Deformation of Quaternary strata and its relationship to crustal folds and faults, south-central Puget Lowland, Washington State

Derek B. Booth
Kathy Goetz Troost — Department of Earth and Space Sciences, University of Washington, Seattle, Washington 98195-1310, USA
Jonathan T. Hagstrum — U.S. Geological Survey, MS-975, Menlo Park, California 94025, USA

ABSTRACT

Folded Quaternary deposits across the south-central Puget Lowland, an area just south of the Seattle fault that extends across the Seattle uplift and its boundary with the adjacent Tacoma basin, provide increased resolution of the character and rate of crustal deformation. They also constrain alternative, and partly incompatible, views of crustal structure previously suggested by geophysical investigations. Tectonic deformation has been progressive for at least the past few hundred thousand years: older sediments display greater deformation than the youngest exposed deposits in the study area. Strain rates across the Seattle uplift have probably been between 0.25 and 1.0 mm/yr during this period, accounting for ~10% of the total strain shortening of the western Washington crust. The Seattle uplift displays Quaternary deformation across its full north-south extent and has structural discontinuities at both its northern and southern boundaries. Previous workers have already established the faulted nature of its northern boundary; exposed Quaternary strata across its southern boundary display intense folding, the location of which generally corresponds to the projection of a "Tacoma fault" suggested by prior geophysical studies.

Keywords: Washington, deformation, folding, Seattle fault, tectonics, Quaternary.

APPROACH

Geologic and Tectonic Setting

The Puget Lowland is a structural basin in western Washington State, bounded by Mesozoic and Tertiary rocks of the Cascade Range on the east and accreted Cenozoic rocks of the Olympic Mountains on the west. It is in a zone of complex and active tectonic stresses, driven by the eastward subduction of the Juan de Fuca plate, northward migration of the Pacific plate along the San Andreas fault, and extension of the Basin and Range Province farther east (Wells et al., 1998). Although the dominant tectonic pattern is that of convergence along a north-trending subduction zone, a series of west- to northwest-trending faults also crosses the lowland (Johnson et al., 1994); the most prominent and potentially hazardous of these is the Seattle fault (Johnson et al., 1999).

The Seattle fault forms the boundary between two major structural features of the Puget Lowland—the Seattle basin to the north and the Seattle uplift to the south—with >9 km of offset in the Eocene rocks between them (Blakely et al., 2002; Sherrod et al., 2004) (Fig. 1). These features are widely recognized, but their geometry and Quaternary deformation rates are still uncertain, in part because one to more than several hundred meters of Quaternary sediments blanket this basement (Jones, 1996). Pratt et al. (1997) first interpreted industry seismic reflection data to suggest that the Seattle fault marks the northward thrusting of a relatively thin (<20 km) layer of the crust; to the south, the adjacent Seattle uplift and Tacoma basin reflect broad, large-amplitude folds in this thrust sheet. They also identified several shorter wavelength and lower amplitude folds superimposed on the Seattle uplift.

Johnson et al. (2004) reinterpreted and augmented Pratt et al.'s (1997) data with additional seismic reflection lines and limited geologic field data, identifying a bedrock ramp between the Tacoma basin and the Seattle uplift (the Rosedale monocline). Sherrod et al. (2004), in contrast, inferred that the southern boundary of the Seattle uplift is also a fault (the Tacoma fault). Brocher et al. (2004) also reinterpreted earlier seismic reflection data, characterizing the Seattle uplift as a passive-roof duplex bounded by the opposing dips of the Seattle and Tacoma faults, resulting in a complex of subsidiary faults and folds in the upper crust and emphasizing the faulted nature at the boundary of the Seattle uplift and the Tacoma basin.

New Geologic Investigations

To interpret prior geophysical and paleoseismic studies of the lowland, we have evaluated the distribution and age of Quaternary deposits across the south-central Puget Lowland, focusing on the Seattle-Tacoma urban corridor where new geologic mapping is ongoing. This area also coincides with the expression of the Seattle uplift and its boundary with the adjacent Tacoma basin. Any tectonic deformation

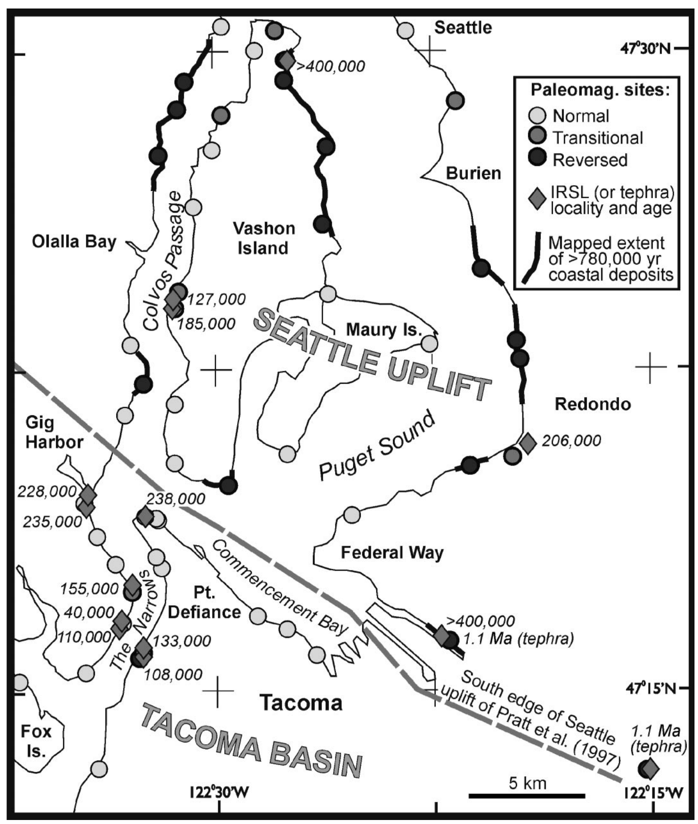

Figure 1. Study area showing generalized location of Seattle uplift and Tacoma basin, infrared-stimulated luminescence (IRSL) sample sites (Mahan et al., 2003), and paleomagnetic sample sites (Hagstrum et al., 2002). Seattle fault zone is few kilometers north of map area. South edge of Seattle uplift corresponds to south edge of Tacoma fault zone as mapped by Sherrod et al. (2004). Coastal deposits older than 780 k.y. were identified from paleomagnetic and IRSL data.

of the crust under the Puget Lowland should also affect overlying Quaternary deposits, and the greater detail afforded by surface exposures should permit increased resolution of the character of that deformation, potentially constraining alternative (and partly incompatible) views of crustal structure suggested by geophysical investigations. Folding of surface deposits may also permit more precise age determination of the rate of Quaternary deformation.

Most of our recent work has involved traditional geologic field methods, particularly the description of geologic deposits, identification of stratigraphic relationships, and age determinations of extensive beach-cliff exposures. Every kilometer of coastline shown in Figure 1 has been walked by either Booth or Troost at least once since 1988; areas with extensive exposures have been traversed two, three, or four times. Structural data used in this report are mostly field-based Global Positioning System (GPS) locations with a horizontal precision of <10 m (see Table DR1[1]).

We have used four established Quaternary dating techniques (Table DR2; see footnote 1): (1) radiocarbon dating, which usefully identifies sediments younger than ~45 k.y.; (2) paleomagnetic determination of fine-grained lacustrine deposits, which broadly identifies deposits older than the last major paleomagnetic reversal at the Brunhes-Matuyama boundary, ca. 780 ka, except where independent age control indicates a younger paleomagnetic excursion; (3) infrared-stimulated luminescence (IRSL), mainly on fluvial sand, to provide stratigraphic constraint on overlying or underlying fine-grained deposits; and (4) fission-track dating on tephra.

Nontectonic Sources of Inclined Beds

To recognize regional patterns of tectonically deformed sediment, we began with a comprehensive examination of all deformed beds that was then filtered by evaluating the various geologic processes that can produce such features. We acknowledge at least four likely nontectonic sources of inclined Quaternary strata in this previously glaciated, geomorphically active terrain:

1. Initial Dips. Fluvial cross-bedding, deltaic deposition into ice-dammed lakes (Bretz, 1913; Thorson, 1989), and widespread ice-contact zones all produce local environments where sand and gravel come to rest at dips from near horizontal to as much as 35°. Because original horizontality can rarely be proven, inadvertent inclusion of misleading data is likely with such deposits (e.g., Johnson et al., 2004, their Fig. 12A). The compilation presented here includes only silt and clay beds, and it includes every such outcrop in the study region that meets the other criteria discussed below.

2. Ice Shove, Ice Shearing, Glaciotectonics. Although the hydrologic and thermal regime at the base of the Puget lobe was not conducive to large-scale freezing and ice transport (Booth, 1991), ice-shove features can be readily observed at the margin of modern temperate glaciers (e.g., Benn and Evans, 1996), developing highly disrupted beds over relatively short distances (1–10 m). Such features are widely reported from around the Puget Lowland and could be problematic for this study, because the direction of any ice-applied stress along the axis of the lowland would follow the ice-flow direction (N6°W in the Tacoma area and N0° in the Seattle area) and would therefore closely parallel the anticipated north-south shortening resulting from regional tectonics (Wells et al., 1998). The presence and scale of ice-contact features, particularly locally steep dips, abundant faulting, and abrupt grain-size changes, are readily observed and are widely displayed. In contrast, broad (i.e., 10^1–10^2 m scale) patterns of consistent or only gently varying bedding suggest minimal influence from this process (in our non-frozen-bed environment) and are the only structural data included here.

Figure 2. Example of deposits displaying deformation of inferred tectonic origin. Bedding strike and dip is N83°W 19°N; site is located at 47.369°N, 122.324°W along east coast of Puget Sound near Redondo (see Fig. 1). View spans ~20 m in lateral extent.

3. Postdepositional Slumping and Consolidation. After deposition, fine and/or organic sediments can slump or consolidate, producing deformation structures over a scale of 0.1–1 m and broader depressions over somewhat larger distances. Discriminating criteria are similar to those for glaciotectonics.

4. Landslides. The bluffs of Puget Sound are localities of abundant landsliding (Tubbs, 1974). Rotational block slides are particularly challenging to this investigation because they can produce moderately to steeply dipping strata over many tens of meters on both the steep bluffs and the adjacent beach. Typical slide geometry, however, yields beds dipping into the hillside and striking subparallel to the bluff face; such conditions have simply been avoided. Other settings, however, may not be as readily recognized. For example, paleolandslides that predate Holocene topography might be exposed in modern beach cliffs; fortunately, the pre-Vashon topography was entirely buried by Vashon-age sediment (Booth, 1994) and probably shared only a few landslide sites with the modern landscape. The chance intersection of the modern coastline with an ancient landslide, however, cannot be eliminated fully.

In summary, many inclined Quaternary deposits exposed at the modern ground surface carry no information about regional structural deformation of the underlying crust. We therefore applied a conservative screen to the raw observations, excluding measurements on granular fluvial sediments, where dips vary markedly over distances $<\sim 10$ m, or in areas of likely landslides. The resulting data set consists of silt and clayey silt deposits, mainly with uniform dips over an outcrop scale of at least several meters to several tens of meters (e.g., Fig. 2). In taking this approach we have undoubtedly excluded some exposures that have a tectonic origin, but the inverse error—that of including exposures that do not have a tectonic origin—should be rare.

Because measurement error can be great in gentle dips, we used a handheld liquid-damped clinometer easily read to within 0.5°. With it we found the strike direction by sighting across at least several meters of a bed well exposed in three dimensions. Measured dips of 2° or less were judged to have a high likelihood of spurious strike direction and so were recorded as horizontal.

RESULTS

Spatial Distribution of Deformation

The overall pattern of inclined beds is mapped in Figure 3. Several features of the regional pattern are evident:

[1]GSA Data Repository item 2004085, Table DR1 (locations of structural data) and Table DR2 (ages), is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

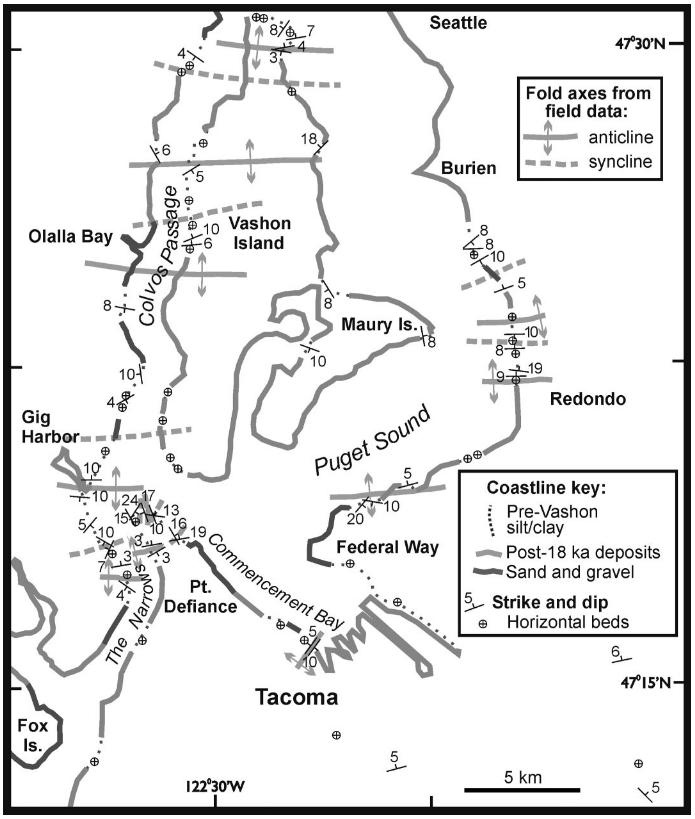

Figure 3. Strikes and dips in Quaternary silt and clay deposits attributed to (or undisturbed by) tectonic movement, together with fold axes defined solely by these field data. Outline of coast displays generalized outcrop distribution: post–18 ka deposits include those of last glacial advance and Holocene landslides, bulkheads, and other structures; sand and gravel deposits span all ages, but potential nonhorizontal deposition renders them unsuitable for inferring crustal deformation.

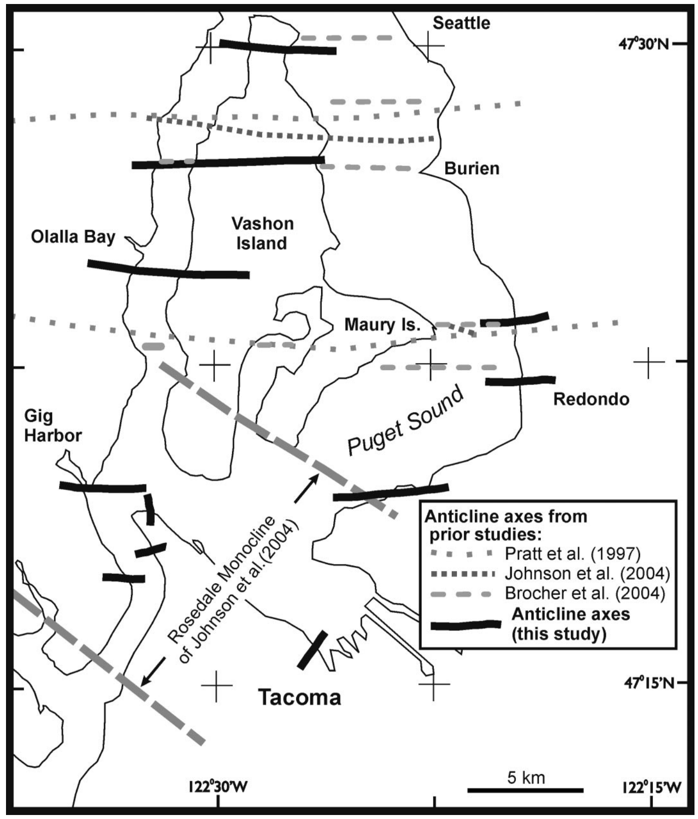

Figure 4. Comparison of published anticline axes from prior geophysical studies with our wholly field-based investigation. No single study is definitive, but overall these data show clear pattern of west-trending fold axes at ~5 km wavelengths that probably reflect underlying bedrock structure.

1. The distribution of reversely magnetized, >780-k.y.-old sediment near sea level (see Fig. 1) reflects the regional structure of the Seattle uplift and the Tacoma basin; it requires a long history of broad Quaternary deformation.

2. The fold axes have an overall west trend across this part of the Puget Lowland, although individual anticline and syncline axes cannot be traced continuously for >~10 km.

3. The wavelength of folding is ~5 km or less. Although the relatively sparse density of recorded bedding suggests the possibility of significantly tighter folds, areas with good and near-continuous beach-cliff exposure suggest that pervasively finer structures have probably not been missed by this reconnaissance.

4. Beds near the southern edge of the Seattle uplift (overlying the Rosedale monocline of Johnson et al., 2004) do not uniformly dip south, and in one part of this region (Point Defiance) they display particularly variable orientations. Structurally lower deposits, however, are generally more common to the north.

Our measured pattern of surface-exposed Quaternary deformation also shows strong correspondence with the crustal folds and blind faults inferred independently from prior geophysical investigations (Fig. 4). Correspondence is very good, particularly north of Redondo, with the data of Brocher et al. (2004), and for trend (and moderately with location) with the data of Pratt et al. (1997) and Johnson et al. (2004). Not every fold is recognized by every study, suggesting that each approach (geophysical and geological) has both strengths and limitations. Their overall consistency, however, argues that our field criteria for identifying tectonically deformed strata are robust and that Quaternary deformation is reproducing the general pattern (and many of the details) of bedrock folds.

Age of Quaternary Deformation

Most generally, the youngest Quaternary sediments in the Puget Lowland are deformed the least. Widespread deposits of the last glaciation display no regionally coherent folding, and even those from the penultimate nonglacial interval (Troost, 1999; Booth et al., 2003) are predominantly horizontal and almost nowhere dip steeper than 5° (except where deformed along the Seattle fault zone; Troost et al., 2004).

The most common pre-last-interglacial sediments at sea level have normally polarized magnetization (Hagstrum et al., 2002) and so are almost certainly younger than 780 ka. Beds in this age range with inclinations of a likely tectonic origin generally have dips of 5°–10°, except on Point Defiance, where fold limbs are commonly steeper. Stratigraphic relationships, infinite radiocarbon ages, and limited IRSL ages (Mahan et al., 2003) indicate that most of these sediments range from one to several hundred thousand years in age.

A significant number of sediments with reversed-polarity magnetizations, and with ages older than 780 ka, are also exposed in the study area (Fig. 1). Several fission-track ages of ca. 1 Ma on the same or adjacent deposits (Westgate et al., 1987; Easterbrook, 1994; Booth et al., 2004), together with stratigraphic relationships and relative-weathering criteria, confirm this presumption. Dips are variable and as high as 19°; as a group, however, they are only modestly steeper than those in deposits younger than 780 ka.

Rates of Strain Shortening

A simple, limiting case of Rockwell et al.'s (1988) model of fold creation under strain shortening suggests the magnitude of crustal shortening across these secondary folds. For simple kink folding (i.e., limbs dip uniformly and the axial extent is negligible), the range of observed dips requires strain shortening of 0.004 (5° dips) to 0.015 (10° dips). An average 1% strain across the 30-km-long Seattle uplift, acquired over a period of a few hundred thousand years, yields a rate of tectonic shortening of $\sim 10^{-3}$ m/yr. Therefore, 1 mm/yr is an upper bound on the rate of strain shortening across the Seattle uplift (exclusive of movement on the Seattle and/or Tacoma faults), given the geometric consequences of nonzero axial fold areas (expressed in part by the abundance of horizontal strata of all ages) and the observed range of dips and ages. Based strictly on the field geologic evidence, our best estimate of this deformation, within a factor of 2, is 0.5 mm/yr. This range accounts for ~10% of the total strain shortening (4–6 mm/yr) variously inferred for the western Washington crust from geologic and Global Positioning System data (Wells et al., 1998; Miller et al., 2001), and it is of the same magnitude of crustal deformation across the Seattle uplift estimated by wholly independent methods by Johnson et al. (1999).

CONCLUSIONS

Surface geologic data are not adequate to define the structure of the Seattle uplift or the geometry of its transition south into the Tacoma basin. However, they impose constraints on past and current models of the deeper crust, models that are based on geophysical data that also have significant limitations. In combination, these disparate data sources describe key elements of the structure and tectonics of western Washington more defensibly, and probably more correctly, than either source alone. The following points are noted in particular:

1. Crustal deformation is clearly expressed across the south-central Puget Lowland through the inclinations of once-horizontal Quaternary sediments. Deformation can be discerned through systematic field observation despite limited exposure and confounding nontectonic processes.

2. Deformation in the study area has been progressive for at least the past few hundred thousand years: older sediments in this period display greater deformation than the youngest exposed deposits. Strain rates across the Seattle uplift have probably been between 0.25 and 1.0 mm/yr during this period, accounting for ~10% of the inferred total strain shortening of the western Washington crust.

3. The Seattle uplift displays Quaternary deformation across its full north-south extent, with structural discontinuities along both northern and southern boundaries. Previous and ongoing work has established the faulted nature of its northern boundary. The geologic data across its southern boundary display multiple fold axes and not a simple monocline; the location of more intense deformation on and near Point Defiance generally corresponds to the suggested projection by others of the Tacoma fault zone.

ACKNOWLEDGMENTS

We thank our colleagues who have freely shared of data, analyses, and speculation, particularly Thomas Brocher, Richard Blakely, Ray Wells, Richard Stewart, Ralph Haugerud, and Samuel Johnson. Donald Easterbrook and Eric Cheney provided very helpful reviews. This work has been supported since 1997 by the Pacific Northwest Urban Geologic Mapping Project, the National Earthquake Hazard Reduction Program, and the Educational Geologic Mapping Program, all of the U.S. Geological Survey.

REFERENCES CITED

Benn, D.I., and Evans, D.J.A., 1996, The interpretation and classification of subglacially-deformed materials: Quaternary Science Reviews, v. 15, p. 23–52.

Blakely, R.J., Wells, R.E., Weaver, C.S., and Johnson, S.Y., 2002, Location, structure, and seismicity of the Seattle fault zone, Washington—Evidence from aeromagnetic anomalies, geologic mapping, and seismic-reflection data: Geological Society of America Bulletin, v. 114, p. 169–177.

Booth, D.B., 1991, Glacier physics of the Puget lobe, southwest Cordilleran ice sheet: Géographie Physique et Quaternaire, v. 45, p. 301–316.

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

Booth, D.B., Troost, K.G., Clague, J.J., and Waitt, R.B., 2003, The Cordilleran ice sheet, *in* Gillespie, A., et al., eds., The Quaternary Period in the United States: International Union for Quaternary Research, Elsevier Press, p. 17–43.

Booth, D.B., Waldron, H.H., and Troost, K.G., 2004, Geologic map of the Poverty Bay 7.5-minute quadrangle, Washington: U.S. Geological Survey Miscellaneous Field Studies Map, 1 sheet, scale 1:24,000 (in press).

Bretz, J.H., 1913, Glaciation of the Puget Sound region: Washington Geological Survey Bulletin 8, 244 p.

Brocher, T.M., Blakely, R.J., and Wells, R.E., 2004, Interpretation of Seattle uplift, Washington, as a passive roof duplex: Seismological Society of America Bulletin (in press).

Easterbrook, D.J., 1994, Chronology of pre–late Wisconsin Pleistocene sediments in the Puget Lowland, Washington, *in* Lasmanis, R., and Cheney, E.S., conveners, Regional geology of Washington State: Washington Division of Geology and Earth Resources Bulletin 80, p. 191–206.

Hagstrum, J.T., Booth, D.B., Troost, K.G., and Blakely, R.A., 2002, Magnetostratigraphy, paleomagnetic correlation, and deformation of Pleistocene deposits in the south-central Puget Lowland, Washington: Journal of Geophysical Research, v. 107, no. B4, 2079, doi: 10.1029/2001JB000557.

Johnson, S.Y., Potter, C.J., and Armentrout, J.M., 1994, Origin and evolution of the Seattle fault and Seattle basin, Washington: Geology, v. 22, p. 71–74.

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

Johnson, S.Y., Blakely, R.J., Stephenson, W.J., Dadisman, S.V., and Fisher, M.A., 2004, Active shortening of the Cascadia forearc and implications for seismic hazards of the Puget Lowland: Tectonics, v. 23, TC1011, doi: 10.1029/2003TC001507.

Jones, M.A., 1996, Thickness of unconsolidated deposits in the Puget Sound Lowland, Washington and British Columbia: U.S. Geological Survey Water-Resources Investigations Report 94-4133, 1 sheet, scale 1:455,000.

Mahan, S.A., Troost, K.G., Hagstrum, J.T., and Booth, D.B., 2003, Dating sediments older than 100 ka in the Seattle-Tacoma urban corridor: A test for infrared stimulated luminescence and thermoluminescence on fine grain deposits: Geological Society of America Abstracts with Programs, v. 35, no. 6, p. 79.

Miller, M.M., Johnson, D.J., Rubin, C.M., Dragert, H., Wang, K., Qamar, A., and Goldfinger, C., 2001, GPS-determination of along-strike variation in Cascadia margin kinematics—Implications for relative plate motion, subduction zone coupling, and permanent deformation: Tectonics, v. 20, p. 161–176, (doi: 10.1029/2000TC001224).

Pratt, T.L., Johnson, S.Y., Potter, C.J., Stephenson, W.J., and Finn, C.A., 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.

Rockwell, T.A., Keller, E.A., and Dembroff, G.R., 1988, Quaternary rate of folding of the Ventura Avenue anticline, western Transverse Ranges, southern California: Geological Society of America Bulletin, v. 100, p. 850–858.

Sherrod, B.L., Brocher, T.M., Weaver, C.S., Bucknam, R.C., Blakely, R.J., Kelsey, H.M., Nelson, A.R., and Haugerud, R., 2004, Holocene fault scarps near Seattle, Washington: Geology, v. 32, p. 9–12.

Thorson, R.M., 1989, Glacio-isostatic response of the Puget Sound area, Washington: Geological Society of America Bulletin, v. 101, p. 1163–1174.

Troost, K.G., 1999, The Olympia nonglacial interval in the south-central Puget Lowland, Washington [M.S. thesis]: Seattle, University of Washington, 123 p.

Troost, K.G., Booth, D.B., and Shimel, S.A., 2004, Surficial geologic map of the Seattle southwest 7.5-minute quadrangle: U.S. Geological Survey Miscellaneous Field Studies Map, 1 sheet, scale 1:12,000 (in press).

Tubbs, D.W., 1974, Landslides in Seattle: Washington Division of Geology and Earth Resources Information Circular 52, 15 p.

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

Westgate, J.A., Easterbrook, D.J., Naeser, N.D., and Carson, R.J., 1987, Lake Tapps tephra: An early Pleistocene stratigraphic marker in the Puget Lowland, Washington: Quaternary Research, v. 28, p. 340–355.

Manuscript received 25 November 2003
Revised manuscript received 9 February 2004
Manuscript accepted 9 February 2004

Printed in USA