

# PREHISTORIC EARTHQUAKES IN THE PUGET LOWLAND, WASHINGTON

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## Abstract

Coastal marsh deposits and lidar topographic data show evidence for past earthquakes on at least eight fault zones in the Puget lowland. Three major fault zones, the Seattle fault zone, Tacoma fault, and the Southern Whidbey Island fault zone (SWIFZ), cut through the heavily populated portions of central Puget Sound. Faults in four other areas, namely the Darrington–Devils Mountain fault zone, Olympia fault, the northern margin of the Olympic Mountains, and the southeastern Olympic Mountains, show that the area of active Holocene faulting extends over the entire Puget Sound lowlands. As recently as 1998, field evidence could confirm only one fault with evidence of past earthquake activity.

Uplifted coastlines and surface ruptures are the field evidence for past Seattle fault earthquakes. Raised intertidal platforms along the Seattle fault zone show that regional uplift of as much as 7 meters accompanied a large earthquake about 1100 years ago. This earthquake also caused a tsunami, which inundated low-lying coastal areas north of Seattle. All of the lidar scarps found in the Seattle fault zone are north-side-up, opposite the vergence suggested for the Seattle fault from regional geological studies. Excavations across these scarps reveal north-dipping thrust faults that roughly follow bedding planes in bedrock and disrupt late Holocene soils. Soil stratigraphy and radiocarbon ages suggest as many as three surface-rupturing earthquakes in the past 2500 years.

Lidar mapping revealed several *en echelon* scarps along the trace of the Tacoma fault. Existence of the Tacoma fault was previously hypothesized on the basis of large-amplitude gravity, aeromagnetic, and seismic-velocity anomalies, shallow marine seismic reflection surveys, glaciolacustrine strandlines, and coastal marsh stratigraphy. Coastal marsh deposits and scarp excavations suggest that the scarps formed during an earthquake on the Tacoma fault ~1100 years ago, possibly by folding above a buried reverse fault.

Coastal marsh stratigraphy, lidar mapping, and fault scarp excavations help define recent activity along the Southern Whidbey Island fault zone (SWIFZ). Abrupt uplift of more than one meter at a coastal marsh on south-central Whidbey Island suggests that a MW 6.5 - 7.0 earthquake on the SWIFZ shook the region between 3200 and 2800 years B.P. Subtle scarps on Pleistocene surfaces are visible on high-resolution lidar topography at a number of locations in the mainland region, often closely associated with aeromagnetic lineaments. In the field, scarps

exhibit northeast-side-up vertical relief of 1 to 5 m. Four excavations across two lidar scarps show that the SWIFZ produced at least four events since deglaciation about 16,400 years ago, the most recent after 2700 years ago.

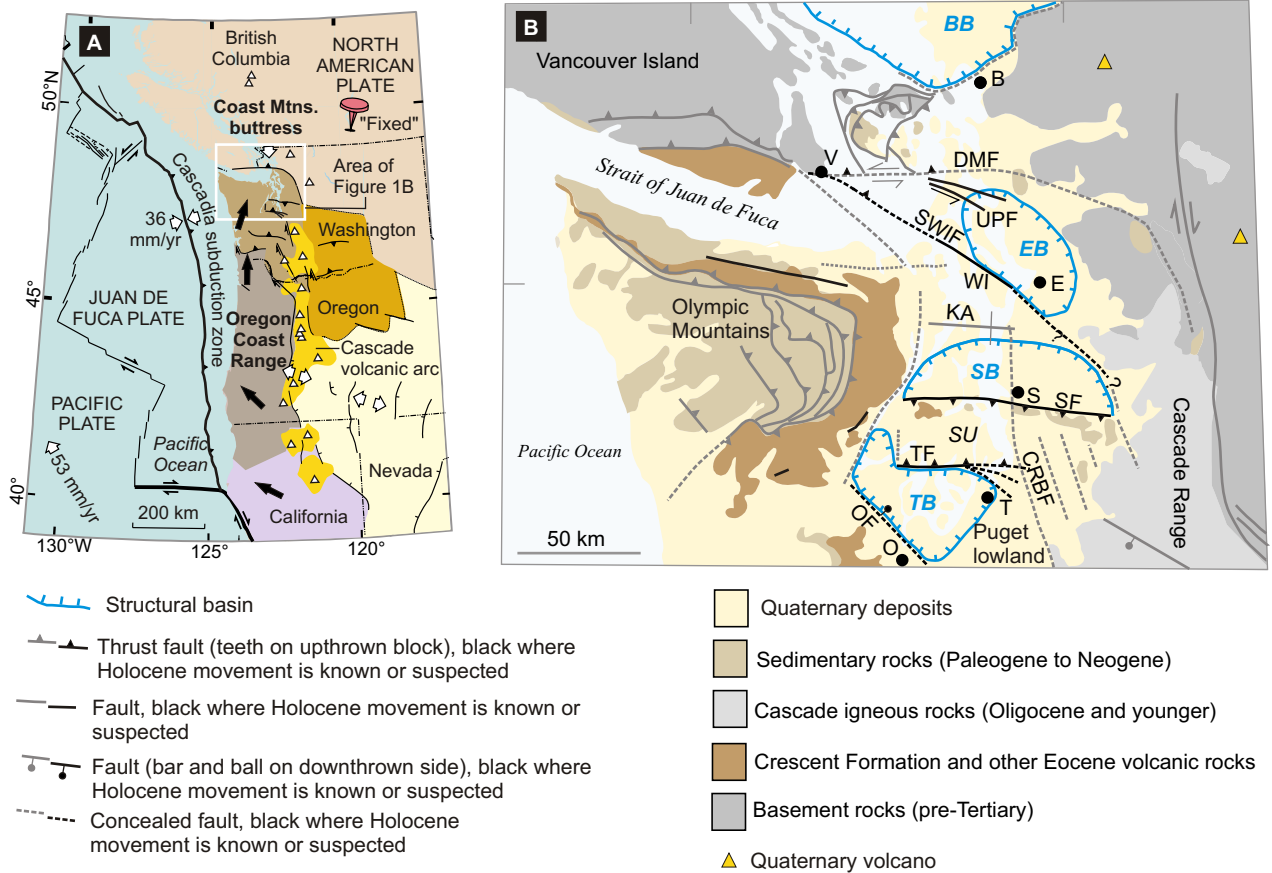
Lidar mapping on northern Whidbey Island revealed the location of a scarp along the broad Darrington–Devils Mountain fault zone. Subsequent excavations across this scarp found evidence for late Holocene oblique left-lateral offset with as much as 2 meters of both vertical and horizontal slip. At the north margin of the Olympic Mountains, scarps along the Little River fault extend over 30 km east-west. At the southeast corner of the Olympic Mountains, lidar mapping shows that the previously recognized southeast-side-up scarps at Price Lake are longer and more numerous than previously thought. Southwest of Price Lake, a 10-km-long, *en echelon* scarp cut across Holocene alluvial fans. An excavation across this scarp showed one episode of movement on a normal fault in the last 3800 years. Further southwest, excavations across the Canyon River fault near Lake Wynoochee showed evidence for oblique left-lateral displacement, with one event in the last 3500 years.

The evidence for Holocene deformation across the entire Puget Sound lowlands is now very pervasive but still incomplete. Lidar scarps have been identified in several areas not associated with the eight zones noted here but have yet to be investigated. Lidar data covers about 70% of the Puget Sound basin, but key areas with suspected crustal faults in northwestern Washington have yet to be flown. Still, the combination of paleoseismological field investigations and lidar imaging allowed remarkable progress in understanding the Holocene earthquake history of greater Puget Sound in just 7 years. The new observations are an important addition to observations used to calculate the National Hazard Maps.

## Introduction

Near-surface faults in the Puget Sound region accommodate contraction of western Washington between the Coast Ranges of Oregon and British Columbia (Wells et al., 1998) (Fig. 1A). The contraction has produced east-trending uplifts, basins, and associated reverse faults that traverse Puget Sound (Fig. 1B). The faults, which separate areas of coastal uplift and subsidence were first identified from geophysical lineaments (Danes et al., 1965). Geophysical data confirm that one fault zone passes beneath Seattle, another just north of Seattle, and also beneath Tacoma (Brocher et al., 2001; Blakely et al., 1999, Blakely et al., 2004). Other faults, revealed with airborne laser mapping, are located throughout the Puget Sound region and confirm that the entire region—from Olympia to the Canadian border—is subject to large, potentially damaging earthquakes (Haugerud et al., 2003)

To date, geologic evidence and lidar topographic data revealed evidence for past earthquakes and surface ruptures along eight fault zones: the Seattle fault zone, Tacoma fault, Southern Whidbey Island fault zone, Olympia fault, Darrington–Devils Mountain fault zone, the northern margin of the Olympic Mountains, the southeastern Olympic Mountains, and the Boulder Creek fault (Fig. 1 and 2). The following discussion summarizes the paleoseismological data from each fault zone.



**Figure 1**—(A) Kinematic model of Cascadia forearc, simplified from Wells and others (Wells and others, 1998) and Wells and Simpson (2001). Northward migration of the Oregon Coast Range squeezes western Washington against North America, producing faults and earthquakes in the Puget Lowland. (B) Generalized map of the Puget Lowland and surrounding regions. BB, Bellingham basin; EB, Everett basin; SB, Seattle basin; TB, Tacoma basin; DMF, Devils Mountain fault; UPF, Utsalady Point fault; SWIF, southern Whidbey Island fault; SF, Seattle fault; TF, Tacoma fault; OF, Olympia fault; V, Vancouver; B, Bellingham; E, Everett; S, Seattle; T, Tacoma; O, Olympia; WI, Whidbey Island; KA, Kingston arch; SU, Seattle uplift. Redrawn from Brocher and others (2001).

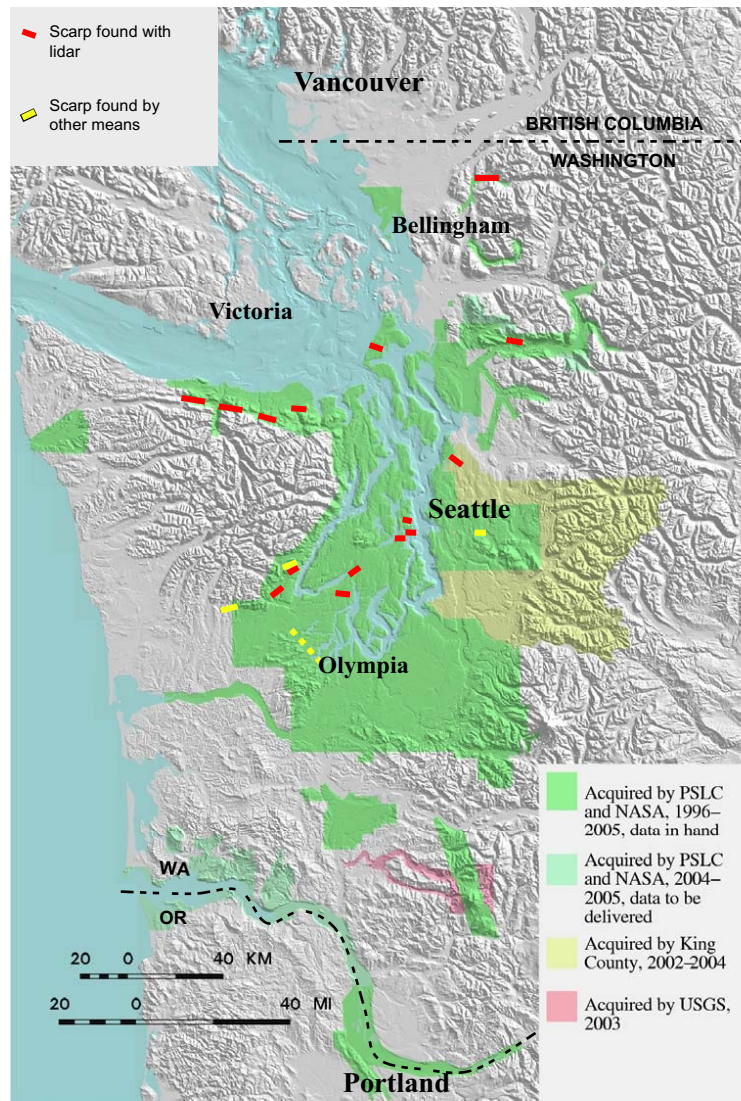


Figure 2. Map of western Washington showing location of acquired lidar and locations of scarps identified using lidar.

### ***Seattle Fault Zone***

Uplifted wave-cut marine platforms were identified a century ago on the west side of Puget Sound and on the east side of Puget Sound near Seattle (Kimball, 1897). Geophysical studies in the late 1960s showed that a fault lies north of the uplifted platform (Danes et al., 1965; Rogers, 1970). Uplifted shells of marine mollusks on the platform provided an early clue that this fault was active in the late Holocene (Yount, 1983; Gower et al., 1985). The uplifted platform is now known to lie within a zone of faults having up to 900 m of Quaternary structural relief (Johnson et al., 1999). The tip of the fault zone likely lies north of Seattle, is buried about 2 km below the ground surface, and dips at a shallow angle to the south (Brocher et al., 2004). Slip on this buried strand about 1100 years ago produced 5–7 m of uplift in a 6-km-wide band south of the fault, while areas to the north subsided as much as a meter (Bucknam et al., 1992; Atwater and Moore, 1992; Jacoby et al., 1992). Detailed study of a marsh straddling the uplifted platform show that meters of uplift occurred only once in the last 7500 years (the event 1100 years ago) and several smaller events that may relate to earthquakes on subsidiary faults within the Seattle fault zone (Sherrod et al., 2000).

Airborne laser mapping along the Seattle fault zone revealed scarps from past surface rupture along subsidiary faults within the Seattle fault zone (Nelson et al., 2003). The Toe Jam Hill scarp is north-side-up, opposite the vergence suggested for the Seattle fault (Johnson et al., 1994; Blakely et al., 2002). The scarp may have formed along a backthrust within the Seattle fault zone. Trenching across the scarp in 1998 and 1999 revealed a north-dipping thrust fault that disrupts late Holocene soils. Soil stratigraphy and radiocarbon ages suggest as many as three surface-rupturing earthquakes in the past 2500 years (Nelson et al., 2002). Southwest of the Toe Jam Hill, laser mapping shows the location of two *en-echelon*, west-trending scarps called the Waterman Point scarp and Glover Point scarp. Both are north-side-up. Three trenches excavated across the Waterman Point scarp in August 2001 exposed a north-dipping fault, on which Oligocene bedrock is thrust south over late Holocene soil (Nelson et al., 2003). Radiocarbon ages from these soils indicate that faulting occurred about 1100 years ago, perhaps in the same event as rupture on the Toe Jam Hill scarp (Nelson et al., 2003, Haugerud et al., 2003).

The scarps and uplifted platform within the Seattle fault zone suggest at least two closely spaced earthquakes along the Seattle fault zone about 1100 years ago. Because the Toe Jam Hill scarp is not present on the adjacent uplifted wave-cut platform, Bucknam et al. (1999) inferred that the last movement on the north-dipping fault predates the Seattle fault earthquake about 1100 years ago. However, the scarps at Waterman Point and Glover Point scarps clearly offset the same 1100-year-old uplifted platform. This implies at least two closely spaced events about 1100 years ago. A north-side-up scarp is also evident in West Seattle, where it cuts the 1100-year-old platform.

### ***Tacoma Fault Zone***

Existence of the Tacoma fault was previously hypothesized on the basis of large-amplitude gravity, aeromagnetic, and seismic-velocity anomalies (Brocher et al., 2001), and coastal marsh stratigraphy (Bucknam et al., 1992). Lidar mapping revealed several *en echelon* north-side-up scarps along the trace of the Tacoma fault that are collectively called the Catfish Lake scarp (Sherrod et al., 2004). Shallow marine seismic reflection surveys at points where the Tacoma fault crosses arms of Puget Sound reveal a large monocline and a tight kink band

(Johnson et al., 2004), The kind band is almost directly below the scarps, suggesting that both formed by movement on a buried reverse fault. Preliminary work, including a trench excavated in October 2002, suggests that the Catfish Lake scarp formed during an earthquake on the Tacoma fault ~1100 years ago. North of the Catfish Lake scarp, *en echelon* segments of the southeast-sideup Sunset Beach scarp extend ~4 km along a northeast trend. The scarp is as high as 8 m. To the southwest, this feature merges with the head scarp of a large, previously undescribed landslide. Possibly the entire feature is the head scarp of an unusual, even larger landslide that rotated clockwise about a vertical axis, though this appears unlikely. Planned excavations across the scarp may resolve this uncertainty.

The scarps coincide with deformed shorelines that straddle the fault and point to an earthquake between A.D. 770 and 1160. A raised tidal flat observed along the north side of the fault in Case Inlet suggests late Holocene uplift. Differences between the modern and raised shoreline elevations, taken from profiles of the lidar data, show ~4 m of uplift. Uplifted tidal flat deposits observed at several sites along the north side of the fault contain marine fossils. Paleoecology of the tidal-flat deposits and overlying upland soils require at least 1.5 m of uplift to change a tidal flat into a freshwater swamp or meadow (Bucknam et al., 1992; Sherrod, 1999, 2000). Plant fossils within the tidal-flat deposits and from overlying freshwater peat limit uplift to between A.D. 770 and 1160. Microfossils recovered from sediments beneath an intertidal marsh at Dumas Bay show that the site remained in the upper intertidal zone while sites to the west were uplifted. The area south of the fault subsided between A.D. 980 and 1190, as shown by a radiocarbon age on the outermost rings of a tree stump (Douglas fir) found in growth position partially exposed on a modern tidal flat at Wollochet Bay.

Radiocarbon ages from uplifted and submerged coastal sites along the Tacoma fault constrain the timing of deformation between A.D. 770 and 1160. An age from leaf bases of *Triglochin maritima* that grew on a freshly uplifted tidal-flat surface at Lynch Cove constrains uplift to shortly before A.D. 880–980. Similarly, freshwater peat deposited between A.D. 1000 and 770 at Burley overlies sand vented onto a raised tidal flat, implying that the ground shook hard enough to liquefy during uplift. At other sites, ages on freshwater swamp peat deposited over tidal-flat deposits loosely constrain uplift between A.D. 890 and 1410. A single age from a submerged tree south of the fault constrains subsidence to between A.D. 980 and 1190.

### ***Olympia Fault***

Geologic evidence collected from several sites along the Olympia fault indicate that a large earthquake struck the region about 1100 years ago (Sherrod, 2001). Buried forest and high marsh soils indicate abrupt changes in relative sea level at four coastal localities in southern Puget Sound. At Little Skookum Inlet and Nisqually River delta, Douglas fir stumps in growth position are buried by salt-marsh peat. Other sites located at the Nisqually River delta, high marsh soils are buried by tidal-flat mud and localized liquefaction coincided with submergence of a high marsh soil. Dramatic changes in seed and diatom assemblages across these contacts confirm rapid submergence. At Little Skookum Inlet and Red Salmon Creek, salt-marsh peat immediately above a buried forest soil contains diatoms indicative of low marsh and tidal-flat environments. At McAllister Creek and Nisqually River, low-marsh and tidal-flat diatoms are abundant in laminated mud directly over high marsh peat. Inferences from modern analogs indicate at least 1 m of subsidence at each site and possibly up to 3 m at Skookum Inlet. Abrupt

burial of lowland soils in southern Puget Sound is best explained by coseismic subsidence. Some of the submergence may be the result of coseismic compaction and postearthquake settlement. Widespread buried soils, large amounts of subsidence, coeval submergence across a wide area, and ground shaking at the time of subsidence all point to a large earthquake between 1150 and 1010 cal yr B.P. in southern Puget Sound as the most likely cause of subsidence.

### ***Southern Whidbey Island fault zone***

The southern Whidbey Island fault zone (SWIFZ) consists of four sub-parallel, northwest-trending fault strands, extending ~100 km from near Vancouver Island to the Washington mainland (Blakely et al., 2004; Sherrod et al., 2005a; Kelsey et al., 2004). The vertical component of displacement changes both across and along the fault and strike slip motion may be important as well.

Abrupt uplift at a coastal marsh on south-central Whidbey Island suggests that the SWIFZ experienced a MW 6.5 - 7.0 earthquake between 3200 and 2800 years B.P. (Kelsey et al., 2004). Uplift is documented through contrasting relative sea level histories at Crockett and Hancock marshes, which straddle one of the strands of the fault zone on Whidbey Island. An earthquake, probably generated on the northern-most strand of the Southern Whidbey Island fault zone, caused one to two m of uplift about 2,800 to 3,200 years ago. Kelsey et al. (2004) speculated that the cause of the uplift is a fold that grew coseismically above a blind fault that was the earthquake source. Both the fault, and the fold at its tip, are imaged on multi-channel seismic reflection profiles in Puget Sound immediately east of the central Whidbey Island site.

The SWIFZ has been hypothesized to extend southeastward beneath the mainland, making landfall between the cities of Seattle and Everett. Linear, low-amplitude aeromagnetic anomalies in this mainland region are on strike with the SWIFZ and may facilitate mapping the SWIFZ onshore. The most prominent of the residual aeromagnetic anomalies, the Cottage Lake aeromagnetic lineament, extends at least 16 km, lies approximately on strike with the SWIFZ on Whidbey Island, and passes within about 27 km of downtown Everett. Glacial deposits are slightly magnetic in this region, as indicated by magnetic susceptibility measurements and a ground-magnetic survey, and, in places, the Cottage Lake aeromagnetic lineament is associated with topographic lineaments. Spectral analysis and modeling experiments indicate that the source of the Cottage Lake aeromagnetic lineament extends to depths greater than 2 km and into Eocene sedimentary strata.

Subtle scarps on Pleistocene surfaces are visible on high-resolution lidar topography at a number of locations in the mainland region, often closely associated with aeromagnetic lineaments. In the field, scarps exhibit northeast-side-up vertical relief of 1 to 5 m. One group of scarps extends a total distance of 18 km along the Cottage Lake aeromagnetic lineament, where they defines two strands: One strand lies east of Crystal Lake while the other follows Little Bear Creek. Four excavations across these two lidar lineaments show evidence for multiple folding and faulting events since deglaciation, most likely above buried reverse/oblique faults. One trench exposed a normal fault, although it was not possible to determine whether slip was caused by glacial or tectonic processes. In this same trench, evidence for younger folding suggests that surface deformation during an earthquake formed the scarp seen on lidar maps near Crystal Lake. Subsequent scarp degradation buried a forest soil, from which charcoal samples indicated that the folding event occurred after 11,670 years ago. Two trenches were also excavated along

the Little Bear Creek lineament near Grace, Washington (Sherrod et al., 2005b). One of these trenches showed evidence for multiple events, including both folding and faulting, with the youngest event disturbing late Holocene wetland soils. In total, paleoseismological evidence suggests that the SWIFZ produced at least four events since deglaciation about 16,400 years ago, the most recent less than 2700 years ago. Liquefaction features near Everett indicate that strong shaking has occurred there at least three times in the last 1100 years, although evidence that those earthquakes occurred on the SWIFZ has not yet been found.

### ***Darrington–Devils Mountain fault zone***

On northern Whidbey Island, at the south margin of the broad Darrington–Devils Mountain fault zone, lidar mapping revealed a west-northwest–trending scarp near Rocky Point. The scarp lies along the Utsalady fault, previously defined on the basis of marine seismic reflection data (Johnson et al., 2001b). Two trenches excavated across the Rocky Point scarp in August 2002 exposed evidence for late Holocene vertical and left-lateral offset (Johnson, et al., 2003).

### ***Northern margin of the Olympic Mountains***

At the north margin of the Olympic Mountains, scarps along the Little River fault extend over 30 km east to west (Haugerud, 2002). At its west end, topographic features are ambiguous: a 10–20-m high south-side-up scarp in bedrock suggests this is a fault-line scarp eroded along an older weakness, although surface offset within a Holocene landslide suggests young deformation. At the east end of the Little River scarp, a 1–2 m north-side-up offset of the late Pleistocene glacially fluted surface almost certainly records postglacial faulting. Farther east, the River Road scarp is a minor north-side-up warp of a latest Pleistocene or early Holocene fluvial surface. These scarps are the focus of on-going research by the U.S. Geological Survey (Alan Nelson, personal communication, 2005).

### ***Southeastern Olympic Mountains***

At the southeast corner of the Olympic Mountains, lidar topography images the previously recognized (Wilson et al., 1979; Hughes, 2005; Blakely et al., 2005) southeast-side-up scarps at Price Lake, and shows that the scarps are longer and more numerous. The ~10-km-long, *en echelon* Frigid Creek scarps cut across Holocene alluvial fans in a zone that extends southwest from Price Lake. Beyond the extent of our lidar data, the Canyon River fault has ~2 m of Holocene offset (Walsh et al., 1999). Scarp geometry suggests reverse and strike-slip motion on the Price Lake, Frigid Creek, and Canyon River structures.

### ***Boulder Creek Fault***

A recent lidar survey along the Nooksack River discloses an east-west fault scarp immediately east of Kendall, WA, 35 km NE of Bellingham (Haugerud et al., 2005). The 4 km-long south-side-up scarp, with a maximum height of 3 m, cuts a latest Pleistocene outwash surface. The scarp lies on the trace of the Boulder Creek fault, originally mapped as a south-dipping normal fault that juxtaposes Eocene Chuckanut Formation with older rocks to the north. Evidently the fault has been reactivated as a thrust under regional N-S compression, an idea proposed by Dragovich et al. (1990) to explain the 1990 Deming earthquake swarm. Geologists

completed excavations across the scarp in November, 2005 and analysis of field data and radiocarbon ages is currently underway. Field data show two buried soils and colluvial deposits beneath the scarp, presumably created by reverse movement on several faults exposed in the excavations. Dip panels within the excavations also point to an earlier episode of folding.

## Conclusions

The evidence for recent, shallow earthquakes across the entire Puget Sound lowlands is now very pervasive. Paleoseismological research, driven by lidar mapping throughout the region, substantially increased our knowledge of active faults in the Puget Lowland over the last seven years. In that short time, the list of known active faults in the region increased from two in 1998 to eight in 2005. Lidar scarps are identified in several areas not associated with the eight zones noted here but have yet to be investigated. Lidar data covers about 70% of the Puget Sound basin, but important areas in northwestern Washington—with suspected crustal faults—have yet to be flown. Still, the combination of paleoseismological field investigations and lidar imaging allowed remarkable progress in understanding the Holocene earthquake history of greater Puget Sound in just 7 years. The new observations are an important addition to observations used to calculate the National Hazard Maps.

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