THE CATFISH LAKE SCARP, ALLYN, WASHINGTON: PRELIMINARY FIELD DATA AND IMPLICATIONS FOR EARTHQUAKE HAZARDS POSED BY THE TACOMA FAULT

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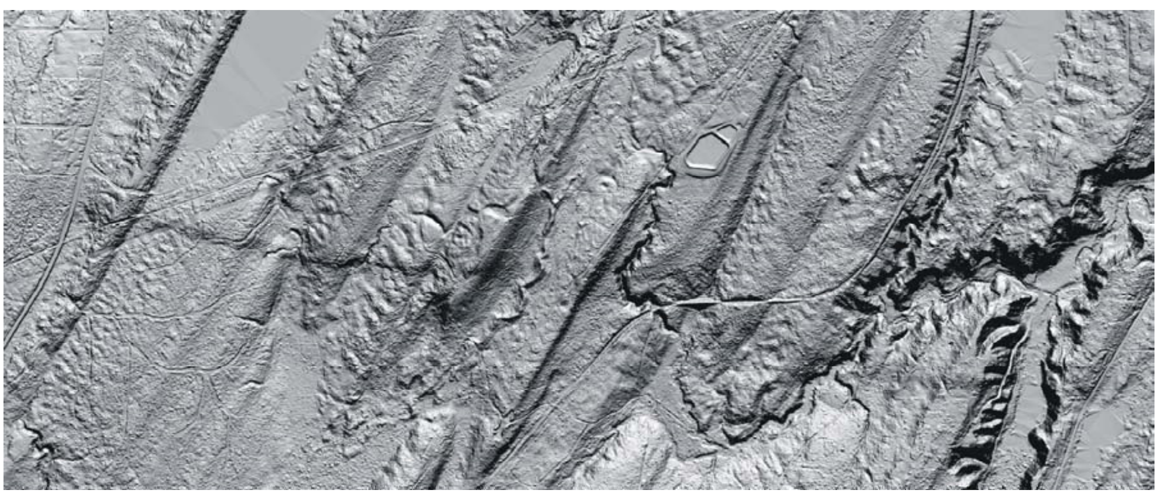

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ABSTRACT

The Tacoma fault bounds gravity and aeromagnetic anomalies for 50 km across central Puget lowland from Tacoma to western Kitsap County. Tomography implies at least 6 km of post-Eocene uplift to the north of the fault relative to basinal sedimentary rocks to the south.

Coastlines north of the Tacoma fault rose about 1100 years ago during a large earthquake. Abrupt uplift up to several meters caused tidal flats at Lynch Cove, North Bay, and Burley Lagoon to turn into forested wetlands and freshwater marshes. South of the fault at Wollochet Bay, Douglas-fir forests sank into the intertidal zone and changed into saltmarsh. Liquefaction features found beneath the marsh at Burley Lagoon point to strong ground shaking at the time of uplift.

Recent lidar maps of the area southwest of Allyn, Washington revealed a 4 km long scarp, or two closely spaced en-echelon scarps, which correspond closely to the Tacoma fault gravity and aeromagnetic anomalies. The scarp, named the Catfish Lake scarp, is north-side-up, trends east-west, and clearly displace striae left by a Vashon-age glacier. A trench across the scarp exposed evidence for postglacial folding and reverse slip. No organic material for radiocarbon dating was recovered from the trench. However, relationships in the trench suggest that the folding and faulting is postglacial in age.

INTRODUCTION

High-amplitude geophysical lineaments in southern Puget Sound define the locations of known or suspected faults in the Puget Lowland (Figs. 1 and 2). These faults include the Seattle, Tacoma, Olympia, and southern Whidbey Island, and bound structural basins beneath the cities of Tacoma, Seattle, and Everett (Brocher et al., 2001). Several faults are suspected of Quaternary offset, and the Seattle fault has Holocene rupture (Bucknam et al., 1992; Nelson et al., 2002).

Holocene earthquakes in the Seattle fault zone deformed shorelines and caused surface rupture on several small faults. Uplifted terraces along the south side of the Seattle fault and a submerged intertidal marsh constrain a large earthquake on the Seattle fault zone to about 900-930 A.D. (Atwater and Moore, 1992; Bucknam et al., 1992). Surface rupture on a series of small en-echelon faults located within the Seattle fault zone suggest as many as three earthquakes in the last 2500 years (Nelson et al., 2002). Trenches across a scarp near Price Lake along the west side of Hood Canal yielded evidence for possibly three Holocene earthquakes (Wilson et al., 1979). However, dense vegetation and thick glacial deposits cover much of the Puget Lowland, confounding attempts to find faults and evidence of past earthquakes.

Topographic maps made using lidar data are key to finding evidence for past surface rupturing earthquakes. Maps produced from lidar surveys can show 'bare-Earth' topography by parsing the data to remove the effects of vegetation on topographic models. Detailed lidar maps show fault scarps within the Seattle fault zone at Toe Jam Hill on Bainbridge Island and Waterman Point near Port Orchard (Nelson et al., 2002). A newly discovered scarp between Catfish Lake and Prickett Lake near Allyn, Washington reveals the first evidence for surface rupture along the Tacoma fault (herein called the Catfish Lake scarp; Fig. 3).

This report summarizes our preliminary findings from an excavation across the Catfish Lake scarp near Prickett Lake, Washington (Fig. 3). The trench, about 35 meters long, exposed Vashon till, sand and gravel-filled channels on the till surface, and an oxidized post-glacial soil. Reverse displacement on two faults and folded till fabrics suggest postglacial movement on the Tacoma fault. Coastal marsh deposits bounding the Tacoma fault zone provide the best evidence for dating the latest episode of movement on the Tacoma fault (Figs. 1 and 6).

The report consists of this pamphlet and six figures printed on a single 36” x 36” sheet. Each figure is reduced in size or simplified for inclusion in this pamphlet. Readers are encouraged to print the larger figures on the 36”x36” sheet for greater detail and clarity.

TACOMA FAULT ZONE GEOPHYSICS

Danes et al. (1965), Gower et al. (1985), and Brocher et al. (2001) summarized geophysical (gravity and magnetic anomaly) evidence for a down-to-the-south structure along the southern flank of the Seattle Uplift. Close correspondence between (A) the SHIPS tomography seismic velocity model at 3 km depth (Brocher et al., 2001), (B) the isostatic gravity data, and (C) more recent aeromagnetic data (Blakely et al., 2002) over the Seattle uplift argues for the presence of large geological structures along both the northern and southern flanks of the Seattle uplift. The Seattle fault zone bounds the northern side of the Seattle uplift, and the Tacoma fault zone bounds the southern flank. Several investigators recently discussed the geometry of the Seattle fault zone based on these and other data (Johnson et al., 1994, 1999 Pratt, 1997; Blakely et al., 2002; ten Brink et al., 2002), where several kilometers of structural relief on the top of the Crescent Formation volcanics is inferred (Johnson et al., 1999; 1994; Brocher et al., 2001).

We identify two prominent lineaments based on geophysical anomalies along the southern and western flanks of the Seattle uplift (labeled lineaments C and G in Figure 2) and two less prominent lineaments (labeled lineaments D and E in Figure 2). Inferred fault strands (dotted lines) are shown for the Seattle fault zone (Blakely et al., 2002), along the Hood Canal (Brocher et al., 2001), and the Coast Range Boundary faults (CRBF) (Johnson et al., 1999).

All three geophysical datasets illustrated in Figure 2 define co-located large amplitude anomalies as well as secondary peaks and valleys. Lineament C, along the southern boundary of the Seattle Uplift, is best defined by the tomography model and gravity data. The abrupt truncation at the west end of lineament C by N-trending lineament G is conspicuous on all three datasets. All three datasets also display peaks at Gold (GoM) and Green Mountain (GrM) in the Seattle Uplift, where Eocene basalts are exposed. On the southeastern end of the uplift, lineaments D and E are defined by the aeromagnetic data and tomography velocity model.

Geophysical anomalies on the southern flank of the uplift are as large or larger than those associated with the better studied Seattle fault zone to the north (e.g., Blakely et al., 2002). This observation suggests that the causative geological structures bounding the southern limb of the Seattle Uplift have significant structural relief. The anomaly amplitudes increase westward, consistent with an inferred westerly increase in structural relief on the Tacoma fault zone (Brocher et al., 2001). In the vicinity of the Catfish Lake scarp, Brocher et al. (2001) inferred 6 to 7 km of structural relief on the top of the Crescent formation volcanics (their Plate 3).

Brocher et al. (2001) observed that the inferred westerly increase in structural relief along the Tacoma fault zone is consistent with the westerly increase in the relative amounts of coseismic uplift of coastal marsh sites along the fault zone. Consistent with this spatial pattern of the relative amounts of coastal marsh uplift, the amplitudes of the geophysical anomalies defining lineament C are the largest in the vicinity of Prickett Lake and the Catfish Lake scarp.

Diffuse crustal seismicity from 1970 to 2001 reported by the Pacific Northwest Seismic Network (PNSN) over the Seattle uplift are shown as filled yellow circles in Figure 2. The diffuse crustal seismicity does not clearly define a trend along lineaments C, D, E, or G.

DESCRIPTION OF GEOPHYSICAL LINEAMENTS

Lineament C

Lineament C is defined by tomography and gravity data as the southern boundary between higher velocities and densities associated with Eocene volcanic basement rocks in the Seattle Uplift and lower velocities and densities associated with the Tertiary and younger sedimentary rocks filling the Tacoma basin. Aeromagnetic anomalies along lineament C increase westward along it and are best developed at its western end.

Lineament D

Lineament D is defined as the southern boundary of a ridge in the tomography velocity model as well as by a low amplitude lineament in the aeromagnetic data.

Lineament E

Lineament E is defined as the northern boundary of the ridge bounded to the south by Lineament D, and like lineament D, is defined by the tomography model and aeromagnetic data.

Lineament G

Lineament G is defined by the abrupt truncation of E-trending lineament C, defined by the tomography model, and gravity and aeromagnetic data. The N-trend of this lineament is best defined by the aeromagnetic data.

TECTONIC GEOMORPHOLOGY

Recent ALSM mapping reveals a subtle landform possibly related to movement on the Tacoma fault (Fig. 3). The feature, extending from Catfish Lake to Prickett Lake, is either a single scarp with a diffuse bend near its center, or it is two shorter en-echelon scarps. The scarp, herein called the Catfish Lake scarp, is a north-side-up scarp trending E-W across the area between Hood Canal and Case Inlet. More importantly, the scarp corresponds closely to regional high-amplitude geophysical anomalies seen in Figure 2. Profiles created using lidar grids in a GIS system show that scarp heights vary from less than a meter to about 3 m in height (Fig. 4).

COASTAL PALEOSEISMOLOGY

Marshes located in several inlets of southern Puget Sound record evidence for deformation during an earthquake on the Tacoma fault zone about 1100 years ago (Figs. 1B and 5). Coasts along the north side of the

Tacoma fault rose at about the same time as uplift and subsidence elsewhere at Puget Sound in A.D. 800-1200. But a site on the south side of the fault subsided as much as a century later.

Uplift to the north of the fault and subsidence to the south occurred most recently in A.D. 800-1200 (Fig. 1B). To the north at Lynch Cove, tidal flats rose as much as 3 m between A.D. 870-990 (Bucknam and Biasi, 1994). Uplift 16 km to the east at Burley allowed woody shrubs to invade former tidal flats in A.D. 770-1000 (Bucknam et al., 1992). Shells in tidal flat mud at North Bay record uplift loosely dated to the past 3000 years. Fossil foraminifera from Dumas Bay limit the eastward extent of uplift north of the fault, for they show that a brackish marsh remained in the intertidal zone throughout the last 2000 years. However, trees at Wollochet Bay, on the south side of the fault, subsided into the intertidal zone in A.D. 980-1190, on the basis of a single radiocarbon age.

The age range of this uplift on the north side of the Tacoma fault includes times of coseismic uplift and subsidence at many sites around Puget Sound. A well-known earthquake raised shorelines along the Seattle fault zone in A.D. 900-930 (Atwater, 1999), and several shores of southern Puget Sound subsided between A.D. 860 and A.D. 940 (Sherrod, 2001). The uplift north of the Tacoma fault therefore coincided with a single large event in A.D. 900-930, or it represents a separate earthquake of about that age. However, the discordant subsidence at Wollochet Bay implies either an earthquake younger than A.D. 900-930 or a postseismic transient.

FAULT SCARP EXCAVATION NEAR PRICKETT LAKE, MASON COUNTY, WASHINGTON

A trench excavated across the Catfish Lake scarp near Prickett Lake exposed Vashon till and postglacial soils developed on till (Fig. 6). Structures observed in the till are consistent with both glaciotectonic deformation, and deformation related to movement on the Tacoma fault. One fault (F3) breaks a postglacial soil horizon (B/E horizon) with about 30 cm of reverse slip.

Clast fabrics in the till suggest postglacial folding. Two types of fabrics are evident: imbricated clasts and crude pebble stratification. Imbricated clasts in the till are more steeply inclined to the north on the north side of F3 between 15m and 21m, and are almost subhorizontal between 0m and 15m. Crude pebble stratification also suggests postglacial folding. Pebble layers in the north half of the trench are almost horizontal while similar layers in the south half of the trench dip to the south. The break between the two fabric orientations is approximately F3, the fault that breaks a Holocene soil horizon (unit 2E/B), and both fabrics suggest anticlinal folding.

No organic material suitable for radiocarbon dating was present in the till or overlying soil horizons. Therefore, relative-age relationships provide the only control on the timing of deformation. Since fault F3 cuts a soil horizon, it is most likely that the last movement on F3 occurred in Holocene time because it would take hundreds to thousands of years to develop soils after deglaciation. Since the till fabric is folded, we conclude that folding could have occurred either under the ice sheet or after deglaciation. Since the fabric orientations change at F3, near where a postglacial soil horizon is displaced, it is likely that folding of the till occurred during faulting rather than during subglacial emplacement of till.

CONVERGENCE OF GEOLOGY AND GEOPHYSICS ALONG THE TACOMA FAULT

The relationship between the fault scarp and regional geophysical anomalies suggests that the scarp formed during a large Holocene earthquake on the Tacoma fault. Because the geophysical anomalies and scarp cross the coastline of Puget Sound at a place where there is evidence for Holocene uplift, the best evidence for dating large earthquakes comes from coastal marshes in southern Puget Sound. To the north of the fault, several sites show evidence for uplifted late Holocene tidal flats (Fig. 1) and one site suggests subsidence to the south of the fault. These sites suggest one, possibly two, earthquakes about 1100 – 1000 years ago on the Tacoma fault.

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LITERATURE CITED

Atwater, B. F., 1999, Radiocarbon dating of a Seattle earthquake to A.D. 900-930, in Seismological Research Letters, Seattle, v. 70, p. 232.

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

Birkeland, P.W., 1999. Soils and Geomorphology. Oxford University Press, New York, 448 p.

Blakely, R. J., Wells, R. E., Weaver, C. S., and Johnson, S. Y., 2002, Location, Structure, and Seismicity of the Seattle Fault Zone, Washington: Bulletin of the Geological Society of America, v. 114,, p. 169-177.

Brocher, T. M., Parsons, T., Blakely, R. A., Christensen, N. I., Fisher, M. A., Wells, R. E., and SHIPS Working Group., 2001, Upper crustal structure in Puget Lowland, Washington: Results from 1998 Seismic Hazards Investigation in Puget Sound: Journal of Geophyisical Research, v. 106, p. 13,541-13,564.

Bucknam, R. C., and Biasi, G. P., 1994, An improved estimate of the time of a prehistoric earthquake in the Southwest Puget Sound region, Washington: Abstracts with Programs - Geological Society of America, v. 26, no. 7, p. 522.

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

Danes, Z. F., Bonno, M. M., Brau, E., Gilham, W. D., Hoffman, T. F., Johansen, D., Jones, M. H., Malfait, B., Masten, J., and Teague, G. O., 1965, Geophysical investigations of the southern Puget Sound area, Washington: Journal of Geophysical Research, v. 70, p. 5573-5580.

Finlayson, D. P., Haugerud, R. A., and Greenberg, H. R., 2001, Building a seamless digital elevation model of the Puget Sound basin, Puget sound regional research 2001: Abstracts & biographies, Puget Sound Water Quality Action Team, Olympia, WA.

Gower, H. D., Yount, J. C., and Crosson, R. S., 1985, Seismotectonic map of the Puget Sound region, Washington, scale 1:250,000.

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, no. 7, p. 1042-1053.

Nelson, A. R., Johnson, S. Y., Wells, R. E., Pezzopane, S. K., Kelsey, H. M., Sherrod, B. L., Bradley, L.-A., Koehler, R. D. I., Bucknam, R. C., Haugerud, R., and Laprade, W. T., 2002, Field and Laboratory Data from an Earthquake History Study of the Toe Jam Hill Fault, Bainbridge Island, Washington: U.S. Geological Survey Open-File Report 02-0060.

Pratt, T.L., Johnson, S.Y., Potter, C.J., Stephenson, W.J., and Finn, C., 1997, Seismic-reflection images beneath Puget Sound, western Washington State -- The Puget Lowland thrust system hypothesis: Journal of Geophysical Research, v. 102, p. 27,469-27,490.

Sherrod, B. L., 2001, Evidence for earthquake-induced subsidence about 1100 yr ago in coastal marshes of southern Puget Sound, Washington: Geological Society of America Bulletin, v. 113, no. 10, p. 1299-1311.

Soil Survey Staff, 1993. Soil Survey Manual. USDA, Soil Conservation Service, Agricultural Handbook No. 18, U.S. Gov. Print. Office, Washington, D.C. 503 pp.

ten Brink, U. S., Molzer, P. C., Fisher, M. A., Blakely, R. J., Bucknam, R. C., Parsons, T., Crosson, R. S., and Creager, K. C., 2002, Subsurface geometry and evolution of the Seattle fault zone and the Seattle basin, Washington: Bulletin of the Seismological Society of America, v. 92, no. 5, p. 1737-1753.

Wilson, J. R., Bartholomew, M. J., and Carson, R. J., 1979, Late Quaternary faults and their relationship to tectonism in the Olympic Peninsula, Washington: Geology, v. 7, p. 235-239.

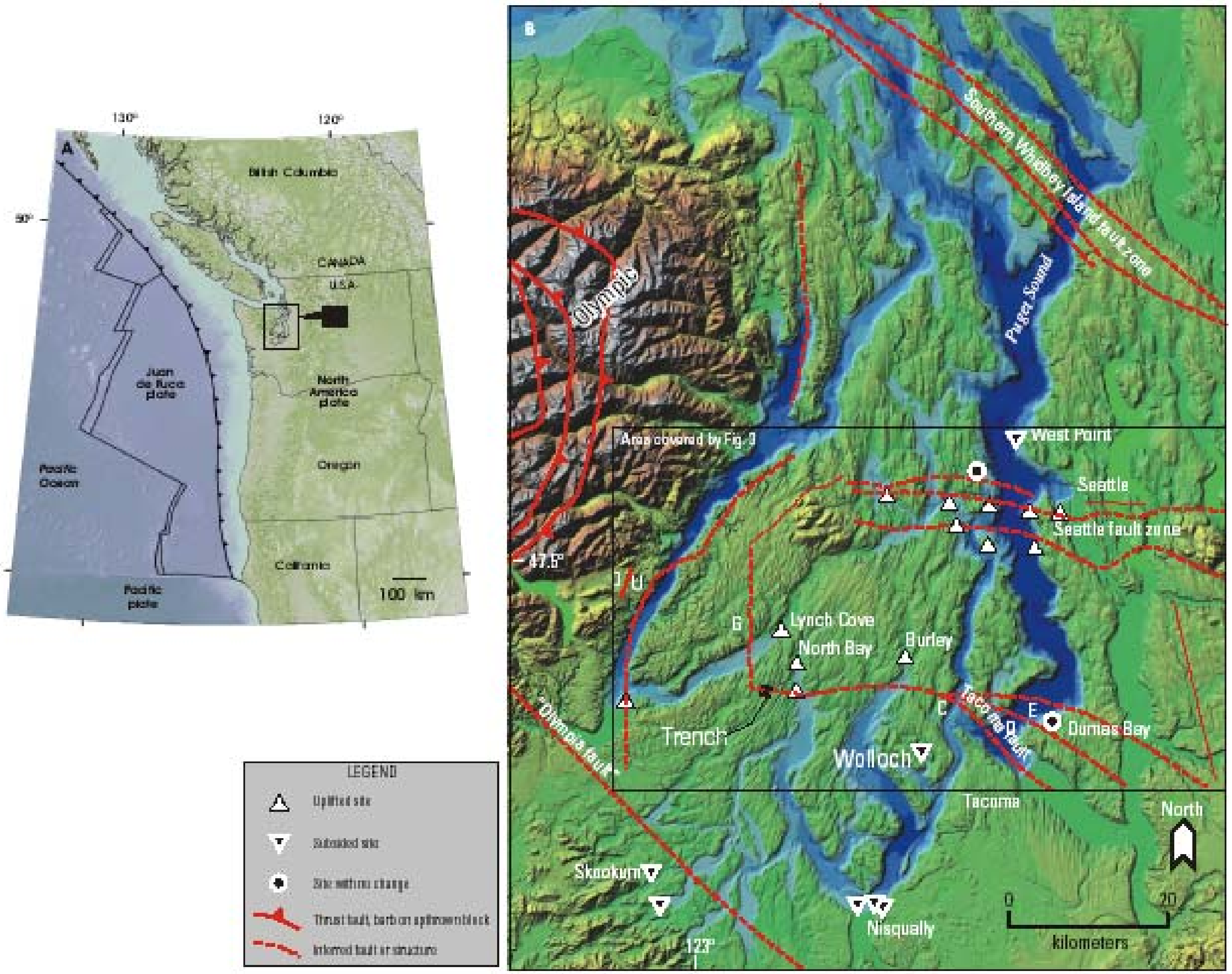


Figure 1. A. Location map of Cascadia, showing relationship of study area to Cascadia subduction zone. B. Location map of Puget Sound, showing sites with evidence for Holocene deformation, trace of geophysical anomaly of the Tacoma fault, and location of scarp along the anomaly. Base map modified from Finlayson, et al. (2001).

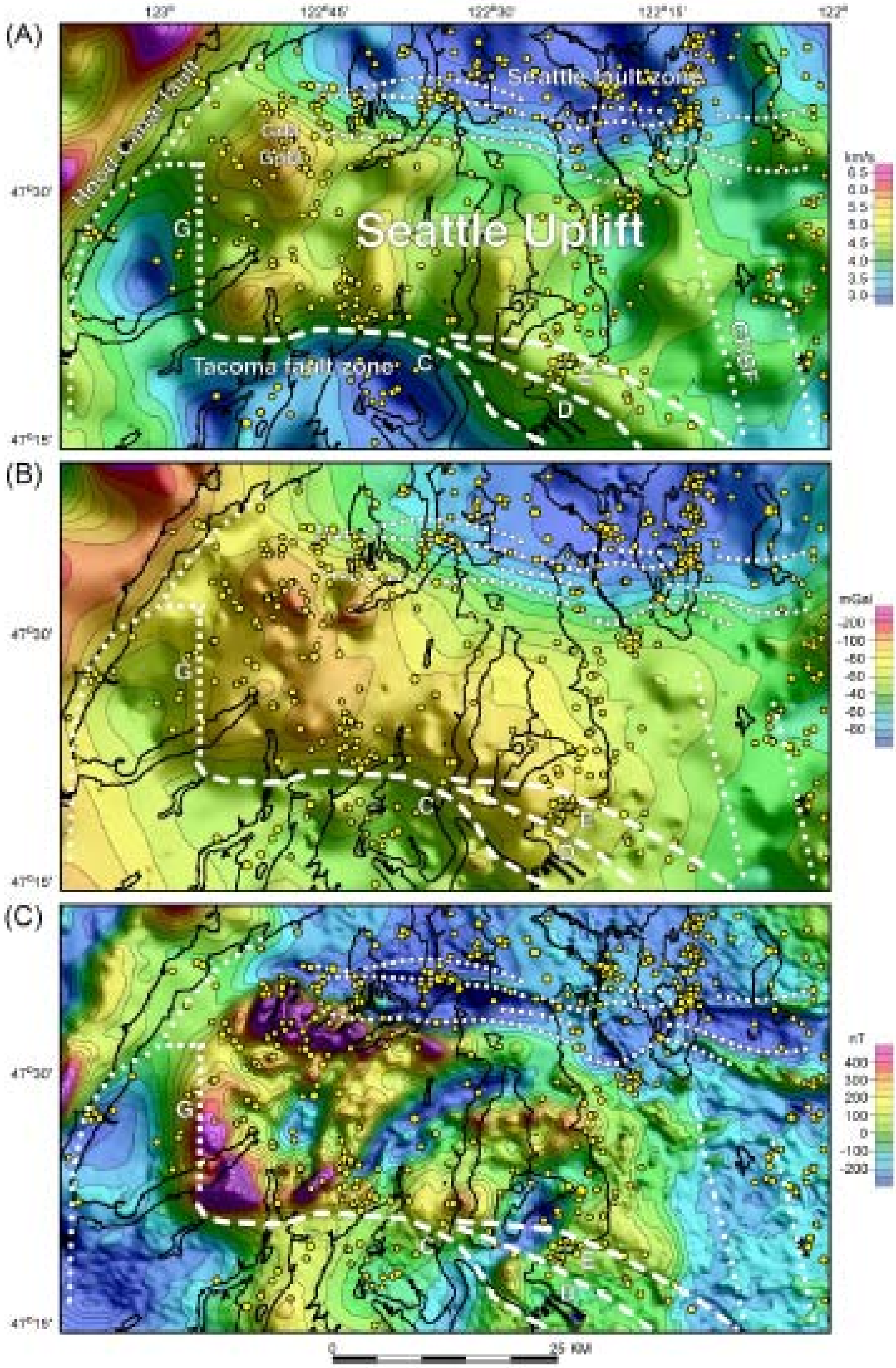


Figure 2. Summary of geophysical data for the Tacoma fault zone (after Brocher et al., 2001). A. Tomographic seismic velocity model at 3-km depth. B. Gravity map. C. Aeromagnetic map.

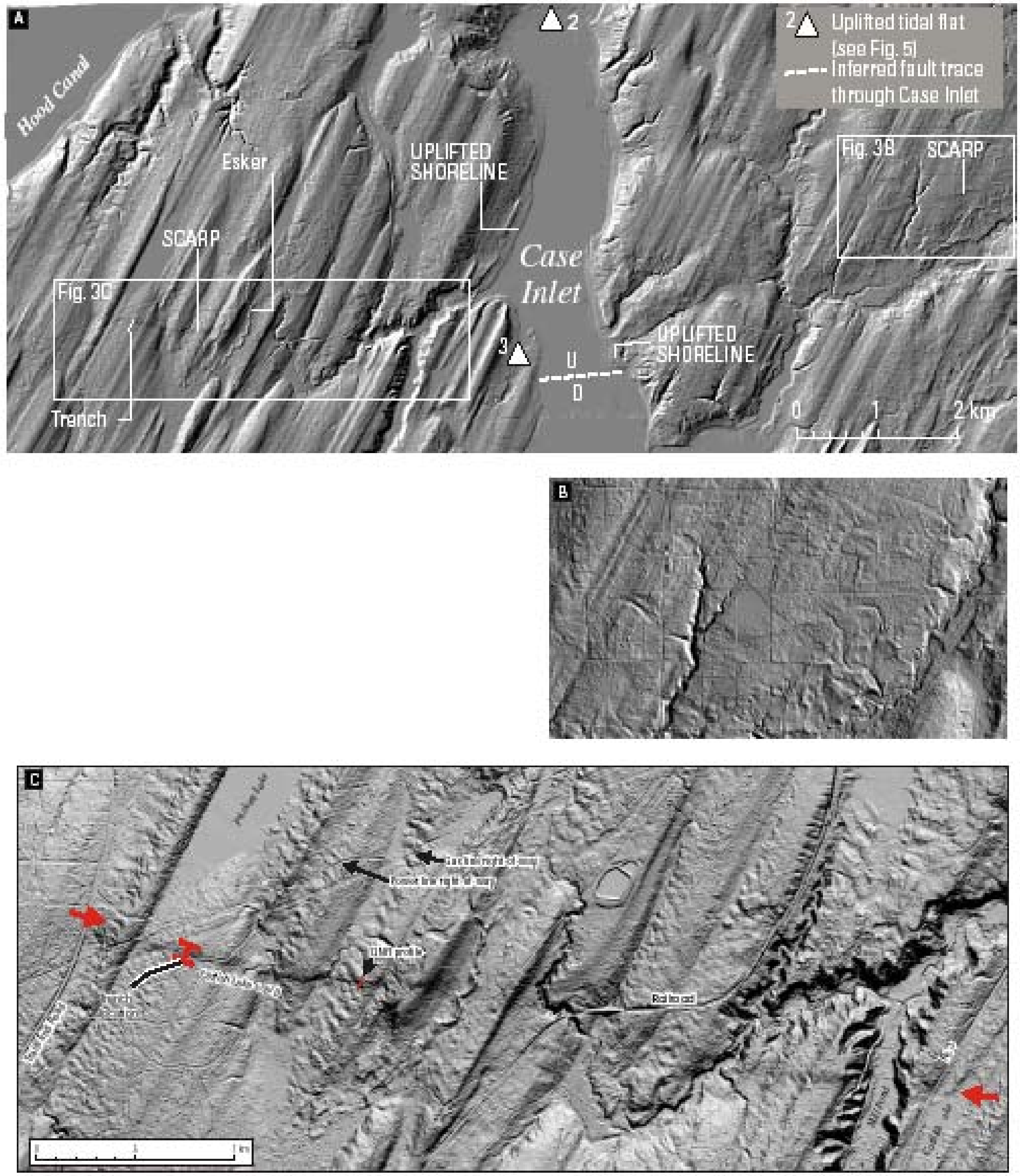


Figure 3. A. Hillshaded digital-elevation model of lidar data near Allyn, Washington. B. Small-scale lidar image of cross-cutting scarps east of Case Inlet. C. Small-scale lidar image of scarp near Prickett Lake and Catfish Lake.

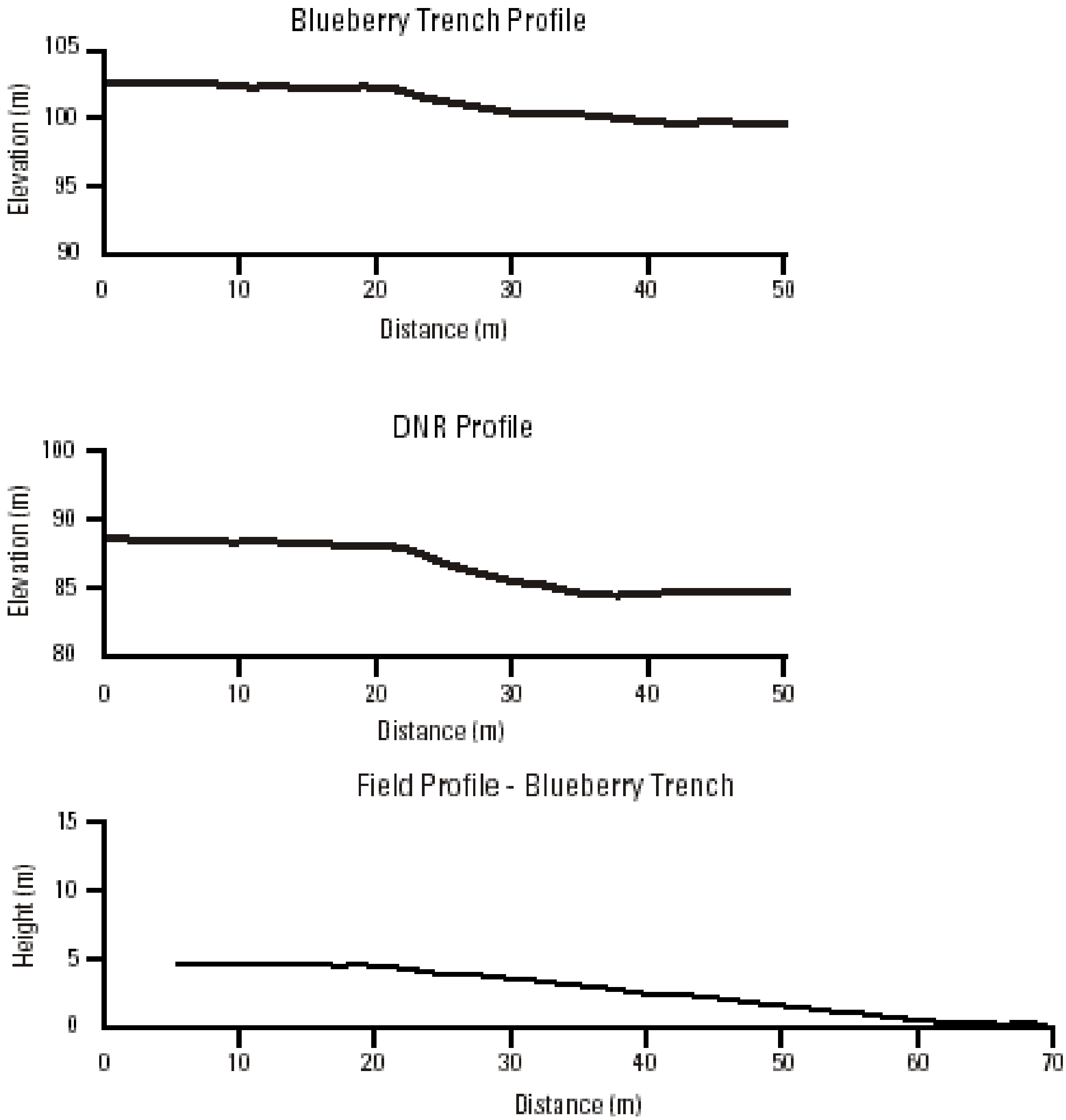
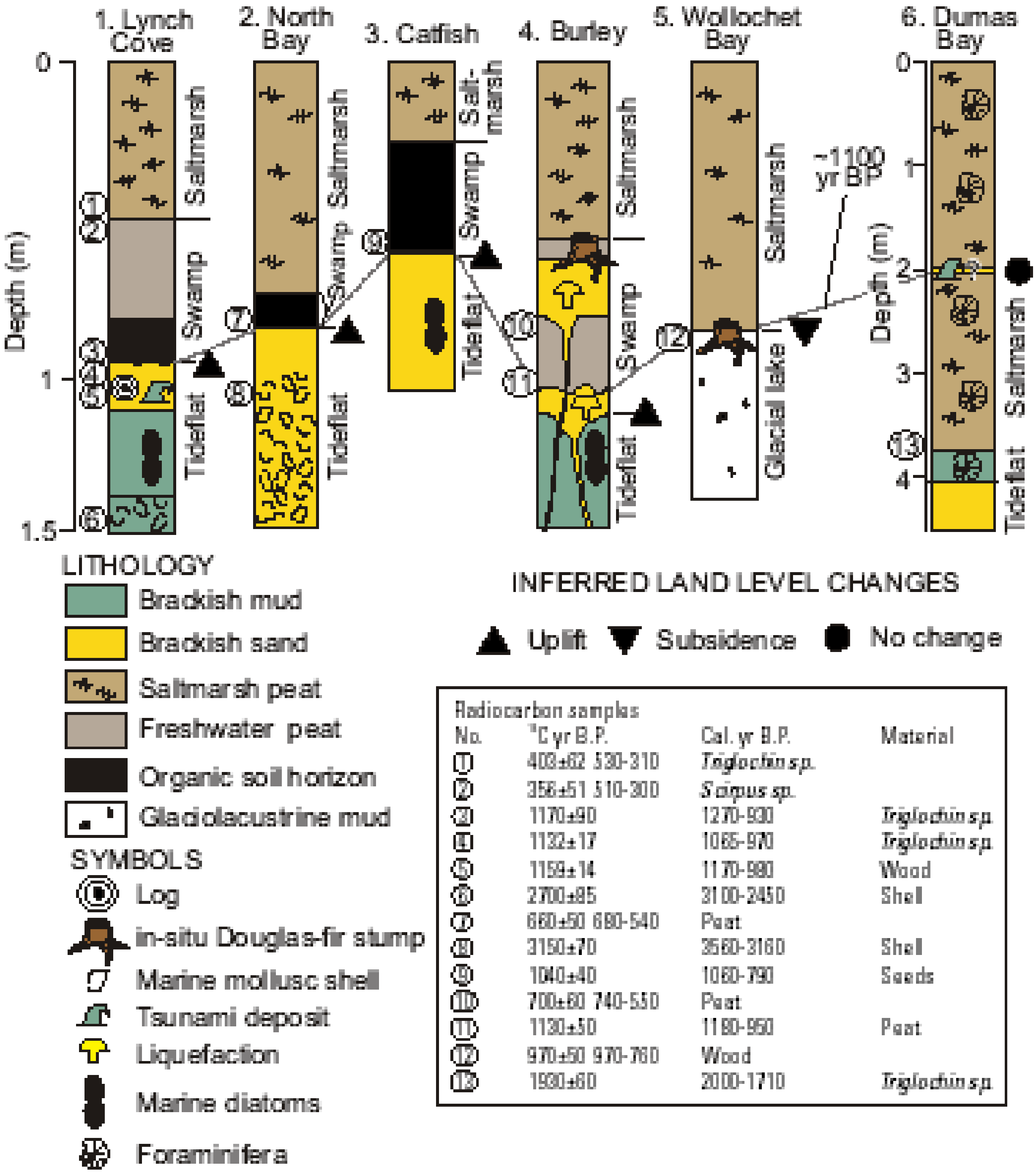


Figure 4. Scarp profiles. Blueberry trench and DNR profiles created using LIDAR data in ArcMap, and measured profile drawn from field data. No vertical exaggeration.



Radiocarbon samples

No.	^{14}C yr B.P.	Cal. yr B.P.	Material
1	403±62 530-310	*Triglochin sp.*	
2	356±51 510-300	*Scirpus sp.*	
3	1170±90	1270-930	*Triglochin sp.*
4	1132±17	1065-970	*Triglochin sp.*
5	1159±14	1170-980	Wood
6	2700±85	3100-2450	Shell
7	660±50 680-540	Peat	
8	3150±70	3560-3160	Shell
9	1040±40	1060-790	Seeds
10	700±60 740-550	Peat	
11	1130±50	1180-950	Peat
12	970±50 970-760	Wood	
13	1930±60	2000-1710	*Triglochin sp.*

Figure 5. Stratigraphy and radiocarbon ages from coastal marshes along the Tacoma fault zone.

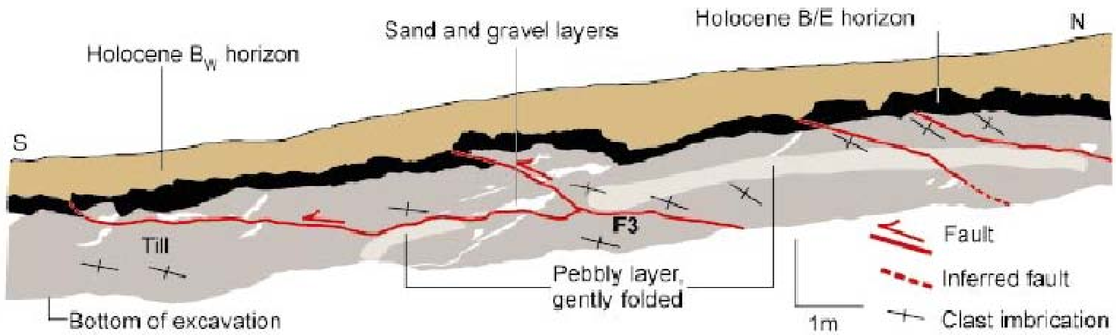


Figure 6. Simplified log of trench (west wall) excavated across the Catfish Lake scarp.