INTRODUCTION

Does the earthquake history of the Tacoma fault, a down-to-the-south zone of folding and faulting that forms the southern boundary of the Seattle structural uplift (fig. 1; Pratt and others, 1997; Johnson and others, 1999, 2004; Brocher and others, 2001, 2004; Blakely and others, 2002; ten Brink and others, 2002; Booth and others, 2004), include a single regional earthquake that raised the Seattle uplift about AD 900–930 (Atwater and Moore, 1992; Bucknam and others, 1992; Sherrod, 2000; Harding, 2002; Haugerud and others, 2003), or multiple late Holocene earthquakes with recurrence intervals of hundreds to a few thousand years (for example, Nelson and others, 2003c; Barnett and others, 2007)? Do Tacoma fault zone earthquakes nucleate on the main north-dipping Tacoma thrust, the south-dipping master Seattle thrust into which it soles, or, as recently suggested for the Seattle fault zone by Kelsey and others (2008), on bedding-plane-parallel faults at much shallower depths (<5 km) expressed at the surface as sets of scarps in the hanging wall of the Tacoma fault (fig. 2)? How does the timing of surface-rupturing earthquakes in the Tacoma fault zone compare with dated earthquakes in the Seattle fault zone to the north (Nelson and others, 2003a, 2003b, 2003c; Sherrod and others, 2003; ten Brink and others, 2006; Kelsey and others, 2008); and on faults on the southeast flank of the Olympic Mountains to the west (Wilson and others, 1979; Hughes, 2005; Blakely and others, 2005; Walsh and Logan, 2007)? Answers to such questions come from interpretations of data like that presented on this map. The answers are a key component in the assessment of hazards from large earthquakes in the southern Puget Lowland (Petersen and others, 2008; Sherrod and others, 2004).

Prehistoric earthquakes of the Tacoma fault zone were first identified through mapping of coseismically uplifted shorelines in the southern Puget Lowland in the early 1990s (Bucknam and others, 1992; Sherrod, 2001), but in the past decade field research has focused on stratigraphic investigations of fault scarps newly mapped on Airborne Laser Swath Mapping (ALSM, an application of LiDAR) imagery (Haugerud and others, 2003). ALSM surveys of the Tacoma fault area (0.5 pulse/m^2) were flown by Terrapoint LLC during the winters of 2000 and 2001 (http://pugetsoundlidar.ess.washington.edu/). Funding and support for data acquisition and processing were provided by the U.S. Geological Survey (USGS), the National Aeronautics and Space Administration (NASA), and the Puget Sound LiDAR Consortium. Haugerud and others (2003) and Sherrod and others (2003, 2004) identified scarps in the hanging wall of the Tacoma fault on high-resolution digital elevation models (DEMs) of topography derived from the ALSM data that were processed to remove vegetation (fig. 3; for example, Harding and Berghoff, 2000; Haugerud and Harding, 2001). Sherrod and others (2003, 2004) mapped the north-side-up Catfish Lake scarps (fig. 4) between Hood Canal and Case Inlet and noted that they closely coincide with regional high-amplitude tomography, gravity, and magnetic anomalies identified by Brocher and others (2001) along the Tacoma fault zone. Other identified scarps included the crisscrossing Stansberry Lake scarps east of Case Inlet and north of the Key Peninsula (fig. 10), and a prominent set of mostly northwest-facing scarps (Sunset Beach scarps) trending northeast from north of Sunset Beach south of Belfair (figs. 3, 11, and 12). An initial trench across the Catfish Lake scarps (Blueberry trench, fig. 4; Sherrod and others, 2003) showed postglacial folding and a small amount of faulting (0.3 m slip), but no ^{14}C datable material was found. On trend with the scarp 5 km to the east, a tide flat along Case Inlet was uplifted 4 m about the same time. Radiocarbon ages from several uplifted and subsided sites near the Tacoma fault zone limit shoreline uplift and inferred coincident folding and faulting along the scarp to AD 770–1160 (Sherrod and others, 2004).

Here we expand the Tacoma fault zone paleoseismic studies of Sherrod and others (2003, 2004) with data from a study of an additional trench across the Catfish Lake scarps (Cedars trench, fig. 4), two trenches across the Stansberry Lake scarps (Micah and Owl trenches) east of Case Inlet on the hanging wall of the fault (fig. 10), and two trenches (Snake and Bees' Nest trenches) and a seismic reflection profile across the northeast end of the Sunset Beach scarps 6–8 km north of the surface projection of the Tacoma fault (figs. 11, 12, and 13). As in similar data compilations for other Holocene faults in the Puget Lowland (Nelson and others, 2002; Sherrod, 2002; Nelson and others, 2003a; Johnson and others, 2003; Sherrod and others, 2003; Blakely and others, 2004; Sherrod and others, 2005a, 2005b; Nelson and others, 2007), we map the three sets of scarps on ALSM imagery (with 2.5-m elevation contours on 1:4,000-scale maps) and show field and laboratory data from trenches and one seismic reflection profile that we will use to address the earthquake history of the Tacoma fault zone in a future report.

PRELIMINARY RESULTS

Trenches were logged at scales between 1:20 and 1:8 (methods similar to McCalpin, 1998, p. 56–75) and compiled on photomosaics of 3- to 8-m-long sections of trench wall consisting of 1-m by 1-m rectified photo tiles (1,000–1,400 pixels/m). The upper 1–3 m of one wall of each trench was sloped 5–10º from vertical for safety, whereas the opposite wall was benched. Adjacent to each trench log on the map is a summary explanation of stratigraphic units and notes about important stratigraphic relations or interpretations of units. Neither the colors (used to show inferred genesis) nor the numbers (used to label stratigraphic units) imply direct chronologic correlation of units from trench to trench. Units on logs are numbered approximately from oldest to youngest and so unit explanations are listed from top to bottom. Although many units overlap in age, unit numbers show how we mapped packages of sediment that were deposited or deformed by similar processes in approximate chronologic sequence. References to methods of description and analysis in figure captions and notes to the radiocarbon data table are included in the cited references listed.

Patterns of folding and faulting exposed in trenches across the three sets of scarps are evidence for deformation in the hanging wall of the Tacoma fault during at least one late Holocene earthquake. At the Catfish Lake scarps, broad folding of more tightly folded glacial sediment in the Cedars trench is younger than 4.3 ka (ka, thousands of years before AD 1950) because detrital charcoal of this age was found in stream-channel sand in the trench beneath the crest of the scarp (fig. 4, Cedars trench log, Table 1). A post-4.3-ka age for folding is consistent with the uplift across the fault zone at AD 770–1,160 identified by Sherrod and others (2004). In the Micah trench, across the younger of the two Stansberry Lake scarps 9 km northeast of the Cedars trench (144th St. scarp, figs. 3 and 10), six maximum ages on detrital charcoal in pre-faulting B and C horizons and three minimum ages on a tree root in post-faulting colluvium limit a single oblique-slip surface faulting event to AD 410–990 (Micah trench log, table 1, figs. 8 and 9). Stratigraphy and sedimentary structures in the Owl trench across the older scarp at the same site (Wright-Bliss Road scarp, fig. 10) show eroded glacial sediments, probably cut by a meltwater channel, with no evidence of post-glacial deformation (Owl trench log). At the northeast end of the Sunset Beach scarps, 7 km north of the Micah trench (figs. 3, 11, and 12), charcoal ages in normal fault zones in the Snake and Bees' Nest trenches—whose scarps face each other across a 92-m-wide graben—give a close maximum age of 1.3 ka for graben formation. The ages that best limit the time of faulting and folding in each of the studied trenches are consistent with the time of the large regional earthquake in southern Puget Sound identified by Bucknam and others (1992), dated by Atwater and Moore (1992), Sherrod and others (2004), and further discussed by Kelsey and others (2008).

Although a few mapped scarps adjacent to the landslide complex north of Sunset Beach along Hood Canal may be landslide head scarps rather than fault scarps, most of the scarps we map on figure 11 are tectonic. Slight up-to-the-south displacement of reflectors on a high-resolution seismic reflection profile that crosses the most northeasterly Sunset Beach scarps suggests that the scarps formed in response to slip on two steeply dipping faults (near common depth points 1,060 and 1,140 on figs. 12 and 13; Liberty and Pratt, 2007). More distinct displacement of deeper reflectors a kilometer to the south probably records uplift with much greater down-to-the-north displacement on a steeply dipping reverse fault (between common depth points 700 and 800 on fig. 13). From this evidence of crustal deformation only hundreds of meters to the south of the trenched scarps, we infer that most of the mapped scarps (fig. 11) record coseismic rupture of surface faults.

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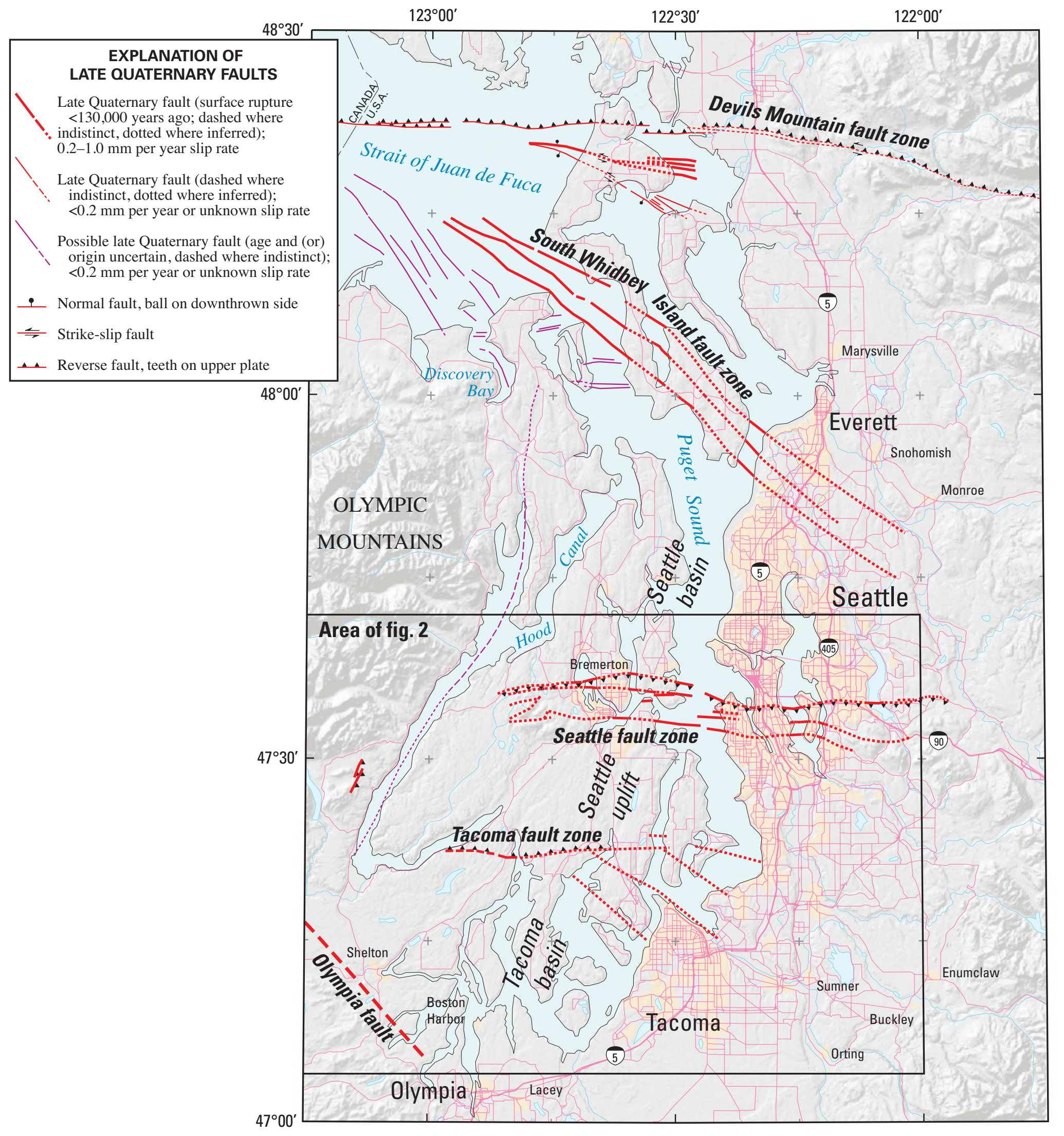

Figure 1. Map of Puget lowland in northwest Washington State showing late Quaternary faults, possible late Quaternary faults, basins, and uplifts (modified from Lidke and others, 2003; Brocher and others, 2004; and Blakely and others, 2004). Area of figure 2 outlined by rectangle (western edge of rectangle extends 4 kilometers beyond edge of figure 1 map).

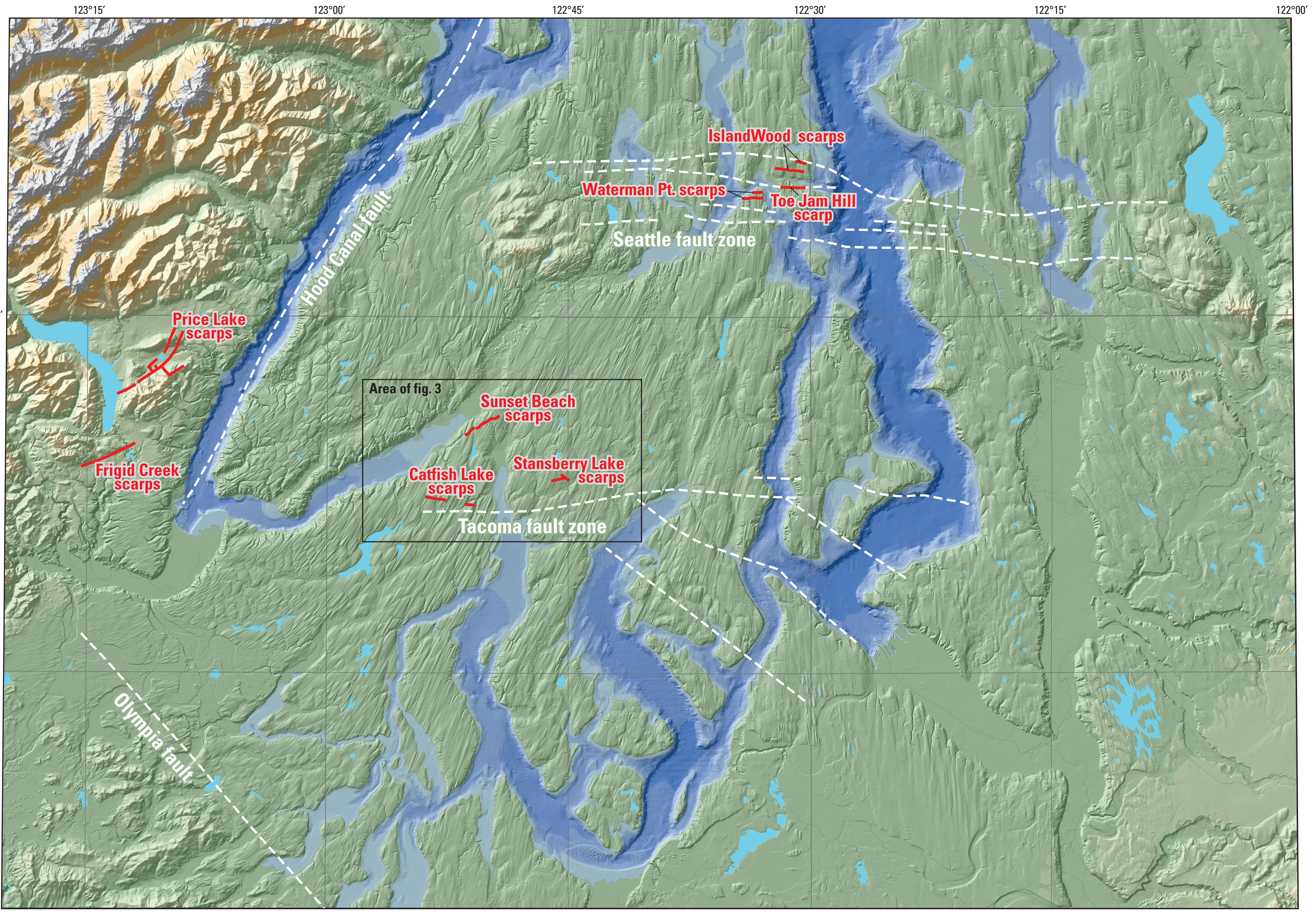

Figure 2. Combined bathymetry and topography of the southern Puget Lowland, Washington State, showing major fault zones and late Holocene fault scarps (base from Finlayson, 2005). Approximate inferred locations of faults (white dashed lines) based on a variety of subsurface evidence summarized by Johnson and others (2004) and Brocher and others (2004). Fault scarps (red lines) as identified on ALSM (airborne laser swath mapping; also known as LiDAR) imagery by many investigators (for example, Harding and Berghoff, 2000; Nelson and others, 2002; Haugerud and others, 2003; Sherrod and others, 2003, 2004, 2005b; and Blakely and others, 2005). Area of figure 3 outlined by rectangle.

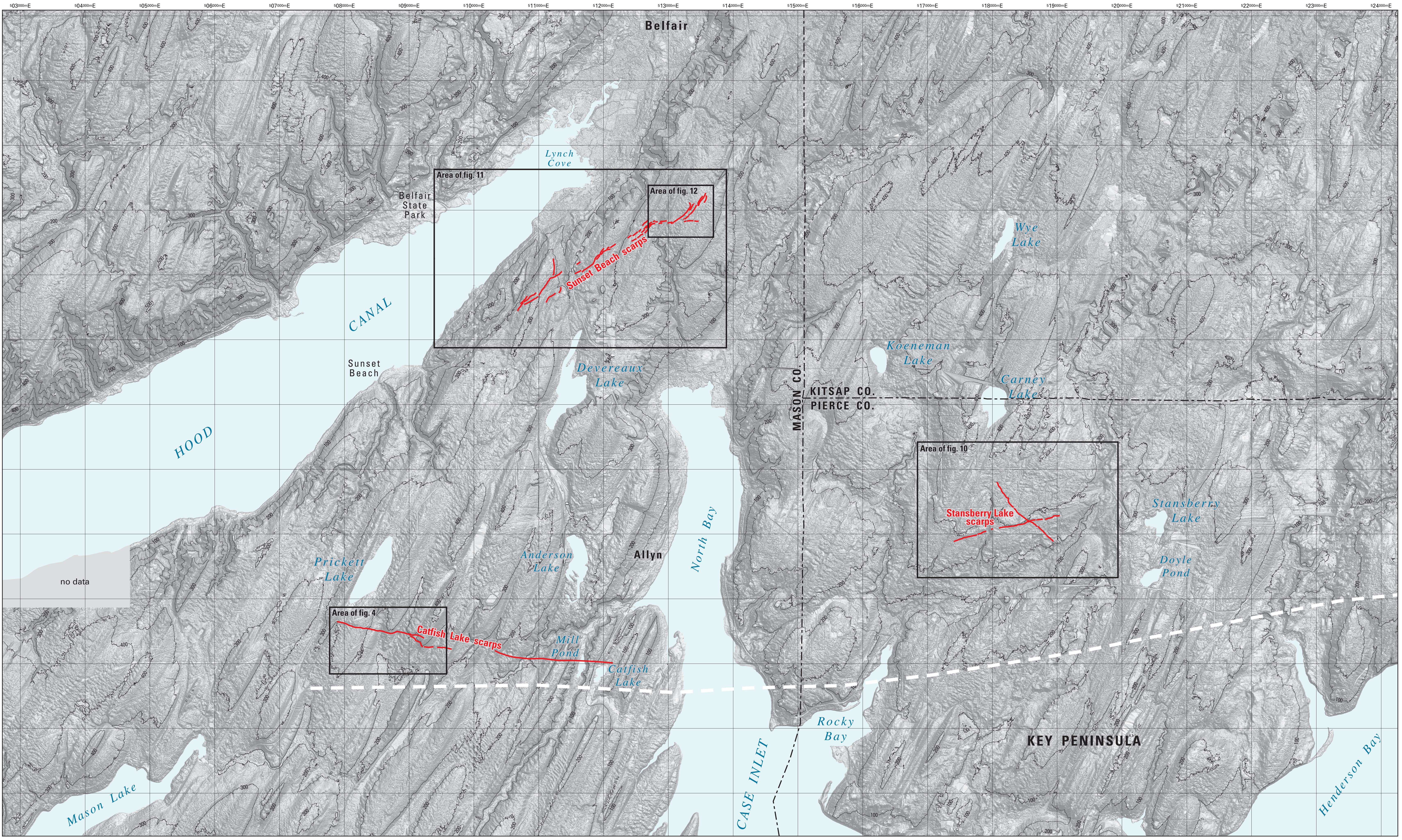

Figure 3. ALSM image showing fault scarps and sites studied in the Tacoma fault zone. Dashed white line is inferred location of Tacoma fault at depth based on geophysical anomalies and seismic reflection profiles (Brocher and others, 2001; Johnson and others, 2004). Red lines mark approximate base of scarps. Pronounced northeast-southwest orientation of many landforms is the result of the advance and retreat of the Puget glacial lobe. Only larger bodies of water are shaded light blue. Contours generated from ALSM data have relative errors of less than ±30 cm. Base contour is mean sea level. The DEM (digital elevation model) consists of two ALSM hillshade layers: top layer azimuth 60°, height above horizon 60°, 5x vertical component, 70% transparent; bottom layer azimuth 360°, height above horizon 60°, 5x vertical component, 70% transparent.

FIELD AND LABORATORY DATA FROM AN EARTHQUAKE HISTORY STUDY OF SCARPS IN THE HANGING WALL OF THE TACOMA FAULT, MASON AND PIERCE COUNTIES, WASHINGTON

By

Alan R. Nelson,[1] Stephen F. Personius,[1] Brian L. Sherrod,[2] Jason Buck,[3] Lee-Ann Bradley,[1] Gary Henley II,[4] Lee M. Liberty,[5] Harvey M. Kelsey,[4]
Robert C. Witter,[6] Richard D. Koehler,[7] Elizabeth R. Schermer,[8] Eliza S. Nemser,[9] and Trenton T. Cladouhos[9]

2008

[1] U.S. Geological Survey, Box 25046, MS 966, Denver, CO 80225
[2] U.S. Geological Survey at Department of Earth and Space Sciences, University of Washington, Seattle, WA 98195
[3] LACO Associates, 21 West 4th Street, Eureka, CA 95501
[4] Department of Geology, Humboldt State University, Arcata, CA 95521
[5] CGISS/Boise State University, 1910 University Drive, Boise, ID 83725
[6] Oregon Department of Geology, Coastal Field Office, Box 1033, Newport, OR 97365
[7] Center for Neotectonic Studies, University of Nevada, Reno, NV 89557
[8] Western Washington University, Department of Geology, Bellingham, WA 98225
[9] Department of Earth and Space Sciences, University of Washington, Box 351310, Seattle, WA 98195

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