Geomorphology 177–178 (2012) 93–107

Contents lists available at SciVerse ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

A Holocene sedimentary record of tectonically influenced reduced channel mobility, Skokomish River delta, Washington State, USA

Maria Elizabeth Martin Arcos *

AMEC, 2101 Webster St., Oakland, CA 94612, United States

ARTICLE INFO

Article history:
Received 30 June 2011
Received in revised form 19 July 2012
Accepted 19 July 2012
Available online 27 July 2012

Keywords:
Coastal geomorphology
Puget Lowland
Tectonic river steering
Submergence
Diatom analysis
Paleoseismology

ABSTRACT

At the Skokomish River delta in Washington State's Puget Lowland, coseismic uplift and tilting trapped the river against a valley wall, resulting in little to no channel migration for the last 1000 years. The most recent earthquake occurred before AD 780–990, based on stratigraphic evidence such as sand blows and abrupt facies changes. Since the hypothesized tilting a 5-km-long section of the river has not migrated laterally or avulsed, resulting in reduced migration and a muddy intertidal flat that is 2 km wider in the east than on the west side of Annas Bay. A ridge running perpendicular to the river may also have restricted channel mobility. The ridge may be either the surface expression of a blind thrust fault or a relict, uplifted and tilted shoreline. The uplift and tilting of the delta can be ascribed to any of three nearby active fault zones, of which the most likely, based on the orientation of deformation, is the Saddle Mountain fault zone, which produced a surface rupture 1000–1300 years ago. The delta has experienced submergence since the earthquake. A forest that colonized an uplifted part of the delta about 800–1200 years ago was later submerged by at least 1.6 m and is now a brackish-water marsh.

1. Introduction

A variety of factors can lead to reduced channel mobility (low rates of migration and avulsion) including human influence, tectonics, topographic features and substrate (Holbrook and Schumm, 1999; Aslan et al., 2005). Rivers avulse for a variety of reasons, including a gradient advantage for the river to take another course (Slingerland and Smith, 1998), channel aggradation (King and Martini, 1984), and favorable substrate or geomorphology along another course (Aslan et al., 2005). Tectonically driven channel mobility is the result of river channels preferentially migrating away from uplift and/or toward subsidence (Holbrook and Schumm, 1999). This study illustrates a case where tectonic uplift dominates over other factors that can control the location of fluvial channels, resulting in reduced channel mobility, due to a bounding valley wall, and the delta building into only one side of the receiving basin.

In modern and ancient fluvial and deltaic systems, tectonically induced migration and avulsion is studied as an indicator for tectonic environment and for the subsequent depositional pattern (Schumm, 1986; Alexander and Leeder, 1987; Holbrook and Schumm, 1999; Gouw, 2007; Matteo and Siringan, 2007); the signal from the interplay of tectonics and river dynamics is not always straightforward. Increased rates of avulsion in rivers and lobe switching in deltas often indicate tectonic activity when other variables are constant (Gouw, 2007). In contrast, in locations where a river runs parallel to the trend of a graben, lower rates of migration can occur if rates of subsidence are high enough to overcome other river characteristics (e.g., stream power, sedimentation) and trap the river against the graben wall (Alexander and Leeder, 1987). Changes to river systems by earthquakes are often transient (Schumm, 1986; Attal et al., 2008), making stratigraphic and geomorphic studies necessary to understand the tectonic history.

Faults and fluvial systems can interact in complex ways and create complicated records in the geomorphology and stratigraphy of the landscape (Schumm, 1986). This study examines a moderately simple fluvial-deltaic system affected by both coseismic uplift and long-term subsidence. The study covers a time period over which sea level and climate has remained almost stable (Eronen et al., 1987; McLachlan and Brubaker, 1995). The system itself is small (4-km wide delta at the river mouth), mesotidal, and experiences little wave activity and longshore drift (Schwartz, 1991). Additionally, in the study area the valley floor consists of alluvium so the river is not affected by changes in lithology.

Within the fluvial/deltaic system of the Skokomish River, this study aimed to determine the geomorphic and stratigraphic effects of Recent faulting on a fluvial deltaic system including the origin of a bight and shore-parallel berm. The results demonstrate a combination of differential uplift (tilting) and receiving basin geometry resulted in reduced channel mobility of the Skokomish River and delta out-building only in the eastern half of Annas Bay (Figs. 1, 2). Tilting, probably associated with the earthquake uplift, resulted in the river channels consistently on the eastern side of the delta for the last 1000 years. To the east, large (~150 m tall) bluffs of glacial sediment slow river migration, with the result that all sediment is discharged to the eastern side of the delta. Thus, the bight on the western side of the delta is interpreted to be an area of non- or low deposition. Interpretation of the shore-parallel berm (herein

* Tel.: +1 206 683 3233; fax: +1 206 543 0489.
E-mail address: memartin@u.washington.edu.

0169-555X/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2012.07.016

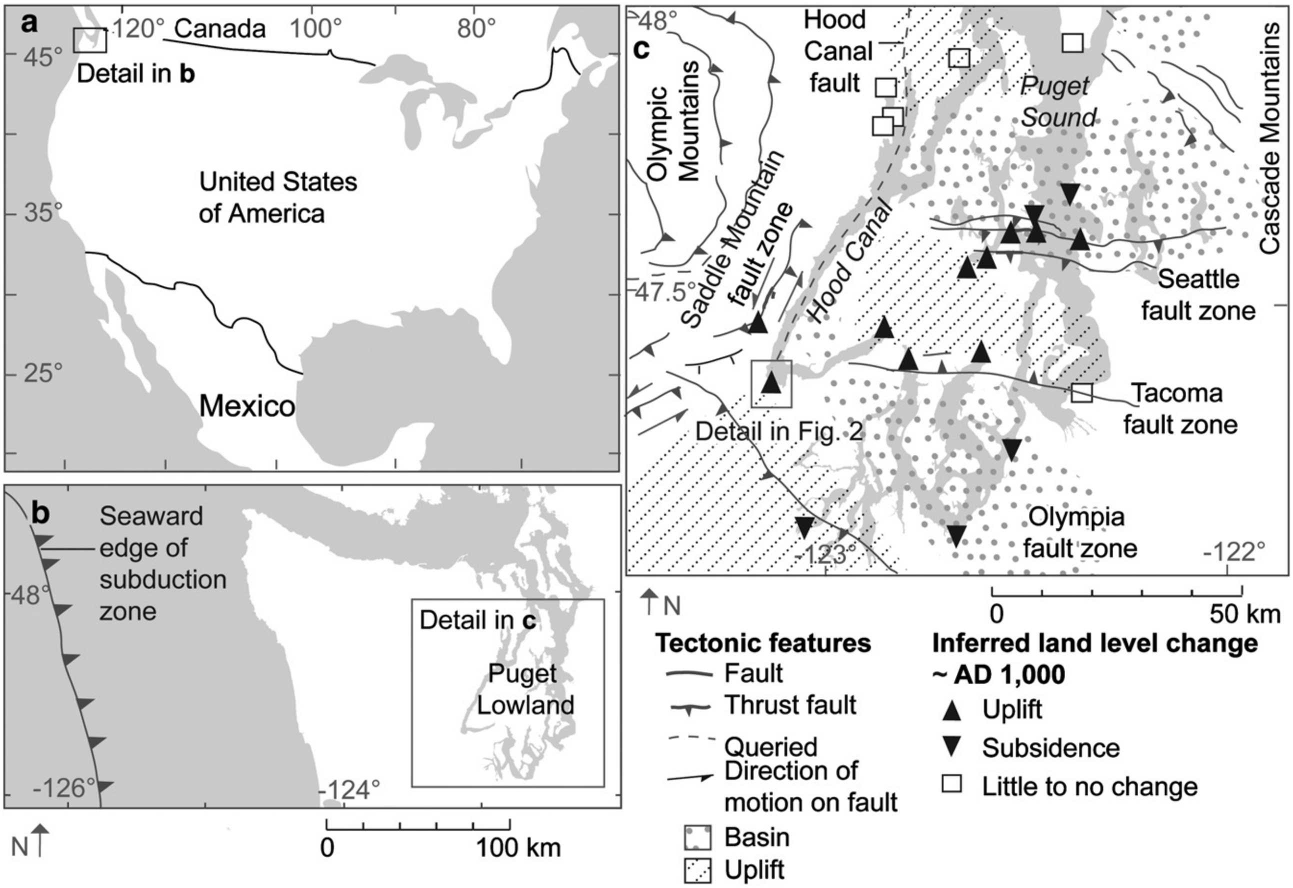

Fig. 1. The tectonic setting of the Puget Lowland and crustal fault locations. a. Regional map. b. Map of Cascadia subduction zone and coastline. c. Map of the Puget Lowland showing active faults and locations of paleoseismic studies. Modified from Blakely et al., 2009. Paleoseismic studies: Eronen et al., 1987; Beale, 1990; Bucknam et al., 1992; Bourgeois and Johnson, 2001; Sherrod, 2001; Blakely et al., 2009; Brian Sherrod, personal communication; Arcos, 2012.

termed the Ridge) remains unresolved, but the geomorphology cannot be explained by south-dipping thrust fault with a back thrust as proposed by Polenz et al. (2010). An alternative interpretation is that the Ridge is an uplifted and tilted former beach berm, with additional alluvial/fluvial modifications.

1.1. Tectonics and fluvial systems

The effects of tectonic deformation on rivers and deltas depend on the characteristics of the fluvial system, the type of faulting, and the orientation of the fault or faults to the river system (Miall, 1981). The effects can include offset stream channels, beheaded channels, changes in sinuosity, abandoned channels, ponding, steering, and variation in erosion rates (Keller et al., 1982; Rockwell et al., 1984; Schumm, 1986; Johnston and Schweig, 1996; Leeder et al., 1996; Peakall, 1998; Kim et al., 2010). For tectonic deformation to steer a river, the tilting rate must be great enough to outweigh the influence of sedimentation, erosion, and river slope (Holbrook and Schumm, 1999; Kim et al., 2010). On a delta, tectonic uplift effectively lowers base level. In response, the grade of the river steepens and, the channel can incise, or sinuosity may increase to maintain river gradient (Schumm, 1993).

Tectonic, climate, and anthropogenic effects can produce similar effects on river systems including increased sedimentation, changes in grade, and downcutting (Schumm, 1986; Gouw, 2007; Attal et al., 2008) but these processes have changed little over the time scale of this study. River channels typically respond more quickly to perturbations than other geomorphic features such as hillslopes and catchments (Fernandes and Dietrich, 1997; Whipple and Tucker, 1999). Climatic changes that influence the stream power such as increased precipitation or landsliding that adds sediment load can drive changes in a river's grade, deposition, or incision (Skylar and Dietrich, 2001; Zaprowski et al., 2005). Increased deposition in the channel can lead to channel migration and avulsion and delta lobe switching (Bryant et al., 1995; Gouw, 2007) During the time period this study covers, the last 2000 years, climate in the Puget Lowland has remained relatively stable, and until widespread logging there was only variation in vegetation in the most sensitive environments (McLachlan and Brubaker, 1995; Gavin and Brubaker, 1999). A stable climate history indicates it is unlikely the study area has experienced changes in sediment budget and stream power due to climate. Few changes to the coastline and river path since the first maps (Fig. 2C) indicated anthropogenic influences including logging and damming of one of the river forks, have not created large-scale changes in the geomorphic features in this study.

1.2. Regional setting

The Skokomish delta lies at the nexus of the Cascadia accretionary wedge and forearc basin—the Olympic Peninsula and Puget Lowland (Fig. 1). Progressive accretion and exhumation of mostly marine sedimentary and volcanic rocks along the subduction zone formed the Olympic Mountains along east verging thrust faults (Cady, 1975; Tabor and Cady, 1978a, 1978b; Brandon et al., 1998; Fig. 1). In contrast, faults in the Puget Lowland are typically east–west trending to accommodate shortening provoked by oblique subduction and by a rotating and northward-moving Oregon forearc (Wells et al., 1998; Mazzotti et al., 2002; McCaffrey et al., 2007). The difference in these regimes generates long-term emergence in the Olympic Mountains and subsidence in the Puget Lowland, with the boundary between this uplift and

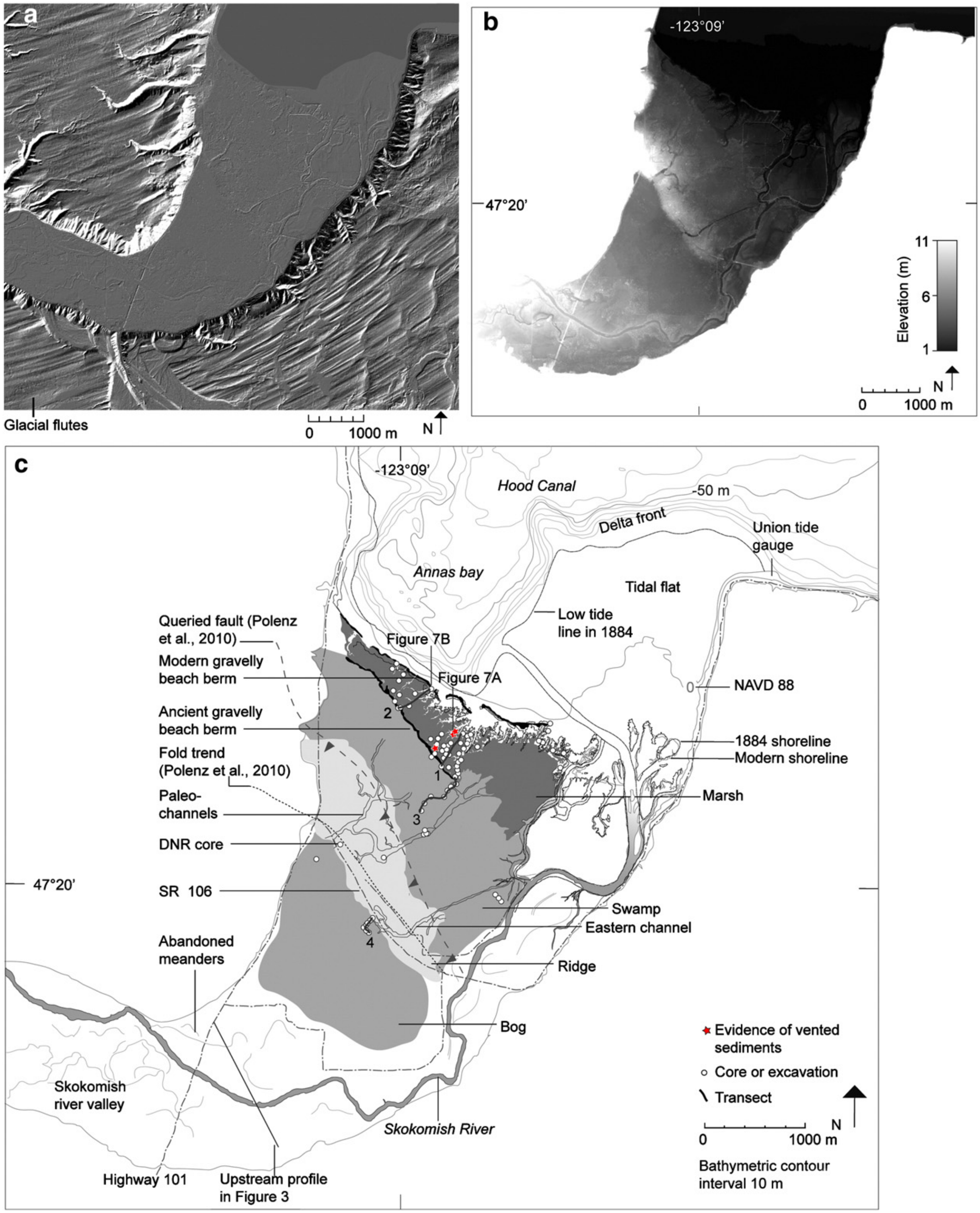

Fig. 2. Maps of the Skokomish delta showing topography and field sites. a. Hillshade LiDAR (Puget Sound LiDAR Consortium, 2005) image of the Skokomish delta and surrounding uplands. Light source is from the southeast. b. LiDAR image shaded from 1 to 11 m elevation detailing the geomorphology of the Skokomish delta and valley. c. Interpreted map of the Skokomish delta including locations of stratigraphic sections and transects. Historic shoreline taken from Gilbert (1884). Delta zones drawn based on a combination of stratigraphy, geomorphology and modern vegetation. LiDAR from a. and b. From the Puget Sound LiDAR consortium.

subsidence falling near the Skokomish delta. Due to different placements of the hinge zone, estimated rates of land-level change for the delta region range from −1 to +1 mm/year (Reilinger and Adams, 1982; Holdahl et al., 1989; Mitchell et al., 1994; Hyndman and Wang, 1995; Long and Shennan, 1998).

1.2.1. Active faults

Strain in the Puget Lowland and differential movement between the lowland and the Olympic Mountains generate shallow crustal faulting. The Puget Lowland contains a series of basins and uplifts mapped based on regional gravity anomalies, and in some locations on offset units and thickened sedimentary strata (Johnson et al., 1994; Blakely et al., 2009; Fig. 1). Some of the boundaries between basins and uplifted areas are active faults (e.g. Seattle fault zone; Bucknam et al., 1992; Johnson et al., 1994); in other locations, the existence of active faults at the geophysical boundary is proposed or disputed (e.g. Hood Canal fault; Johnson et al., 1994; Haug, 1998; Blakely et al., 2009).

Multiple fault zones in the vicinity of the Skokomish delta have experienced Holocene ruptures. Several kilometers to the northwest of the Skokomish delta, the Saddle Mountain fault zone trends along the southeastern edge of the Olympic Mountains (Fig. 1C). This fault zone accommodates the north–south contraction of the Puget Lowland as it moves along the Olympic Mountains, and includes west side-up, north-east trending thrust faults and also contains normal faults indicating potential step-over (Witter et al., 2008; Blakely et al., 2009). Holocene activity on the Saddle Mountain fault zone includes rupture around AD 650–1050 (Hughes, 2005), which created an east-side-up scarp and dammed streams (Carson, 1973; Wilson et al., 1979). Also in the region, the lesser-understood east–west-trending Olympia fault zone (Sherrod, 2001) bends northward toward the Skokomish delta; geophysical anomalies in conjunction with marsh submergence between AD 800 and 940 locate the fault (Fig. 1C; Sherrod, 2001; Blakely et al., 2009). Additionally, two other faults zones in the Puget Lowland, the Seattle and Tacoma fault zones, exhibit evidence of earthquakes about 1000 years ago (Bucknam et al., 1992; Sherrod et al., 2004). The trace of the Tacoma fault zone in the western Puget Lowland is not known (Fig. 1). The Seattle fault zone is proposed to cross Hood Canal about 30 km north of the Skokomish delta (Blakely et al., 2009).

1.2.2. Late Pleistocene Puget ice lobe

Pleistocene glaciation modified much of the Puget Lowland. The last advance of the Puget lobe, locally the Fraser glaciation, reached its peak in the Vashon stade about 15,000 years ago (Booth, 1994; Porter and Swanson, 1998). Till, outwash deposits, and lake deposits are associated with the Fraser glaciation. These unconsolidated deposits and those of prior glaciations blanket much of the Puget Lowland, including the plains flanking the Skokomish delta (Fig. 2). In other locations in the lowland, linear offset of glacial features is evidence of Holocene fault activity (Nelson et al., 2003; Sherrod et al., 2004, 2008). The walls of the Skokomish Valley consist of older glacial deposits capped with Fraser deposits (Carson, 1976; Polenz et al., 2010). Since the last glacial retreat, the general region of the Skokomish Valley has experienced approximately 50 m of post-glacial isostatic rebound, which completed about 8000 years ago (Thorson, 1989).

1.2.3. Holocene sea level

Prior sea-level studies in the Puget Lowland indicate rapid sea-level rise in the early Holocene followed by slow rise. With the retreat of the continental ice sheets, sea level rose quickly, and then about 5000 years ago the rate of sea-level rise slowed in the Puget Lowland (Dragovich et al., 1994; James et al., 2009). In the western Puget Lowland, a peat record from northern Hood Canal shows a gradual sea-level rise from about 6 m lower than present sea level 6000 years ago, with less than 1 m of sea-level rise in the last 1000 years (Eronen et al., 1987). Other peat records from six marshes also show <1 m sea-level rise in the last thousand years (Beale, 1990). Locally, the sea-level record is complicated by active tectonics.

1.2.4. Skokomish River and delta

The Skokomish River forms a delta at the elbow of Hood Canal where the fjord bends 145° from a north–south direction to a northeast–southwest direction (Fig. 1). To reach Hood Canal, the Skokomish River flows through a 16 km-long, glacially-carved, alluvium-blanketed valley. The north fork of the river has been dammed since the 1920. The modern delta (Fig. 2) consists of salt- and freshwater marshes and swamps that are pristine in some areas, while in other portions are diked and drained for farming. Currently, the modern inter- to subtidal delta is out-building seaward on the eastern side of the valley (Fig. 2), whereas the shoreline is retreating on the western side. A lack of Holocene river terraces indicates the valley has been mostly aggradational since the stabilization of sea level (Bountry et al., 2009).

Of the rivers flowing into in the Puget Lowland, the Skokomish has the seventh highest mean annual discharge and the fifth highest annual sediment load (Czuba et al., 2011). For the Skokomish River, the annual sediment load is 144,000 m/year (Downing, 1983) and the mean annual discharge is 37 m^3/s (Embrey and Frans, 2003). Channel sediment in the delta consists mostly of sand and pebbles (Bountry et al., 2009). A short fetch in Hood Canal reduces storm wave potential. Hood Canal has some of the lowest rates of net longshore transport in Puget Sound, measured in the order of 80–200 m^3/year (Wallace, 1988), and the region around the Skokomish delta has no appreciable net drift alongshore (Schwartz, 1991).

Evidence for lateral migration of the Skokomish River diminishes downstream. In alluvium like the Skokomish River valley, lateral river migration typically ranges from 1.2 to 6 m/year (Kukal, 1990). Upstream of the Highway 101 bridge (Fig. 2), the river channel has migrated as much as 170 m since 1938 (Bountry et al., 2009; comparison with aerial photos in the Puget Sound River History Project), and the entire valley bottom is crossed by abandoned meander channels (Fig. 2). Downstream of the Highway 101 bridge, by contrast, no more than 20 m of natural channel migration has taken place in historical time, and abandoned meanders are limited to the eastern side of the delta. Furthermore, based on river slope relative to delta slope, upstream of the Highway 101 bridge, the Skokomish River has a high avulsion potential, while downstream of the bridge the river has low avulsion potential (GeoEngineers, Inc., 2006). The river channel has been in approximately the same position since at least the first maps in the 1880 (Gilbert, 1884; Fig. 2).

2. Materials and methods

2.1. Fieldwork

This study compares landforms, modern vegetation, and late Holocene stratigraphy along four transects perpendicular to the modern shoreline (Figs. 2, 4). On transects 1 and 2, species cover abundance is used to identify vegetation zones, as in Sherrod (1999). On other transects, vegetation types and species for each core location were noted, but percent cover was not counted. Vegetation summaries for each area are in supplement S1. For transects 1 and 2 on the Marsh (Fig. 2), distance and elevation were surveyed using a transit level (error $\pm$ 2 cm), and the surveyed tide level was compared to the tide gauge record at Union (Fig. 2). For transects 3 and 4 tall vegetation and wet, unstable ground made leveling impractical, so elevations were taken from Light Ranging and Distance (LiDAR) data from the Puget Sound LiDAR Consortium (error $\pm$30 cm). Fieldwork took place in the summers of 2008–2010. A hand-held GPS was used to locate each site (location where stratigraphy was investigated).

This study used outcrops, gouge cores, and soil-augers to examine stratigraphy at over 100 sites (Fig. 2). Wherever possible the stratigraphy from cleaned banks of tidal creeks and streams was used. Gouge cores were pushed down to refusal in gravel, sand, or stiff mud, or to the 5 m depth extent of the extensions carried. This study also examined samples taken by the Washington State Department of Natural Resources (DNR).

2.2. Laboratory work

Digital elevation models from LiDAR data from the Puget Sound LiDAR Consortium were used to compare elevation transects and delta morphology. The LiDAR data were also used to look for potential fault scarps in the glacially fluted uplands along the Skokomish River valley.

Plant material for radiometric dating was cleaned in the laboratory and sent to Beta Analytic. All ages in this study were AMS ages. Calendar age was calibrated using IntCal 09 (Reimer et al., 2009). When possible, the species of material for dating was identified using the reference collection of the University of Washington herbarium.

This study used plant macrofossils and diatoms to help infer environments of deposition, particularly relative to tide levels. Plant macrofossils were identified with a binocular microscope and the reference collection of the University of Washington herbarium. Diatom slide preparation followed the procedures of Patrick and Reimer (1966). Counts of between 400 and 1200 diatom valves allowed for the diversity of the fossil assemblage, with more diatoms counted on slides that had high concentrations of one species. For samples 4a and 8a and all samples from the DNR core (Fig. 2), low diatom density in samples prevented the counting of 400 valves. Percentages of diatom species are based on the total count per sample.

To compare modern samples from different Puget Lowland locations with paleosamples from the Skokomish delta, canonical correspondence analyses of diatom assemblages were conducted using the software package CANOCO (Ter Braak, 1987–1992) and the modern assemblage catalog of over 100 samples of Puget Lowland coastal environments expanded from Sherrod (1999). The method relates species assemblage data to environmental variables (elevation and salinity) to produce transfer functions for predicting environment of assemblages of unknown origin. Modern diatom data were plotted against salinity and a Standardized Water Level Index (SWLI; Horton et al., 1999). Because the modern catalog was collected at sites with different tide ranges, the SWLI was used because it uses a linear height normalization technique to assign samples a common datum.

3. Results

3.1. Geomorphology and stratigraphy

The delta downstream of the highway 101 bridge can be divided into four areas based on modern landforms, vegetation and environment, as well as on stratigraphy. From north to south they are the (delta) Marsh, Swamp, Ridge and Bog (Fig. 2). Following a description of large-scale delta morphology, the stratigraphy and geomorphologic features of each of the four areas will be summarized and discussed.

3.1.1. Delta morphology

3.1.1.1. Topography and bathymetry. The intertidal zone in the eastern side of the bay extends 2 km further seaward than the western side of the bay (Fig. 2C). At the western end of Annas Bay, the unvegetated intertidal zone is ~150 m wide and on the eastern side it is ~2500 m wide (Figs. 2C, 3H). Both sides of the bay have similarly steep slopes from the intertidal zone to 50–70 m depth. Prior work linked the deeper bathymetry in the western bay to landslides removing delta sediments (Polenz et al., 2010).

Profiles perpendicular to the river in the Marsh, Swamp, Bog and Ridge slope down to the river, to the southeast, whereas a profile upstream of these areas slopes up to the river (Fig. 3). The Marsh, Swamp, Ridge and Bog all have a cross-delta slope of 0.30–0.40 m per km (slope of 0.0003 to 0.0004) down to the river and the Ridge slopes 2.10 m per km (slope of 0.0021; Fig. 3). In contrast, the profile from farther upstream shows the river levees as the highest part of the profile (Fig. 3G, upstream).

3.1.1.2. Berms. At the landward end of transects 1 and 2 (Fig. 4), about 500 m from the shoreline, a narrow berm with a slight elevation increase over the salt marsh permits growth of trees and woody vegetation. In the underlying stratigraphy, a woody peat unit on both sides of the berm thins to 20 cm or less over a pebble-rich gravel at the berm. The gravel unit below the peat has a similar morphology to the modern gravel berm at the front of the delta. Herein, this feature is referred as the "ancient gravelly berm".

A relatively broad ridge, herein referred to as the Ridge, crosses most of the Skokomish delta about 2.5 km up valley from and approximately parallel to the modern delta's shore (Figs. 2, 3). It descends southeastward from 5 m above the adjoining delta to level near the river. The slope of the Ridge is steeper to the south and more gradual to the north. The Ridge is widest where active and inactive channels cut through. Much like the modern beach berm and the "ancient gravelly berm", the Ridge consists of pebble-rich gravel.

3.1.1.3. Paleochannels. In the Swamp and cutting across the Ridge are several seaward-branching channels (the "paleochannels" in Fig. 2c). The western channels drain very slowly, as they are blocked by vegetation and peat. The western channels are of similar width to the modern Skokomish channel and its distributaries. The eastern channel currently drains the Bog across the Ridge.

3.1.2. Marsh

3.1.2.1. Stratigraphy. Transects 1 and 2 in the Marsh have a similar stratigraphy to each other of muds and gravels overlain by woody peat and then muddy peat (Figs. 4, 5). The basal pebble gravel and mud deposit varies in grain size, but in general contains more pebbles toward the eastern end of the delta. The woody peat becomes muddier upward and the muddy peat thins landward. Between the seaward ends of transects 1 and 2, five seeds from the base of the woody peat had a calibrated radiocarbon age of AD 780–990 (Table 1).

In transect 2, an *in situ Pseudotsuga menziesii* (Douglas fir) stump rooted into mud is eroding out of the woody peat (Figs. 4, 5). Though wood is common in the peat, this stump was the only location where enough wood was visible to determine the stump was *in situ*. Thin roots (<2 cm in diameter at the distal end) extend from the trunk more than 3 m and are horizontally rooted in the mud, indicating the stump is in growth position. The death of the tree was assigned a calibrated age of AD 920–1180 (Polenz et al., 2010; Table 1). The stump is currently eroding out into the intertidal zone 1.6 m below the lowest living conifer (*Picea sitchensis* (Sitka spruce). No *P. menziesii* currently grows on this part of the delta.

Diatom analysis of the mud and woody peat at the location of the *P. menziesii* stump indicates brackish conditions for the top of the mud and base of the peat (Fig. 5, site 3; Fig. 6 samples 3a and 3b); a seeming contradiction that is discussed in S1. In addition, foraminifera tests in this unit indicate an intertidal marsh setting for the woody peat in this location. Higher in the section, the peat becomes muddier and dominated by salt-tolerant species including *Triglochin maritimum* (arrowgrass) leaf bases and *Distichlis spicata* (saltgrass) rhizomes.

In two locations, a sand body more than 30 cm thick splits the peat-mud contact. In both locations, the sand body thins to zero in less than 10 m horizontally from the sand's thickest point. In one location, the sand body is associated with an injected sand dike (Fig. 7a). These sand bodies are interpreted to be sand blows related to earthquake-induced liquefaction (Martin and Bourgeois, 2012).

3.1.3. Swamp

3.1.3.1. Stratigraphy. Cores along transect 3 (Fig. 4) reveal a similar stratigraphy to the Marsh, that is, peat overlying muddy deposits and sand. The transect starts on the berm at the end of transects 1 and 2. The peat thickens to the south off the berm, and the underlying gravel of the berm is replaced by mud (Fig. 4). In the middle of the Swamp, cores revealed sand overlain by up to 150 cm of mud and 30–120 cm of peat. In some cases, the lowest 20–40 cm of the mud was silty to sandy. The mud contains brackish to low-marsh diatom species.

In three cores taken closer to the river (Fig. 5, site 7), sand was overlain by more than a meter of mud that in turn was overlain by a muddy peat with remains of *Typha latifolia* (cattail) and foraminifera. The mud

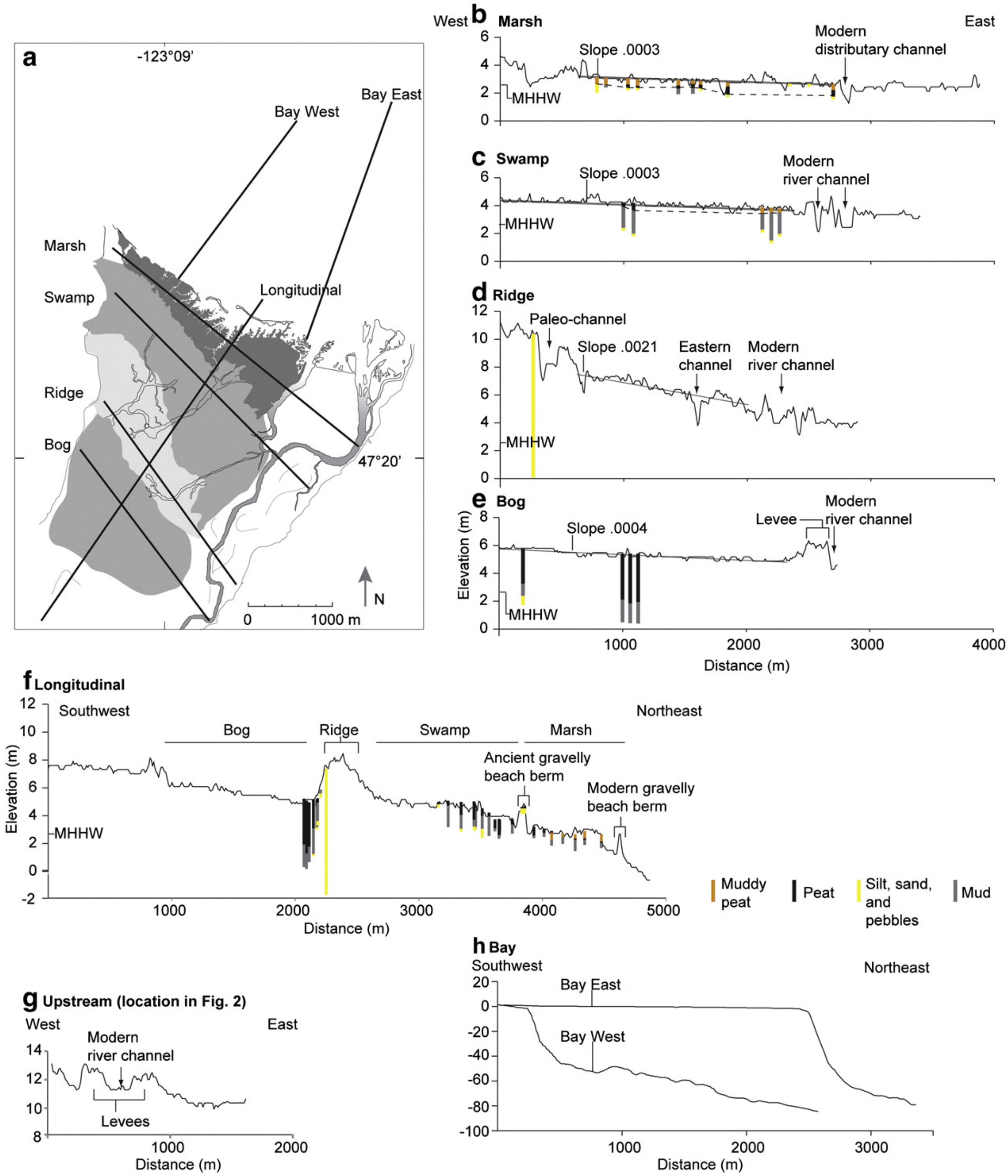

Fig. 3. Topographic profiles of the Skokomish delta taken from LiDAR data showing a southeastern slope to all areas of the delta. In the profile from upstream the river levees are the highest point of the profile while in the profiles from the study area the northwest end of the profile is always the highest. Stratigraphic sections within 75 m of the profiles are plotted on the profiles. MHHW is Mean Higher High Water at the Union tide gauge (Mofjeld et al., 2002). Zero elevation is the NAVD88 datum. Dashed line in the Marsh and Swamp profiles marks the surface uplifted about 1000 years ago. a. Map of profile locations, b. Marsh, c. Swamp, d. Ridge, e. Bog, f. Longitudinal, g. Upstream profile location on Fig. 2. h. Bay East and Bay West profiles from the combined bathymetry and topography of Finlayson (2005).

contains freshwater and brackish diatoms and the muddy peat contains brackish diatoms (Fig. 6 samples 7a and 7b).

3.1.4. Ridge

3.1.4.1. Stratigraphy. Because the ridge consists of mostly coarse grains, no cores were collected on the Ridge for this study, but samples from a core obtained by Washington State Department of Natural Resources (Polenz et al., 2010, Fig. 2, DNR core) were examined. Most of the 25-m core consisted of pebble gravel and yielded no diatoms or macrofossils with which to determine depositional environment. Charcoal in this muddy sand had a calibrated radiocarbon age corresponding to 6650–6470 BC (Polenz et al., 2010; Table 1).

3.1.4.2. Paleochannel stratigraphy. Two sets of cores taken in the paleochannels show evidence of modern and ancient freshwater deposition. At site 8, cores reveal 20–30 cm of peat over a sand-rich gravel. Low abundance prevented the counting of 400 diatom frustules in the sandy

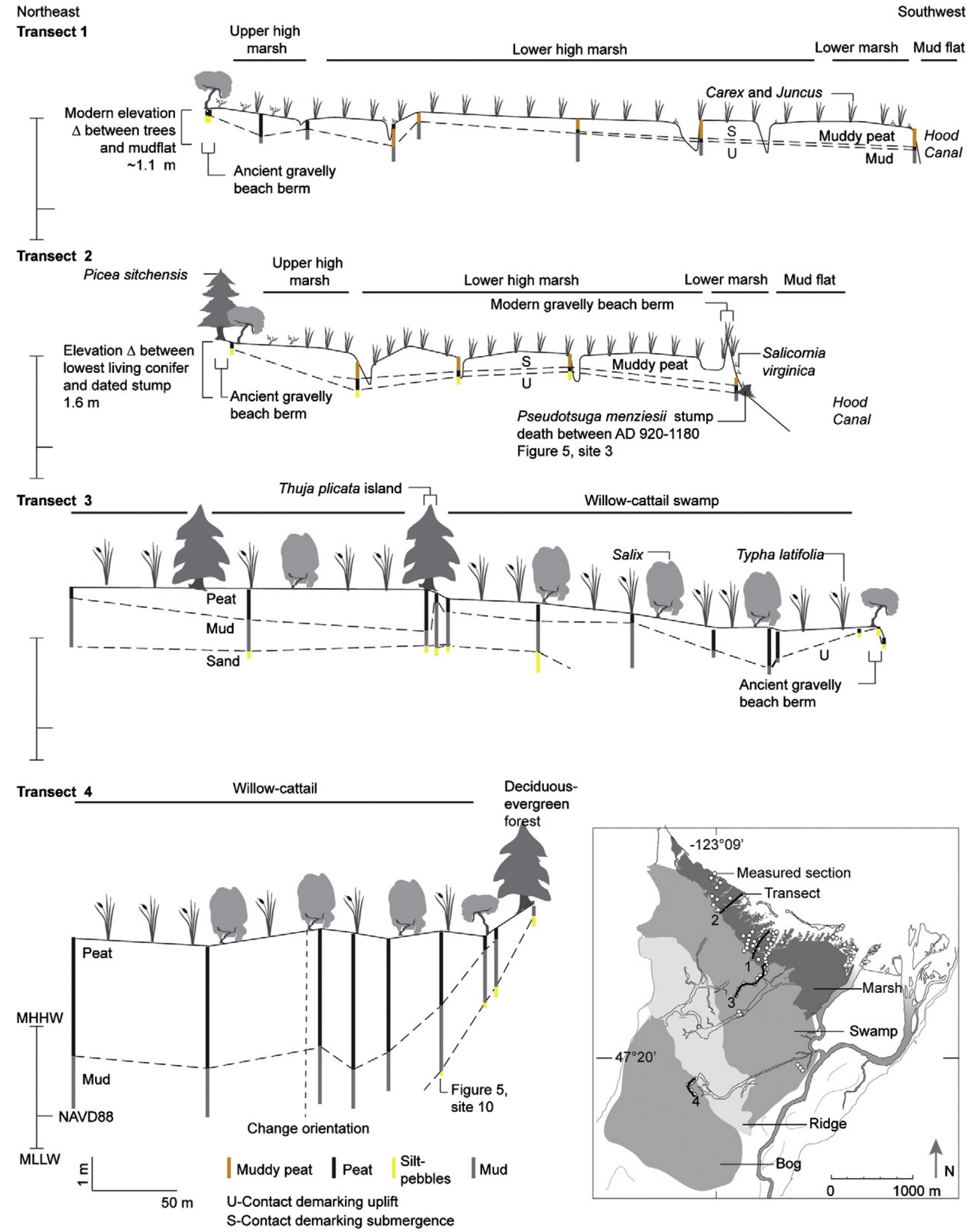

Fig. 4. Vegetation and stratigraphic transects from the four delta zones. Stratigraphy indicates uplift and later submergence in the Marsh and Swamp and peat and mud thinning onto the Ridge from the Bog. Transect 3 does not follow a linear path, the profile was made by projecting elevation and stratigraphy onto a straight path between the start and endpoint.

gravel, but those counted indicate fresh to brackish deposition (Fig. 5, site 8, Fig. 6, sample 8a). *P. sitchensis* needles from the bottom 5 cm of the peat had a calibrated age of AD 1680–1940.

Seaward of site 8, in one of the channel branches (Fig. 5, sites 4 and 5), vegetation covers most of the surface, but patches of open water exist. Large portions of the channel where these cores were taken are floating marsh with pockets of water a meter or more deep. Cores reveal sand or gravel overlain in some cases by 1–10 cm of mud, in turn overlain by a meter or more of peat and water (Fig. 4). A *P. sitchensis* seed from the basal 3 cm of peat had a calibrated radiocarbon age of AD 1290–1410.

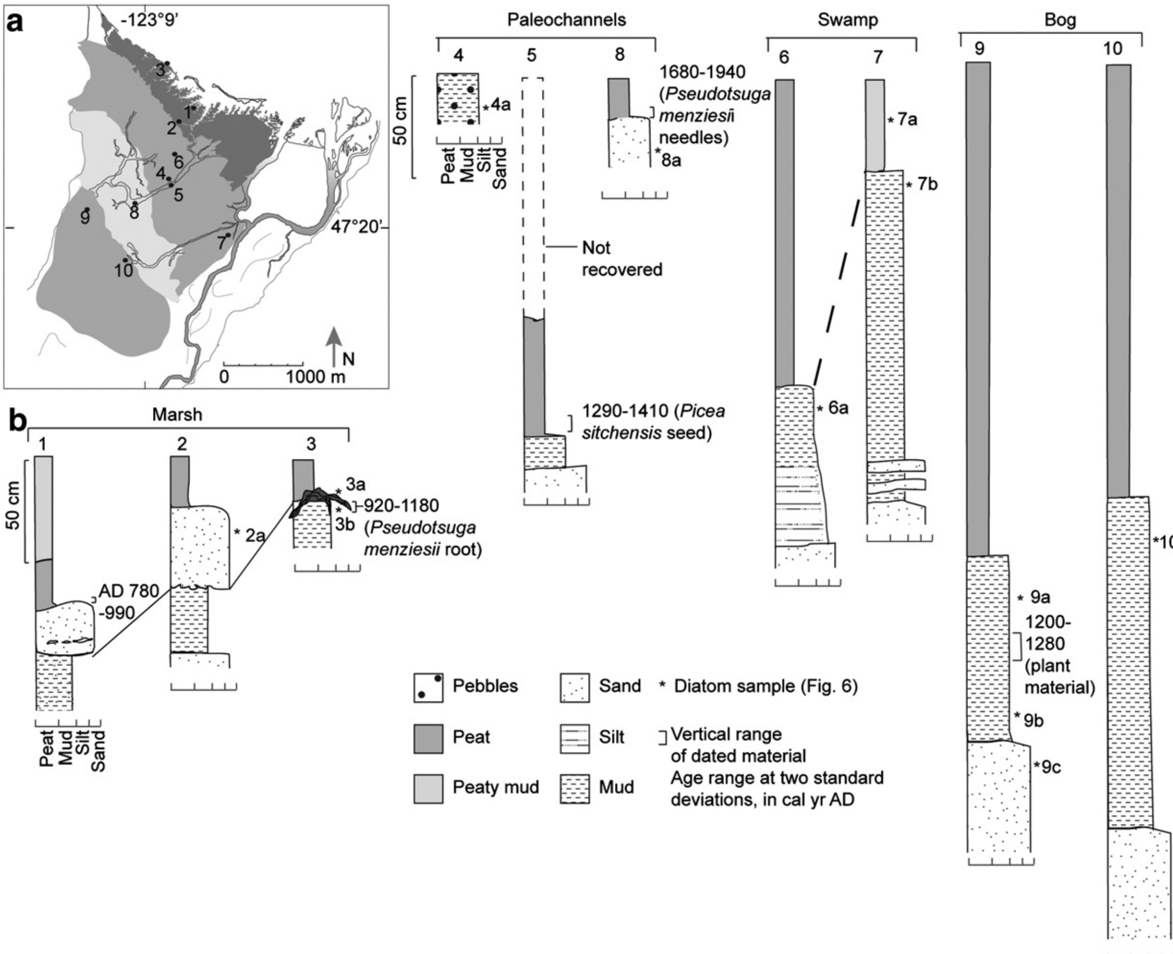

Fig. 5. Stratigraphic sections with location of radiocarbon ages and diatom samples. a. Map of location of stratigraphic columns. b. Stratigraphic columns from the Marsh, paleochannels, Swamp and Bog. Y. Sawai counted diatom sample 6a.

The channel banks consist of a pebble-rich gravel with freshwater diatoms (Fig. 5, sample 4a).

3.1.5. Bog

3.1.5.1. Stratigraphy. Cores along transect 4 (Fig. 4) revealed sand overlain by up to 2 m mud and up to 2 m wet, loose peat. At the southern end of the transect, the 5 m extent of the corer used in this study did not reach the base of the mud unit. Both the sand and mud layers thin toward the north onto the Ridge. Diatoms from transect 4 (Fig. 6, samples 10a and 10b) indicate freshwater deposition.

To the west of transect 4 the vegetation transitions to a *Vaccinium oxycoccos* (cranberry)–sphagnum bog with scattered *Salix* spp. (willow). It is in this zone that Polenz et al. (2010) collected a core and took plant material from the mud which gave a calibrated age of AD 1200–1280 (Fig. 5, site 9). Diatom analysis from samples of this core show all units are from a freshwater environment, with a slight saltwater influence in the mud (Fig. 6, sample 9a). The mud unit in the Bog is different than

Table 1
Radiocarbon ages from the Skokomish delta.

Site	Measured 14 C year BP	Calibrated 2 sigma range	Material	Layer	Limiting	Author	Sample ID
1	1130 ± 40 BP	AD 780–990	Seeds	Basal 2 cm peat	Minima for uplift	This study	Beta 263045
DNR core	7740 ± 50 BP	BC 6650–6470	Charcoal	School drill, 71 ft depth	Maxima for Ridge formation	Polenz et al. (2010)	Beta 272798
9 (DNR Bog core)	780 ± 40 BP	AD 1200–1280	Plant material	Bog, 9′6″–9′8″ depth (in mud)	Maxima for peat formation	Polenz et al. (2010)	Beta 273145
3	1050 ± 60 BP	AD 920–1180	Submerged tree	Rooted into peat-mud contact	Minima for uplift	Polenz et al. (2010)	Beta 273144
8	90 ± 40 BP	AD 1680–1940	*Pseudotsuga menziesii* needles	Basal 3 cm peat	Minima for channel abandonment	This study	Beta 282145
5	600 ± 40 BP	AD 1290–1410	*Picea sitchensis* seed	Basal 5 cm peat	Minima for channel abandonment	This study	Beta 282144

All ages in this study were AMS ages. Calendar age was calibrated using IntCal 09 (Reimer et al., 2009) using the online program OxCal (https://c1arch.ox.ac.uk/oxcal/). Fig. 5 plots stratigraphic locations of samples.

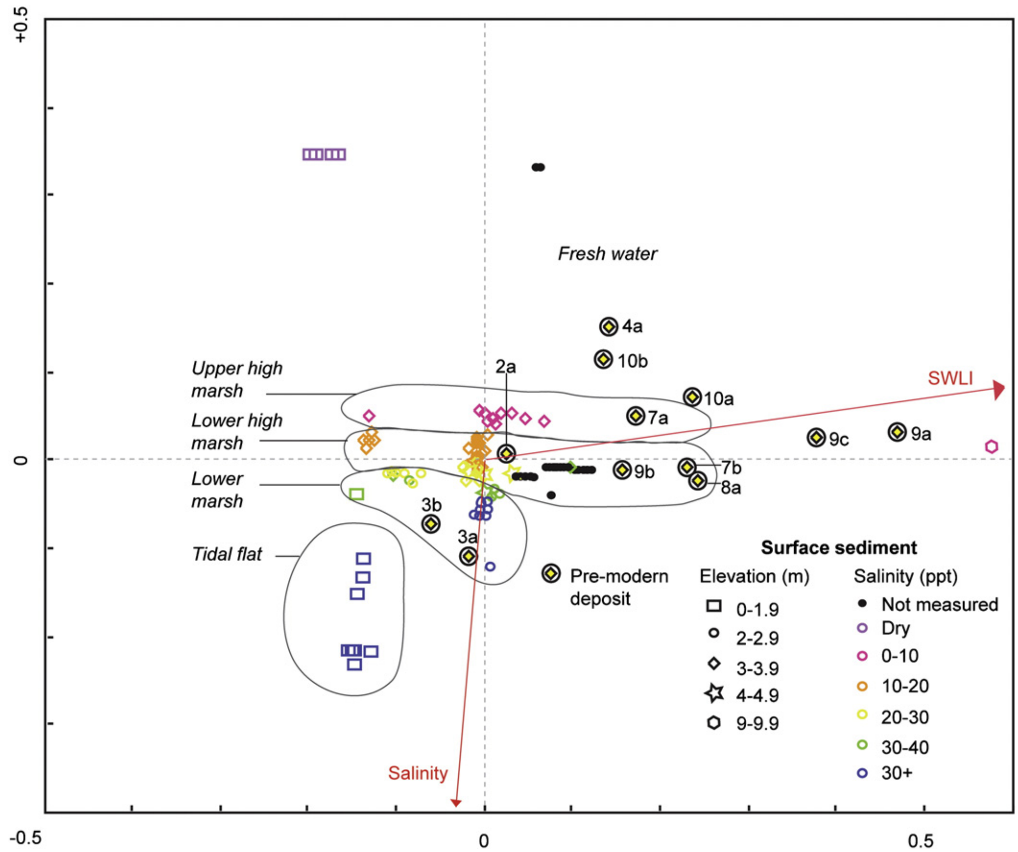

Fig. 6. Diatom analysis. Samples plotted against modern data, salinity and Standard Water Level Index (SWLI). Stratigraphic depth and location of samples are in Fig. 5. Symbols and colors show the salinity and elevation of modern samples. Paleosamples are plotted based on diatom species overlap with modern samples.

the mud unit in the Swamp and Marsh. The Bog mud is younger and is freshwater in contrast to the brackish mud to the north of the Ridge.

3.2. Chronology

The Ridge is the oldest feature mapped in this study. The single age from the Ridge in conjunction with an absence beneath the Ridge of units present below the Swamp and Bog indicate that the Ridge is older than 1000 years. Moreover, the units in the Bog thin onto the Ridge indicating the Ridge was a topographic feature during deposition of the mud.

Radiocarbon ages from the Marsh, Swamp and Bog indicate that facies changes in all areas may have occurred at the same time. Ages from seeds and the tree stump in the Marsh indicate that the transition from brackish mud to peat occurred before AD 780–990 (Table 1). Ages from channels that cut the Ridge and Swamp indicate that the channels were abandoned before AD 1290–1410. The transition from sand to mud in the Bog occurred before AD 1200–1280, and the overlying transition to peat occurred after this time.

4. Discussion

4.1. Tectonic Interpretations

4.1.1. Earthquake about 1000 years ago

4.1.1.1. Shaking and uplift. Paleoecology and stratigraphic features in the Marsh and Swamp indicate coseismic uplift on Skokomish delta about 1000 years ago (before AD 780–990; Table 1). There are several indicators of this earthquake. 1) In the Marsh and Swamp, brackish deposits abruptly change to freshwater deposits (Fig. 4), indicating uplift. In the modern environment the elevation change from intertidal mud to an environment supporting conifers is 1.0–1.5 m asl. 2) The stratigraphy skips the marsh facies expected in normal facies migration or vertical marsh accretion (Middleton, 1973). The expected transition would be brackish mud to salt-marsh peat and then to high marsh to trees. 3) This abrupt facies change occurred at a time when sea level in the Puget Lowland was relatively stable or slowly rising (Eronen et al., 1987; Beale, 1990), therefore signals of relative sea-level fall (i.e., uplift) are unexpected. 4) In the Marsh, the facies change is coupled with vented sands, an indicator of strong shaking (Obermeier, 1996; Tuttle, 2001; Martin and Bourgeois, 2012).

Environmental changes discussed above and differences in heights of modern and ancient geomorphic features indicate coseismic uplift of a minimum of 1 m in the Marsh. The difference in height of the modern and ancient gravelly beach berms is approximately 2 m (Fig. 3, longitudinal profile). Other factors such as wave height and sediment supply can influence ridge height. Reduced sediment supply due to the dam on the north fork of the Skokomish River, location of the berm relative to the sediment source (river mouth) and variations in wave height due to differences in modern and ancient bathymetry could lead to variations in berm height without tectonics. Therefore, the conservative estimate of uplift is more than 1 m.

The gravel berm that marks the boundary between the delta front and the Swamp (Figs. 2, 4, the ancient gravelly berm) is interpreted to have been the active beach berm at the time of uplift. The presence of brackish mud in the stratigraphy of the Swamp, landward of the ancient berm, indicates that the berm acted as a protective barrier, as does the modern berm, which protects large mudflats along the middle shoreline of the delta (Fig. 2). The ancient berm ends to the east at a set of branching paleochannels that possibly represent a distributary system at the time of uplift.

Stratigraphic evidence for the earthquake about 1000 years ago in the Bog is not as clear as in the Marsh and Swamp stratigraphy. The facies

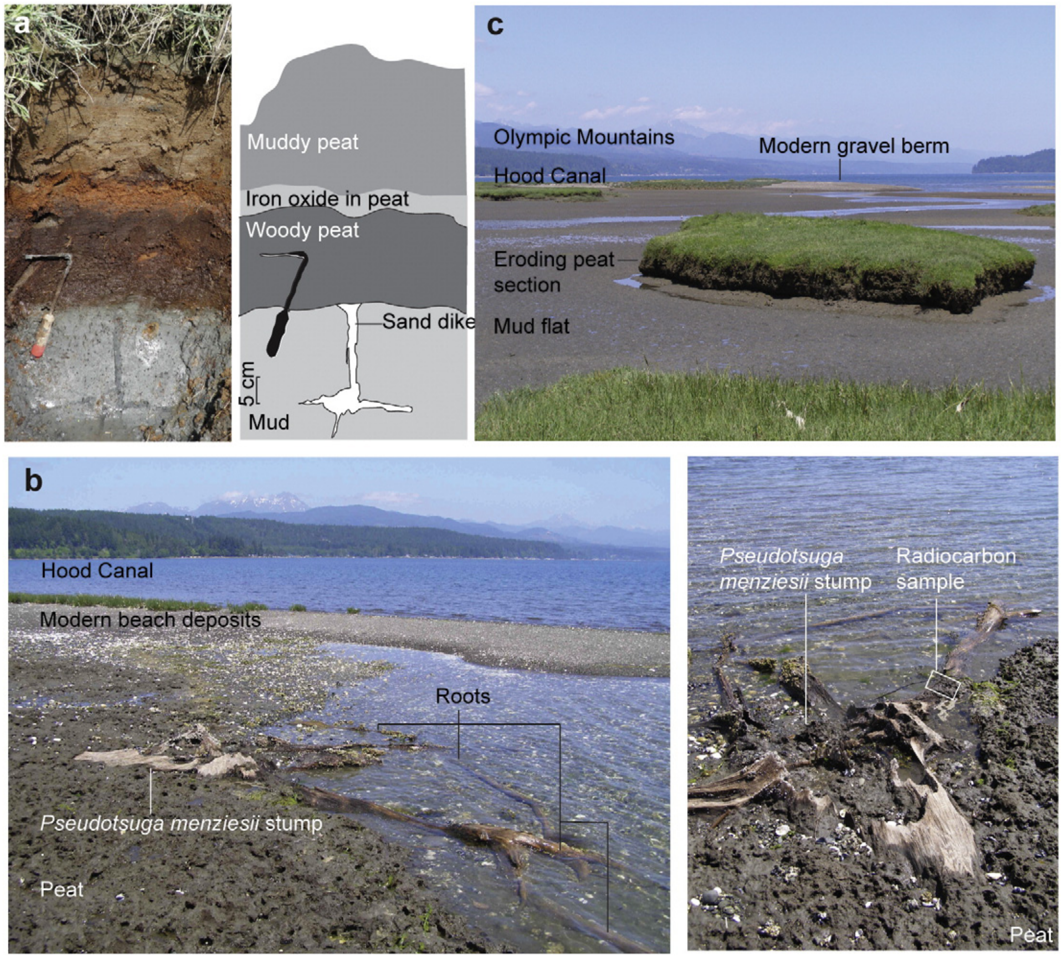

Fig. 7. Photographs of the Marsh detailing key features indicating uplift and later submergence. a. Photograph of an injected sand dike terminating at the brackish mud-woody peat contact. Within 5 m of photograph there is vented sand at the brackish mud-woody peat contact. b. Photograph of a *Pseudotsuga menziesii* stump eroding out of peat in the modern intertidal zone. This stump is at the seaward end of Transect 2 from Fig. 2, site 3. c. Photograph looking north of intertidal environment of the Marsh and eroding peat facies.

change in the Bog from sand to mud occurs at approximately the same time as uplift in the Marsh and Swamp (before AD 1200–1280). However, these changes are from one freshwater environment to another and could represent a progression from higher-energy to lower-energy environment. The mud facies in the Bog has no modern equivalent on the delta. The base of the mud in the Bog is more than 2 m below the mud-peat contact that demarks the uplift in the Marsh and Swamp and 4 m below the modern river surface (Fig. 3). The low elevation of the base of the mud indicates there may have been a paleo-depression where water could pond and deposit fine-grained sediment. Ponding could have been due to tectonic changes in drainage or to earthquake-induced landslides increasing input of muddy sediment from Pleistocene lake deposits upstream (Smith et al., 2007).

4.1.1.2. Tilting and faults. The uninterrupted stratigraphy across the Marsh, Swamp and Bog and the morphology of the delta indicate that the river has not migrated or avulsed across the field area since the time of uplift about 1000 years ago. In all of these areas, fine-grained sedimentary units and peat are traceable from the east to west (Fig. 3), and no abandoned meander channels cut the landscape as they do farther upstream (Fig. 2). Furthermore, the morphology of the intertidal and subtidal delta, with deep water off the western delta and wide, shallow flats off of the eastern delta (Fig. 2), indicate the river mouth has remained on the eastern side of the delta for at least 1000 years, feeding sediment to that part of the shoreline.

Shoreline-parallel profiles across the Skokomish delta do not have the typical morphology of deltas in non-tectonic areas (Fig. 3). In most deltaic settings the areas that receive flood sediment, i.e. areas close to the river, are higher than the surrounding delta. In contrast, at the Skokomish delta, profiles perpendicular to the river through the Marsh, Swamp, Ridge, and Bog all descend toward the river (Fig. 3). In addition, the stratigraphic contacts across the delta show a similar trend of being lower in the east than in the west (Fig. 3). Other studies on the Skokomish have shown that the river channel is aggrading (Jay and Simenstad, 1996; Stover and Montgomery, 2001), and has been doing so through most of the late Holocene (Bountry et al., 2009). The combination of an aggrading channel and stable channel position on the east side over the last 1000 years should result in the east side building up more than the west side of the subaerial delta. This should result in the east side of the river valley and subaerial delta (Marsh, Swamp, and Bog) being higher than the west. However, the opposite is true.

Tectonic uplift most likely generated the tilt of the Skokomish delta, and the fault that generated the uplift/tilting was most likely the Saddle Mountain fault zone as the geometry and location of other faults in the area are not as consistent with the pattern of uplift. The uplift and tilt are consistent with an east-dipping thrust, like Saddle Mountain fault zone, and there was an earthquake on that fault zone within the error of radiocarbon ages of the uplift on the Skokomish delta. The Ridge as the geomorphic expression of a fault, as suggested by Polenz et al. (2010), could not have caused the tilting because the slope angle is the same on either side of the Ridge (Fig. 3). Moreover, the Ridge is perpendicular to the trend of tilting. It is possible that an unknown fault generated the uplift.

Nearby and also with known ruptures within dating error of uplift on the Skokomish delta are the Olympia, Tacoma and Seattle fault zones (Fig. 1). However, their trend toward the west is not well understood. The trace of the Olympia fault zone (Blakely et al., 2009) is projected to be south of the delta, and is south side-up, making the Olympia fault zone an unlikely candidate for delta uplift. The trace of the Tacoma fault zone is not known in the vicinity of the delta. It is a north side-up thrust, so in order for the Tacoma fault zone to induce uplift on the delta, it would need to be located south of the delta, for which there is currently no evidence. The proposed trend of the Seattle fault zone in the area is more than 20 km away and therefore unlikely to cause deformation at the Skokomish delta (Blakely et al., 2009). In the eastern Puget Lowland, deformation from a Seattle fault-zone earthquake about 1000 years ago is traced less than 15 km perpendicular to the axial surface of the fault (Bucknam et al., 1992).

4.1.1.3. Co-incidence of uplift and tilting. The event that uplifted the Marsh and Swamp also most likely caused the delta tilting. The tilting occurs in areas that were part of different depositional environments before the earthquake. The Marsh and Swamp were intertidal flats, the Ridge was either alluvial or forest and the Bog was fresh water. It is unlikely that these three depositional environments all had similar slope directions without tectonic land-level change. The origin of the tilt may be due to differential uplift during the earthquake, which generated land-level change on the delta. An alternative would be that differential subsidence has generated the tilt.

If the muddy-peat-to-mud contact at site 7 (Fig. 5) from the eastern part of the Swamp represents the same time horizon as the mud-peat contact in the middle of the Swamp at site 6 (Fig. 4, transect 3; Fig. 5, site 6 and 7), then the tilt was probably generated at the time of uplift. The uplift contact is lower in elevation at site 7 on the eastern side of the delta than at site 6 in the middle of the delta—a trend that holds true in the Marsh as well (Fig. 3A, B). At site 6, there is a transition between brackish mud and freshwater peat, whereas at site 7, the transition is between two brackish facies. This difference could indicate that site 7 was uplifted less than site 6. However, the continued brackish deposition at site 7 may also be due to the proximity of this low-lying site to the Skokomish River, its floodwaters, and tides.

4.1.1.4. Tectonic origin of reduced channel migration and channel abandonment. The tilting of the delta trapped the river on the eastern side of the delta. The tectonic tilt makes the preferred path of the river to the east and the valley wall blocks the river from migrating farther east. Such low rates of channel migration are rare in non-bedrock settings (Kukal, 1990). Even at the low end of river migration rates in alluvium (1 m/year) the channel would have migrated up to 1 km in the last 1000 years. The Ridge may also play and have played a role in blocking river migration, but the tilt and reduced river migration for 1.5 km upstream of the Ridge indicate that tilt is the main factor discouraging lateral migration. Further, the low channel migration rate in historical times and the eastern side of the delta remaining the lowest part of the delta indicate the river will not likely avulse or migrate in the near future.

The reduced channel mobility resulted in some regions of the delta receiving more sediment for the last 1000 years. Because the western side of the delta is eroding (Fig. 7c) and the eastern side is prograding, the intertidal zone of the bay is asymmetric. Also, the regions along the river receive flood deposition. In general, peat overlying the earthquake contact in the Marsh and Swamp becomes thicker closer to the river (Fig. 3). This indicates the original tilt of the delta may have been greater and through time deposition may flatten the delta surface.

Similar to other studies of rivers, the tectonic deformation along the Skokomish delta only affects several kilometers of the river. The extent to which an earthquake affects a river depends on the amount of deformation, the fault characteristics (e.g., dip, style) the characteristics of the river (e.g., slope, discharge, and channel substrate) and the frequency of events (Burbank and Anderson, 2011). Skokomish river valley, tilting is only measurable for the 5 km closest to the shore. More than 5 km upstream, abandoned meanders channels span the entire valley and the river is not confined to one side of the valley. In other examples of similar scales of deformation and alluvial channels, the earthquake affects are typically observable for less than 10 km along the river. For example, at similar river in a glacially carved valley with an alluvial channel, Collins and Montgomery (2011) concluded the 5.5 m of uplift (ten Brink et al., 2006) on the Seattle fault zone affected landforms in the Duwamish river valley in the Puget Lowland for less than 5 km from the delta. Broader and epeirogenic deformation can lead to broader special effects of tectonics on rivers (Holbrook and Schumm, 1999).

The paleochannels cutting perpendicular to the Ridge and Swamp may have become relict during the event that tilted the delta. The seaward branching morphology of the paleochannels indicates they were probably distributary channels flowing into tidal flats of what are now the Marsh and Swamp. Based on dates from peat forming in the channel, they were abandoned before AD 1290–1410. These channels may represent abandoned channels of the Skokomish River, or an older drain for the Bog similar to the modern eastern channel. In both hypotheses, the tilting of the delta may have caused abandonment of the channels by making the preferred flow gradient toward the east. Alternatively, beavers, log jams, humans, or other non-tectonic processes may have blocked the drainage.

4.1.2. Origin of post-earthquake submergence

Since the time of abrupt uplift, the front of the delta has been submerged at least 1.6 m. This number is based on the elevation difference between the current elevation of the about 1000 year old *P. menziesii* stump on transect 2 and the lowest elevation that conifers currently are growing on the delta (Fig. 4). The presence of salt-tolerant diatoms in the lower part of the peat above and near the *P. menziesii* stump indicates this area returned to the intertidal zone soon after, possibly causing the tree to die. Submergence of the delta may be part of the reason for currently dying trees and expanding wetlands noted by Bountry et al. (2009). Submergence may be due to a combination of sea-level rise, slow tectonic subsidence and compaction of delta sediments. Other sea-level studies found less than 1 m relative sea-level rise in the last 1000 years for the Puget Lowland (Eronen et al., 1987; Beale, 1990). Therefore, 0.6 m or more of relative sea-level rise is due to compaction and tectonics. Much of the stratigraphy of the Skokomish delta is sand and pebbles therefore; the delta likely experiences less subsidence due to compaction than finer grained deltas.

4.1.3. Origin of the Ridge

A combination of depositional and tectonic processes formed the geomorphology of the Ridge. The ridge is highest on its western end near the outlet of two drainages from the uplands, indicating alluvial fan deposition at the base the drainages off the highlands may augment the Ridge height and width near the valley wall. Also, the Ridge is widest and has the most gradual slope near the paleochannels and eastern channel (Fig. 2). Similar to the modern distributary channels depositing the modern delta lobe, deposition associated with these paleo- and eastern channels widened the ridge structure and diminished the seaward slope of the Ridge.

The delta has been affected by tectonics, but the location of the fault and the exact role the fault plays in forming the Ridge geomorphology has not been resolved. The Ridge may be the expression of a blind fault or may have formed due to a combination of tectonic and beach processes (Fig. 8). Three lines of evidence support the Ridge being the surface expression of a fault: 1) an aeromagnetic boundary crosses the delta (Blakely et al., 2009), 2) the Ridge is an anomalously high, linear feature in an alluvial plain, and 3) pre-Fraser glacial beds to the west of the Ridge dip to the south (Polenz et al., 2010).

Several factors, however, complicate the hypothesis that the Ridge is the surface expression of a fault. 1) Though there is up to 5 m difference in elevation between the Ridge and the Bog, less than 200 m west along the trend of the Ridge, there is no offset in the glacially fluted uplands (Fig. 2a). In the fault hypothesis, it is a coincidence that the Holocene fault deformation ends at an erosional boundary. 2) Aeromagnetic boundaries have non-unique solutions (Saltus and Blakely, 2011). Boundaries can indicate active faults but they can also indicate a variety of other boundaries including inactive faults, landslide scarps and lithologic boundaries. 3) Similar slopes, parallel to the Ridge, in both the Bog and Swamp indicate a source of uplift other than the Ridge. Therefore, if the Ridge is the geomorphic expression of a fault, there is either differential subsidence on the delta (the eastern delta subsiding more than the western side) or a fault not parallel to and underlying the Ridge generating the tilt. 4) The current fault model (Polenz et al., 2010) contradicts the stratigraphic evidence for an earthquake. Based on the south-dipping thrust fault model, the Bog should have been uplifted and the Marsh should have dropped during fault rupture. There is strong stratigraphic evidence for uplift in the Marsh. 5) This study uncovered no stratigraphic evidence for multiple, large earthquakes in the last 1000 years on the delta and no evidence for two separate events, one generating the uplift in the Marsh and Swamp and one tilting the delta. Therefore, the simple solution is the same event caused both.

If the Ridge is the geomorphic expression of a fault, a north-dipping fault better explains the stratigraphic evidence for an earthquake than the south-dipping fault mapped based on an aeromagnetic boundary (Polenz et al., 2010). Uplift in the Marsh and Swamp indicates these areas are above the hanging wall. A topographically low sand-mud contact and the thick mud deposits in the Bog could be evidence of earthquake-induced subsidence. The morphology of the Ridge, with a steep southern edge and more gradual northern slope is simpler to explain with a north-dipping fault than a south-dipping fault and anticline (Polenz et al., 2010). A north-dipping fault would still require a separate fault or tectonic activity to explain the tilt in the delta.

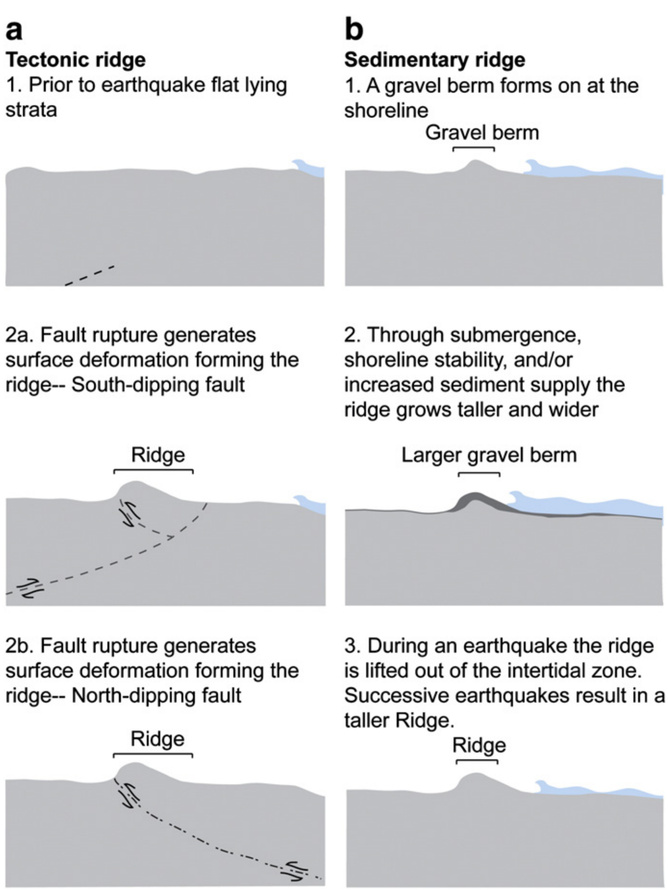

Fig. 8. Hypotheses for formation of the Ridge by either (a) Surface deformation by a blind thrust fault. South-dipping fault model from Polenz et al. (2010) and north-dipping fault alternative. Or (b) Formation by coastal processes and later uplift out of the intertidal zone by an earthquake.

An alternative interpretation of the Ridge is that it formed as a shoreline berm (Fig. 8), just as a narrow gravel berm flanks the modern marsh (Fig. 2, modern gravelly berm). Former stability of the shoreline location, higher sediment supply, higher wave heights, and slow submergence such as that experienced by the delta in the last 1000 years, could have made the ridge wider and taller than the modern berm, as observed in the development of gravel berms in other locations (Orford et al., 1996; Taylor and Stone, 1996; Wells, 1996). Submergence can initiate or accelerate ridge formation by remobilizing sediment in the beach (Meyers et al., 1996), and as long as sediment supply is high, the ridge will continue to grow rather than to erode (Anthony, 1995). If the Ridge formed during a period of high sedimentation, shoreline stability and/or rising sea level, subsequent coseismic uplift could have lifted the Ridge out of the intertidal zone. Multiple earthquake events (uplift and tilting) could account for the greater height of the western part of the Ridge relative to the modern berm and also its greater tilt relative to the Marsh, Swamp and Bog. Also, the majority of the Ridge has received little to no deposition but the Marsh, Swamp and Bog have. The initial slope may have been flattened by deposition and the initial slope in the Marsh, Swamp and Bog may have been greater.

The berm hypothesis is supported by several observations. 1) The Ridge is parallel the modern and ancient beach berms. 2) The sediment forming the Ridge is gravel, similar to that forming the modern and ancient beach berms. 3) The Ridge is cut by distributary channels similar to the modern berm. 4) The morphology of the Ridge is present only in the Skokomish River valley. Deposition features, like berms, typically end at topographic boundaries like the walls of the Skokomish River valley.

Several observations do not support the Ridge originating as a beach berm. 1) The Ridge is longer than the modern beach berm. This may be an issue of wave energy. The extensive modern intertidal zone on the eastern side of the delta reduces wave energy and transport of sediment by storms, reducing the potential for berm formation on the east side of the delta. 2) The Ridge is taller and wider than the modern berms. This may be the result of multiple uplift events, and widening by alluvial and fluvial processes. 3) The beach berm hypothesis does not explain the dipping glacial beds to the west of the delta. 4) Similarly, the beach berm hypothesis does not explain the aeromagnetic anomaly that cuts across the delta (Fig. 9).

4.1.4. Delta asymmetry and channel migration

Modeled and experimental work on channel mobility in tectonically active areas provides insights for the Skokomish delta. Channels tend to migrate away from greatest uplift and toward greatest subsidence (Holbrook and Schumm, 1999). Most studies of the interaction of fluvial deposition and tectonics study normal faulting and submergence (e.g. Allen, 1978; Martin et al., 2009; Kim et al., 2010). While the Skokomish delta is submerging, uplift has had the dominant role in shaping the delta geomorphology and depositional environments. Nonetheless, many of the effects of submergence in fluvial systems also occur in systems experiencing uplift. Based on other studies of fluvial systems influenced by tectonics, for the Skokomish to be steered, the rate of tilting must be greater than river migration (Holbrook and Schumm, 1999; Kim et al., 2010). In other experiments, aggradation and submergence result in higher rates of channel mobility (Martin et al., 2009). Though aggradation of channels and submergence are ongoing at the Skokomish delta, the channel is not migrating. In part, this is due to the valley wall preventing the channel from migrating farther east, resulting in a stable channel position. Low channel mobility indicates the tilting of the delta currently is the largest influence on channel stability, outweighing the aggradation and submergence.

4.1.5. Comparisons to other systems

The Skokomish delta is a case study of the effects of differential uplift on a fluvial–deltaic system. Similar to the tectonic control of river channel migration in extensional environments (Schumm, 1986; Alexander and Leeder, 1987; Peakall, 1998), the position of the Skokomish River in the study area is controlled by tectonic tilting. With tectonically controlled river channel mobility there are typically two cases, one where river migration is increased and one migration is decreased when the river becomes trapped by a bounding wall; the Skokomish River falls into the latter category. Unlike cases where subsidence causes the river to be trapped against a graben wall (e.g., Alexander and Leeder, 1987), differential uplift, rather than subsidence, is forcing the stable location of the Skokomish channel. In addition, the tilting is forcing the stable location active delta lobe as well as the river channel.

Delta systems dominated by waves or tides would not record delta tilting and reduced channel mobility in the same manner as the Skokomish delta. Higher tidal currents, wave activity, or longshore drift would result in redistribution of sediment within the bay and along the coastline. In these settings, the geomorphic and sedimentary record of uplift and tilting would not be as apparent as in the lobe of sediment in river-dominated Skokomish system. Nonetheless, in the Skokomish delta both the Ridge and delta stratigraphy, do record tilting and would likely do so in different types of deltaic settings. Modern and ancient river-dominated delta systems in marine and lacustrine environments could show similar records in tectonically active environments.

The preservation over longer timescales of tilting and reduced channel migration would occur under two conditions: 1) if future tilting continued to steer the river to the eastern side of the valley, or 2) if continued submergence and deposition protected the stratigraphy from future erosion by the meandering river. Future tilting events could result in the river eroding into the eastern wall of the valley and river migration to the east,

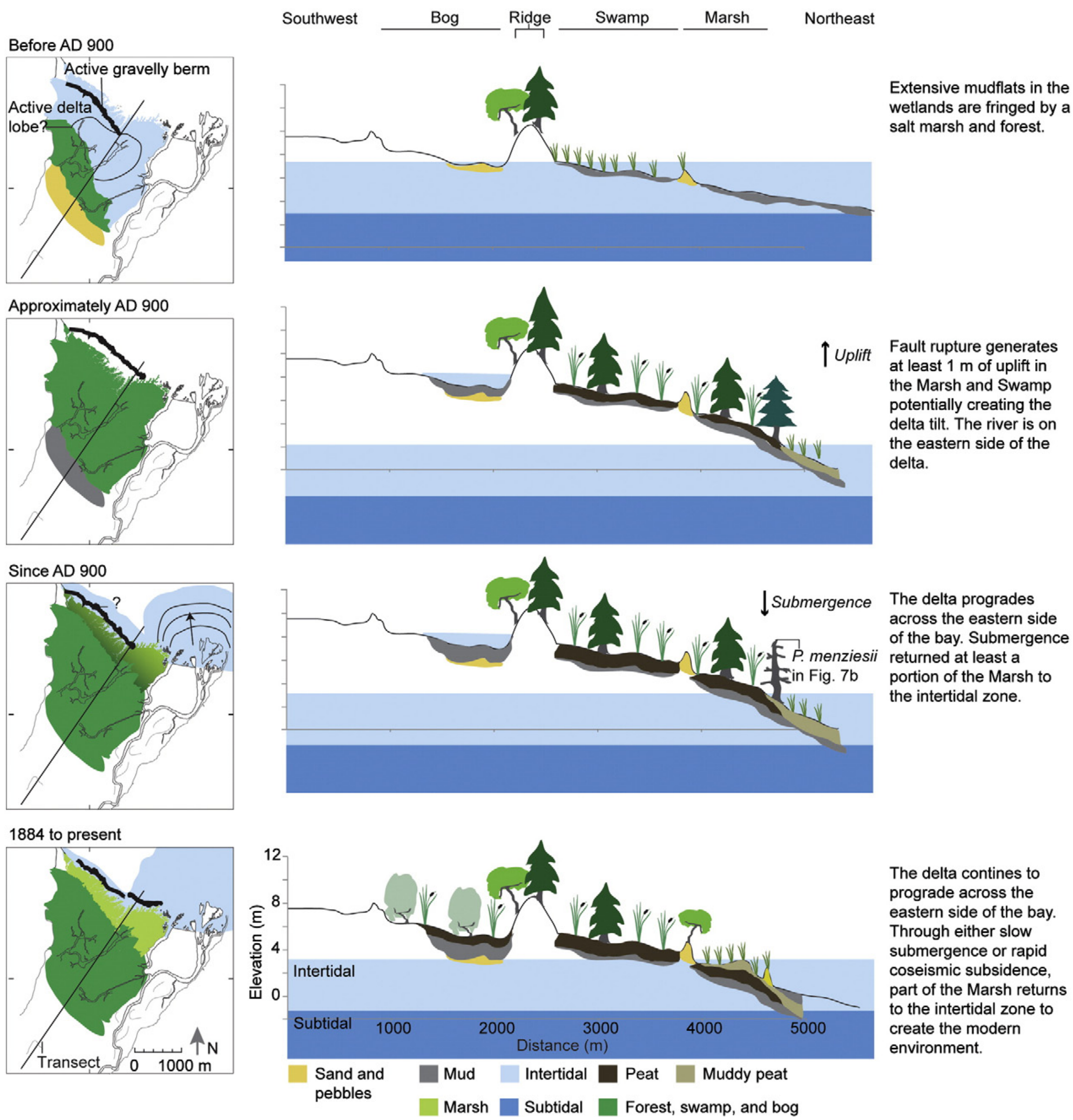

Fig. 9. Cartoon of delta history showing uplift and later submergence of the delta. a. Pre-earthquake the Ridge was the approximate location of the shoreline. b. Post-earthquake uplifted environments. c. Environments reflecting the return of the front of the delta to intertidal conditions. d. Modern environment.

similar to tectonic river steering in other locations (Schumm, 1986; Alexander and Leeder, 1987; Peakall, 1998). Continued submergence without tilting would result in the river filling in sediment across the delta front and the preservation of tilting in the stratigraphy but not the morphology of the delta.

5. Conclusions

A millennium after tectonic land-level change on the Skokomish delta, the effects of the earthquake are still acting on the landforms, stratigraphy, and ecology of the delta system. This earthquake, tentatively linked to a NE–SW striking thrust fault in the Saddle Mountain fault zone, resulted in at least 1 m of uplift on the delta front and in the triggering of sand blows. Postulated differential uplift during the earthquake resulted in eastward tilt of the delta. This earthquake also may have caused the abandonment of channels on the western side of the delta and trapped the mouth of the Skokomish River on the eastern side of the delta. The river remaining on the eastern side of the delta for at least 1000 years has resulted in a 2 km-wider unvegetated intertidal zone in the eastern than in the western bay (Fig. 9).

This study presents two cases where features interpreted as geomorphic evidence of catastrophic events instead may be depositional features. The asymmetric intertidal zone is not a large landslide scarp but a product of the Skokomish River forced to one side of the delta for at least 1000 years. The Ridge too may be a depositional feature influenced by both uplift and submergence.

This study also demonstrates some of the difficulties in making paleoseismic studies in tectonically complex areas. First, uplift and submergence both play a role in shaping the delta morphology. Though the geological record of the earthquake is of uplift, many areas of the delta show net submergence. Uplift is evident in the tilt of the delta, the forcing of the river to the east, and the morphology of the Ridge according to both hypotheses. Submergence is evident on the erosional front of the western delta, and possibly the aggradation of the river channel in the field area.

Acknowledgments

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number *07HQGR0009*. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government. Further support came from an ExxonMobil student grant and fellowship assistance from the University of Washington Department of Earth & Space Sciences. Yuki Sawai identified diatoms for one site. This manuscript benefitted greatly from comments from B. Atwater, J. Bourgeois, C. Nittrouer, B. Sherrod, and K.L. Webster.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.geomorph.2012.07.016.

References

Alexander, J., Leeder, M.R., 1987. Active tectonic control on alluvial architecture. SEPM Special Publications 39, 243–252.
Allen, J.R.L., 1978. Studies in fluviatile sedimentation; an exploratory quantitative model for the architecture of avulsion controlled alluvial sites. Sedimentary Geology 21, 129–147.
Anthony, E.J., 1995. Beach ridge development and sediment supply: examples from West Africa. Marine Geology 129, 175–186.
Arcos, M.E.M., 2012. The A.D. 900–930 Seattle-Fault-Zone Earthquake with a wider coseismic rupture patch and postseismic submergence: inferences from new sedimentary evidence. Bulletin of the Seismological Society of America 102, 1079–1098.
Aslan, A., Autin, W.J., Blum, M.D., 2005. Causes of river avulsion: insights from the late Holocene avulsion history of the Mississippi River, USA. Journal of Sedimentary Research 75, 650–664.
Attal, M., Tucker, G.E., Whittaker, A.C., Cowie, P.A., Roberts, G.P., 2008. Modeling fluvial incision and transient landscape evolution: influence of dynamic channel adjustment. Journal of Geophysical Research 113, http://dx.doi.org/10.1029/2007JF000893.
Beale, H., 1990. Relative rise in sea-level during the past 5000 years at six salt marshes in northern Puget Sound, Washington. Shorelines and Coastal Zone Management Program. Washington Department of Ecology, Olympia, WA. 55 pp.
Blakely, R., Sherrod, B.L., Hughes, J.F., Anderson, M.L., Wells, R.E., Weaver, C.S., 2009. Saddle Mountain fault deformation zone, Olympic Peninsula, Washington: western boundary of the Seattle uplift. Geosphere 5, 105–125.
Booth, D.B., 1994. Glaciofluvial infilling and scour of the Puget Lowland, Washington, during ice-sheet glaciation. Geology 22, 695–698.
Bountry, J.A., Godaire, J.E., Klinger, R.E., Varyu, D.R., 2009. Geomorphic analysis of the Skokomish River, Mason County, Washington. U.S. Dept. Interior. SRH-2009-22, 130 pp.
Bourgeois, J., Johnson, S.Y., 2001. Geologic evidence of earthquakes at the Snohomish delta, Washington, in the past 1200 yr. Geological Society of America Bulletin 113, 482–494.
Brandon, M.T., Roden-Tice, M.K., Garver, J.I., 1998. Late Cenozoic exhumation of the Cascadia accretionary wedge in the Olympic Mountains, northwest Washington State. Geological Society of America Bulletin 110, 985–1009.
Bryant, M., Falk, P., Paola, C., 1995. Experimental study of avulsion frequency and rate of deposition. Geology 23, 365–368.
Bucknam, R.C., Hemphill-Haley, E., Leopold, E.B., 1992. Abrupt uplift within the past 1700 years at southern Puget Sound, Washington. Science 258, 1611–1614.
Burbank, D.W., Anderson, R.A., 2011. Tectonic Geomorphology. Wiley-Blackwell, Oxford, U.K. 320 pp.
Cady, W.M., 1975. Tectonic setting of the Tertiary volcanic rocks of the Olympic Peninsula, Washington. Journal of Research of the U. S. Geological Survey 3, 573–582.
Carson, R.J., 1973. First known active fault in Washington. Washington Division of Geology and Earth Resources Newsletter 1, 1–2.
Carson, R.J., 1976. Preliminary Geologic Map of North-central Mason County. Wash. Div. Geol. & Earth Resources, Washington. OFR 76–2.
Collins, B.D., Montgomery, D.R., 2011. The legacy of Pleistocene glaciation and the organization of lowland alluvial process domains in the Puget Sound region. Geomorphology 126, 174–185.
Czuba, J.A., Magirl, C.S., Czuba, C.R., Grossman, E.E., Curran, C.A., Gendaszek, A.S., Dinicola, R.S., 2011. Sediment load from major rivers into Puget Sound and its adjacent waters. USGS Fact Sheet 2011–3083, 4 pp.
Downing, J., 1983. The Coast of Puget Sound: Its Processes and Development. University of Washington Press, Seattle, Wash.126 pp.
Dragovich, J.D., Pringle, P.T., Walsh, T.J., 1994. Extent and geometry of the mid-Holocene Osceola Mudflow in the Puget Lowland: implications for Holocene sedimentation and paleogeography. Washington Geology 22, 3–26.
Embrey, S.S., Frans, L.M., 2003. Surface-water quality of the Skokomish, Nooksack, and Green-Duwamish Rivers and Thornton Creek, Puget Sound basin, Washington, 1995–98. USGS WRIR 02–4190, 192 pp.
Eronen, M., Kankainen, T., Tsukada, M., 1987. Late Holocene sea-level record in a core from the Puget Lowland, Washington. Quaternary Research 27, 147–159.
Fernandes, N.F., Dietrich, W.E., 1997. Hillslope evolution by diffusive processes: the timescale of equilibrium adjustments. Water Resources Research 33, 1307–1318.
Finlayson, D.P., 2005. Combined Bathymetry and Topography of the Puget Lowland, Washington State. University of Washington Press, Seattle, Washington.
Gavin, D.G., Brubaker, L.B., 1999. A 6000-year soil pollen record of subalpine meadow vegetation in the Olympic Mountains, Washington, USA. Journal of Ecology 87, 106–122.
GeoEngineers, Inc., 2006. Channel migration and avulsion potential analyses, Skokomish River Valley Mason County, Washington. Mason County Public Works Department. 2221-026-00, 17 pp.
Gilbert, J.J., 1884. United States Coast & Geodetic Survey Topographic Sheet, Hoodís Canal, Annas Bay, Washington Territory, T-1560b. Accessed through the Puget Sound River History Project.
Gouw, M.J.P., 2007. Alluvial architecture of fluvio-deltaic successions: a review with special reference to Holocene settings. Netherlands Journal of Geosciences 86, 211–227.
Haug, B.J., 1998. High resolution seismic reflection interpretations of the Hood Canal-Discovery Bay fault zone; Puget Sound, Washington: Portland State University, Master's Thesis, 102 pp.
Holbrook, J., Schumm, S.A., 1999. Geomorphic and sedimentary response of rivers to tectonic deformation: a brief review and critique of a tool for recognizing subtle epeirogenic deformation in modern and ancient settings. Tectonophysics 385, 286–306.
Holdahl, S.R., Faucher, F., Dragert, H., 1989. Contemporary vertical crustal motion in the Pacific Northwest. In: Cohen, S., Vanicek, P. (Eds.), Slow deformation and transmission of stress in the earth: American Geophysical Union Monograph, 49, pp. 17–29.
Horton, B.P., Edwards, R.J., Lloyd, J.M., 1999. Reconstruction of former sea-levels using a foraminiferal-based transfer function. Journal of Foraminiferal Research 29, 117–129.
Hughes, J.F., 2005. Meters of synchronous Holocene slip on two strands of a fault in the western Puget Sound lowland, Washington. Eos 86, S51C–S1020C.
Hyndman, R.D., Wang, K., 1995. The rupture zone of Cascadia great earthquakes from current deformation and the thermal regime. Journal of Geophysical Research 100, 133–154.
James, T.S., Gowan, E.J., Hutchinson, I., Clague, J.J., Barrie, J.V., Conway, K.W., 2009. Sea-level change and paleogeographic reconstructions, southern Vancouver Island, British Columbia, Canada. Quaternary Science Reviews 28, 1200–1216.
Jay, D.A., Simenstad, C.A., 1996. Downstream effects of water withdrawal in a small, high-gradient basin: erosion and deposition on the Skokomish River delta. Estuaries 19, 501–517.
Johnson, S.Y., Potter, C.J., Armentrout, J.M., 1994. Origin and evolution of the Seattle fault and Seattle basin. Geology 22, 71–74.

Johnston, A.C., Schweig, E.S., 1996. The enigma of the New Madrid Earthquakes of 1811–1812. Annual Review of Earth and Planetary Sciences 24, 339–384.
Keller, E.A., Bonkowski, M.S., Korsch, R.J., Shlemon, R.J., 1982. Tectonic geomorphology of the San Andreas fault zone in the southern Indio Hills, Coachella Valley, California. Geological Society of America Bulletin 93, 46–56.
Kim, W., Sheets, B.A., Paola, C., 2010. Steering of experimental channels by lateral basin tilting. Basin Research 22, 286–301.
King, W.A., Martini, I.P., 1984. Morphology and Recent sediments of the lower anastomosing reaches of the Attawapiskat River, James Bay, Ontario, Canada. Sedimentary Geology 37, 295–320.
Kukal, Z., 1990. Rates of geological processes. Earth-Science Reviews 28 (258 pp.).
Leeder, M.R., Mack, G.H., Peakall, J., Salyards, S.L., 1996. First quantitative test of alluvial stratigraphic models: Southern Rio Grande Rift, New Mexico. Geology 24, 87–90.
Long, A.J., Shennan, I., 1998. Models of rapid relative sea-level change in Washington and Oregon, USA. The Holocene 8, 129–142.
Martin, M.E., Bourgeois, J., 2012. Vented sediments and tsunami deposits in the Puget Lowland, Washington—differentiating sedimentary processes. Sedimentology 59, 419–444.
Martin, J., Sheets, B., Paola, C., Hoyal, D., 2009. Influence of steady base-level rise on channel mobility, shoreline migration, and scaling properties of a cohesive experimental delta. Journal of Geophysical Research 114.
Matteo, Z.R.P., Siringan, F.P., 2007. Tectonic control of high-frequency Holocene delta switching and fluvial migration in Lingayen Gulf Bayhead, Northwestern Philippines. Journal of Coastal Research 23, 182–194.
Mazzotti, S., Dragert, H., Hyndman, R.D., Miller, M.M., Henton, J.A., 2002. GPS deformation in a region of high crustal seismicity: N. Cascadia forearc. Earth and Planetary Science Letters 198, 41–48.
McCaffrey, R., Qamar, A., King, R.W., Wells, R.E., Khazaradze, G., Williams, C.A., Stevens, C.W., Vollick, J.J., Zwick, P.C., 2007. Fault locking, block rotation and crustal deformation in the Pacific Northwest. Geophysical Journal International 169, 1315–1340.
McLachlan, J.S., Brubaker, L.B., 1995. Local and regional vegetation change on the northeastern Olympic Peninsula during the Holocene. Canadian Journal of Botany 73, 1618–1627.
Meyers, R.A., Smith, D.G., Jol, H.M., Peterson, C.D., 1996. Evidence for eight great earthquake-subsidence events detected with ground penetrating radar, Willapa Barrier, Washington. Geology 24, 99–102.
Miall, A.D., 1981. Alluvial sediment basins: Tectonic setting and basin architecture. In: Miall, A.D. (Ed.), Sedimentation and tectonics in alluvial basins: Geol. Surv. Canada, Special Pub., 23, pp. 1–33.
Middleton, G.V., 1973. Johannes Walther's law of the correlation of facies. Geological Society of America Bulletin 84, 979–988.
Mitchell, C.E., Vincent, P., Weldon, R.J., Richards, M.A., 1994. Present-day vertical deformation of the Cascadia margin, Pacific Northwest, United States. Journal of Geophysical Research 99, 257–278.
Mofjeld, H.O., Venturato, A.J., Titov, V.V., Gonzalez, F.I., Newman, J.C., 2002. Tidal datum distributions in Puget Sound, Washington, based on a tidal model. NOAA Tech. Memo. OAR PMEL-122, 35 pp.
Nelson, A.R., Johnson, S.Y., Kelsey, H.M., Wells, R.E., Sherrod, B.L., Pezzopane, S.K., Bradley, L.-A., Koehler III, R.D., Bucknam, R.C., 2003. Late Holocene earthquakes on the Toe Jam Hill fault, Seattle fault zone, Bainbridge Island, Washington. Geological Society of America Bulletin 115, 1388–1403.
Obermeier, S.F., 1996. Use of liquefaction-induced features for paleoseismic analysis—an overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleo-earthquakes. Engineering Geology 44, 1–76.
Orford, J.D., Carter, R.W.G., Jennings, S.C., 1996. Control domains and morphological phases in gravel-dominated coastal barriers of Nova Scotia. Journal of Coastal Research 12, 598–604.
Patrick, R., Reimer, C., 1966. The diatoms of the United States exclusive of Alaska and Hawaii. Monographs of the Academy of Natural Sciences of Philadelphia 13 688 pp.
Peakall, J., 1998. Axial River evolution in response to half-graben faulting: Carson River, Nevada, U.S.A. Journal of Sedimentary Research 68, 788–799.
Polenz, M., Czajkowski, J., Legorreta, G., Contreras, T., Miller, B., Martin, M.E., Logan, R.L., Carson, R.J., Johnson, C.N., Skov, R.H., Mahan, S., Cohan, C.R., 2010. Geologic map of the Skokomish Valley and Union 7.5-minute quadrangles, Mason County. Washington State Department of Natural Resources OFR. 2010–3.
Porter, S.C., Swanson, T.W., 1998. Radiocarbon age constraints on rates of advance and retreat of the Puget Lobe of the Cordilleran Ice Sheet during the Last Glaciation. Quaternary Research 50, 205–213.
Puget Sound LiDAR Consortium, 2005. PSLC 2002—Bare Earth LiDAR DEM raster digital data. www.pugetsoundlidar.org2005.
Puget Sound River History Project, a. Skokomish River Areal PhotographsAccessed 9 December 2010 http://riverhistory.ess.washington.edu/ims/.
Reilinger, R., Adams, J., 1982. Geodetic evidence for active landward tilting of the Oregon and Washington coastal ranges. Geophysical Research Letters 9, 401–403.
Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E., 2009. INTCAL 09 and MARINE09 radiocarbon age calibration curves, 0–50,000 years Cal BP. Radiocarbon 51, 1111–1150.
Rockwell, T.K., Keller, E.A., Clark, M.N., Johnson, D.L., 1984. Chronology and rates of faulting of Ventura River terraces, Cal. Geological Society of America Bulletin 95, 1466–1474.
Saltus, R.W., Blakely, R.J., 2011. Unique geologic insights from “non-unique” gravity and magnetic interpretation. GSA Today 21, 4–10.
Schumm, S.A., 1986. Alluvial river response to active tectonics. Active Tectonics. National Academy Press, Washington, D.C., pp. 80–94.
Schumm, S.A., 1993. River response to baselevel change: implications for sequence stratigraphy. Journal of Geology 101, 279–294.
Schwartz, M.L., 1991. Net Shore-drift in Washington State. Washington Department of Ecology, Olympia, WA. Publication 00-06-31.
Sherrod, B.L., 1999. Gradient analysis of diatom assemblages in a Puget Sound salt marsh—can such assemblages be used for quantitative paleoecological reconstructions? Palaeogeography, Palaeoclimatology, Palaeoecology 149, 213–226.
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 113, 1299–1311.
Sherrod, B.L., Brocher, T.M., Weaver, C.S., Bucknam, R.C., Blakely, R.J., Kelsey, H.M., Nelson, A.R., Haugerud, R., 2004. Holocene fault scarps near Tacoma, Washington, USA. Geology 32, 9–12.
Sherrod, B.L., Blakely, R.J., Weaver, C.S., Kelsey, H.M., Barnett, E., Liberty, L., Meagher, K.L., Pape, K., 2008. Finding concealed active faults: extending the southern Whidbey Island fault across the Puget Lowland, Washington. Journal of Geophysical Research 113.
Skylar, L.S., Dietrich, W.E., 2001. Sediment and rock strength controls on river incision into bedrock. Geology 29, 1087–1090.
Slingerland, R., Smith, N.D., 1998. Necessary conditions for a meandering-river avulsion. Geology 26, 435–438.
Smith, G.R., Montgomery, D.R., Peterson, N.P., Crowley, B., Goedert, J., 2007. Spawning sockeye salmon fossils in Pleistocene of Skokomish Valley, Washington. Quaternary Research 68, 227–238.
Stover, S.C., Montgomery, D.R., 2001. Channel change and flooding, Skokomish River, Washington. Journal of Hydrology 243, 272–286.
Tabor, R.W., Cady, W.M., 1978a. The structure of the Olympic Mountains, Washington—analysis of a subduction zone. U.S. Geol. Surv., Professional Paper 1033, 25 pp.
Tabor, R.W., Cady, W.M., 1978b. Geologic map of the Olympic Peninsula, Washington. U.S. Geol. Surv. MIS I-99 .
Taylor, M., Stone, G.W., 1996. Beach ridges: a review. Journal of Coastal Research 12, 612–621.
ten Brink, U.S., Song, J., Bucknam, R.C., 2006. Rupture models for the A.D. 900–930 Seattle fault earthquake from uplifted shorelines. Geology 34, 585–588.
Ter Braak, C.J.F., 1987–1992. CANOCO—A FORTRAN Program for Canonical Community Ordination. Microcomputer Power, Ithaca, New York, USA.
Thorson, R.M., 1989. Glacio-isostatic response of the Puget Sound area, Washington. Geological Society of America Bulletin 101, 1163–1174.
Tuttle, M.P., 2001. The use of liquefaction features in paleoseismology: lessons learned in the New Madrid seismic zone, central United States. Journal of Seismology 5, 361–380.
Wallace, R.S., 1988. Quantification of Net Shore-Drift Rates in Puget Sound and the Strait of Juan de Fuca, Washington. Journal of Coastal Research 4, 395–403.
Wells, L.E., 1996. The Santa Beach Ridge Complex: sea-level and progradational history of an open gravel coast in Central Peru. Journal of Coastal Research 12, 1–17.
Wells, R.E., Weaver, C.S., Blakely, R.J., 1998. Forearc migration in Cascadia and its neotectonic significance. Geology 26, 759–762.
Whipple, K.X., Tucker, G.E., 1999. Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs. Journal of Geophysical Research 104, 17,661–17,674.
Wilson, J.R., Bartholomew, J.R., Carson, R.J., 1979. Late Quaternary faults and their relationship to tectonism in the Olympic Peninsula, Washington. Geology 7, 235–239.
Witter, R.C., Givler, R.W., Carson, R.J., 2008. Two post-glacial earthquakes on the Saddle Mountain West fault, southeastern Olympic Peninsula, Washington. Bulletin of the Seismological Society of America 98, 2894–2917.
Zaprowski, B.J., Pazzaglia, F.J., Evenson, E.B., 2005. Sediment and rock strength controls on river incision into bedrock. Journal of Geophysical Research 110, http://dx.doi.org/10.1029/2004JF000138 (19 pp.).