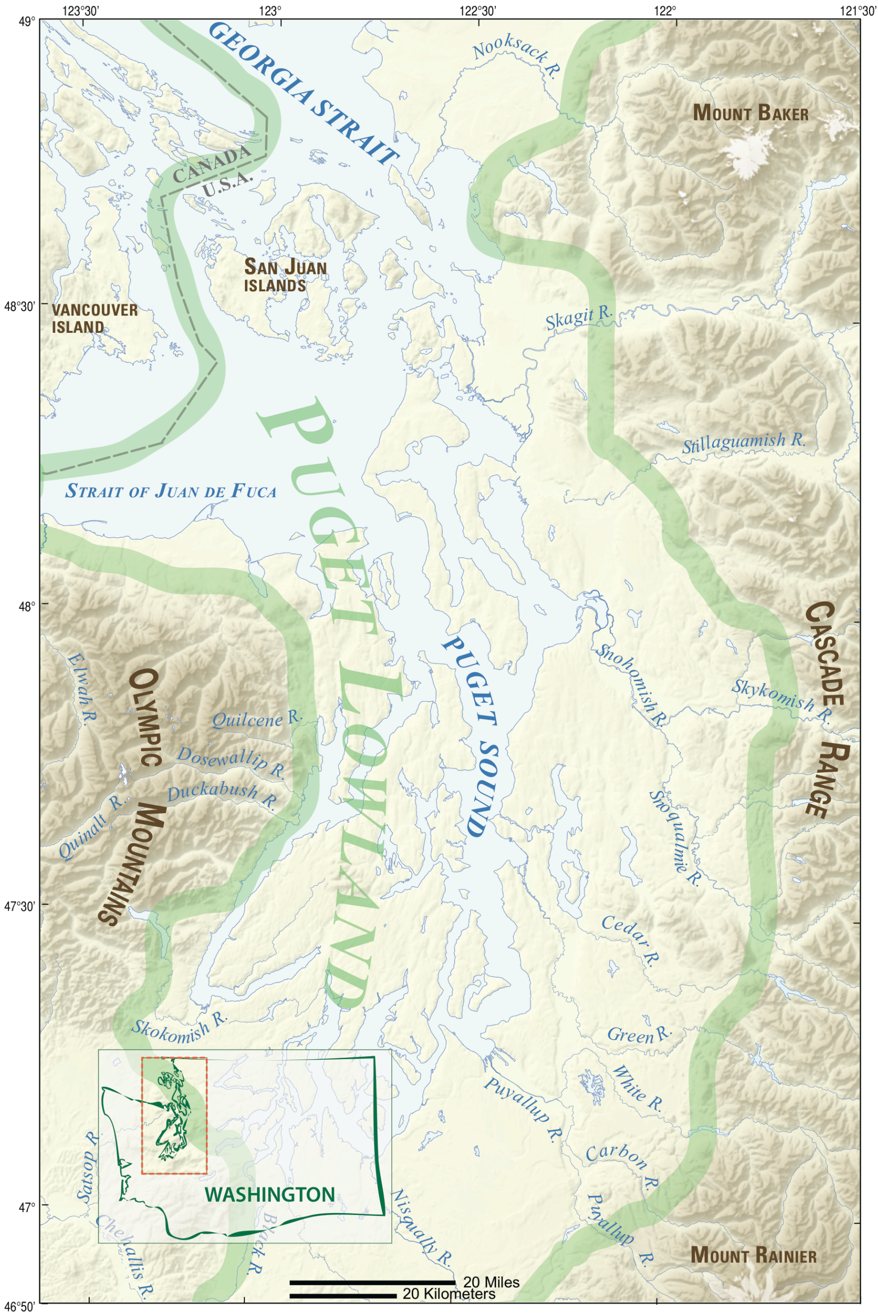

Figure 1. Map showing Puget Lowland region described in atlas, which includes Puget Lowland (green outline), eastern part of Olympic Mountains, western part of Cascade Range, and southern part of Georgia Strait. For simplicity and to incorporate most datasets relevant to shallow faults, in the text, Puget Lowland refers to the entire map extent shown in figure 1 and in maps.

Figure 2. Tectonic-block model of Cascadia fore-arc terranes, modified from Wells and Simpson (2001) and Wells and others (1998). Gray arrows indicate relative plate motion. Block motion (circled numbers) is in mm/yr. Rotation of Sierra Nevada block and of Oregon Coast Range block about their respective Euler poles induce north-south shortening of western Washington against backstop of the Canadian Coast Mountains. Red arrows indicate north-south shortening of Puget Lowland region. Orange triangles denote Cascade Arc volcanoes.

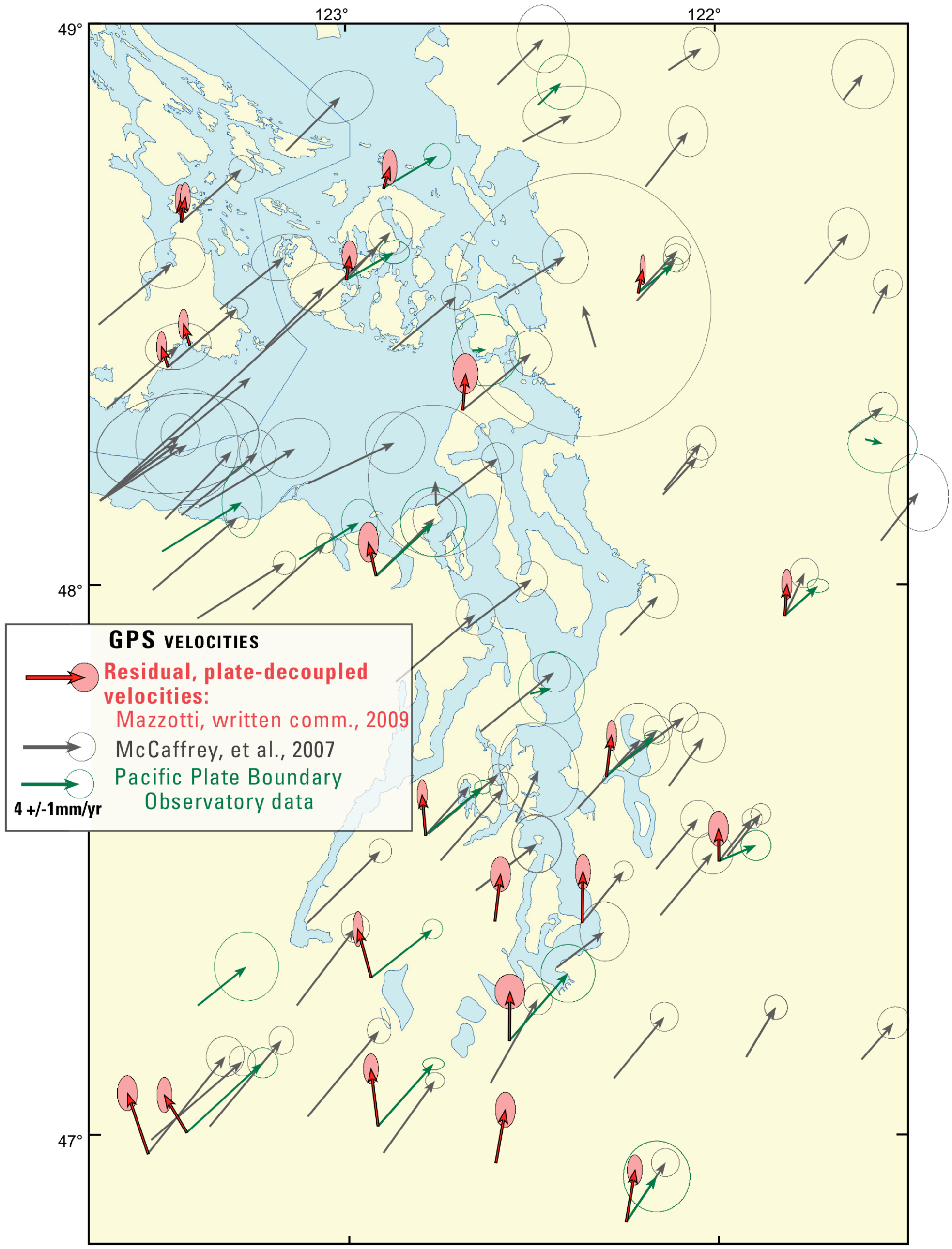

Figure 3. Map showing GPS velocities derived from continuous and campaign survey sites, modified from Mazzotti (written commun., 2009). Black and green arrows predominantly reflect interseismic loading of the Cascadia subduction zone (CSZ) (McCaffrey and others, 2007; Plate Boundary Observatory, 2008). Red arrows are residual GPS velocities of crust after interseismic loading signal of CSZ is removed (Mazzotti and others, 2003; written commun., 2009). Error ellipses are circles at tips of velocity vectors.

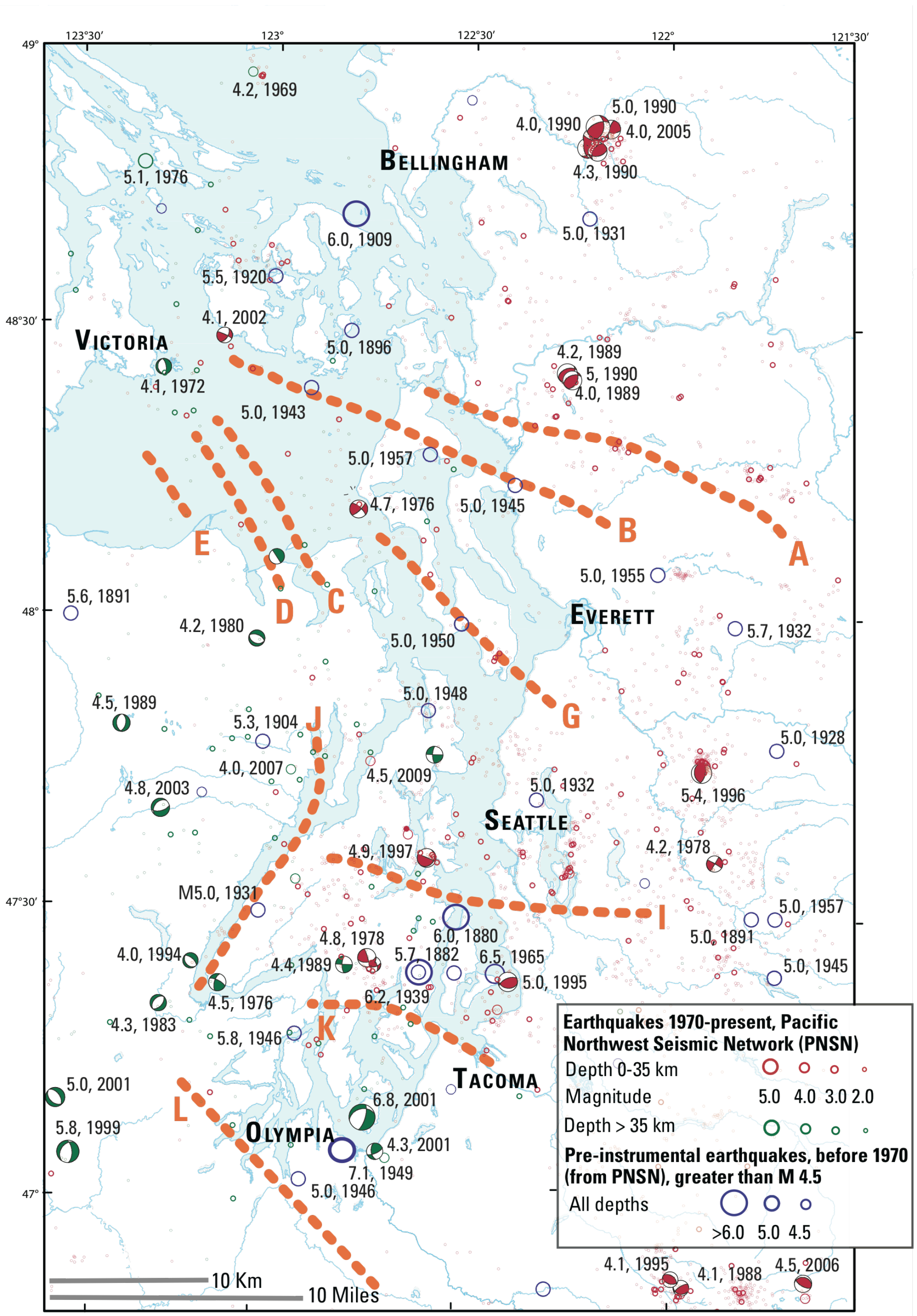

Figure 4. Map showing inferred Quaternary fault structures in Puget Lowland mapped before 1985 (orange dashed lines) from Gower and others (1985); structures are labeled A-L. Shallow earthquakes (<35 km) denoted by red circles; deep earthquakes (>35 km) by green circles. Pre-instrumental (earlier than 1970) earthquakes denoted by purple circles. Focal mechanism ("beach ball") color and symbol size corresponds to same depth and magnitude as earthquakes (PNSN, 2008).

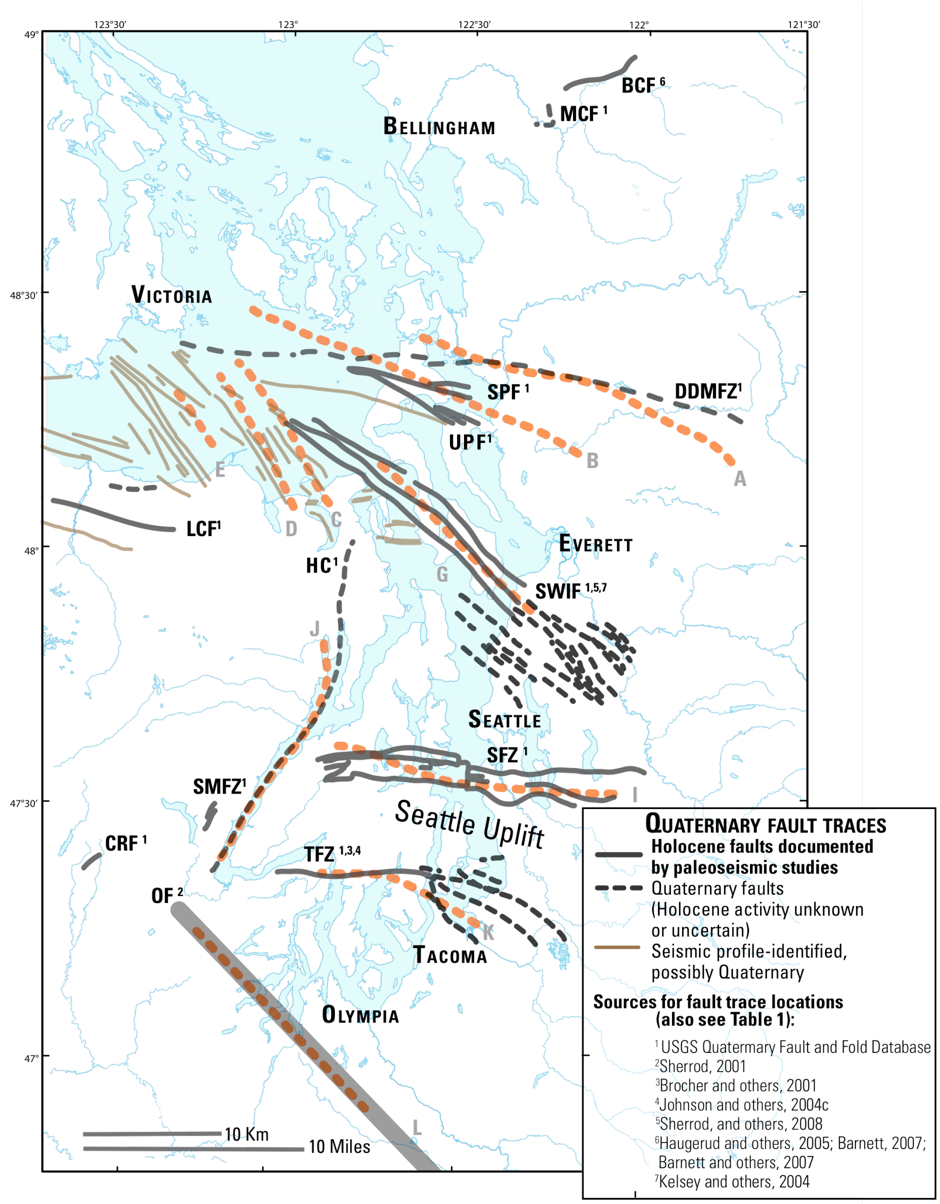

Figure 5. Map showing Quaternary fault traces, including active fault zones, mapped before 2009 in the Puget Lowland, from USGS Quaternary Fault and Fold Database (USGS, 2006) and subsequent studies. Faults that have documented Holocene earthquakes are shown in black; faults that have unknown Holocene activity, but probable activity during Quaternary, in gray. Newly mapped fault traces not included in USGS Quaternary Fault and Fold Database also are shown. Inferred Quaternary fault structures from Gower and others (1985) are denoted by orange dashed lines and labeled in gray. Abbreviations: BCF, Boulder Creek Fault; CRF, Canyon River Fault; DDMFZ, Darrington-Devils Mountain Fault Zone; HC, Hood Canal Fault; LCF, Lake Creek-Boundary Creek Fault; MCF, Macaulay Creek Fault; OF, Olympia Fault; SFZ, Seattle Fault Zone; SMFZ, Saddle Mountain Fault Zone; SPF, Strawberry Point fault; SWIF, South Whidbey Island Fault; TFZ, Tacoma Fault Zone; UPF, Utsalady Point Fault.

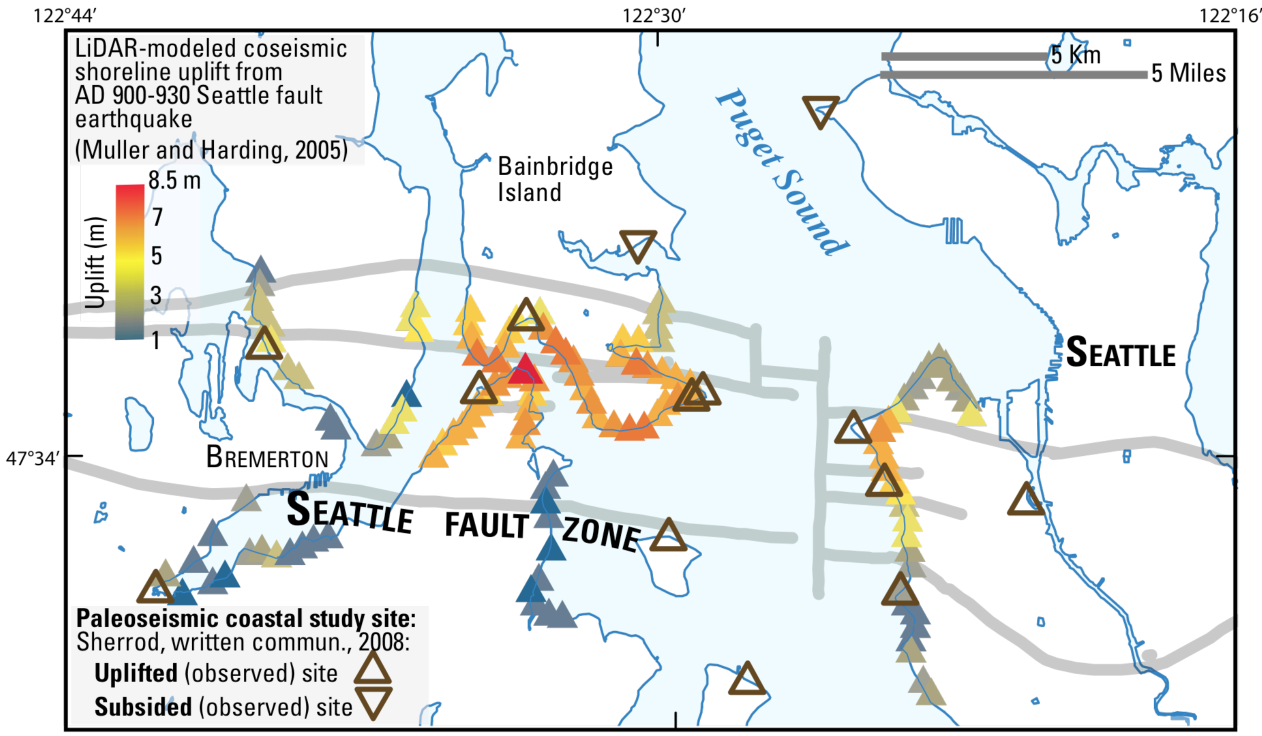

Figure 6. Map showing LiDAR-modeled coseismic shoreline uplift from A.D. 900-930 Seattle Fault earthquake (Muller and Harding, 2005). Colored triangles denote uplift in meters. Open brown triangles mark observed uplift or subsidence from coastal study sites (Sherrod, 2001, 2004b). Seattle Fault Zone traces shown in gray.

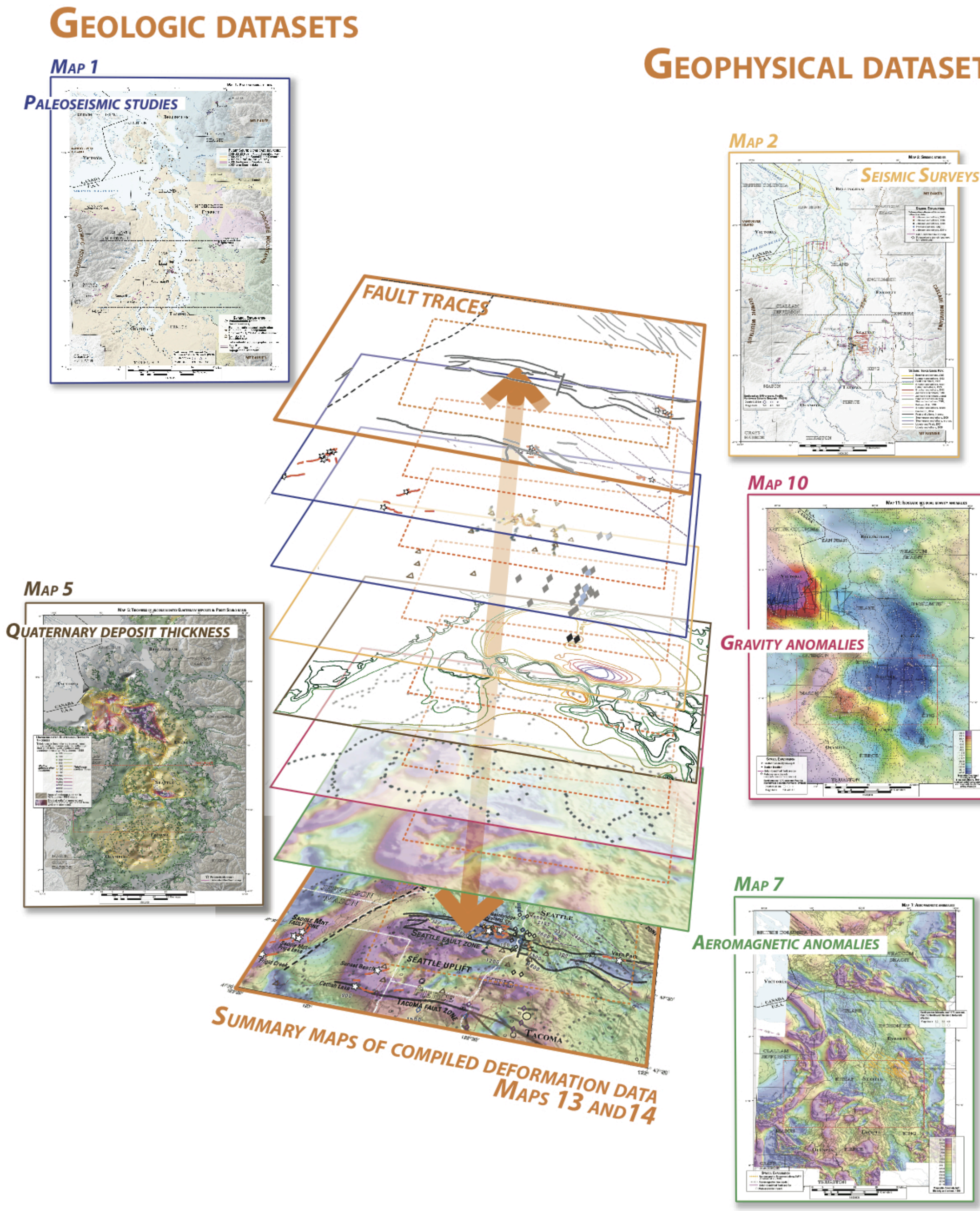

Figure 7. Schematic depiction of how data layers from maps (Maps 1 through 12) have been compiled in summary maps 13 and 14. Box color links data layers to corresponding maps. Wide array of geological and geophysical data underpins location and characterization of fault zones; for example, location of Seattle Fault Zone (dashed, orange box) is based on evidence from trench excavations, seismic profiles, basin geometry, shoreline deformation, and potential-field anomaly maps. Data layer maps, from top to bottom: fault traces, scarp and trench locations, coastal deformation studies, deformation observed in seismic data, Quaternary deposit thickness, gravity anomalies, aeromagnetic anomalies, and summary map of compiled data layers.

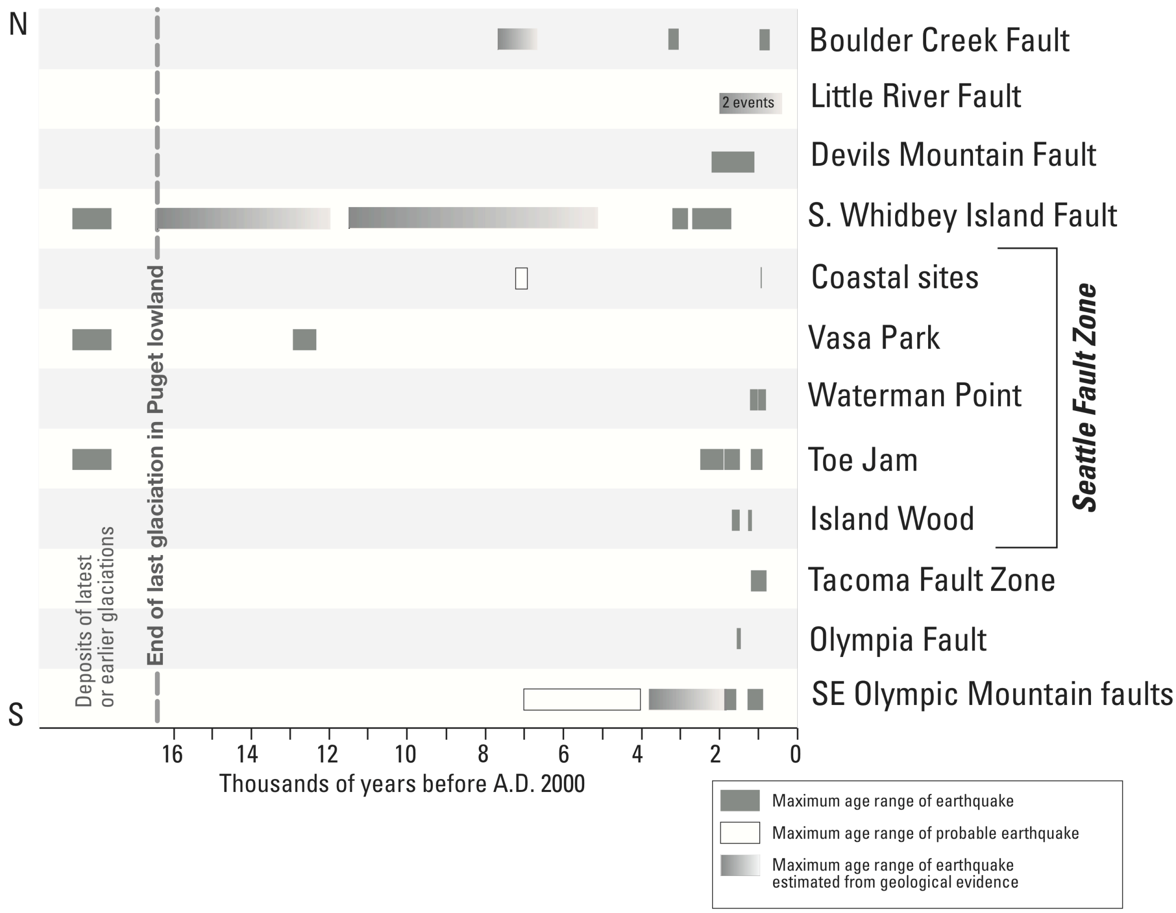

Figure 8. Diagram of known ground-surface deformation in Puget Lowland caused by earthquakes on shallow faults since end of last glaciation. Grey bars denote maximum age range for earthquakes on faults. Data derived from trench excavations, other paleoseismic studies, and dating of faulting-related organic material when possible (Sherrod, written commun., 2008).

Table 1: References for Puget Sound faults and associated paleoseismic and geophysical studies featured in atlas. Fault classification from U.S. Geological Survey Quaternary Fault and Fold Database (http://earthquake.usgs.gov/regional/qfaults). Class A faults have been tectonically active during Quaternary, on the basis of geologic mapping of inferred deformational features. Class B faults show geologic evidence that demonstrates Quaternary activity, but the evidence is not as strong as for Class A faults.

Fault Name (Class)	Paleoseismic studies	Seismic studies related to fault	Potential-Field studies exist for fault zone location	Lidar data exist for fault zone location	Other studies including geologic mapping
	Trench excavation[1] **Paleoecology/shoreline study[2]**		**Gravity[3]** **Magnetic[4]**		
Canyon River Fault (Class A)	Walsh and Logan, 2007[1]		Finn and others, 1991[3] Blakely and others, 1999[4]		Tabor and Cady, 1978 Walsh and Logan, 1997 Lidke, 2003c Dragovich and others, 2002 Babcock and others, 1992
Saddle Mountain Fault (Class A)	Wilson, 1975[1] Wilson and others, 1979[1] Hughes, 2005[2] Witter and others, 2006[1] Witter, and others, 2009[1] Czajkowski and others, 2009[1] Barnett and others, 2009[1]		Blakely and others, 1999[4] Blakely and others, 2005[4] Finn and others, 1991[3] Blakely and others, 2009[4]	Haugerud and others, 2003 2000-2007 Puget Sound Lidar Consortium Survey	Carson, 1970, 1973 Wilson, 1975 Tabor and Cady, 1978 Wilson and others, 1979 Dragovich and others, 2002 Lidke, 2003d
Tacoma Fault (Class A)	Bucknam and others, 1992[2] Sherrod, 1998[2] Sherrod, 2001[2] Sherrod and others, 2002[2] Sherrod and others, 2004a[1,2] Sherrod and others, 2004b[1] Nelson, 2007[1]	Pratt and others, 1997 Brocher and others, 1999 Brocher and others, 2001 Johnson and others, 2004c Mitchell and others, 2008	Danes and others, 1965[3] Blakely and others, 1999[4] Finn and others, 1991[3]	Haugerud and others, 2003 2000-2007 Puget Sound Lidar Consortium Survey 2003 King County Lidar survey data	Gower and others, 1985 Jones, 1996 Brocher and others, 2004b

Table 1 continued

Seattle Fault (Class A)	Atwater and Moore, 1992[2] Jacoby and others, 1992[2] Troost, 1994[2] Atwater, 1999[2] Bucknam and others, 1999[2] Bourgeois and Johnson, 2001[2] Sherrod and others, 2001[1] Nelson and others, 2002[1] Sherrod, 2002[2] Nelson. and others, 2003a[1] Nelson and others, 2003b[1] Muller and Harding, 2006[2] Kelsey and others, 2009[2]	Johnson, S. Y. and others, 1994 Pratt, T.L. and others, 1997 Johnson and others, 1999 Fisher and others, 1999 Brocher and others, 2000a, 2000b Brocher and others, 2001 Calvert and others, 2001 Brocher and others, 2002 Brocher and others, 2004a Johnson and others, 2004c Liberty and Pratt, 2008 Pratt, 2008 Karel and Liberty, 2008 Liberty and Pratt., 2008	Danes and others, 1965[3] Blakely and others, 1999[4] Blakely and others, 2002[4] Finn and others, 1991[3] Anderson and others, 2008[3,4]	Haugerud and others, 2001 Haugerud. and others, 2003 Haugerud and Tabor, 2008 2000-2007 Puget Sound Lidar Consortium Survey 2003 King County Lidar survey data	Gower and others, 1985 Jones, 1996 Haeussler and others, 2000 Booth and others, 2003 Booth and others, 2005 Troost and others, 2005 Johnson, 2004
Hood Canal Fault (Class B)		Johnson and others, 1994 Pratt and others, 1997 Rohwer,1994 Cuellar, 1994 Haug,1998	Danes and others, 1965[3] Blakely and others, 1999[4] Finn and others, 1991[3]	2000-2007 Puget Sound Lidar Consortium Survey	Gower, H.D. and others, 1985 Jones, 1996 Dragovich and others, 2002 Lidke, 2003a
Southern Whidbey Island Fault Zone (Class A)	Kelsey, and others, 2004[1] Sherrod and others, 2005a[1] Sherrod and others, 2005b[1] Sherrod and others, 2008[1]	Wagner and Tomson, 1987 Johnson and others, 1996 Johnson and others, 1999	Blakely and others, 1999[4] Blakely and others, 2004[4] Finn and others, 1991[3]	Haugerud and others, 2003 2000-2007 Puget Sound Lidar Consortium Survey 2003 King County Lidar survey data	Gower, 1980 Gower and others, 1985 Jones,1996 Johnson, 2004a
Lake Creek-Boundary Creek Fault/Little River Fault (Class A)	Nelson and others, 2007[1]		Finn and others, 1991[3]	Haugerud, 2002 Haugerud and others, 2003 2000-2007 Puget Sound Lidar Consortium	Brown and others, 1960 Tabor and Cady, 1978 Dragovich and others, 2002 Lidke and others, 2003e
Devils Mountain Fault Zone (Class A)	Dragovich, 2007[1] Personius, 2009[1]	Johnson and others, 2001b	Blakely and others, 1999[4] Finn and others, 1991[3]	Haugerud and others, 2003 2000-2007 Puget Sound Lidar Consortium Survey 2002-2003 NASA/USGS Lidar Survey	Lovseth, 1975 Tabor and others, 1988 Whetten and others, 1988 Tabor, 1994 Jones, 1996

Table 1 continued

					Johnson, and others, 2001a Dragovich and DeOme, 2006 Hayward and others, 2006 Dragovich and Stanton, 2007
Utsalady Point Fault (Class A)	Johnson and others, 2003a[1] Johnson and others, 2004b[1]	Johnson and others, 2001b	Johnson and others, 2001b[3] Blakely and others, 1999[4] Finn and others, 1991[3]	Haugerud and others, 2003 2000-2007 Puget Sound Lidar Consortium Survey	Gower, 1980 Jones, 1996 Johnson and others, 2003b
Strawberry Point Fault (Class A)	Johnson and others, 2003a[1] Johnson and others, 2004b[1]	Johnson and others, 2001b	Blakely and others, 1999[4] Finn and others, 1991[3]	Haugerud and others, 2003 2000-2007 Puget Sound Lidar Consortium Survey	Gower, 1980 Jones, 1996 Johnson, 2001
Macaulay Fault (Class B)			Blakely and others, 1999[4] Finn and others, 1991[3]	USGS North Puget Sound Lidar Survey	Misch, P., 1966 Brown, 1987 Lidke, 2003b Qamar, and Zollweg, 1990 Dragovich and others, 1997a Dragovich and others, 1997b Dragovich and others, 2002
Boulder Creek Fault (not classified in USGS Quaternary Fault and Fold database)	Barnett and others, 2006, 2007[1,2] Siedlecki, 2007[1]		Blakely and others, 1999[4] Finn and others, 1991[3]	Haugerud and others, 2005 USGS North Puget Sound Lidar Survey	Misch, 1966 Johnson, 1984 Brown, 1987 Dragovich and others, 1997a Dragovich and others, 1997b Dragovich and others, 2002
Olympia Fault (not classified in USGS Quaternary Fault and Fold database)	Sherrod, 2001[2] Sherrod, 1998[2]		Finn and others, 1991[3] Blakely and others, 1999[4]		

Table 2: Puget Sound paleoseismic trench studies shown on all maps and inset maps (maps 1-14).

Trench Name	Reference	Associated Fault	Documented Holocene faulting	Fault type	Offset
Canyon River	Walsh and Logan, 2007	Canyon River Fault	Yes	Reverse and left lateral	Southeast side up
Frigid Creek	Blakely and others, 2009	Frigid Creek Fault	Yes	Normal	Up to northwest
Saddle Mountain Fault Zone	Wilson, 1975; Wilson and others, 1979; Witter and others, 2009; Czajkowski and others, 2009; Barnett and others, 2009	Saddle Mountain and Dow Mountain Faults	Yes	Reverse and strike slip	Saddle Mountain East and West faults: east side up; Dow Mountain fault: NE side up
Catfish Lake	Sherrod and others, 2004a, 2004b	Tacoma Fault	Yes	Reverse	North side up
Sunset Beach	Nelson, 2007	Tacoma Fault	Yes	Normal	Souteast side up
Waterman Point	Nelson and others, 2003a	Waterman Point Fault/Seattle Fault Zone	Yes	Reverse	North side up
Bainbridge Island	Nelson and others, 2002, 2003a, 2003b	Seattle Fault Zone	Yes	Reverse	North side up
Vasa Park	Sherrod, 2002	Seattle Fault Zone	Yes	Reverse	South side up
Brightwater-Woodinville	Sherrod and others, 2005a, 2005b, 2008	Southern Whidbey Island Fault Zone	Yes	Reverse	Northeast side up
Lake Creek-Boundary Creek	Nelson and others, 2007	Lake Creek-Boundary Creek Fault	Yes	Oblique and right and left lateral	
Whitman Bench	Dragovich, 2007; Personius, 2009	Darrington-Devils Mountain Fault Zone	No		
Lake Creek	Personius and others, 2009	Darrington-Devils Mountain Fault Zone	Yes	Right lateral	
Rocky Point	Johnson and others, 2003a, 2004b	Utsalady Point Fault	Yes	Reverse and left-lateral	Northeast side up
Kendall and Smuggler	Barnett, 2007; Barnett and others, 2007; Siedlecki, 2007	Boulder Creek Fault	Yes	Reverse-oblique	South side up