NEOTECTONICS AND SHORELINE CHANGE, SAMMAMISH DELTA, LAKE WASHINGTON

(Project #1434-HG-97-GR-03057)

Final Report

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Non-technical Summary (December, 1998)

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The main objective of our project was to establish the rate and pattern by which the shoreline of Lake Washington, near Seattle, has risen through the postglacial epoch. Such a relationship between the rise of the shoreline (transgression) and time is called a submergence curve. We created it by radiocarbon dating the contact between submerged terrestrial peat and the overlying organic lake sediments (gyttja) at the north end of the lake, where the terrain is most stable tectonically. Our surprise conclusion is that the surface elevation of the lake during most of the postglacial epoch (about 13,000 and 3,000 years BP) was controlled not by the alluvial sediment at its outlet, but by sea level. This conclusion invalidates the use of the lake shorelines as an accurate water plane separate from that of sea level, for reconstructing tectonic deformation. Only during late Holocene time, since approximately 3000 years BP, has the lake outlet been independent of sea level. Thus, it is no surprise that the only tectonic uplift event recognized by our earlier work on the shoreline

deposits of Washington was associated with the 1100 year old earthquake event. Evidence for earlier or multiple earthquake uplift events was not found.

Introduction

The northernmost strand of the Seattle Fault Zone (SFZ) ruptured about 1100 years ago, producing a locally destructive earthquake, and co-seismic uplift exceeding seven meters in the central Puget Lowland (Figure 1; Adams, 1992). Evidence drawn from a variety of sources -- bedrock geology, topography, reflection seismology, geophysical anomalies, paleoseismology, ambient seismicity -- indicate that the SFZ results from strong north-south compression, and is probably the surface expression of a regionally important blind thrust fault beneath this heavily settled metropolitan region (Finn, 1990; Johnson et al., 1994; Gower et al., 1985; Pratt et al., 1997; Ma et al., 1996). It is an earthquake threat to be seriously reckoned with.

Tectonic Setting

The driving force for the Puget Lowland thrust sheet (PLTS) is inferred to be the northward component of oblique subduction by the Juan de Fuca Plate, although the plate coupling stress appears to be weak. In the southern Puget Lowland, the PLTS appears to follow a mid-crustal, decollement along which stress is apparently accommodated by ductile shear. In the center of the Lowland, between Tacoma and Seattle, the thrust apparently rises along a bed-parallel ramp, which steepens further into an imbricate array of high-angle reverse faults which are expressed by bedrock outcrops, high local relief, and elevated topography in an block of the crust known as the Seattle Uplift (one or more of the faults appears to have been reactivated as an antithetic normal fault). These vergence-perpendicular reverse faults are segmented by dextral strike slip faults, which underlie the elongate bays and lakes of the Puget sound area (Johnson, 1997).

Northern motion of the hanging wall of the thrust has raised dense Eocene ocean-floor volcanics (Crescent Formation) above the unconsolidated Neogene sediments on the footwall block, creating one of the strongest gravity gradients known (5 mgal km^{-1}; Finn et al., 1991). North of the uplift lies the Seattle Basin, which resembles a miniature foreland basin in that its origin results from flexural loading . Approximately 10 km of sedimentary strata have accumulated in Seattle Basin since late Eocene time, and the evidence for crustal contraction and vertical uplift is especially strong for the last few million years. For example, a small basin at the south end of Lake Washington contains as much as 600 meters of Quaternary strata (Sam Johnson, personal comm.). Quaternary sediments beneath Puget Sound have been folded into a pattern suggesting active fault slip at a rate consistent with vertical uplift of latest glacial deposits (Vashon = 18-20 ka; Thorson, 1993, 1996). Pre-Vashon glacial strata in the South Whidbey Island Fault Zone have also been strongly arched and faulted (Johnson et al., 1996).

Near surface data from the Puget Lowland, or those collected during the historic period provide little, if any, support for the thrust sheet model (Figure 1b). Horizontal strain, as measured geodetically, does not show the expected northward contraction of the network (Savage et al., 1991); rather, it portrays a pattern of weak forearc compression parallel to the direction of subduction (68^{o} azimuth). The regional pattern of measured vertical land movements reconstructed from first-order leveling, and extended to 1899 with tide-gauge data, exhibits a regional pattern of that, although complicated by significant anomalies, is also consistent with active subduction (Holdahl, et al., 1989). Direct measurements of *in situ* strain are limited and ambiguous. Microearthquakes, especially for those in the upper crust, are weakly localized along strike-skip faults, but otherwise exhibit an unusually diffuse pattern concentrated in the area beneath the Seattle uplift (Ludwin et al., 1991). Ironically, damaging historic earthquakes in the Puget Sound area occur, with rare exception, beneath the North American continental crust, rather than within it (Rogers et al., 1996).

The apparent conflict between geologic and historic data is an artifact of the chronological aperture used by these different approaches. At time scales of 10^{5}-10^{7} yr the monotonic driving stress caused by the interaction of three plates -- North America, Pacific, and Juan de Fuca -- cannot be released evenly in time or space because the crust beneath the Puget Lowland is brittle and extremely heterogeneous. A host of specific physical mechanisms -- inelastic effects, block rotation, contagion (stress transfer), thrust propagation, temporal clustering -- are available to render a predictable pattern of applied stresses into a nearly intractable pattern at shorter time scales (Yeats et al., 1997; Rogers et al., 1996). At its simplest, the conflict may boil down to the fact that the historic period lies within the recovery phase of the earthquake cycle for the PLTS.

Thus, tectonic models, which are so vital for establishing the conceptual framework on which earthquake hazards are assessed, lack the chronological sensitivity for predicting *any trends*, much *less earthquake trends*, during the human time frame. Conversely, historic data have the required temporal sensitivity, but the record is much too short to be of great significance , especially where the strain rates are so low . Paleo-seismic techniques, especially at the millennial scale, are clearly required.

Shoreline Paleoseismology

Lake Washington provides an ideal place to reconstruct the long-term surface tectonic deformation associated with the Puget Lowland Thrust Sheet. The southern third of the lake extends across all known and inferred strands and folds of the Seattle fault zone, a listric, high-angle reverse fault in bedrock that has been active since the Eocene (Johnson et al., 1994). The northern two-thirds of the lake transects the Seattle Basin, a strongly asymmetric flexural basin. The lake is deepest (and Holocene peat the thickest) immediately north of the fault, suggesting that tectonic stresses may be reflected in both the present topography and its shoreline stratigraphy.

East of Lake Washington at Alki Point, Seattle (Thorson, 1996) and Restoration Point (Bucknam, 1995) displacement during the 1100 yr coincided with back-tilting of the uplifted block. Differential late Holocene displacements along the shoreline of Lake Washington north and south of the Seattle Fault Zone (Thorson, 1977) showed that this style of motion may also characterize the eastern part of the fault zone where it crosses Lake Washington. In this vicinity, abrupt regression took place on the uplifted block, with uniform submergence to the north, in the Seattle Basin. The best evidence for shoreline uplift to the north is from the spit at Nelson Point in Juanita Bay, which is reviewed later in this document.

Lake Washington occupies one of the narrow, steep-walled troughs of Puget sound that were cut by meltwater and ice erosion beneath the Puget lobe of the Cordilleran Ice Sheet prior to 14 ka (Booth and Hallet, 1993). The southern end of the lake rose above sea level by 13 ka, converting the basin to freshwater (Leopold et al., 1982). Lake level has since been regulated by the height of an alluvial fan / delta built by the Cedar River at its mouth, which has aggraded strongly during Holocene time, depositing nearly twenty meters of interbedded sand, silt, and peat since the Mazama tephra, about 6.9 ka (Mullineaux, 1970; Bacon, 1983). Since that time, the shoreline has been characterized by net transgression, the development of a broad wave-cut platform above 15 m depth, and the maintenance of steep bluffs along the shoreline.

Lake Washington was changed dramatically during navigation "improvements" during the early 20th century (Chrzastowski, 1983) . Pre-historically, the lake was rather stagnant (Edmonson, 1992), and its only important inlet was the Sammamish River. Discharge from the Cedar River, at least under normal conditions, bypassed the lake via the Black River, Cedar River inflow taking place only during strong floods. The total flux of mineral sediment to the lake bottom was low because fluvial inputs were supply limited (Booth, 1993) and because wave power was limited by fetch; where erosion did occur, the beaches became quickly armored (Downing, 1983). The shoreline is now carefully regulated to a mean height of 21.0 feet above tidal datum (MLLW), which is 8.9 feet lower than its unregulated average height prior to the 20th century, and no longer experiences the former seasonal variability of about seven feet. The benthic deposits of the lake are difficult to sample, owing to their high water content, weak strength, and high compressibility. They are carefully and thoroughly reviewed by Karlin and Abella, 1996).

Research Methods

Coring

Twelve aluminum vibracores were taken from the northern end of Lake Washington in October, 1997, using a barge operated by Marine Sampling Systems, of Burley Washington (Figure 2.) Each core was taken using a 17-foot-long (5 m) aluminum tube that was lowered into the muck, then vibrated into position to refusal. Four days of field work were required to complete the sampling.

One core JB-1 was taken from Juanita Bay, just inside of a pronounced, relict bar at the same general elevation as the delta platform of the Sammamish River, in what turned out to be a favorable cross-check on our results. The bar morphology was confirmed by several sonar traverses, and its composition by a bucket dredge, which brought up loose sandy gravel. This relict bar and its lagoon formed at a time when the shoreline was stable enough for a spit to propagate nearly across Juanita Bay, followed by a transgression rapid enough to allow preservation of the relict bar.

The remaining core localities were arranged in the form of an “X-shaped” traverse centered in the middle of the delta platform (SR7). Two cores in progressively deeper water (SR4 and SR3), and two in progressively shallower water (SR5 and SR6) are linked into a north-northeast trending longitudinal traverse. A cross-traverse, trending west-northwest, and consisting of cores SR10 on the west and SR9 on the east, intersected the longitudinal traverse at SR7. Location coordinates were determined with a Loran GPS system. Depth measurements were taken by shipboard sonar.

Coring was difficult owing to the soft, almost undefined contact between the algal gyttja and the water. To take the cores, an A-frame was lowered to a position just above the soft bottom of the lake. The core barrel was then lowered through the gyttja until it began to penetrate firm material (peats and sand / gravel), after which the A-frame was allowed to sink for stable support. The depth to the base of the core below lake level (+6.89 m above mean sea level) was determined by adding the depth of the core barrel to the depth, as determined by a pressure transducer at the top of the core barrel, which projected above the muck. This allowed us to reconstruct not only the depth of penetration, but the rate at which penetration occurred, a surrogate for the bulk strength of the sediments being penetrated. This allowed us to accurately establish the elevation of the base of the core barrel; based on repeated trials, we estimate the error associated with datum is less than a half-meter, although cannot defend this error statistically. Basic data for each of our cores is summarized in Table 1.

Laboratory

Cores were spilt in Seattle. Half were archived at the University of Washington where Estella Leopold and here graduate students are in the process of describing the paleoecology of the cores. A summary of their paleoecological findings will be published with our results. The second split was shipped to Thorson's lab at the University of Connecticut, where they were inventoried and described.

Compaction is a serious problem under some circumstances (Aaby, 1986). Its effects were minimal in our study because all of our measurements were made form the base of the core, because the marsh sequence was thin and lay above stiff sands, and the because the overlying gyttja had low bulk densities.

Core descriptions were done following conventional procedures by breaking up each core into units and subunits. The qualitative abundance of mineral vs. organic matter was self-evident when the cores were allowed to dry. Each was divided into units and subunits. Confirmation of the Mazama tephra was made by a routine petrographic scan, with no further analyses made. No more than one tephra was present within every core. After description, it became apparent that nearly all of the cores had the same basic three-part stratigraphy, which was first described and interpreted by Gould, Buddinger, and Ragan (n.d.), and in which sand and gravel of the delta platform is overlain first by a complex marsh peat, then by an overlying gyttja unit extending to the surface.

Dating

Samples for radiocarbon dating were selected on the basis of available material near the significant lithological breaks between facies. To the extent possible, we attempted to date the top of the peat facies in every core. All of the samples were run by Beta Analytic, Inc. Two of the samples were given extended counting.

Project Results

Dating

Dating is summarized in Table 2. All together 13 radiocarbon dates, 6 of which were AMS dates, were obtained during this study. All include 13C corrections and have very small analytical errors. The oldest date of 8670+/-70 years BP, is also the lowest relative to sea level; the youngest date of 850+/-60 is the highest. The Mazama tephra, present in 5 cores, dates to 6900 yr BP.

Three Facies:

Laboratory descriptions of each core were complex and tedious, consisting of variations in sedimentary structures, composition, texture, contacts, sequences, secondary disturbances, etc. At this stage of our analysis, we interpret all of the details to reflect highly local, idiosynchratic variations on the delta platform involving seasonal shoreline variations, flood events, reworking, and bioturbation. They are not worth reviewing here, because they added nothing to the basic story. We discovered this only after weeks of analysis. All of our stratigraphic analysis can be distilled down to three basic facies first recognized by Gould and his colleagues in the 1950s. We summarize them in Figure 3.

Clastics: consisted almost entirely of inorganic mud with interbedded sand horizons, erosional at the top, and coarsening upward. The absence of detrital organic remains was conspicuous.

Interbedded Marsh Sequence. This facies was easy to recognize by the presence of discrete detrital and in-situ horizons of peat, often with whole logs and woody debris. Beds and lenses of sand, some of which were cross-bedded, were common within the peat sequence. Organic silt and fibrous gyttja were also present in minor amounts.

Gyttja.: Overlying the marsh sequence was massive to weakly banded lacustrine unit consisting largely of fine-grained organic detritus. All but the lowest part of this sequence was highly disturbed by our coring technology. This material has been exhaustively described by other investigators (e.g. Karlin and Abella, 1996) and was not a focus of our studies.

Growth of the Delta

The relatively flat surface of the delta platform coincides with the well-defined wave cut platform first described by Gould and Budinger, 1958, as well with the submerged bar which guards the entrance to Juanita Bay. The wave-cut platform, now plainly visible on NOAA bathymetry at the quadrangle scale (Figure 2), extends to depth of approximately 15 meters, and appears to be independent of lithologic variation in the lake-Quaternary glacial cover. The coincidence in elevation between the wave cut platform, the bar at Juanita Bay, and the Sammamish Delta platform suggests that they were driven by the same lake level variations at the outlet, and that the delta platform itself may be, in part, erosional. The three facies of the delta platform are, however, generally conformable, indicating progressive submergence, rather than erosion.

Chronological control for the wave-cut shoreline is absent, except at its highest point, where it was being cut in 1917, just before the lake surface was lowered. The thin accumulation of lagoon sediments (-4.70 and -5.13 m elevation) behind the relict bar at Juanita Bay (Figure 3) yielded a basal peat date of 6030 +/- 50 yr BP, which is also close to the age of submergence.

Seven dates from the central part of the delta platform, including the occurrence of the Mazama tephra in 5 of the cores, indicates that much of its surface was covered by a freshwater marsh from about the time of the Mazama tephra until sometime after about 3780 +/-50 yr BP. Curiously, the transition from marsh to gyttja at the top facies is rather abrupt in most places. Additionally, the amount of mineral sediment within the overlying gyttja is slight, regardless of how sandy the estuarine sediments were. This suggests that the Sammamish River during this interval was not particularly active in terms of sediment input. Furthermore, there is no indication that the mid-late Holocene lake level was ever stable enough to permit either aggradation of the delta or the development of an erosional scarp at a higher level. This suggests that the bulk of the delta fill must date from late-glacial times, when the sediment load from the Sammamish River was higher, and to a time when the lake surface was relatively stable.

The bathymetric profile of our longitudinal traverse suggests that there are three general levels to the delta platform. Its outer fringe from SR-4 to SR-3 and its inner fringe from SR-5 to SR-6, both have a steeper slope than the bulk of the platform. I suggest that the bulk of the delta platform was created during a time when the rate of transgressison was slower than either before or after. This period of relative stability could have taken place during the mid-Holocene deceleration in the rate of sea level rise, yet before the Duwamish embayment was filled at the site of the present Black River. By association, this would also have been the time when the bulk of the wave-cut platform was cut.

Submergence Curve

Submergence of the Sammamish Delta platform began about 8670 yr BP, and was still on-going when the lake was lowered for navigation purposes in 1917. Each data point on the curve represents a radiocarbon sample taken near the top of the fibrous peat unit of the estuarine marsh, and is thus a closely limiting minimum age; the data points are drawn large enough to capture the vertical error and dating error. Our curve, reproduced as Figure 4, shows that the level of “Lake” Washington was coincident with that of marine sea level for most of Holocene time. Data for sea level shown in open squares were obtained from the review by Dragovich et al., 1994, and include the full range in error.

The Osceola Mudflow, which occurred about 5700 yr BP, was a critical event in the history of Lake Washington. At that time, the Duwamish embayment was an open marine estuary, to which both the Cedar River and Lake Washington drained. The present floodplain of the Black River was not yet built. After the Osceola Mudflow, a laharic fill of the White River Valley, the Duwamish Valley filled rapidly the delta of the Duwamish River prograded northward. Curiously, its form was nearly identical to that of the Sammamish delta as it moved northward. Dragovich et al, (1994) estimated that progradation too place at an average post-Osceola rate of 9 m/yr. At this rate, the 20 km between the delta front at Osceola time (near Auburn) and the outlet of Lake Washington would have filled in about 2200 years. This would bring the edge of the Duwamish delta to the present position of the Black River floodplain at about 3400-3500 yr BP. Interpolation of our Lake Washington submergence curve suggests that the lake rose above contemporaneous sea level at about this time. Thus, the removal of Lake Washington from direct control by sea level was a delayed consequence of the Osceola mudflow, without which the lake would probably still be died to sea level.

Isostatic recovery was a second important control on the submergence of Lake Washington. It is clear from the work of Leopold et al., 1982 and Rigg and Gould, that Lake Washington has remained freshwater since about 13,000, when it emerged above sea level. All of these old dates, however, are on sedimentary peat, or gyttja, rather than on terrestrial, nearshore peat. It may be no accident that no terrestrial peat is present at Mercer Slough, Union Bay, Juanita Bay, or the Sammamish Delta that predates the interval 9,000-7,500 yr BP, which is the period of maximum emergence in the Puget Lowland, which took place because local isostatic recovery was essentially complete long before sea level stabilized. Because the oldest terrestrial peat in Lake Washington coincides both in age and elevation with contemporaneous sea level, I suggest that the transgression of lake Washington began at this time, rather than much earlier.

Historical Stages of lake Washington

Research to present has demonstrated three stages in the history of Lake Washington: an early marine phase associated with isostatic depression; a long postglacial phase associated with a dam at the mouth of the Cedar River, and a brief modern phase since lake lowering in 1917. Our work on the Sammamish delta confirms the existence of these stages. But our work, crude as it is, also indicates that this history is far too simple. We interpret the existence of a minimum of six stages, each with its own threshold event.

- Stage 1. Prior to 13,000, the lake was a marine embayment during a time of rapid, but decelerating isostatic uplift.

- Stage 2. About 13,000 yr BP it became an isolated freshwater lake when, under periglacial conditions, the alluvial fan at the mouth of the Cedar River prograded rapidly across the south end of the lake, permanently isolating it from the sea.

- Stage 3. Between 13,000 and ca. 9000-7500 yr BP the lake persisted as an isolated body of freshwater with a stable (or possibly declining) level draining across what is now a buried relict fan. At this time, the fan at the mouth of the Cedar River had been uplifted (isostatically) above sea level, allowing the river to channelize itself to the west, making it difficult to prograde northward. If, however, the flow was periodically avulsed to the north, the bulk of its sediment would have been diverted into the south end of the lake, rather than raising its outlet. During this stable phase: (1) the wave-cut platform around the lake shoreline was initiated, (2) the great bulk of the Sammamish delta accumulated, and (3) sedimentary peat accumulated in protected embayments like Mercer Slough and Union Bay. At this time there was little net transgression, if any, although the shoreline may have fluctuated.

- Stage 4 took place between 7500-9000 and about 3000 yr BP. This stage began when sea level reached the former stable (entrenched lag) outlet of Lake Washington, flooding it, and beginning a transgression tied to rising Holocene sea level (e.g. Stanley and Warne, 1994). The sedimentation rate of the Cedar river was sufficient to keep pace with rising sea level, allowing the lake to remain freshwater. Its outlet over the Cedar River delta, was fixed to near sea level via a negative feedback mechanism in which the delta could not aggrade, otherwise its channel was rapidly downcut through the soft sediments to equalize base level on both sides. Transgression took place in small increments (ca. 20-70 cm; Figure 5) as flood events in the Cedar River lead to a slackwater accumulation at the point of flow divergence, leaving behind a net increment of transgression (Figure 6). Were it not for the size of the delta, and the limited change in elevation, this aggraded zone in the channel would likely have been eroded.

- Stage 5. Between about 3000 yr BP and the year 1917, the lake rose in response to the height of the Duwamish floodplain to the west, during a time of relatively stable sea level. The Duwamish continued to rise as its delta prograded northward, and the rate of rise, was controlled by the delta geometry. A steadily rising Duwamish River to the west and an accumulating fan of the Cedar River to the east, would have maintained the present floodplain of the Black River as a backswamp, which would likely have been submerged completely during periods of regional flooding. Its gradient was so low, that levee breaks from the Duwamish may have even back-flooded Lake Washington if the Duwamish River crested before the Cedar. The aggradation mechanism at the outlet to the lake was nearly identical to that of the preceding period, and its rate was, within the limits of chronological control, comparable, although for different reasons.

- Stage 6. Beginning in 1917, the lake was drained via an excavated canal which lowered the lake surface by about 8.9 feet, decomposing the peat accumulated during the last several thousand years, and exposing the wave cut platform. The lake bottom has changed dramatically in response to the reconfiguration of its drainage.

Discussion

The recent (1100 yr BP) paleo-earthquake in the shallow crust beneath Seattle poses a vexing problem for paleoseismological analysis because of its enormous displacement (> +7 m), and because it is the only such event known in the postglacial record (Bucknam et al, 1996). Although claims for frequent damaging earthquakes in the Seattle area have been put forth (Karlin and Abella, 1996), alternative explanations based on more mundane explanations, are now available (Thorson and Leopold, 1996). Despite more than a decade of intensive research in the central Puget Lowland, nothing even remotely comparable to the 1100 year event has been found. Thus, there is no known recurrence interval, no “characteristic” earthquake, and no constrained way of estimating its magnitude.

In spite of these uncertainties, Pratt and others (1997), using inferred fault geometry, estimate that an exceptionally large magnitude (M=7.6 to 8) earthquake would be required to generate the observed Restoration Point uplift by thrusting. Convincing geologic evidence for the catastrophic ground motion expected from such an event, however, is limited to the presence of rockfall avalanches in the southeastern Olympic Mountains (Schuster et al., 1992), which lie further from the zone of fault rupture than comparable settings in the Cascade foothills, and closer to the plate boundary, where mega-thrust events are generated (Atwater, 1987). The sub-aqueous landslides in Lake Washington were likely associated with shaking, but they could have also been triggered by transient changes in pore pressure associated with submergence or by seiching in the elongate closed basin. The contemporaneous tsunami (Atwater and Moore, 1992) reflects the displacement of water. The Restoration Point uplift appears to have been anomalously large, relative to its strike length (Wells and Coppersmith, 1994; Stewart and Hancock, 1994). There is little question, that the 1100 year event represents contraction on the northernmost strand F of the SFZ, yet it remains unclear how much of the thrust zone was involved.

Resolving this issue requires that the co-seismic displacement along the fault (Restoration Point Uplift) be interpreted within the context of the earthquake cycle. The backwards extrapolation of measured historic trends will not suffice because this technique requires a ninefold extension of the notoriously short record. Nor will the forward extrapolation of geologic trends whose temporal resolution is an order of magnitude lower than required. The strategy of capturing a discrete event amidst the pattern of background change was clearly the key to the recognition, and subsequent verification of multiple, late-Holocene thrust earthquakes on Washington's outer coast by Atwater (1987). Robert Bucknam and his colleagues are following a similar strategy in Puget Sound, but their progress has been confounded by the low rate of background strain and more complex geology. We adopted this strategy in our search for a paleoseismological signal from the freshwater marshes of Lake Washington.

The results of this project can be applied to the dilemma posed by the 1100 year event in five ways, four of which are reviewed below.

- First, and most simply, we looked for evidence of the event in the disturbed tops of our course, and found nothing notable.
- Secondly, we examined the submergence curve of the Sammamish Delta for anomalies that may be of tectonic origin.
- Thirdly, the recovery of Mazama tephra in peat at the north end of the Lake allowed its use as a strain marker for comparision with other known occurrences of tephra in peat.

- Fourthly, we review evidence for abrupt uplift.
- Finally, we develop an alternative explanation for the so-called seismic turbidites used as evidence for the frequent recurrence of large earthquakes.

Inflections in Submergence Curve

We had hoped that the submergence curve could be more detailed so that inflections upon it might be interpreted tectonically. Our data are insufficient to do this. Now that we know its basic form, however, upgrading the quality of the submergence curve is simply a matter of more cores, more dates, and more money. Curiously, the elevation of Lake Washington at the moment when it was lowered 9 feet was about two meters above the long-term trend for Holocene time. Whether this is due to uplift of the outlet to the south, or to more rapid rates of transgression cannot be determined, although the former case is more probable, especially since other rates (sea level, progradation of the Duwamish, and the allometric constraint on vertical accretion of the Cedar River Delta) have all slowed.

A corollary to our finding that the submergence of the Sammamish Delta tracked sea level for much of the Holocene is that there must have been no net subsidence of the area relative to sea level. It is neither higher nor lower than contemporaneous sea level, at least within the error associated with marine deposits.

Strain marker

A shoreline marker for shoreline deposits of Lake Washington could be used to capture the 1100 year co-seismic offset within the background of inter-seismic strain, which, in turn, could be used to constrain different elastic dislocation models (Stein and Yeats, 1989) for the 1100 year thrust event. Finally, we have found such a marker -- the contact between the 6,900 year old Mazama tephra (Nelson et al., 1988; Sarna-Wojcicki, 1983; Bacon, 1983; Powers and Wilcox, 1964) and the contemporaneous marsh peat on which it fell -- but the water-level resolution of the marker is low. In principle, use of this marker is similar to Thorson's use of late-glacial deltas to reconstruct the net crustal deformation in the Puget lowland (Thorson, 1989; 1993), but the spatial resolution is improved by an order of magnitude, the chronological resolution is cut in half, and the data set lies in a complete transect across the Seattle Fault zone. A similar technique, but one using a shorter transect involving a Pleistocene lake-bottom marker (Lawton Clay) has been proven effective in imaging the details of crustal displacement during the 1100 year event (Thorson, 1996).

The Mazama tephra has been carefully dated in a variety of settings, including Lake Washington (Leopold et al., 1982; Karlin and Abella, 1996). We will adopt the general age of 6900 yr. This tephra can be readily identified in the field because it is the only known distinctive tephra within the marsh stratigraphy of Lake Washington. Its phenocryst mineralogy is dominated by plagioclase, hypersthene, horneblende, augite, apatite, and a glass chemistry characterized by low silica, and high iron and titanium content (Sarna-Wojcicki, 1983). Where we have encountered the Mazama, it is a white, glassy, graded, primary airfall tephra approximately 2-4 cm thick that is bioturbated, but intact. Re-deposition of ash in an aqueous environment -- indicated by the presence of depositional laminae, the absence of uniform particle size grading, and interstratified organic remains -- did not take place in our marsh deposits.

We know of four localities from Lake Washington where the Mazama is caught within marsh peat which accumulated near a shoreline. Fortuitously, the localities extend the full length and width of the lake:

- Sammamish Delta: The Mazama tephra was found in five cores from the delta platform, four of which are shown on Figure 3.. It lies within fibric estuarine peat presently being examined for paleoecologic setting, ranging in elevation from **–5.45 to –9.35** meters, with a mean value of **-6.96** meters below sea level.
- Union Bay; McManus (1963) described a distinctive layer of Mazama tephra within terrestrial peat at a depth of 12.5 m beneath Union Bay, on the western side of the Lake. Using a lake-level height of +6.89, the tephra fell on the marsh when it lay at an elevation of **–5.61** m.
- Mercer Slough; Leopold et al. (1982) and Newman (1983) located Mazama tephra at a depth of 13.5 m on the eastern side of the lake at the southern edge of the Seattle Basin. This depth corresponds to an elevation of **–6.61 m**.
- Renton Delta; Mullineaux described a conspicuous ash interpreted as the Mazama tephra in Holocene sediments at the fringe of the Cedar River Delta at the southern edge of the Lake. He reported the tephra to lie at a depth of about 60 feet (18.29 m) below a surface about 10 feet above lake level, which is 6.89 m elevation. This places the ash at an elevation of **-8.61** m. This sample was from distal fine-grained alluvium, and has likely been compacted by the overlying alluvium. Thus, it provides a minimum, rather than actual, depth for the contemporaneous lake level.

The range in elevation for the tephra at the Sammamish Delta (-0.45—9.35) encompasses the full range in elevation for the tephra at the other three sites (-5.61-<-8.61), meaning that, for all practical purposes, the datum surface is horizontal, within an error of +/- 2 meters over a distance of 26 km, a trend that extends across the strand of the SFZ that ruptured 1100 years ago. This indicates that substantial displacement (>4 m) has not occurred. Previously, in an unpublished proposal, we interpreted that there was a slope to this tephra horizon. Now we are aware of its variable depth.

The present differential subsidence between Seattle and Tacoma based on tide-gauge and first-order leveling data (2.86×10^{-8} yr^{-1}) over a comparable distance of 40 km (Holdahl, 1989) falls within the error of the tephra datum horizon. This interpretation applies regardless of whether data point at Renton lies in a separate tectonic basin (Sam Johnson, personal communication, Nov. 1997). The much slower long-term subsidence of the Seattle Basin, which has been tilting southward since the late Eocene (40 Ma), also falls within the error associated with the tephra horizon. When measured over the total sediment thickness (9-10 km) along its full length (25 km) and age (40 Ma), the post-late Eocene rate of subsidence in the Seattle Basin yields a net tilt of 0.83×10^{-8} yr^{-1}, assuming that the basin is pinned at the Kingston Arch.

Thus, modern instrumental subsidence is rapid by geologic standards, and is taking place during a regime where the evidence for north-south contraction in the shallow crust is weak, yet this is the time in which the Restoration Point uplift occurred. This apparent paradox deepens the enigmas surrounding the origin of the 1100 year event, and raises the possibilities that one or more subsidiary factors were at work. For example, the 1100 year event: May have been triggered externally, either by a subcrustal earthquake or from the subduction zone to the southwest; May have been amplified by compression associated with downward flexure; May have been associated with delayed vertical stress associated with glacio-isostatic relaxation, a speculation for which there is both theoretical support (Johnston, 1987) and geologic evidence (Dragovich, et al., 1987). More explicitly, deglaciation in the northern Puget was accompanied by a delayed ($1\text{-}3 \times 10^3$ yr), localized ($10^2\text{-}10^3$ km^2), temporally unique block-like uplift of the surface *exceeding 30 meters* that seems was bounded by a pair of conjugate thrust faults. Something similar, but much lower and later, *could have* taken place beneath Seattle.

We are attempting to improve the resolution of the tephra data horizon. In Mercer Slough, we have characterized the elevation zonation of peats for the following associations, and have calibrated them against a detailed vegetation map commissioned by the City of Bellevue (1988): Wood-dominated terrestrial, *Alnus rubra/Loicera involucrata-Rubus spectabilis/Lysichitium americanum*; Wood and herbaceous peat at the shoreline, *Fraxinus latifolia-Alnus rubra/Lonicera involucrata* Near-shore (<0.15 m), *Spirea douglasii/Phalaris arundinacea, Typha latifolia-Juncus effusus.*

Abrupt Uplift

One of our stated goals of this research project was to look for evidence of the 1100 year old earthquake in the Sammamish River stratigraphy, which were so prominent in our earlier investigations of the modern shoreline. Although there were isolated bands of sand and concentrations of organic matter high in the cores that could be related to the 1100 year event, they did not provide unambiguous, or even suggestive, evidence for the event. Evidence probably was present in the upper gyttja horizons, which were too soft for us to sample with our technology.

Recent interpretation of evidence from three of the fourteen freshwater estuaries reported by Thorson (1977) -- Mercer Slough, Yarrow Bay, and Juanita Bay -- can be synthesized into a model for abrupt uplift of the shoreline, as well as the origin of prominent pulses of alluminosilicate detritus (silt bands) claimed by Karlin and Abella as evidence for recurrent earthquakes. Our three localities form a transect on the eastern side of the lake in the direction of increasing storm wave energy (Downing, 1983, p. 63). Modern shoreline features are incipient relative to those active in 1916 when the artificial regression of nearly 3 meters caused beaches to be abandoned, freshwater marshes to be degraded by surface soils, and wave-cut cliffs to become stabilized.

Yarrow Bay: Yarrow Bay provides a representative example of the Holocene marsh stratigraphy in the Seattle Basin. Core LW95-7/18 #1, the deepest from a transect across a north-facing embayment protected from strong waves, begins at a depth of nearly five meters with oxide mottled "blue clay," a provincial term for the stony glaciomarine and glaciolacustrine sediments that underlie much of the Lake Washington Basin. An overlying muddy sand with fragments of detrital wood records the initial submergence of the site by the transgressing lake, an event now estimated to be 3000 yr BP based the arrival of the Duwamish Delta to the present site of the Black River.

Most of the Yarrow Bay core is dominated by fibrous peat containing a mixture of plant fragments and gyttja, and which contains only small amounts of intermixed sand grains and mud derived from the small stream traversing the marsh; distinct lenses, bands or beds of silt are absent. This interval--containing as many as ten horizons that are either enriched in wood and(or) highly decomposed -- culminates with the undecomposed remains of rooted herbaceous plants in growth position that are surrounded by a matrix of gray lacustrine silt transported to the site as suspended load from the bay. This mineral silt grades first upward into shallow aquatic gyttja with a radiocarbon age of 1390 +/- 90

^{14}C yr B.P, then into fibrous and woody peat that are presently decomposing to form an incipient soil.

Most of the core accumulated during an episodic transgression of the Holocene shoreline. Each wood layer is a recurrence horizon, representing the shallow submergence of a formerly stabilized, shrub-covered surface, later followed by the accumulation of nearshore aquatic peat in shallowing water. Based on the frequency of wood layers, and probable age for the basal peat of about 3,000 years, each recurrence event had an amplitude of about 30-60 cm, and a recurrence interval of several hundred years. The radiocarbon age for the peat is compromised by an unknown carbon-reservoir error ranging from +700 years for open-lake gyttja to zero for fully terrestrial deposits (Karlin and Abella, 1995). Thus, the minimum limiting radiocarbon age for the bulk sample is too old by several hundred years. Given the range of uncertainty for the date (700-1400 yr BP), this unique significant influx of mud from the open lake coincides with the 1100 year old paleoearthquake.

Juanita Bay: Lakeshore wave energy reaches its maximum concentration at Juanita bay, where the lake's largest spit-lagoon complex (Nelson Point), its broadest beach (Juanita Beach Park), and its tallest wave-cut bluffs (Kirkland Bluffs) are linked as relict lakeshore system.

The Nelson Point spit, extending nearly 500 meters northward into Juanita Bay, was built by littoral transport of sediments eroded from the Kirkland Bluffs -- now largely stabilized -- which contain Pleistocene diamicts and slackwater muds in a bluff up to 30 m high and 3 km long. The spit is composed almost entirely of shingle/cobble gravel and coarse gravely sand, reaches a maximum height of about 3 meters above the present lake level, and is only slightly recurved to the east. It was growing slowly prior to the artificial lowering of the lake in 1916, but is now relict and thoroughly developed for homesites. The wave cut platform at the base of the bluffs to windward, was unusually large for the shoreline.

An older, now largely submerged, spit lies between Nelson Point and the southern margin of Juanita Bay. It is smaller, more recurved, broader, and is less gravely than the one at Nelson Point (which partially buries the lower, older one) and lies as a low peninsula within the present lagoon. This setting is similar to one described by Firth and others (1995) in which an older spit composed of glacial gravel was overwashed by a strong tsumani, followed by the development of a larger, younger one in response to an increased sediment flux from re-activated cliffs. Similarly, the field relations at Juanita require the following sequence of events: (1) slow growth of the sand-dominated older spit along a shoreline elevation approximating that of the present lake; (2) abrupt submergence and partial destruction of the older spit, possibly by a tsunami; (3) simultaneous destabilization of windward bluffs previously mantled by forested colluvium; (4) northward sediment transport of gravel in the swash zone at a rate that blocked wave access to the older spit; (5) eventual stabilization leading to the re-formation of a sediment-starved beach.

The nucleation of a new, and larger, spit is also evident within core LW95-8/18 #2 from the leeward lagoon. There, the highest organic peat is abruptly overlain by up to 40 cm of fine sandy mud that accumulated in the protected embayment, and which is now exposed at the surface. The contact between these units exhibits a sharp contrast in the macrofossil assemblage from wood-dominated peat to a lacustrine gyttja containing abundant aquatic seeds. The abrupt transition from nearshore peat to aquatic muddy sand, was almost certainly related to reactivation of Nelson Point Spit.

On the opposite side of Juanita Bay, a relict late Holocene wave-cut platform is eroded into late Pleistocene alluvium to the same height as the spit at Nelson Point. The upper part of its relict swash zone lies about 40-90 m landward and about 1.5-2 m above the present regulated shoreline, which now crosses an artificially graded and maintained section of an the swimming beach. The sediments immediately beneath the modern beach are dominated by massive and well-bedded medium to fine sands with detrital wood fragments. Based on their position relative to the wave cut platform just shoreward, they would have lain just offshore in the breaker zone of a sand-dominated dissipative shoreline prior to lake-level lowering. At a depth of about 1 m below the lake level we consistently encountered a conspicuous interbedded layer containing organic fine sand, cross-laminated cleanly washed sand, fibrous peat layers, and bark-covered wood chunks up to 10 cm in diameter interpreted as alluvium. One of these logs yielded a date of 1460 +/- 90 14C yr B.P.

We interpret these relationships to indicate: (1) abrupt transgression in which the former lagoon was submerged, (2) erosion of the younger (now exposed) wave-cut platform (Lorang et al., 1993), (3) abandonment of the higher beach during artificial lake-level lowering. If the pair of wave-cut platforms correlate to the pair of spits at Nelson Point, both took place sometime after 1.4 ka, yet long enough ago so that the coastal landforms were well developed. This interval encompasses the age of the equally unique submergence event at Yarrow Bay, and the well-established 1100-yr paleoearthquake.

In our earlier work on the Sammamish Floodplain, which lies at the head of the delta (Thorson; 1977) we reported the presence of a conspicuous horizon containing one or more coarse, cleanly washed graded sand beds (also containing abraded, detrital wood fragments) near the top of several Liivingstone cores. Following the work of Atwater and Moore (1992) we interpret this horizon to result from a co-seismic tsunami generated by the abrupt late-Holocene uplift recorded at Yarrow Bay, Nelson Point, and Juanita Beach. These cores were obtained from what was then the northermost, and shallowest part of the delta platform in a setting that would have intensified the effects of shoaling and transport of coarse sediment from offshore into the otherwise fine-grained deposits.

Abrupt changes in hydrostatic pressure caused directly by submergence of the Lake Washington shoreline (positive in the Seattle Basin, negative on the uplifted block) or indirectly by seiches, may have played a critical role in triggering the landslides bordering Lake Washington, all of which took place near water level. Submergence would have created a transient phase of vertically-directed seepage pressure along zones of high permeability, followed by a permanent decrease in effective normal stress. In contrast, emergence of a steep, saturated slope undergoing rapid drainage would have caused a net loss in lateral support and an increase in horizontal seepage. Both conditions, are particularly important for generating large block failures in consolidated glacial sediments of the type known to occur locally only at the edge of Lake Washington (Logan and Walsh, 1995).

Seismic Turbidites?

Sediment released from Kirkland bluffs during the 1100 year event was fractionated into a proximal gravel fraction stored in the spit at Nelson Point, a sandy mud fraction to the leeward, and a silt fraction that moved offshore, and was dispersed throughout the lake, some of which must have reached Yarrow Bay. Midway between these two points lies coring site TT-147-1, which is where silt bands in the deepwater record are most clearly expressed and well-dated (Figure 5). Karlin and Abella (1995) recognized that diatoms from shallow-water habitats (as well as a few from eroded Pleistocene glaciomarine deposits) are reworked into the lake-bottom silt bands, and that fluvial inputs are inadequate to account for their mass and lithology, so conspicuously absent of tephra fragments. We agree that an in-lake source is required to account for the silt bands. The field evidence from Yarrow and Juanita Bays, however, when viewed together, indicates that the sediment peat was derived primarily from erosion of the subaerial perimeter, although subaqueous landslides and debris flows undoubtedly contributed some sediment.

Mercer Slough: The submergence record at Yarrow Bay is and poorly dated, relative the much deeper peat sequences known from Mercer Slough

(Rigg and Gould, 1957; Leopold et al., 1982). To examine the pattern of submergence prior to 1100 yr BP in more detail, we re-measured and re-described an archived core (Core B) from Mercer Slough, which was described in detail by Newmann (1983). The lower half of the 18 meter core consists primarily of highly organic peat, dominated by mass and detrital gyttja. The top ten meters of the core is dominantly terrestrial in character. It terminates at the surface in a massive mineral silt now obliterated by the modern (regressive) soil, and which can be traced offshore and correlated to the 1100 year old silt event. Discrete woody in the upper ten meters are evident as abrupt decreases in the concentration of wood, or as transitions from blackened wood fragments, many with roots in growth position, to either fibrous peat or organic. We identified 21 reversals from the top of the core to the beginning of the wood-peat reversals, which we dated at 6100 +/- 160 to 1030 +/- 100 uncalibrated 14C yr B.P.

Each of the reversals indicates a transition from the terrestrial surface of a Spagnum marsh to a shallow aquatic environment (Newman, 1983). Although both conditions can exist simultaneously in a mire, the high frequency of reversals following a similar pattern in a single core indicates that they represent discrete submergence events, in this case, with an amplitude averaging 0.52 m and a recurrence interval of 270 years. Given the often arbitrary distinction between wood layers and gyttja layers, this recurrence interval for submergence horizons at Mercer Slough is strikingly similar to the recurrence interval for silt bands in the deepwater stratigraphy at Site TT-147-1 (270 years) for the same interval of time, suggesting that the two phenomena are causally related.

The silt bands that punctuate the otherwise monotonous diatomaceous gyttja of Lake Washington -- one of which is unequivocally associated with the paleoearthquake of 1100 yr BP -- have been carefully described by Karlin and Abella (1995). Although the origin(s) of the bands is still uncertain, Karlin and Abella interpret them as turbidites associated with subaqueous slumping initiated by seismic shaking during multiple prehistoric earthquakes. Their interpretation of a high-frequency (300-400 yr) earthquake signal is an anomaly in comparison with other paleoseismic indicators from the Puget Lowland (Bucknam, 1995), which yield evidence for only one unequivocal paleoearthquake. Also puzzling is the quasi-periodic nature of the alleged earthquake signal, given the extreme heterogeneity of the shallow crust and its complex Quaternary history (Thorson, 1996). Despite these objections, their interpretation of frequent late Holocene earthquakes remains for lack of an alternative mechanism to account for the silt bands.

We argue that <u>most</u> pulses of deepwater sedimentation were caused not by density-driven subaqeuous underflows, but by the vertical settling of Pleistocene glacial sediment eroded from perimeter bluffs, and advected within the epilimnion to the center of the lake by storm waves. Most episode of bluff erosion were initiated by an abrupt, albeit small, submergence event, which drowned, and therefore destabilized the forested colluvium around the lake perimeter. Most submergence events were caused by a rise in lake outlet, on the fan of the Cedar River at the lake's southern end. Finally, most episodes of outlet growth took place during flood events of the Cedar River on its rapidly accreting delta. Our model allows for the uniqueness of the 1100 year event (in terms of cause) while simultaneously allowing for its monotonous similarity to the other silt bands. If correct, it renders the paleoseismological interpretations of the silt bands moot.

The prehistoric outlet for Lake Washington, now obliterated by the city of Renton, was captured by a historic engineering map reproduced as Figure 6 that was prepared prior the artificial channelization of the Cedar River into Lake Washington (U.S. Coast and Geodetic Survey, 1902). At that time, the main channel had a broad, anastamosing pattern that entered the delta from the southeast, then curved around to join the Black River just below the southern margin of the lake. The original motive for channelization was the noted instability of its channel, and its southward erosion, which was undercutting prime real estate in the tun-of-the-century Renton. Five additional relevant features were portrayed on the map: the presence of a former abandoned, sand filled channels and sloughs, water-flow paths on the delta for some recent flood, the surface elevation of the delta plain to the nearest foot, the bathymetry of the channel, and the configuration of a flood-delta in the lake.

During the portrayed flood, the entire delta plain was submerged, and the upper section of the Black River was reversed, allowing the construction of a northward-directed flood delta into the southern part of the lake. Chinook Indians referred to this part of the Black River as*Mox La Push*, or river with “two mouths” (Buerge, 1985), a condition likely maintained because the mouth of the Cedar River lies directly opposite the junction between the troughs of Lake Washington and the Duwamish Valley. A “two mouth” configuration provides a mechanism for raising the lake outlet during floods because the bifurcation of flow at the delta apex would have created a broad slackwater zone within the main channel of the Black River immediately downstream from a sediment-laden river in flood. Any net deposition in this zone not later eroded when the Black resumed its southern flow would have raised the level of the outlet.

Deposition of sediment in the channel may have been the only mechanism involved in raising the outlet. But the apparent sharpness and regularity of both the silt bands and the recurrence horizons suggests that pulses of aggradation followed longer periods of stability. We suggest that such stability was caused by periodic avulsion of the main channel (Smith et al., 1989) to the south at times when aggradation towards the south end of the lake became so high that flow was diverted to the west. Flow to the west may also have been influenced by period avulsion of the Duwamish River from its Holocene channel, switching from the eastern side of its floodplain, where an abandoned meander belt is preserved (Palmer et al., 1994) to its western edge, where it is now permanently channeled.

Conclusions

- The shoreline of Lake Washington has a complex history that can be divided into six stages.
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- During most of Holocene time (until about 3000 yr BP) the shoreline elevation of Lake Washington was a dependent variable tied directly to sea level, which governed the height of the alluvial delta at the mouth of the Cedar River.

- Only after the Duwamish River prograded to the present site of the Black River about 3000 yr BP. did the postglacial outlet of Lake Washington rise above sea level.

- There is strong evidence (uplifted spits, submerged lagoon deposits, a pulse of mineral sediment on marshes, possible tsunami deposits, block landslides) for abrupt submergence of the northern part of the lake during the 1100 year event.

- A paleo-geodetic reference horizon defined by the Mamama tephra in freshwater peat has too poor a resolution to confirm slow rates of subsidence or depression along a transect parallel to the Seattle uplift / Seattle basin, but it is sufficient to constrain it within a vertical range of several meters.

- Multiple silt bands in the benthic stratigraphy are probably due to pulses of shoreline erosion associated with avulsion events on the Cedar River delta.

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