Coastal Bluffs and Sea Cliffs on Puget Sound, Washington

By Hugh Shipman

Introduction

Puget Sound and Georgia Strait form an inland sea that straddles the U.S.-Canadian border and that lies within a north-south trending depression separated from the Pacific Ocean by the Olympic Mountains and Vancouver Island. Of Washington State's approximately 4,000 kilometers of marine shoreline, more than 3,400 occur within this inland sea (fig. 1). Coastal bluffs are the most common landform encountered on this shoreline.

Rapid population growth in the region has greatly increased development along the shoreline. With the low-lying river deltas already developed as ports and cities by early in the past century, much of the current pressure is taking the form of residential construction along the bluffs. Unfortunately, much of this development occurs with little awareness of the risks associated with erosion and landsliding, the costs of successfully mitigating the bluff hazards, or the role of the bluffs in maintaining both the geological and biological integrity of Puget Sound's beaches and ecology.

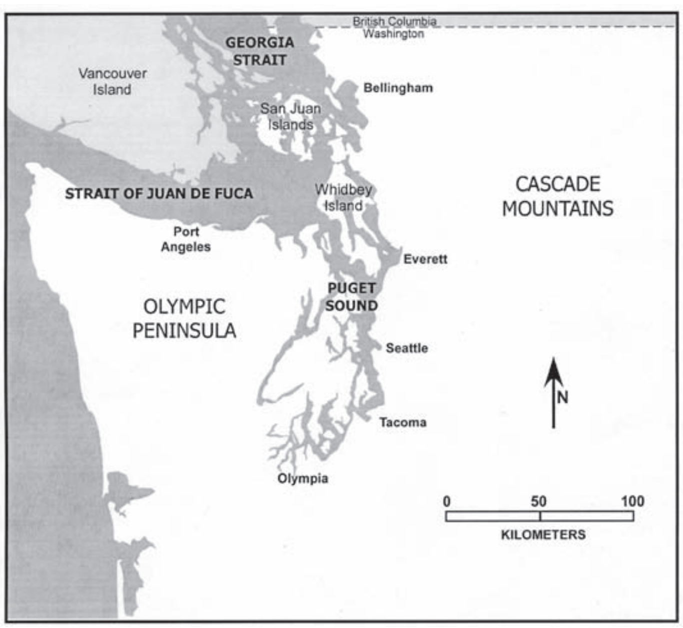

Figure 1. Map of Western Washington, showing Puget Sound, the Georgia Strait, and the Strait of Juan de Fuca. The greatest urban development occurs in the Tacoma-Seattle-Everett corridor.

Previous work on the geology of Puget Sound bluffs appears in broader discussions of coastal geomorphological processes (Downing, 1983; Terich, 1987) and Puget Sound oceanography and geology (Burns, 1985), in descriptions of landslide hazards (Thorsen, 1989; Gerstel and others, 1997; Shipman, 2001), or studies and maps of regional geology (Easterbrook, 1994; Washington Department of Ecology, 1978-80). The purpose of this chapter is to review current knowledge of the distribution and character of coastal bluffs on Puget Sound and the processes that shape them.

Geologic Setting

Western Washington lies on the tectonically active western margin of North America. Subduction of the Juan de Fuca Plate under the continent has resulted in the formation of the Cascade volcanoes and regional deformation that causes uplift of the ocean coastline and subsidence of the Puget Lowland. The late Pleistocene sediments of the Puget Lowland are underlain by a complex series of fault-controlled bedrock basins.The Puget Lowland has been repeatedly occupied by glaciers that have advanced from the north, the most recent of which was the Puget Lobe during the Vashon advance between 15,000 and 13,000 years ago (Booth, 1994). The ice extended south of Olympia in the Puget Sound and a separate lobe extended westward along the Strait of Juan de Fuca. The surficial geology of the Puget Lowland largely reflects the influence of this last glacial advance.

Holocene sea level history has differed regionally due to large variations in the rates and magnitude of isostatic rebound in the early Holocene and due to gradual tectonic tilting (Shipman, 1990). Currently, the southern part of Puget Sound is submerging as much as 3 mm/yr, whereas the northern Puget Lowland remains relatively stable with respect to global sea level.

Puget Sound consists of a complex network of deep linear basins (more than 200 m in places) and its coastline is characterized by a narrow shore platform. The mean tidal range increases from 2 m near Port Angeles to 4 m at Olympia. Beaches are composed primarily of gravel, though variability is high, reflecting differences in sediment sources and complex redistribution of sediment by waves and longshore currents. The highly convoluted shoreline results in rapid changes in shoreline orientation and in the compartmentalizing of longshore drift (Schwartz and others, 1989).

Extent and Distribution of Bluffs and Sea Cliffs in Washington

Coastal bluffs occur throughout the Puget Lowland. No systematic geomorphologic classification of the shoreline is available that would allow a reliable calculation of the length of shoreline characterized by coastal bluffs. The best estimate of the distribution of coastal bluffs comes from mapping of slope stability in the 1970s (table 1), but these figures emphasize unstable slopes and readily identifiable landslides and under-represent the total extent of coastal bluffs (and completely ignore rocky shores and bedrock sea cliffs). In northern portions of the Puget Lowland (Skagit, San Juan, and Whatcom Counties), the relative proportion of coastal bluffs along the shoreline decreases due to the greater extent of bedrock shores, the larger proportion of depositional beaches and spits, and the presence of several large river deltas.

Table 1. Miles of shoreline mapped as unstable in the Coastal Zone Atlas of Washington (Washington Department of Ecology, 1978-1980). (Figures do not include Clallam County along the Strait of Juan de Fuca).

County	Miles of Shorelines	Miles Unstable	Percentage
Island	221	112	51%
Jefferson	195	81	42
King	113	66	58
Kitsap	246	50	20
Mason	218	96	44
Pierce	232	72	31
San Juan	376	13	3
Skagit	189	46	24
Snohomish	74	19	26
Thurston	111	50	45
Whatcom	118	36	30
TOTAL	2093	641	31%

Modified from Downing, 1983. Data from Washington Department of Ecology, 1978-1980.

Formation of Coastal Bluffs

Puget Sound's coastal bluffs are relatively recent geologic features, having formed only since glaciers retreated from the region 14,000 years ago. In fact, bluffs are believed to have largely developed only after sea level reached its current levels about 5,000 years ago and the modern shoreline began to evolve. The widespread occurrence of bluffs on Puget Sound is a direct consequence of the shaping of the landscape by the last glaciation, which deposited an extensive blanket of poorly consolidated sediment across the region at elevations above modern sea level and which left a complex system of deep channels that has resulted in a very long, convoluted shoreline.

Booth (1994) observed that the overall elevation of the upland surface within the Puget Lowland was established by the deposition of a broad outwash plain in front of the advancing ice. This surface was subsequently modified by the passage of the glacier, which left a relatively thin, but highly irregular layer of till and recessional deposits on the outwash surface. Post-glacial erosion and redeposition, by both fluvial and hillslope processes, further modified this landscape, but in general, the 100-150 m elevation of much of the Lowland still reflects the original outwash surface.

Whereas the deposition of sediments above modern sea level set the stage for the formation of the coastal bluffs, the length of the shoreline and the extensiveness of the bluffs is related to the reach of marine waters far into the Puget Lowland by a complex network of deep troughs. Most of these troughs are believed to have been formed as subglacial meltwater channels (Booth, 1994). These interconnected, north-south trending basins dominate the modern landscape.

In the northern part of the Puget Lowland, this simple picture of an outwash plain dissected by deep meltwater channels becomes more complicated. Complex isostatic rebound and sea level history, widespread deposition of glacial marine drift, and the abundance of bedrock terrain left a more variable landscape than farther south. In addition, the expansion of several large deltas at the base of rivers draining the Cascades has modified large portions of the northeastern coastline of Puget Sound.

Rocky shorelines are common in many portions of the northern sound where bedrock is exposed at the coast. Steep cliffs are not unusual, but these features are rarely actively eroding sea cliffs (fig. 2). Rather, they represent glacially scoured knobs and hills of moderate relief that have experienced little marine erosion due to their resistant lithologies and the modest wave energy of the sound. Marine erosion may have removed a veneer of glacial sediment, but the resis-

Figure 2. Basalt sea cliff in the San Juan Islands of northern Puget Sound. The base of the cliff is marked by a narrow erosional ramp. Erosion rates here are negligible, with the exception of rare block falls.

tant bedrock has undergone little change, except possibly the formation of a narrow ramp on higher energy shorelines or in more erodible lithologies.

Composition of Coastal Bluffs

Coastal bluffs along Puget Sound have eroded into a sequence of late Pleistocene glacial and interglacial sediments, most of it consisting of glacial drift deposited during the latest (Vashon) advance. Where pre-Vashon units are exposed at sea level, they are typically interglacial sediments or in some locations, drift from earlier glaciations (Easterbrook, 1986, 1994). The Vashon-age drift commonly consists of older lakebed silts and clays deposited in pro-glacial lakes (the Lawton Clay in central Puget Sound), a thick package of advance outwash sands and gravels (locally referred to as Esperance sand), and a capping glacial till (Vashon Till). In some locations, the till is overlain by glacial marine drift, recessional outwash, or post-glacial lake sediments.

Although the Vashon-age geologic units are widely distributed within the Puget Lowland, they exhibit significant spatial variability in thickness, elevation, and composition. This heterogeneity leads to rapid lateral variation in geologic characteristics such as hydrology, mass-wasting, and erodibility, and therefore the character of the bluffs can change over distances as short as hundreds of meters. This spatial variability, the difficulty in distinguishing Vashon-age deposits from earlier glacial sediments, and limited exposures due to colluvial cover and heavy vegetation, makes detailed mapping of geology difficult. Inferences about stratigraphy, even where adjacent outcrops are relatively close, are often inaccurate.

Glacial till is usually highly resistant to erosion and typically forms steeper cliffs and slopes. Glacial marine drift resembles till in its poorly-sorted character and its tendency to form steep faces but was not compacted by overriding ice and is generally less resistant to erosion than the till. Vashon-age advance outwash deposits and pre-Vashon fluvial sediments show modest consolidation but vary in their resistance to erosion and slope-forming properties depending on texture, hydrology, and other factors. Recessional gravels that have not been overridden by ice are typically very poorly consolidated, erode quickly, and often form angle-of-repose slopes.

Morphology of Coastal Bluffs

The height and shape of bluffs on Puget Sound can vary greatly due to differences in upland relief, geologic composition and stratigraphy, hydrology, orientation and exposure, erosion rates, mass-wasting mechanisms, and vegetation (fig. 3). Many of these factors are interrelated and can change rapidly along the shoreline, leading to diverse bluff morphologies along fairly short reaches.

Bluff heights range from less than a few meters to over 100 m, depending on the elevation of the upland surface into which the shoreline has advanced. Low banks and bluffs occur where relief is low or where shoreline retreat has only cut into the lowest portion of a more gradual slope. Higher bluffs generally occur where substantial retreat has occurred in areas of high relief.

Bluff Profile

Bluff profiles reflect a complex combination of lithology, toe erosion, and upslope mass-wasting. The simplest bluffs are those dominated by a single lithology and a single erosional process. High bluffs of glacial outwash gravel on the west side of Whidbey Island and at Cattle Point on San Juan Island form remarkably uniform slopes at the angle of repose of the unconsolidated material (fig. 3*A*). In contrast, bluffs consisting solely of glacial till or marine drift may form near-vertical banks (fig. 3*C*).

Most bluffs, however, are cut through a sequence of sedimentary units, each with distinct slope-forming properties. This can lead to complex bluff profiles containing both steep and gradual segments (fig. 4), depending on the lithologic, hydrologic, and mechanical properties of individual units. Poorly consolidated sands and gravels become slope-forming units, whereas glacial till and lacustrine silts and clays are often cliff-forming.

The presence of distinct stratigraphic elements also impacts hydrologic characteristics that influence mass-wasting mechanisms, leading to more complex profiles. For example, many high bluffs on Puget Sound are marked by a mid-slope bench that forms at the contact between permeable advance outwash deposits and underlying impermeable lakebed clays. Saturation along this contact drives upslope failures that result in more rapid retreat of the top of the slope than the base, causing the bench to widen. These benches, which can vary from a few meters to 100 m in width, may exhibit highly irregular topography as a result of their origin in landslides from the upper cliff (fig. 5).

Erosion Processes on Coastal Bluffs

The general model of bluff recession involves a cyclic process by which wave action removes material at the toe of the slope creating an unstable bluff profile that eventually leads to mass-wasting and the delivery of new material to the base of the slope. On Puget Sound, this process is complex—adjacent segments of the shoreline may be at different stages in the cycle, the mechanisms of erosion and mass-wasting may differ over short distances, and the time scales and frequencies which control toe erosion may be different than those that control slope processes. Regardless, erosion mechanisms can be divided into those that are best distinguished as related to wave action and toe erosion and those that are related to hillslope processes. The former affect the long-term retreat of the bluff, whereas the latter affect the shape of the bluff.

Wave-Induced Erosion

Waves can directly erode either in-place geologic materials exposed at the toe of the slope or they can erode colluvial materials delivered to the beach by mass-wasting. Although some wave-induced erosion appears to involve direct mechanical plucking or abrasion of blocks of material, most sedimentary units appear to erode as a result of repeated wetting and disaggregation of more coherent materials until waves can simply wash away the granular detritus. Some direct erosion has been attributed to battering by floating logs, which are abundant on Puget Sound beaches. In many situations, however, woody debris is believed to actually protect the toe from wave attack.

The width and height of the beach and berm control the frequency with which the toe of the bluff can be directly attacked by waves. Most bluffs on Puget Sound rise behind narrow sand and gravel beaches (fig. 6). Berm width depends primarily on sediment availability, whereas berm height depends on tide range, wave exposure, and sediment type. Berm crests typically form about one-half meter above Mean Higher High Water (MHHW). For waves to directly attack the bluff toe, water levels must either exceed the height of the berm, which requires storm waves to coincide with unusually high tides, or the berm itself must be eroded away.

Hillslope Processes

Raveling.—Poorly consolidated deposits of glacial outwash sands and gravels may erode primarily through raveling of the bluff face (fig. 3*A*). Failures tend to be progressive, beginning with undercutting at the toe by wave action, then gradually expanding upslope. Raveling tends to occur in areas where loose sediments are eroding rapidly enough so that vegetation cannot become established or in areas that for other

Figure 3. Examples of coastal bluffs from different parts of Puget Sound. *A*, High bluffs composed entirely of poorly consolidated recessional outwash gravels. *B*, 100-m high bluff in Tacoma consisting primarily of advance glacial outwash. Vegetation establishes rapidly after periodic failures. *C*, 15-m bluff in southern Puget Sound. Compact glacial sediments form near-vertical face; vegetation occurs along top of bluff and on colluvial material at toe of slope. *D*, Upper portion of these 40-m bluffs in northern Puget Sound are gradually sloped and heavily vegetated, whereas lower slopes are steeper and more exposed.

Figure 4. High bluffs near Port Townsend illustrate role of distinct stratigraphic units in defining bluff profile. Upper unit of glacial till fails in vertical slabs and does not support vegetation. Central sandier outwash unit is at angle of repose, with substantial revegetation between erosional events. Lower glacial unit is subject to wave action when storms and high tides coincide and when beach volume is reduced.

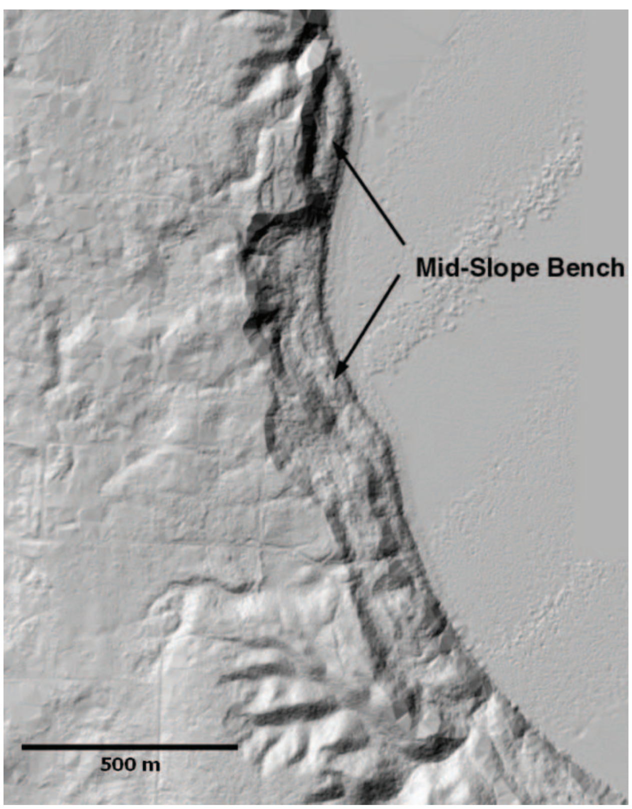

Figure 5. High-resolution image of topography obtained with LIDAR (Light Detection and Ranging) along complex coastal bluff in central Puget Sound. Mid-slope bench occurs along the contact between underlying glacial clays and overlying sandy outwash, where hydrologic conditions lead to instability. In some locations, the bench itself has been affected by deep-seated sliding. (Puget Sound LIDAR Consortium)

reasons cannot support woody vegetation that would bind soils into larger coherent units.

Soil creep.—Soil creep is commonly observed on steep, vegetated slopes where discrete slope failures have not occurred. Creep is a slow process and slopes prone to more rapid failures do not tend to remain intact long enough for creep phenomena to become significant. Long-term creep can lead to the gradual buildup of living roots and woody material at the toe of the slope which appears capable of providing significant stability to the toe of some slopes.

Block failure.—Coherent geologic units, such as glacial till and glacial marine drift, tend to fail as blocks on near-vertical slopes. When basal support is lost, through direct undermining by waves or by erosion of underlying units, failures occur along joints or tension cracks that form parallel to the bluff face. Block failures are typically a meter or less in thickness, although faces with greater relief seem capable of generating thicker failures. Failures often expose planar root mats that extend many meters in depth, but the degree to which roots and water exacerbate fracture development or simply take advantage of their presence is unknown.

Hydrology. — Both surface runoff and seepage can modify bluffs, although the Puget Sound region's heavy vegetation generally limits significant surface erosion to situations where runoff has been concentrated by human actions or to locations where vegetation has been removed from easily eroded soils, such as on a recent landslide. Surface erosion can range from the development of small rills on slopes to deep gullies and ravines. Groundwater seepage along distinct stratigraphic horizons can result in sapping of sandy soils and the undercutting of overlying units. Finally, although freezing temperatures are not common along the sound, extended freezes can lead to substantial ice buildup at seepage zones and there is evidence that this can precipitate failures either by increasing pore pressures behind the bluff face or by simply loading an already steep slope.

Figure 6. Typical mixed sand and gravel beach at base of high coastal bluff on Puget Sound. Berm, which consists of sandy material overlying a coarse gravel core, protects slope toe from wave action except when storm waves coincide with unusually high tides.

Coastal Slope Stability

Most bluff retreat on Puget Sound occurs through landsliding. Slope failures can range from shallow slides a few meters across to reactivations of existing, deep-seated landslides many hundreds of meters in size (Thorsen, 1987; Shipman, 2001).

Shallow Landslides

Most landslides that occur on Puget Sound's bluffs consist of shallow landslides and debris avalanches (fig. 7). Shallow landsliding is pervasive along many shoreline reaches, although any one site may slide only once every 30 or 40 years. These landslides typically involve only a thin layer (<1-2 m) of soil and associated vegetation. Some extend the entire height of the bluff, but others only affect a portion of the slope. Shallow failures may occur as small slumps, debris avalanches, or as topples of overlying glacial till. Single slides may occur by several mechanisms — for example, a block failure of glacial till high on a bluff may develop into a debris avalanche as it moves downslope.

Slides are usually triggered by heavy rainfall over a period of hours to days (Coe and others, 2000). They are easily caused by drainage failures or modest redirection of surface drainage. Heavy rainfalls during the winter of 1996-97 led to widespread shallow landsliding throughout much of central Puget Sound (Baum and others, 1998; Shipman, 2001).

Large Slumps and Landslides

Puget Sound is subject to occasional, much larger, landslides that may involve many tens of thousands of cubic feet of material (fig. 8). These slides are much less common than shallower slides, but would be devastating if they occurred in a developed area. Understanding of the geologic conditions that give rise to these large slides is poor, but such slides seem to be associated with higher bluffs and have been triggered both by elevated groundwater levels (Arndt, 1999) and by seismic activity (Chleborad, 1994).

Prehistoric Landslide Complexes

The Puget Sound shoreline contains many large prehistoric landslides, portions of which may reactivate during particularly wet periods. These slides, which typically consist of

Figure 8. Large landslide north of Seattle that occurred in January 1997, following heavy rains. Note distinct mid-slope bench to the right of the landslide, marking the contact at the base of the glacial outwash. The landslide, which pushed a train into the Sound, involved a deeper failure in the underlying clay units. The toe of slope had been protected by the railroad grade at beach level for approximately 100 years and was not involved in the slide.

Figure 7. Shallow landslide extending entire height of bluff on Puget Sound. Landslide was likely triggered by saturated conditions at contact between lakebed clays and overlying outwash sand (note dark band above bottom portion of bluff).

Figure 9. Large, prehistoric landslide on Whidbey Island. Portions of this slide periodically reactivate during wet weather. The toe of this landslide occurs slightly below beach level in this area. The landslide extends almost 2 km along the shoreline.

a complex of individual slide blocks, may reach several hundred meters inland and extend more than a kilometer along the shoreline (fig. 9). Movement is often less than a few meters during any particular event and may only affect a small area of the larger slide complex, though in some cases deep-seated movement can trigger additional, shallow slides. Reactivation is related to regional ground-water levels and appears to require extended periods of wet weather, possibly extending over years (Shipman, 2001).

Factors Affecting Slides

The occurrence of landslides is governed by numerous factors, though geology, hydrology, and slope steepness are the most significant. Most landslides on Puget Sound occur in response to either heavy precipitation or elevated groundwater conditions (Thorsen, 1987). Different rainfall regimes may lead to different kinds of slides, reflecting the ability of heavy precipitation to saturate shallow soils or of extended wet periods to lead to a rise in regional groundwater levels. During the winter of 1996-1997, two major episodes of landsliding followed heavy rainfalls, a majority of which were relatively shallow failures. In contrast, during the winter of 1998-1999, shallow landslides were infrequent, but prolonged wet conditions led to the reactivation of numerous large, deep-seated landslides (Shipman, 2001).

The geology of the bluffs affects the geotechnical properties of the bluff soils, but its most significant impact on stability appears to be stratigraphic and hydrologic. Most landslides in the region occur where permeable sand and gravel units lie directly on top of less permeable silts and clays, allowing a perched water table to develop and soils to become locally saturated (Tubbs, 1974). The most common scenario is where advance outwash overlies proglacial lakebed clay. Groundwater percolates downward in the porous outwash and laterally toward the bluff face along the contact with the finer grained underlying material. When water levels rise, increased pore pressures lead to weakness and failure. Similar geologic conditions exist where glacial sediments overlie bedrock and where recessional outwash is found above impermeable glacial till.

Steeper slopes are generally more prone to failure as gravitational stresses are greater, but variations in rock strength and differences in hydrologic conditions make it difficult to predict landslides based on slope alone. On coastal bluffs, erosion of the toe by wave action ultimately leads to steepening of the slope and the increasing likelihood of failure, but whereas toe erosion is a relatively slow process on most Puget Sound bluffs, landslides typically occur in response to transient increases in groundwater or soil saturation. As a result, wave action and undercutting may set the stage for future slope failures but rarely precipitate landslides. The common practice of constructing shoreline bulkheads to prevent coastal bluff erosion often overemphasizes the role of waves in determining slope stability.

Earthquakes

The Puget Sound region is a seismically active region, but the role of earthquakes on the bluffs is poorly understood. Chleborad (1994) describes a large landslide on the Tacoma Narrows that is believed to be associated with the 1949 Olympia earthquake (magnitude 7.1). This slide involved as much as 100,000 m^3 of material and narrowly missed a residential community built along the shore. Relatively few landslides occurred following the Nisqually Earthquake of February 2000 (magnitude 6.8). This has been attributed to a dry winter and less observed groundshaking than expected.

Karlin and Abella (1992) dated large landslides in Lake Washington (east of Seattle) to the last major earthquake on the Seattle Fault, about A.D. 1,000, and it is reasonable to expect that similar landslides may have also occurred along the marine shoreline in the vicinity of the fault (which runs east and west across Puget Sound from Seattle to the Bremerton area). Such features may not be as well preserved in the more active marine environment, where tidal currents modify the submarine deposits of slides and wave action gradually removes subaerial exposures. Recent laser-based (LIDAR) topographic mapping has identified or confirmed the presence of several large landslide features along the shoreline in close proximity to mapped faults.

Rates of Bluff Recession

Long-term bluff recession rates on Puget Sound reflect three primary factors, including wave action, bluff geology, and beach characteristics (Shipman, 1995; Washington Department of Ecology, 1978-80; Keuler, 1988). Waves provide the energy necessary to erode the toe of the bluff and to remove eroded sediment from the site. Geology determines the resistance of the bluff to erosion and its susceptibility to mass-wasting processes that deliver easily erodible material to the base of the slope. The width of the beach and the height of the beach berm control the frequency and intensity with which waves can reach the bluff toe.

Wave Exposure

Wave action within Puget Sound is generated almost exclusively by local storms, as the influence of ocean swell diminishes rapidly eastward within the Strait of Juan de Fuca. Wave energy during storms is related to wind speed and duration and the length of open water across which the wind blows. As a result, the exposure of particular sites along Puget Sound is a function of their orientation to dominant winds and the local fetch. The relatively small size of waves (compared to open ocean waves), combined with the presence of deep water close to shore, means that most wave energy reaches the beaches and is not dissipated offshore. At extreme high tides, storm waves can overtop the beach berm and directly erode the toe of the bluff or colluvial debris deposited at the slope toe by mass wasting.

Geology

Some geologic materials resist the erosive action of waves better than others. Erosion rates on rocky shorelines are at least an order of magnitude less (Keuler, 1979; Shipman, 1995) than on shorelines consisting of poorly consolidated Pleistocene sediments. More resistant lithologies, such as crystalline rocks, well-cemented gravels, and highly indurated diamicton (pre-Vashon tills, in particular), often form distinct protuberances along the shoreline. Lateral changes in the lithology exposed at the toe of the bluff can result in irregularities in shoreline shape (fig. 10).

Figure 10. Irregular shoreline along western shore of Whidbey Island. Wave exposure is relatively uniform along this reach, and shape of shoreline is related to lithology and longshore redistribution of sediment by littoral processes. Beach in foreground is a barrier. Sharp point in mid-distance occurs where a resistant glacial till unit emerges at the toe of the bluff. (Photo by Gerald Thorsen).

Beach Conditions

A wide beach can protect the bluff from wave action. Energy is dissipated over a larger area and in the movement of beach materials. Similarly, a high gravel berm can isolate the bluff toe from all but the most severe wave events. On Puget Sound, drift logs that commonly accumulate on the berm can redirect or absorb wave action prior to its reaching the bluff face. Beaches vary greatly along the Puget Sound shoreline, both in morphology and in sediment type, leading to lateral changes in beach height and berm width. This in turn affects how waves interact with the bluff toe.

Where beaches are broad, due to a recent influx of sediment or proximity to a groin or other drift obstruction, bluff erosion may be locally reduced (fig. 11). Conversely, where beaches are starved of sediment due to either natural or artificial circumstances, the erosion rate of associated bluffs may accelerate. Jacobsen and Schwartz (1981) noted that bluff morphology systematically changes through individual littoral cells — that beaches generally widen and bluff erosion rates decrease in a downdrift direction. In general, on the sound, rapid erosion rates are most common on bluffs at the origin of littoral cells where beaches are minimal and eroded sediment is readily carried away by longshore transport.

Long-term bluff retreat depends on continued downcutting of the nearshore platform (Davidson-Arnott and Ollerhead, 1995; Trenhaile, 1997; Kamphius, 1987). In some locations on Puget Sound, beach sediments are sufficiently thick and continuous that they appear to protect the platform from abrasion and scouring, whereas in others, the platform is exposed or only intermittently covered with sediment. Similarly, on some shorelines a coarse cobble and boulder lag deposit armors the lower intertidal platform, limiting platform erosion and therefore bluff retreat rates.

Figure 11. Offset in bluffs resulting from the presence of large glacial erratic in the nearshore. Wave action and longshore drift are from left to right. The boulder acts as a groin—on the left side the beach is relative stable, but erosion has been exacerbated on its downdrift side.

Rates

Little systematic study of bluff recession rates has been carried out within the Puget Sound region, limiting knowledge of actual rates and understanding of the relative importance of different factors in determining rates. No regular monitoring of bluff erosion occurs, although interest has been expressed in doing this by local volunteer groups (Thorsen and Shipman, 1998). Relative erosion rates have been assessed qualitatively, typically using bluff steepness or vegetation (Keuler, 1988; Washington Department of Ecology, 1978-1980; Terich, 1987), but quantitative erosion rates are limited to just a few studies (summarized in Shipman, 1995).

Historical aerial photographs have been of limited use for evaluating bluff recession rates on Puget Sound. Few good photos are available prior to the 1950s. Heavy vegetation often obscures both the bluff toe and the top edge of the bluff and the highly irregular orientation of the shoreline makes consistently good lighting conditions unlikely. As with other methods, the slow, but highly episodic, character of bluff recession requires long-term records in order to get sufficient recession distances to document reliably (Keuler, 1988).

Keuler's study (1988) of erosion rates in the Port Townsend and Whidbey Island areas involved revisiting survey monuments for which original descriptions and location information provided clues as to the position of the shoreline, typically the toe or top edge of the bluff. Monuments had often been lost or could not be relocated, but where they could be found, an erosion rate could be established for time frames that in some cases spanned many decades.

The total amount of late-Holocene bluff recession along some shorelines can be estimated from the width of the nearshore platform, at least in places where a distinct erosional edge to the platform can be reliably identified (Keuler, 1979). These platforms range from a tens of meters to hundreds of meters in width. Inferring modern rates from platform width is problematic, as rates may have changed over time due to the widening platform, variation in geology and topography, and possible changes in rates of sea level change.

The highest erosion rates measured on Puget Sound and in the Georgia Strait occur in poorly consolidated late Pleistocene sediments where wave exposure is high. Van Osch (1990) noted bluff recession rates of 60 cm/yr at Cowichan Head north of Victoria and 30-50 cm/yr at Point Grey near Vancouver, B.C. Galster and Schwartz (1990) found that erosion rates of bluffs west of Port Angeles were as much as one meter per year before the shoreline was armored. Keuler (1988) determined rates of over 30 cm/yr on Smith Island, the western shore of Whidbey Island, and the northern side of Protection Island, all with substantial exposures along the Strait of Juan de Fuca.

These rates are not typical, however, and recession rates appear more commonly to be on the order of a few centimeters a year, or less, in most areas. Rates vary temporally and at any given site, retreat is likely to occur as a single mass-wasting event every few decades. Wave erosion is highly episodic, driven by combinations of unusually severe storms and high tides (or even temporarily elevated sea levels as was observed during the 1998 El Niño). Slope failures are also episodic and tied to heavy precipitation. Beach fluctuations that might effect bluff erosion can also vary over periods of years due to storm conditions or sediment supply variations.

Spatial variability in erosion rates appears remarkably high. Even along shorelines with generally similar exposure and lithology, rates can vary significantly (Keuler, 1988). We believe this reflects small variations in shoreline orientation and beach characteristics, combined with lateral variability in the geology exposed on the platform and at the bluff toe (fig. 10).

Development on Coastal Bluffs

Pressure to build along coastal bluffs is rising rapidly with the increasing population growth and urbanization of the Puget Sound region. Much of the shoreline lies within a short distance of the major metropolitan centers of Seattle, Tacoma, and Everett. The area has seen a significant shift in the character of shoreline development from small seasonal retreats and retirement cabins to large primary residences. The style and size of new waterfront homes and the extent of landscaping is typical of that seen in affluent suburban developments in nonshoreline areas. The demand for waterfront and bluff property is driven primarily by access to the water and unimpeded views of the Sound and nearby mountains.

Development along bluffs most commonly occurs at the top of the bluff (fig. 12). The distance a building is set back from the bluff edge depends on local regulations, the history and age of the structure, the topography of the site, lot lines, and the original property owner's concept of risk and their desire for views. Property owners often build as close to the

Figure 12. Homes built along the top edge of a bluff in southern Puget Sound. Setback requirements vary among jurisdictions. The desire for views typically leads property owners to build as close to the bluff as regulations allow.

edge as allowed, in large part to maximize views in an otherwise forested area. The risk to bluff top homes is relatively low as a consequence of slow erosion rates, although a property owner's perception of danger may be greatly enhanced by periodic landslides or related bluff failures.

In several locations around the sound, development has occurred at the base of steep coastal bluffs. In some cases, homes are built on spits, stream deltas, or related depositional landforms that have accreted waterward of the bluff toe. In other cases, development occurs on artificial fill placed across the backshore or beach. On Whidbey and Camano Islands, in central Puget Sound, numerous residential developments were created in the 1950s and 1960s by constructing bulkheads on the beach below a high bluff and then using hydraulic methods to wash bluff material in as landfill. The legacy of such development is rows of homes at water level, constructed on unengineered hydraulic fill, and located at the base of unstable bluffs 40-70 m high (fig. 13).

In some locations, homes (and in the case of Tacoma's Salmon Beach, an entire community) were constructed on piles over the beach at the base of high bluffs (fig. 14). Such development would not be allowed today for many safety and environmental reasons, but where it already exists, we observe regular conversion of small cabins into large homes and periodic slide damage to homes.

Although the steeper coastal bluffs largely preclude development on the slopes themselves, development can and does occur in less extreme situations. Building is common on more gradually sloping portions of complex coastal slopes and, in particular, on the mid-slope benches that characterize many bluff shorelines. These areas often appear to offer prime building sites in otherwise difficult to build areas. Unfortunately, these benched slopes often reflect unstable geologic conditions (fig. 15). Another circumstance where building occurs on the slopes themselves is in areas where property lines, old unregulated building practices, or modern heavily engineered development have led to homes being constructed on piles or multilevel foundations either above or into the face of steep slopes.

Human Impacts On Bluffs

Humans are in themselves an agent of bluff erosion, at least in their capacity to trigger landslides or increase erosion through careless or imprudent development practices. The occurrence of landslides and the continued erosion of coastal bluffs is a natural process, but humans, primarily through their propensity to modify natural hydrology, can easily exacerbate unstable conditions or trigger slides.

Puget Lowland is a heavily forested area with high precipitation. Surface runoff and subsurface saturation are highly

Figure 14. Salmon Beach community in Tacoma. Homes built over beach on piles at base of high bluff are periodically damaged or destroyed by landslides.

Figure 13. Residential development on artificial fill below high bluffs on eastern Whidbey Island.

Figure 15. Homes destroyed by landsliding along Magnolia Bluff in Seattle during the winter of 1996-97. Homes had been built on a mid-slope bench formed by past erosion and landsliding.

sensitive to the abundance and type of vegetation. Land development and clearing of vegetation can result in changes in subsurface hydrology that increase the likelihood of slope failures. Collecting runoff in drain systems can reduce localized saturation of bluff soils and thereby increase stability, but conveyance systems concentrate flow and are subject to failure if not designed, constructed, or maintained properly. In Seattle, more than 70 percent of slope failures in the heavy rainfall events of early 1997 were at least in part due to human actions (Shannon and Wilson, 2000). Less frequently, direct modification of the bluff by placing fill on the upper slope or by excavating into lower portions of the slope triggers failures.

Bluff Stabilization

A wide variety of techniques are employed to stabilize coastal bluffs on Puget Sound. Some of these techniques address waves and toe erosion, whereas others deal more specifically with mass-wasting and slope stability. Most bluff stabilization and erosion control on Puget Sound occurs on residential property, which generally dictates the scale (in size and cost) of particular solutions. Increasing property values during the last decade have led to an increase in both the quality of site evaluations and the sophistication of technical fixes.

Drainage

The least expensive and most common measure taken by bluff top property owners to reduce slope problems is to collect surface drainage from gutters, drives, and French drains and to convey it directly to the beach, reducing opportunities for surface erosion or saturation of bluff top sediments. On residential sites, this is typically done with flexible pipe and is rarely engineered. Such methods can be effective but often create new problems when pipes are inadequately designed or are not maintained, because failures result in collected flows discharging directly onto soils high on the bluff.

Increasingly sophisticated drainage measures have been employed in recent years, both on private sites and on public projects. Vertical dewatering wells (either gravity drained or pumped) are occasionally used and the region is seeing an increase in the use of directional drilling to construct horizontal drain systems. Variability in subsurface conditions and flow makes the success of such systems dependent on accurate geologic analyses of water bearing strata. Whereas short horizontal wells drilled into the bluff face were traditionally difficult and expensive to construct due to equipment access, newer directional drilling techniques allow wells to be drilled from several hundred meters landward of a bluff, under any structures, and then out the bluff face. This may also better facilitate cleanouts and maintenance, a common problem with horizontal drains.

Bulkheads

Shoreline bulkheads are used extensively on Puget Sound to address wave-induced toe erosion. Numerous materials are used, including concrete, wood, and rock, and a variety of designs are employed, including gravity walls, cantilevered structures, riprap revetments, and sheet pile walls. Currently, the most commonly built structure is a steep rock bulkhead or rockery, usually built from readily available basalt. These structures are typically less than 2 m high and are required by regulations to be located as close to the bluff toe as possible.

The effectiveness of bulkheads varies considerably. The wave environment in most of Puget Sound is sufficiently protected that structures need not be massive to address local wave conditions, but bulkheads are often seen as a panacea for slope stability problems that are only indirectly associated with wave action. On many shoreline bluffs, particularly those where recent erosion has been notable and where property owners are likely to consider bulkheads, the slope is already over-steepened and more likely to fail during a heavy rainfall than during high wave conditions. Many of the landslides during the heavy rainstorms of 1996-97 occurred on slopes where bulkheads had protected the toe for many decades.

Slope Engineering

Although bulkheads are commonly used to protect the toe of slopes from wave action, in some cases (for example, after a failure of a coastal bluff already protected by a bulkhead) property owners have built multiple-stage retaining walls, reinforced soil embankments, or have otherwise modified the geometry of the entire bluff. In the case of deeper sliding, toe buttresses have been constructed, but regulations preventing encroachment across the beach increasingly discourage such solutions. Biotechnical stabilization methods have received much interest in recent years, in part because of their potential for addressing slope stability problems in environmentally sensitive areas, but their actual application has been limited.

Management and Regulation

Development along coastal bluffs presents a variety of problems for coastal planners and resource managers. These range from protecting people from natural hazards to protecting nearshore ecology from the impacts of human land use practices. Several regulations affect development along coastal bluffs on Puget Sound. The Shoreline Management Act (SMA) and the Growth Management Act (GMA) are both State laws that provide guidelines under which local regulations are developed and implemented. Because local governments differ significantly in their approaches to land use planning and in their technical capabilities, there is much variability in how individual counties and cities manage their coastal bluffs, despite the common basis in state-level regulation. Identification of potentially unstable coastal bluffs is often guided by maps developed in the 1970s shortly after passage of the State's Shoreline Management Act (fig. 16). This mapping still provides the basis for many local planning decisions[1].

Construction setbacks are the standard approach for guiding new development away from bluff hazards, but setbacks vary considerably between jurisdictions and property owners often seek and obtain variances to build closer to bluffs than the code recommends. Setbacks can range from arbitrary minimums to distances based on the height of the slope. Recent updates to Critical Areas Ordinances (under Growth Management) and Shoreline Master Programs (under the Shoreline Management Act) in some jurisdictions have increased setbacks, driven both by renewed awareness of landslide hazards brought by the winter of 1997-98 and by greater emphasis on protecting shoreline habitat through avoiding development that is likely to require shoreline structures in the foreseeable future.

Bulkheading of coastal bluffs has become a significant management issue in recent years on the sound (Canning and Shipman, 1995). The practice has been a standard tool for addressing bluff erosion for decades, but increased awareness of environmental problems associated with these structures (Macdonald and others, 1994) has led to scrutiny of individual projects and review of broader policies. In addition, numerous failures of bluffs above existing bulkheads raises questions about the efficacy and safety of these solutions in certain situations.

Concerns about the environmental impacts of constructing bulkheads on coastal bluffs include possible loss of sediment supplies to downdrift shorelines, changes in beach profiles and beach substrate, modifications to riparian vegetation or beach hydrology, and simply the gradual loss of the upper beach as shoreline retreat continues in front of fixed structures. Geologically, sediment starvation is the primary issue as most Puget Sound beaches are fed by bluff erosion. At Ediz Hook in Port Angeles, armoring of eroding bluffs was the major cause of extensive beach erosion and expensive mitigation in the form of beach feeding with cobble-size material (Galster and Schwartz, 1990).

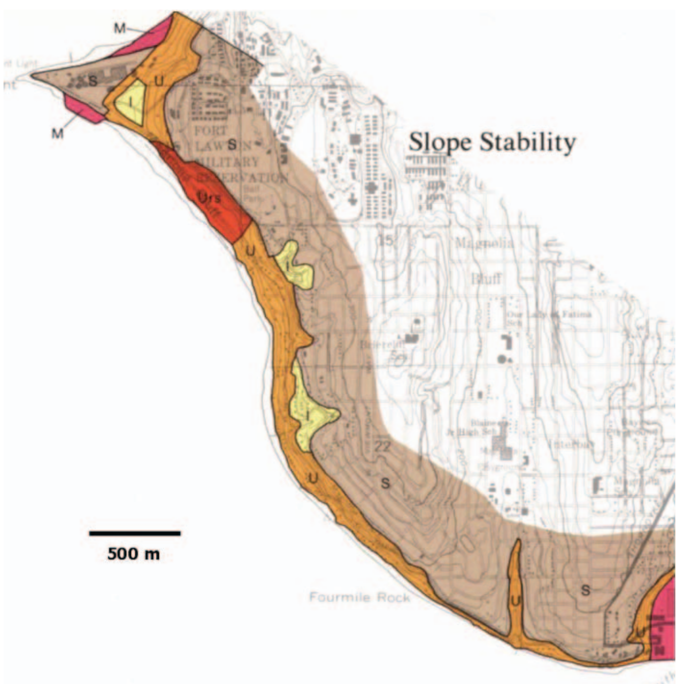

Figure 16. Map of coastal slope stability for residential portion of Seattle, from Coastal Zone Atlas of Washington (Washington Department of Ecology, 1978-1980). U indicates Unstable; Urs indicates recent landslides (as of late 1970s). Such maps exist for most of Puget Sound.

Summary

Much of the Puget Sound shoreline is characterized by coastal bluffs cut into poorly consolidated glacial and interglacial sediments. Bluff recession rates are relatively slow, in part due to the protected nature of the sound, and erosion is dominated by hillslope processes and landslides. Erosion rates are controlled by wave exposure, bluff geology, and beach characteristics. Because bluff erosion both supplies sediment to the beach and is regulated by the condition of the beach, a complex relationship exists between bluff and beach processes.

Bluffs are in high demand for residential development due to their proximity to the water and their spectacular views. The extensive development of coastal bluffs, however, sets the stage for serious long-term management problems. Large numbers of homes have been constructed in locations that if not hazardous now, will be in several decades. In addition, engineering measures intended to address bluff erosion pose serious implications for the long-term health of the region's beaches.

Research Needs

Remarkably little systematic research has been carried out on Puget Sound bluffs, despite their prevalence, the hazards associated with their development, and the growing interest in the relationship between bluff erosion and nearshore ecological health. Types of research that would be useful include:

- Existing geologic mapping of the sound is outdated and often inaccurate. Traditional mapping that emphasizes the spatial distribution of units does not

[1] These maps are available on the Washington Department of Ecology's Puget Sound Landslides website (http://www.ecy.wa.gov/programs/sea landslides/).

necessarily present stratigraphic information well. New mapping, including more detailed examination and portrayal of shoreline stratigraphy, is critical to understanding coastal bluff processes.

- Recently, high resolution topographic data have been collected for much of the Puget Lowland using LIDAR (Light Detection and Ranging) technology. These data provide valuable information about bluff morphology and slope processes that were not available before. Little detailed analysis of these data has been carried out so far.
- Erosion rates have been acquired for only a few locations. A long-term monitoring program, coupled with detailed studies of specific sites, could provide a basis for estimating erosion rates throughout the Puget Sound region.
- Little is understood of littoral processes, sediment budgets, or of shoreline evolution on the sound. What information is available is largely qualitative. Quantitative, process-oriented studies will greatly improve our understanding of the bluffs and their change over time.

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Monty A. Hampton and Gary B. Griggs, Editors

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FRONT COVER
Photograph taken just before the 1997-98 El Niño storms, showing the northward view along the approximately 30-m tall sea cliff at North Explanade beach in Pacifica, California. The soft cliff shows signs of erosion, and a rip-rap sea wall is being constructed at the cliff base to protect houses along the cliff edge. The sea wall was not completed before the storms, and the cliff retreated more than 10 m (see later photograph on page 1). Most of the houses along the cliff were condemned and razed after the storm season.