Glaciofluvial infilling and scour of the Puget Lowland, Washington, during ice-sheet glaciation

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ABSTRACT

The Puget lobe, the southwesternmost extension of the Cordilleran ice sheet, last advanced into the Puget Lowland of western Washington at about 15 ka. The advancing ice sheet deposited voluminous sediment on a prograding, proglacial outwash plain that extended from the Olympic Mountains to the Cascade Range, herein recognized as the "great Lowland fill." Subsequent overrunning by the ice sheet excavated deep linear troughs now occupied by the large lakes and marine waters of Puget Sound. Excavation of these troughs and valleys of the Puget Lowland required the net transport of about 1000 km^3 of sediment, almost entirely during ice occupation and primarily by subglacial water. These landforms of glaciofluvial deposition and erosion define the modern landscape here, emphasizing the importance of these processes in the region's geomorphology.

INTRODUCTION

The Puget Lowland of western Washington State displays abundant effects of ice-sheet occupation, a result of multiple advances of the Puget lobe of the Cordilleran ice sheet (Fig. 1) during several episodes of Pleistocene glaciation (Easterbrook, 1986). Below an altitude of about 1000 m, nearly the entire land surface has been created or modified by glacial processes. Because deposits of the most recent advance, the Vashon stade of the Fraser glaciation (Armstrong et al., 1965), are abundant and well exposed, the region provides an exceptional opportunity to examine the connection between glacier dimensions (reconstructed by Thorson [1980], Waitt and Thorson [1983], and Booth [1986]), glacier processes, and the geomorphic products of the glacier system. In particular, the modern landscape displays the effects of massive proglacial infilling followed by subglacial scour on a truly regional scale.

INFILLING OF THE PUGET LOWLAND DURING THE VASHON STADE

Great Lowland Fill

As the ice sheet advanced, proglacial rivers carried fluvial sediment away from the front of the ice. First named the Esperance Sand Member of the Vashon Drift by Mullineaux et al. (1965), this sediment is recognized in virtually every part of the Puget Lowland. Crandell et al. (1966) first suggested that this deposit may have been continuous across the modern-day arms of Puget Sound; Clague (1976) inferred that a correlative deposit (the Quadra Sand) probably also filled the Georgia Depression farther north.

In the Puget Lowland, sediment infilling was particularly likely, because the basin became a closed depression once the ice advanced south past the entrance of the Strait of Juan de Fuca, blocking the only sea-level drainage route. First lacustrine sediment (the Lawton Clay Member of the Vashon Drift; Mullineaux et al., 1965) and then outwash would have accumulated into ice-dammed lakes. The outwash initially would have prograded as deltas, analogous to those seen during ice recession (Thorson, 1980); with sufficient time for sediment accumulation, however, an extensive low-gradient outwash plain should have developed in front of the advancing ice sheet (Boothroyd and Ashley, 1975), herein recognized as the "great Lowland fill." With continued ice-sheet advance and outwash deposition, this surface ultimately would have graded to the basin outlet in the southern Puget Lowland.

The fill's depositional history is well determined and limited to at most 2000 or 3000 yr. This outwash of the ice-sheet advance did not inundate the Seattle area until shortly before 15 ka (W-1227;

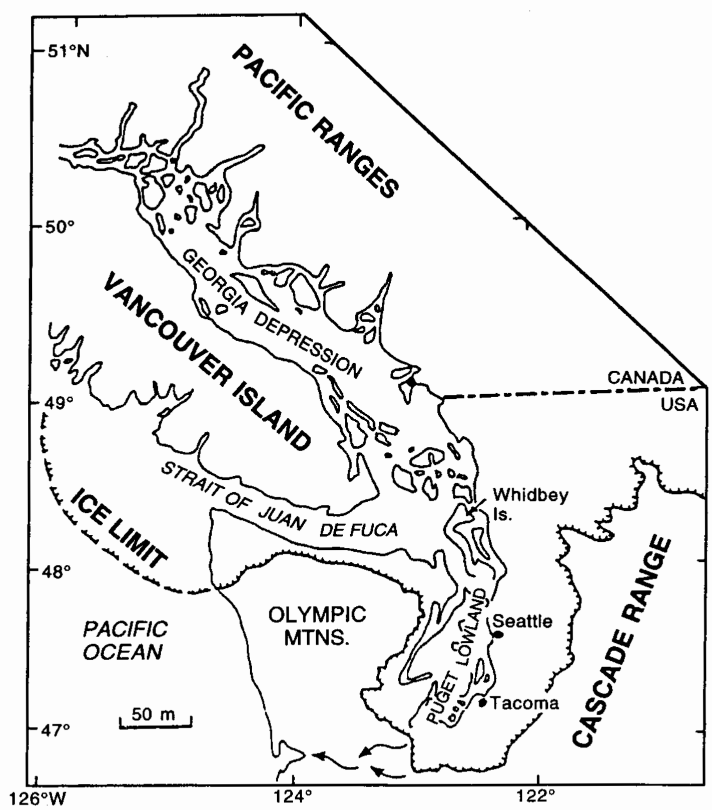

Figure 1. Location of Puget Lowland in northwestern Washington, showing southwestern limit of Cordilleran ice sheet (hachured line) during Vashon stade of Fraser glaciation, about 15 ka. When advancing ice blocked Strait of Juan de Fuca, meltwater from Puget lobe drained south and west through spillway system (arrows) that ultimately drained to Pacific Ocean (after Booth 1986, Fig. 1).

Mullineaux et al., 1965). Initial deposition may have begun as long as a few thousand years earlier, but until drainage out of the Strait of Juan de Fuca was blocked (about 16 ka), aggradation farther south would have been limited. Deposition must have been complete across the entire Lowland prior to ice maximum at about 14.5 ka (Booth, 1987) because basal till, reflecting the overriding by the ice sheet itself, caps the advance outwash almost everywhere.

Reconstructing the Fill

If this model of proglacial sedimentation is correct, the relict Lowland-wide outwash surface should be recognizable from landforms that best reflect the original altitude of the surface, if that surface existed. Geologic mapping throughout the region (see index map in Booth, 1991) demonstrates that the elevation of most topographic prominences across the Puget Lowland is, in fact, determined by the thickness of Vashon advance outwash. Existing mapping is not adequate, however, to accurately locate the elevation of the contact between this outwash and the overlying basal till. As a result, the till thickness, typically only several metres (and so only a few percent of the outwash thickness), must be ignored for purposes of this reconstruction.

By plotting the location and altitude of hilltops underlain by glacial sediment, I have generated a smooth topographic map of the original proglacial outwash surface (Fig. 2). With typical surface elevations of 120–150 m and highly variable basal elevations (but most commonly between 0 and 75 m; e.g., Booth, 1991), the reconstructed deposit averaged about 100 m thick. The axial slope of the reconstructed surface in the southern Lowland reflects drainage out the south end of the Puget Lowland, over the Black Hills and into the Chehalis River. That slope is not corrected for isostatic rebound (Thorson, 1989), because original deposition would have occurred prior to depression of the crust by the weight of the ice sheet. This outwash surface is not simply an artifact of the mapping conventions. Once recognized, its presence is readily apparent throughout the Puget Lowland (Fig. 3). Despite subsequent, localized excavation and incision (see below), this surface persists today as the most prominent single landform of the entire region.

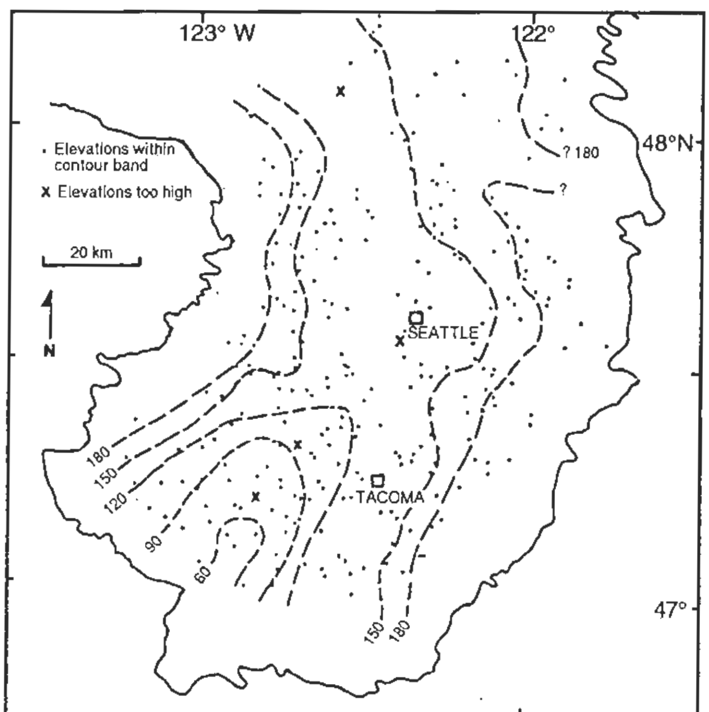

Figure 2. Smoothed topography of great Lowland fill. Mapped points form data set from which contours were generated; only those few noted as too high (X) are inconsistent with contours as drawn and also are not recognizably bedrock supported. Contours (dashed lines) in metres.

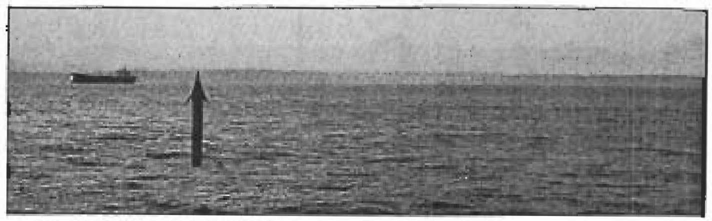

Figure 3. View of great Lowland fill, looking west from Seattle toward Olympic Mountains. Fill surface forms dark band (arrow), with altitude here of about 140 m above sea level.

Although the overall morphology of this surface is evident in both the modern landscape and the reconstruction, a few enigmatic characteristics remain. In particular, the surface is strongly concave along its eastern and western margins. To the east and southeast, isolation of progressively higher elevation drainage channels by bedrock spurs, coupled with inwash of fluvial sediment from extensive mountain drainages of the Cascade Range and Cascade volcanoes, readily explains the topographic relief. To the west, however, the contributing lateral drainage area is much smaller, yet the east-west gradient is even steeper. In the northwest corner of the Lowland, lateral channels are also isolated by bedrock spurs and help explain the elevation differences. Yet, in the southwest corner, the surface topography almost entirely reflects a broad, southeast-sloping plain of till-mantled outwash without bedrock constraint. The area of maximum elevation extends along and beyond the southwest end of Hood Canal, the westernmost trough in the Puget Lowland (Fig. 4). This correspondence suggests a region of enhanced sediment deposition immediately down-glacier of a major erosional feature (see next section), which was subsequently overridden by the advancing ice sheet.

The other unusual characteristic of the reconstructed surface is the mapping of particularly low axial elevations near the basin outlet. These locations probably reflect this reconstruction's unrecognized inclusion of recessional-outwash deposits that are incised into the older advance-outwash surface. The magnitude of this introduced error is unknown but probably affects reconstructed elevations only over a relatively small area, within about 30 km of the basin outlet.

GLACIOFLUVIAL EROSION OF THE LOWLAND TROUGHS

Prominent in any map of the Puget Lowland is the system of subparallel troughs (Fig. 4) that today extend to depths as great as 400 m below the surface of the glaciated uplands. These troughs were once thought to result from ice tongues occupying, and so preserving or enhancing, a preglacial drainage system (Willis, 1898). Because of proglacial lakes, however, any such tongue would have floated without any bed contact at all. Another obvious alternative, incision by subaerial channels during deposition of the outwash, is impossible because the lowest trough elevation is almost 300 m *below* the basin outlet. Thus, trough formation must postdate deposition of the great Lowland fill.

If the outwash surface was originally smooth, then the differences in altitude between the reconstructed surface and the modern topography will yield the volume of subsequently eroded material (Fig. 5). By this calculation, nearly 1000 km^3 of sediment has been

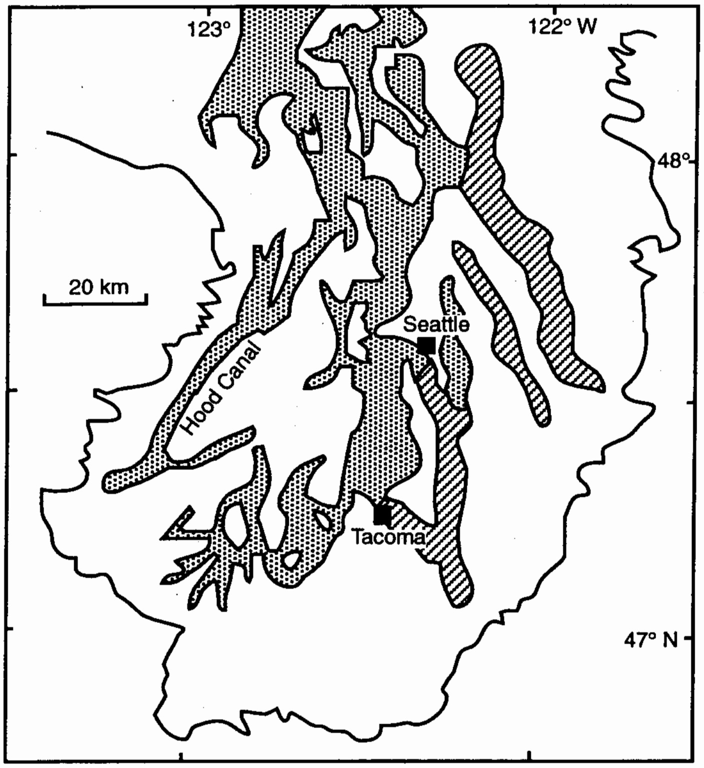

Figure 4. Limits of Puget lobe at maximum stage, showing modern topographic expression of deep lowland troughs, filled either with water (dot pattern) or Holocene sediment but inferred to have existed in late-glacial time (diagonal rule pattern).

eroded, equivalent to a layer about 100 m thick over the ice-occupied area of the Puget Lowland as a whole and remarkably similar to the estimated average thickness of the original fill. Of this eroded volume, trough erosion accounts for well over three-fourths; smaller upland valleys and channels supplied the balance. Because most of the troughs are several times deeper than the fill is thick, most of the eroded sediment must have been pre-Vashon in age.

This erosion into the great Lowland fill must have occurred after advance and outwash deposition and before subaerial exposure of the glacier bed during the ice recession. Significant postglacial erosion is precluded, because many of the eroded troughs are still mantled with basal till (see, for example, Booth, 1991) and filled with deposits of recessional-age lakes (Thorson, 1989). Thus, the troughs were formed primarily (or exclusively) by subglacial processes and probably throughout the period of ice occupation.

Postglacial processes have not significantly altered the products of subglacial erosion. For example, tidal currents in the modern channels of Puget Sound do not transport even chemical constituents out of the Strait of Juan de Fuča (Carpenter et al., 1985). Holocene erosion by rivers also has only limited effect, because denudation rates for the region (as inferred from modern drainage-basin sediment loads; e.g., Nelson, 1971) integrated over the past 13 ka are about two orders of magnitude too low. Lahars, however, have been locally important to the modern morphology of those troughs lying east and southeast of the city of Tacoma (Fig. 4).

These troughs were probably carved primarily by subglacial meltwater (see also Booth and Hallet, 1993). Their morphology is relatively unchanging between ice-sheet interior and ice margin, despite dramatically different ice fluxes (but not subglacial water fluxes; Booth, 1986) in these two environments. This inference also matches that of other recent investigators of Pleistocene glacier-occupied troughs and tunnel valleys, with remarkably similar dimensions and relief, in New York (Mullins and Hinchey, 1989), Ontario (Shaw and Gilbert, 1990), Nova Scotia (Boyd et al., 1988), and Germany (Ehlers, 1981).

The magnitude of subglacial fluvial erosion required to accomplish this geomorphic work is large but plausible. Glacial meltwater streams have notoriously high sediment concentrations. Measured annually averaged values include 0.0026 and 0.0049 m^3/m^3 (total load; Chernova, 1981) and 0.001 m^3/m^3 (suspended load; Gustavson and Boothroyd, 1987); reported peak suspended loads span about 2 orders of magnitude with a median value of about 5000 mg/L (which is ca. 0.003 m^3/m^3) (Smith, 1985). If it is recognized that peak concentrations may significantly exceed average concentrations and if one adopts both Smith's (1985) and Drewry's (1986) judgment that suspended load is about half of the total load in these environments, then 0.002 is a conservative estimate of total sediment concentration by volume. Multiplied by the average water discharge of 3000 m^3/s (Booth, 1986), the average sediment transport rate was about 0.2 km^3/yr. At this rate, the calculated eroded volume of the great

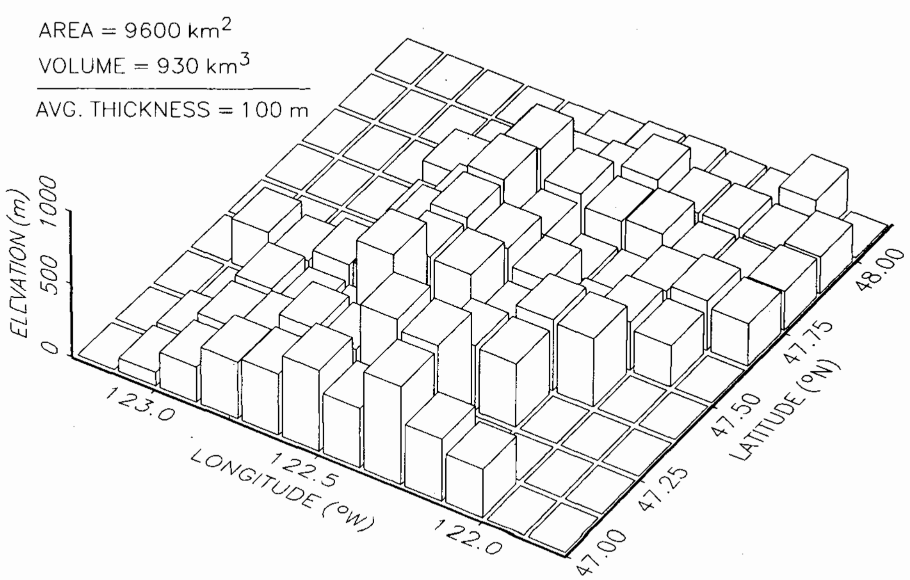

Figure 5. Eroded volume of great Lowland fill, calculated from difference between original fill surface (from Fig. 2) and modern topography. Because land exposures are sparse north of entrance to Strait of Juan de Fuca, this surface is only well defined in central and southern Puget Lowland. Each block represents area of one 7.5′ quadrangle.

Lowland fill (ca. 1000 km^3) could have been transported in about 5000 yr.

This time estimate is about twice what was actually available, requiring either (1) strong topographic relief in the proglacial outwash surface during deposition, a physically implausible condition; or (2) actual average sediment concentrations about double what is assumed here by analogy to modern flows. This second option is quite likely, either because small modern glaciers are imperfect analogues for the Puget lobe or because catastrophic discharges (as elsewhere suggested by, e.g., Sharpe and Shaw [1989] and Shaw and Gilbert [1990]) accomplished most of the sediment transport episodically at very high concentrations.

DISCUSSION

This reconstruction of the late-glacial erosional and depositional history of the Puget Lowland affects several interpretations of glacial processes. First, the rate of ice-sheet advance may be limited not by climatic factors but rather by rates of sediment production and deposition (Booth, 1987). High ablation rates along an aqueous (calving) margin (Meier and Post, 1987) probably limited ice advance to the rate at which outwash sediment prograded. Thus, the estimated rates of ice advance for the Puget lobe reflect only a *lower* bound on the independent magnitude of climatic forcing during the Vashon stade.

This model of glaciofluvial deposition and erosion also challenges some commonly held assumptions about the relative importance of ice and water in the glacial environment. Although direct ice action may, generally, be a more significant agent of geomorphic work than fluvial action (Drewry, 1986), an opposite relation in near-margin areas is suggested here. The reconstructed late-glacial history of the central Puget Lowland—that of voluminous sedimentary infilling followed by locally intense linear scour—is largely a history of fluvial activity, and the modern landscape still plainly reflects those processes.

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