Liquefaction Susceptibility for the Sumner 7.5-minute Quadrangle, Washington

by Joe D. Dragovich and
Patrick T. Pringle
with a section on liquefaction
by Stephen P. Palmer

WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES

Geologic Map GM-44
September 1995

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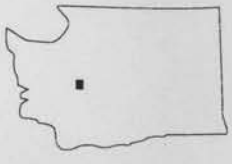
The information provided in this map cannot be substituted for a site-specific geotechnical investigation, which must be performed by qualified practitioners and is required to assess the potential for and consequent damage from soil liquefaction.



Location of
quadrangle

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Jennifer M. Belcher - Commissioner of Public Lands
Kaleen Cottingham - Supervisor

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Liquefaction Susceptibility for the Sumner 7.5-minute Quadrangle, Washington

by Joe D. Dragovich and Patrick T. Pringle, with a section on liquefaction analysis by Stephen P. Palmer

SUMMARY

The liquefaction susceptibility map of the Sumner 7.5-minute topographic quadrangle* is based on analyses of 153 geotechnical borings obtained from the Washington Department of Transportation, the Pierce County Department of Public Works, and several private geotechnical firms. We assigned geologic deposits in the study area to one of three susceptibility rankings on the basis of analyses of the geotechnical data and historical reports of liquefaction during the 1949 magnitude 7.1 Olympia and 1965 magnitude 6.5 Seattle–Tacoma earthquakes.

This map and the accompanying analyses are intended to provide land-use planners, emergency-response personnel, geotechnical consultants, building developers and contractors, and private citizens with a qualitative assessment of the potential for soil liquefaction during an earthquake.

The map is meant only as a general guide to delineate areas prone to liquefaction. This map cannot be substituted for a site-specific investigation to assess the potential for liquefaction and consequent damage for a given project.

This map cannot be used to determine the presence or absence of liquefiable soils beneath any specific locality because of the regional nature of these maps (as determined by their scale, 1:24,000) and because the data used in the liquefaction susceptibility assessment have been subdivided on the basis of regional geological mapping.

Category I deposits are composed of artificial fill and modified land, post-Vashon (Holocene) alluvium, and the Electron Mudflow. Some historic liquefaction sites are close to abandoned river channel segments of the Puyallup and White Rivers. These areas may have a locally very high susceptibility to liquefaction because of their recent age, high proportion of sand-size sediment, and (or) because of their position in topographically low areas that are likely to have a shallow ground-water table.

Category II deposits, consisting of late Pleistocene sandy glaciolacustrine sediments, Holocene lacustrine deposits and mass-wasting deposits, are ranked as having a low to medium liquefaction susceptibility. No geotechnical data were available for these deposits. Late Pleistocene sandy glaciolacustrine sediments have a moderate liquefaction susceptibility elsewhere (Palmer and others, 1995). These deposits are dominantly sandy and, because of their deposition during Vashon glacial recession, were not overridden by the glacial ice sheet and compacted. In areas of shallow ground water, these deposits may be susceptible to liquefaction. Holocene lacustrine deposits are primarily composed of peat and silt, with only scattered sandy sections, and would typically be considered as having a low liquefaction susceptibility. However, several peat deposits contain sand layers as much as 4 feet (1.2 meters) thick (Crandell, 1963), which may be liquefiable. Also, Chleborad and Schuster (1990) report a possible instance of liquefaction in a Holocene lacustrine deposit in the Big Soos Creek drainage in the Auburn quadrangle directly north of the Sumner quadrangle.

Mass-wasting deposits include both colluvium and Quaternary landslide debris. Because it typically occurs in small deposits, colluvium was not mapped by Crandell (1963) and Fiksdal (1979) and thus is not shown on Plate 1. Colluvium may consist primarily of loose material deposited by raveling or surface erosion of steep hillsides (for example by rilling), whereas material mapped as landslide debris typically comprises deposits from individually discernible landslides originating from discrete failure planes. Landslides and ground cracks were reported in colluvial deposits during the 1949 and 1965 earthquakes. Although these ground failures may not necessarily have been caused by liquefaction, it seems prudent to consider the possibility of liquefaction-induced ground failures in the mass-wasting deposits, for instance, because they are commonly areas of elevated pore pressure. Moderately sloping deposits of colluvium occur along the bases of many valley wall slopes. However, because these deposits were not mapped at this scale, there may be some small areas of Category II deposits not depicted on Plate 1.

* This pamphlet accompanies the liquefaction susceptibility map for the Sumner quadrangle.

Some valley wall areas display irregular topography whose origin is poorly understood. Two large areas (0.14 and 0.28 mi^2 or 0.7 and 0.36 km^2 respectively) of irregular topography in the west half of sections 12 and 13 west of McMillin were mapped as ice-contact collapse features by Crandell (1963); Fiksdal (1979) noted similar ice-contact collapse features. However, on aerial photographs these features appear to be large, deep-seated landslides. A visit to the site revealed locally disrupted pavement but no evidence of recent major slope movement except at smaller scarps adjacent to the valley wall that Fiksdal (1979) identified as active landslides. The latter could be minor scarps or shallow landslides (such as debris avalanches) emanating from the disrupted part of a larger deep-seated failure (that is, a slump-earthflow). If these features are deep-seated landslides, they are at least as old as the Electron Mudflow (which occurred about 600 years ago) because there is no evidence of a landslide deposit on the Electron Mudflow just below the potential slide. We have mapped these features as mass-wasting deposits.

Category III deposits include all other Vashon and older glacial and nonglacial deposits and exposures of the Osceola Mudflow. Category III also includes the Vashon recessional deposits, except sandy glaciolacustrine sediments (see above). Ice-contact stratified drift of Crandell (1963) and ice-contact collapse features of Fiksdal (1979) have been denoted with hachures on Plate 1 because they have never been overridden by ice (and therefore should be less well consolidated than glacially overridden sediments) and (or) may have been loosened during collapse. It seems plausible that these deposits would have a greater liquefaction susceptibility than those that were overridden; the sparse data available, however, show no significant difference. Furthermore, sandy interlayers in areas of shallow ground water could result in locally higher liquefaction susceptibility.

Quantitative evaluation of geotechnical data obtained from the Vashon glacial and the pre-Vashon glacial and nonglacial deposits indicates they have a low susceptibility to liquefaction.

The Osceola Mudflow (shown with a horizontal line pattern on Plate 1) is a poorly sorted, cohesive lahar from Mount Rainier composed of gravel- to boulder-size clasts in a silty, sandy matrix. Crandell (1971) shows the silt content of the mudflow ranges from 20 to 28 percent and the gravel content ranges from 28 to 34 percent for eight samples. The high silt and gravel content of this deposit should significantly inhibit its susceptibility to liquefaction. Additionally, the upper part of the Osceola Mudflow is highly cemented due to weathering; this impervious cap would tend to diminish any surface manifestation of liquefaction of the underlying material. Crandell (1971) does note that the Osceola Mudflow "becomes highly unstable when disturbed and when near its liquid limit, which ranges from 22 to 30 percent; seemingly, the bearing strength of the deposit would be low in areas of high water table." Geotechnical analyses performed as part of this study suggest that unweathered portions of the Osceola Mudflow may be susceptible to liquefaction.

No instances of liquefaction were reported during the 1949 and 1965 Puget Sound earthquakes in the areas of Osceola Mudflow outcrop, and the outcrop area of these deposits is considered to have a low liquefaction susceptibility.

Liquefaction studies in adjacent quadrangles have mapped Tertiary bedrock as a fourth category with low to no liquefaction susceptibility. However, there are no mapped exposures of Tertiary bedrock in the Sumner quadrangle, and no bedrock was penetrated in any of the geotechnical borings. Bedrock in areas mantled by glacial or both glacial and Osceola Mudflow deposits is probably deeper than 100 feet (31 m). Depth to bedrock in the Sumner quadrangle ranges from 1,400 ft (425 m) to 800 ft (245 m) and increases to the north-northwest (Hall and Othberg, 1974; Buchanan-Banks and Collins, 1994).

INTRODUCTION

The Washington Department of Natural Resources, Division of Geology and Earth Resources (DGER), is actively investigating earthquake hazards statewide and has received funding from the National Earthquake Hazards Reduction Program to conduct earthquake hazard mitigation studies. DGER has concentrated its technical programs on mapping Quaternary deposits in the Puget Sound region that are subject to seismically induced ground failures. The purpose of this study is to present a map showing liquefaction susceptibility in the Sumner 7.5-minute quadrangle (Fig. 1 and Plate 1); the quadrangle includes part of the alluvial valley along the lower reach of the Puyallup River, parts of its tributaries Fennel Creek and Prairie Creek, the lower reaches of the White River (formerly the Stuck River in the Duwamish valley), and part of an upland glacial drift plain.

Liquefaction occurs when a water-saturated, relatively loose, granular (sandy) soil loses strength during vibratory shaking such as that generated by an earthquake. Below the ground-water table, all the void spaces among soil particles are filled with water. The weight of the overlying soil mass is supported by grain-to-grain contact. Strong shaking during a large earthquake can disrupt the grain-to-grain contact, causing a decrease in the grain support. If strong shaking lasts long enough, the grain structure of the liquefiable soil may completely collapse. If the pore water cannot flow out of the collapsing pore space, the pore-water pressure increases. In the extreme case where the grain support is completely lost, the water pressure must increase to bear the entire weight of the overlying soil mass. At this point the granular soil is liquefied and will behave as a viscous fluid. The liquefied soil is then subject to extreme lateral deformation because it does not provide much resistance to horizontal forces. Youd (1973) provides a good overview and discussion of liquefaction.

The liquefaction map of the Sumner 7.5-minute quadrangle (Plate 1) and the accompanying analyses are intended to provide land-use planners, emergency-response personnel, geotechnical consultants, building developers and contractors, and private citizens with a qualitative assessment of areas potentially subject to soil liquefaction during an earthquake. The map is meant only as a general guide to delineate areas more prone to liquefaction. *The map is not a substitute for a site-specific investigation to assess the potential for liquefaction and consequent damage for any development project.* Because of the regional nature of the map (scale 1:24,000) and because the data used in the liquefaction susceptibility assessment have been subdivided on the basis of regional geological mapping, this map cannot be used to determine the presence or absence of liquefiable soils beneath any specific locality. *Site-specific geotechnical investigations performed by qualified practitioners are required to make this determination.*

GEOLOGY OF THE SUMNER QUADRANGLE

The discussion of the geology of the Sumner 7.5-minute quadrangle is a summary of Crandell (1963), Luzier (1969), and Fiksdal (1979). A generalized geologic map of the Sumner quadrangle is shown in Figure 2. Although sedimentary rocks and intrusive rocks of Tertiary age crop out in nearby areas, these rocks are not exposed in the study area and were not penetrated in the borings. Descriptions of these rocks can be found in Gard (1968), Mullineaux (1970), Walsh (1987), and Walsh and others (1987).

Pleistocene glacial and nonglacial deposits unconformably overlie Tertiary bedrock in the study area (Fig. 2). The youngest of these glacial units was deposited during the Vashon Stade of the Fraser Glaciation (ca. 14,000 years ago). Vashon till and outwash veneer the broad drift plain that defines the Puget Lowland between the Olympic Mountains and the foothills of the Cascade Range. In the study area, river valleys that reach Puget Sound are incised more than 300 ft (92 ft) into the

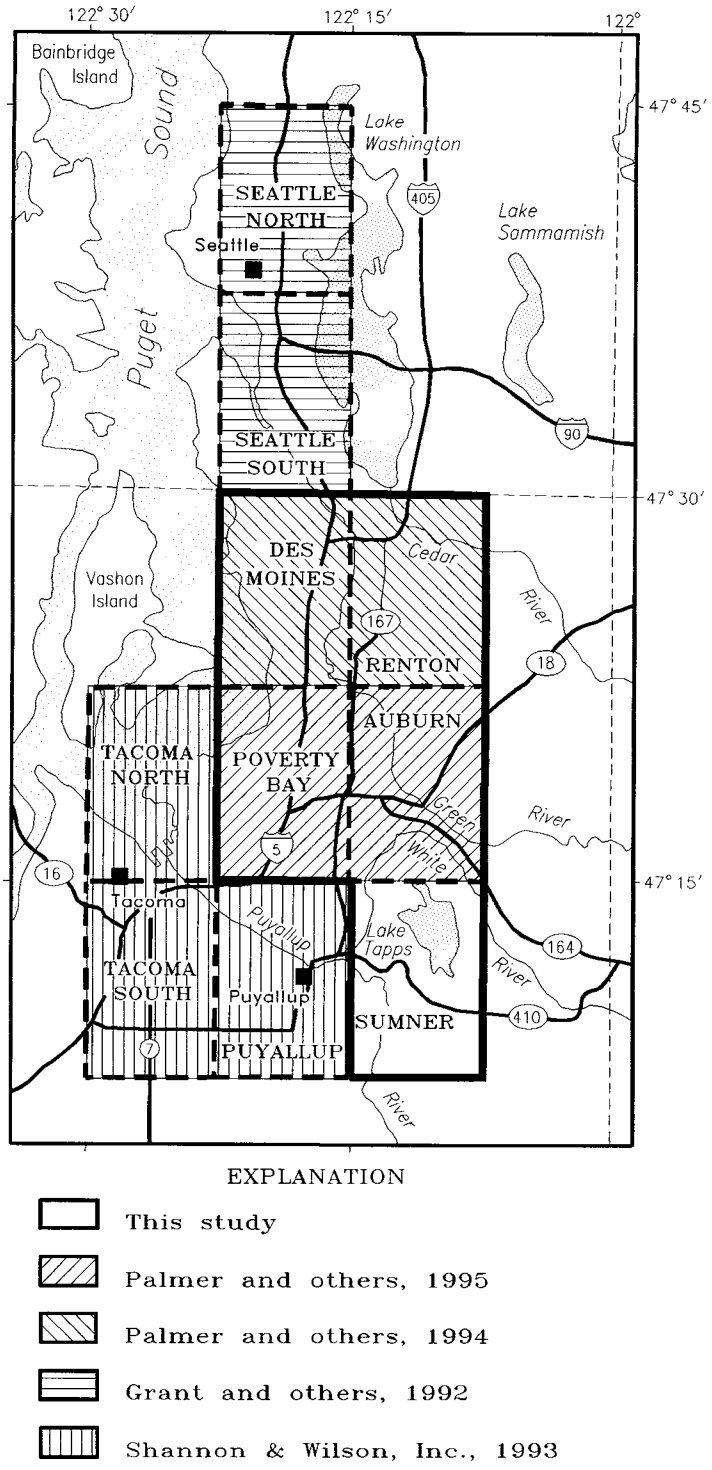


Figure 1. Location map showing the Sumner 7.5-minute quadrangle, Washington, and adjacent quadrangles for which liquefaction studies have been completed.

drift plain. Some of these valleys may be inherited glacial outwash valleys from the Vashon Glaciation (Booth and Hallet, 1993).

Sedimentary and fragmental volcanic deposits younger than the Vashon Drift are also present in the study area (Fig. 2). The 5,700-year-old Osceola Mudflow (Crandell, 1971; Scott and others, 1992) occurs at the surface in the eastern and southern sectors of the Sumner quadrangle and can be identified in the subsurface in the Puyallup and Duwamish (White River) valleys. This mudflow probably originated as an eruption- or explosion-generated debris avalanche (sector collapse) of at least 0.91 mi^3 (3.8 km^3)(Dragovich and others, 1994) of material that flowed down the upper White and West Fork White Rivers and into the Puget Lowland. According to Crandell (1971), the pre-Osceola White River was a tributary of the Puyallup River that followed the South Prairie Creek valley southeast of Orting. A lobe of the mudflow filled this valley and, at the same time, a larger amount of debris spread across the drift plain, spilling into the Puyallup River valley through Fennel Creek as well as into the Duwamish valley near Auburn, mostly through what is the modern valley of the White River. Some of this material spilled over into the Green River drainage and entered the Duwamish valley through that channel.

On the basis of well records, Luzier (1969) found that the Osceola deposits are 265 ft (81 m) below sea level at a site 4 mi (6.5 km) north of Auburn. The deposit is found at this depth because the Duwamish valley was an arm of Puget Sound at that time (Fig. 3) (see also Dragovich and others, 1994). Crandell (1963) mapped an important surface exposure of the mudflow in a cutbank of the Puyallup River at Sumner (Fig. 2, see also Fig. 5) and suggested that the mudflow extended in the subsurface to Puyallup.

For the Sumner quadrangle, we document the overall distribution of the Osceola Mudflow in the subsurface and connect the subsurface deposits with surface exposures farther east on the glacial drift plain. (Also see Dragovich and others, 1994.) Subsurface identification and correlation of the Osceola Mudflow deposit in the Sumner quadrangle (and adjacent areas) were based on several characteristics markedly similar to those observed in upstream outcrops (Crandell and Waldron, 1956; Crandell, 1963; Scott and others, 1992). The similarities include:

- extremely poor sorting (Fig. 4A),
- low density (as determined from blow count data, Fig. 4C; see also Fig. 11),
- normal grading as shown by amounts sand/sand+silt+clay with depth (J. Vallance, McGill University, written. commun., 1994),
- a large proportion of angular clasts from Mount Rainier,
- numerous wood fragments,
- a gray color with mottled yellow patches and sulfurous smell,
- similar stratigraphic position (Figs. 5 and 6), and
- a thickness range and mudflow top gradient (paleoslope) and elevation range consistent with both upstream surface exposure information and the drastic thinning and deepening of the mudflow off delta fronts west of Puyallup and north of Sumner (Dragovich and others, 1994).

Figure 2. Generalized geologic map of the Sumner 7.5-minute quadrangle, Washington. Asterisks are approximate locations of individual boreholes; filled triangles are clusters of closely spaced boreholes (number of boreholes superscripted); squares are the approximate locations of the centers of various communities.

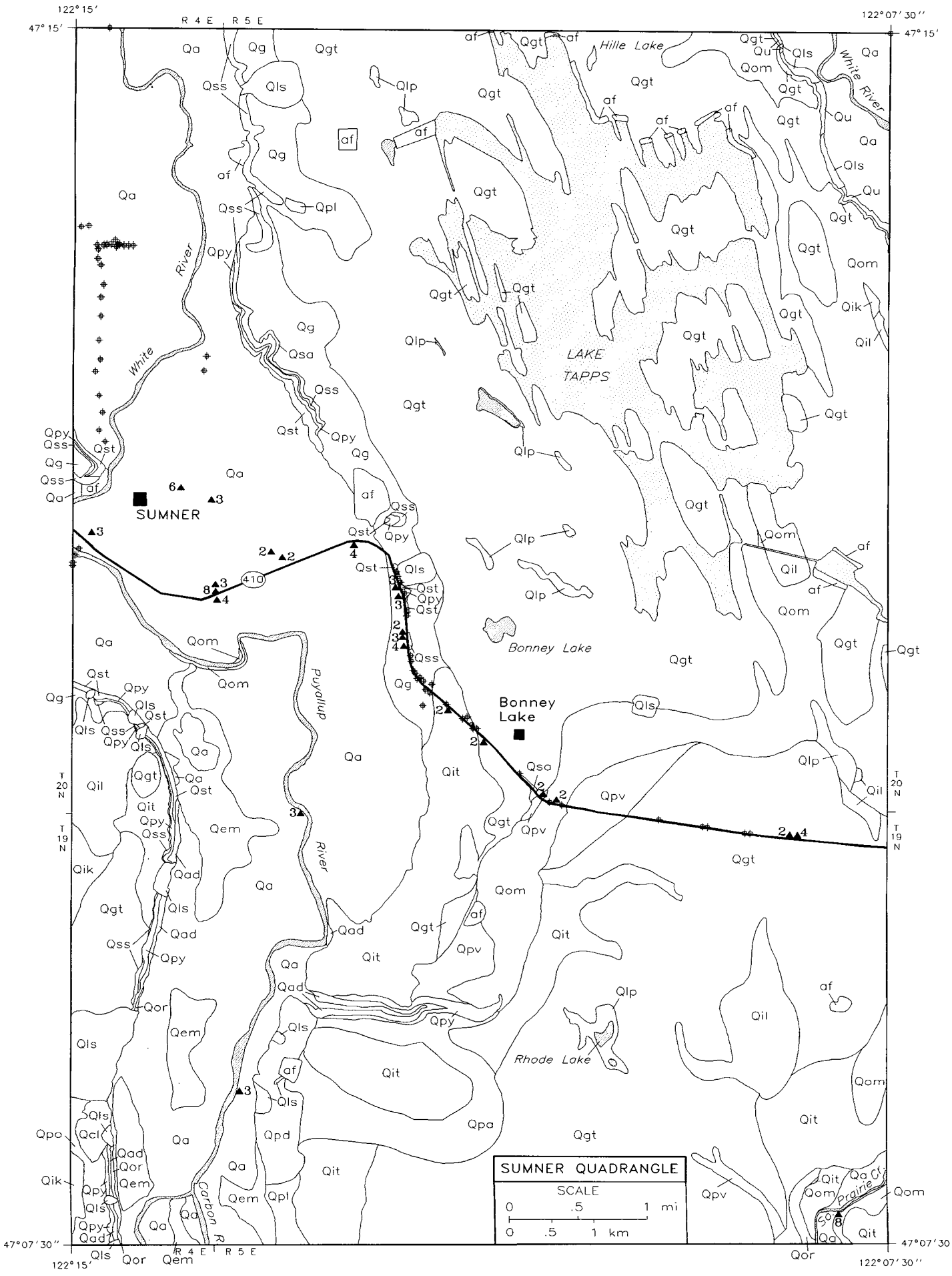
EXPLANATION

af	Artificial fill; undifferentiated
Qa	Quaternary alluvium; stratified clay, silt, sand, and gravel
Qls	Quaternary landslide deposits; largely massive diamicton*; includes slump-earthflow, debris avalanche, and talus deposits
Qlp	Lacustrine deposits; stratified silt, sand, and peat
Qem	Electron Mudflow; diamicton*; volcanic rock fragments (largely Mount Rainier provenance) in clayey, sandy matrix; deposited about 530 years ago (radiocarbon years)
Qom	Osceola Mudflow; diamicton*; volcanic rock fragments (largely Mount Rainier provenance) in clayey, sandy matrix; deposited about 5,000 years ago (radiocarbon years)
Qcl	Ice-contact collapse features and (or) ancient landslides; mainly stratified drift; hummocky, irregular surface. Mapped in part as Qpo and Qpv by Crandell (1963). Amount of overlying postglacial slumping undetermined
	Recessional outwash and ice-contact stratified drift; sand and gravel deposited in front of or adjacent to glacier; subdivided as follows:
Qik	Kame and kame-field gravel
Qit	Kame-terrace gravel
Qil	Lacustrine sand
Qpv	Valley-train deposit; predominantly well-sorted sand and gravel
Qpo	Outwash-plain deposits; predominantly well-sorted sand and gravel
Qpd	Delta gravel
Qpl	Lacustrine sand
Qpa	Undifferentiated stream deposits
Qgt	Glacial drift; chiefly compact till, diamicton*
Qsa	Advance stratified glacial drift; outwash sand and gravel deposited in advance of the Vashon glacier
Qg	Glacial drift; undifferentiated
Qu	Pre-Vashon glacial units; undifferentiated
Qss	Salmon Springs Drift; chiefly oxidized sand and gravel
Qpy	Puyallup Formation; chiefly unoxidized sand and gravel and very compact mudflows of Mount Rainier provenance deposited in lowland during nonglacial period
Qst	Stuck Drift; chiefly very compact till deposited by the Puget lobe of the Cordilleran ice sheet and oxidized sand and gravel
Qad	Alderton Formation; chiefly unoxidized sand and gravel and very compact mudflows of Mount Rainier provenance deposited during nonglacial period
Qor	Orting Drift; deeply oxidized sand and gravel

**Diamicton: a nonsorted or poorly sorted, noncalcareous, terrigenous sediment that contains a wide range of particle sizes, such as a sediment with sand and (or) larger particles in a muddy matrix.*

——— – – – Contact, dashed where inferred

We constructed upper surface contour and thickness (isopach) maps for the mudflow from the borehole data, including information from water well logs and geotechnical borings. (See Dragovich and others, 1994, for methods.) Figures 6 and 7 show the extent and geometry of the Osceola de-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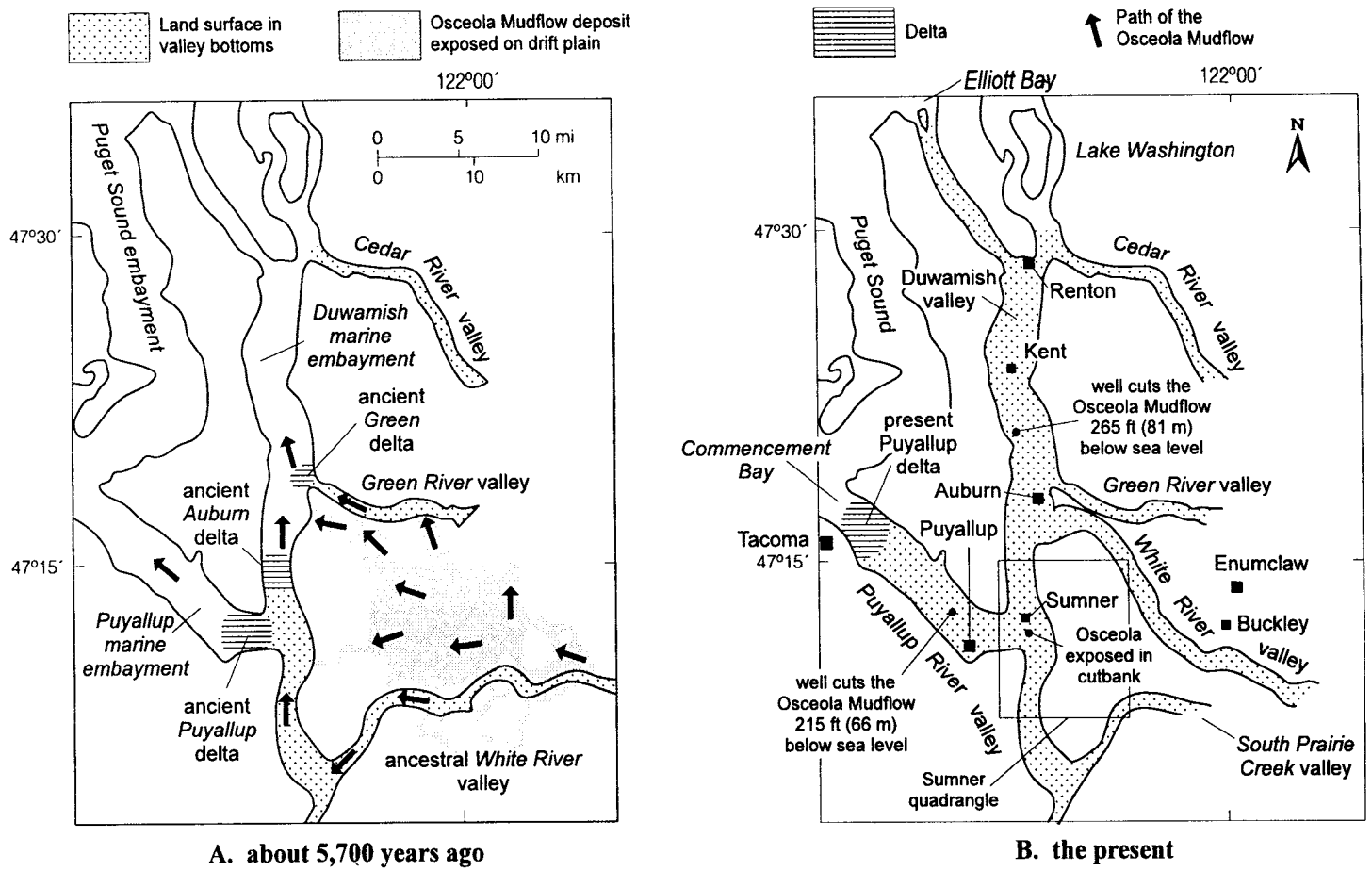
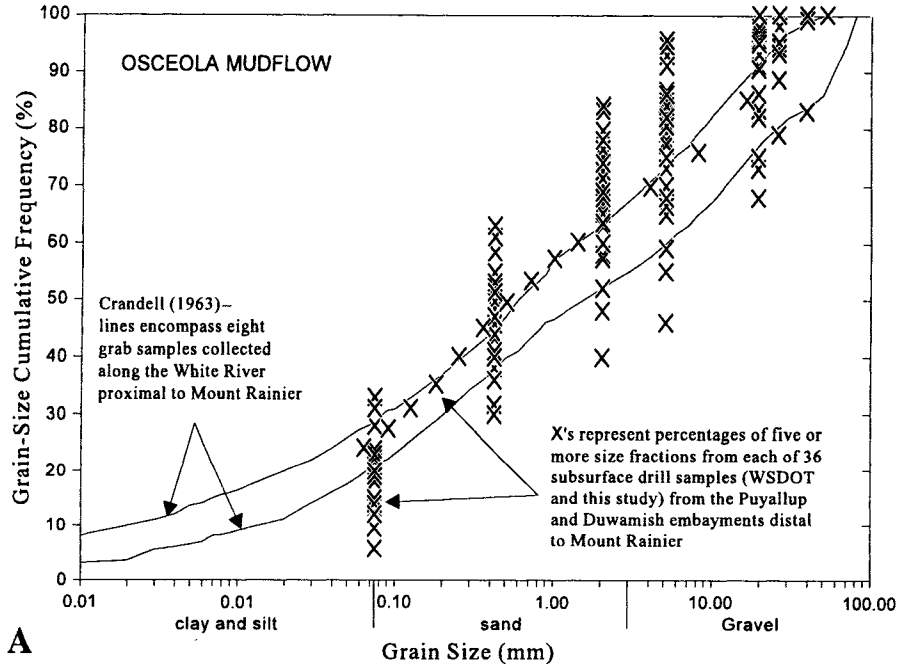


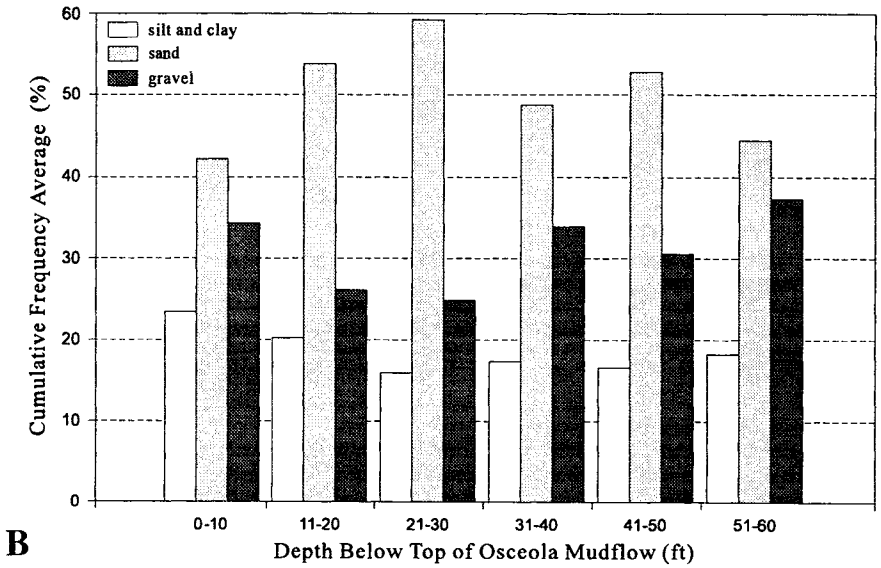
Figure 3. Comparison of the modern shoreline of Puget Sound (B) with that immediately after deposition of the Osceola Mudflow (A). Dark shading on the drift plateau shows the area of mudflow exposures at the surface. In the valleys, the mudflow is found in the subsurface beneath more recent valley deposits. The location of the Sumner quadrangle is shown in B. Well 22/4 35H2 (in the Auburn quadrangle, directly north of the Sumner quadrangle) penetrated the Osceola deposit 265 feet below sea level; the Duwamish embayment was formerly an arm of Puget Sound. Compare this depth with data given in Figure 6. Modified from Luzier (1969) and Dragovich and others (1994).

posit in the subsurface based on these subsurface data. The surface exposure of the Osceola farthest downstream is exposed in the cutbank of the Puyallup River near the Puyallup River Bridge at Sumner (Figs. 2 and 5). At this location the upper surface of the mudflow deposit is at an elevation of about 50 ft (15 m). To confirm the identification of the Osceola Mudflow in the subsurface, we submitted a small piece of wood from the Puyallup River Bridge deposit for radiocarbon dating. The uncalibrated radiocarbon age of 4,700 ± 60 yr B.P. (sample number Beta-66269) confirms that this unit is the Osceola deposit. We also submitted twigs obtained from a presumed Osceola Mudflow drill sample obtained by the Washington Department of Transportation (WSDOT) below the State Route 167/32nd Street interchange north of Sumner. The uncalibrated radiocarbon age of 5010 ± 80 yr B.P. (sample number Beta-65937) for this sample is well within the age envelope of the Osceola Mudflow determined in other studies and further confirms the identification of the Osceola Mudflow in the subsurface.

The contours of the upper surface of the Osceola deposit mimic pre-mudflow physiography (Fig. 6). At present sea level, a pre-Osceola Mudflow arm of Puget Sound would have extended south up the Duwamish valley to about the city of Sumner; a delta foreslope would lie just north of the quadrangle as noted in figure 3 of Dragovich and others (1994). Similarly, in the Puyallup valley an arm of the sound would have extended east to about the city of Puyallup. Geotechnical data from the Poverty Bay, Auburn, and Puyallup quadrangles (Fig. 1) indicate a significant increase in the slope of the upper surface of the Osceola Mudflow (from less than 2 to more than 7 percent) in the Auburn quadrangle within a 2-mi (3 km) stretch north of the northern boundary of the Sumner quadrangle (Dragovich and others, 1994). The mudflow apparently flowed over a delta in this area. Evidence for a similar delta can be seen in data from borings slightly west of the City of Puyallup. Figures 7 and 8, isopach maps, provide a three-dimensional perspective of the Osceola Mudflow and alluvium geometries, respectively. This stratigraphic information on the depth and thickness of the Osceola deposit is important in light of the low density of the mudflow deposit as indicated by low blow-count values, water-saturation of the unit in low areas, and resulting low bearing strength (discussed later in this report).

Deposits of younger lahars and lahar runouts from Mount Rainier further aggraded the lower valleys (Crandell, 1971; Scott and others, 1992; Vallance, 1994). Much of this aggradation may have begun about 2,300 radiocarbon years ago when lahars generated by the largest postglacial eruption of Mount Rainier deposited massive amounts of sand in the lower reaches of the Puyallup and White Rivers. Sandy deposits ('black sands') from this eruptive episode apparently liquefied during the Puget Sound earthquakes of 1949 and 1965 (Chle-





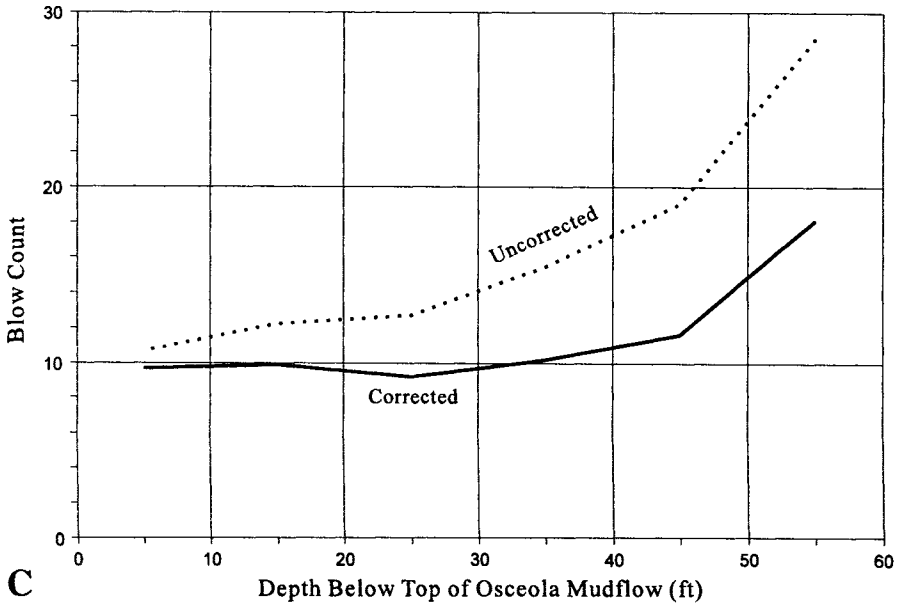


Figure 4. A. Grain-size cumulative frequency diagram for 36 subsurface samples of the Osceola Mudflow (Washington State Department of Transportation [WSDOT] data indicated by X's) and 8 grab samples (Crandell, 1963; data envelope defined by the two lines). The WSDOT samples come from the Duwamish and Puyallup embayments (See Fig. 3), far downstream from the Crandell samples. J. Vallance (McGill University) and K. Scott (U.S. Geological Survey) have unpublished data that show that average grain size and sorting increase with distance from Mount Rainier due to stream bulking with better sorted sand and gravel that typically lack any finer materials. The reduction in gravel content may be an artifact of the sampling method (the split spoon drill samplers have a 1.5-in. [3.8 cm] aperture) and the reduced volume of downstream samples. The sampling bias is greater in the coarser fractions, suggesting that some downstream sorting in the subsurface deposit is real. **B.** Average cumulative frequency in percent by generalized size fractions versus depth below the top of the Osceola Mudflow based on gradation tests of 36 drill samples. The distribution of the data reflects overall normal grading of the gravel fraction. **C.** Blow counts versus depth below the top of the Osceola Mudflow. The rising blow counts with depth may be attributed to the corresponding increase in gravel. However, recalculating blow counts to accommodate increased effective stress with depth indicates only a slightly greater blow count at 41 to 50 ft (13–15 m) than at depths between 0 and 10 ft (3 m).

borad and Schuster, 1990; Palmer and others, 1991; Pringle and Palmer, 1992). For example, the Round Pass Mudflow probably reached the Puget Lowland about 2,600 radiocarbon years ago. Deposits of many other lahars have been documented upstream of the Sumner quadrangle in both the White and Puyallup River valleys, and many of these flows had downstream equivalents that inundated the lowlands. The stratigraphic position of most of these lahars in the Sumner quadrangle is poorly known. These deposits include the 2,300-yr-old volcanic sand deposits near the city of Puyallup (Palmer and others, 1991; Pringle and Palmer, 1992) and younger lahar deposits in the White River drainage (Scott and others, 1992).

The post-Osceola White River drains into the Duwamish valley at Auburn. Post-Osceola aggradation in this reach eventually filled an arm of Puget Sound (between the city of Sumner and Lake Washington) and constructed a fan of debris that redirected the lower Puyallup River into the Puyallup embayment. Similar sands are commonly found on top of the Osceola Mudflow. Figure 8 shows the amount of post-Osceola alluviation based on our analysis of the data. This map can be used to estimate the depth to the top of the Osceola Mudflow in the valley.

In the Puyallup River, a sandy lahar or loose, sandy alluvium is typically found be-

neath deposits of the 600-yr-old Electron Mudflow. Only silty or sandy alluvium is found on top of the Electron deposits in the Puget Lowland. Transport of sandy material into the lower Duwamish valley continued after the deposition of the Electron Mudflow because terrace-capping deposits of sandy (noncohesive) lahars or lahar runouts are found upstream of the Duwamish valley in the White and Puyallup valleys (Crandell, 1971; Scott and others, 1992). These deposits overlie the W tephra layer from Mount St. Helens erupted in A.D. 1480 and are younger than the Electron Mudflow.

Before 1906, the White River bifurcated as it reached the floor of the Duwamish valley (Willis and Smith, 1899). The White River flowed northward into the Green River, and the Stuck River flowed southward as a tributary of the Puyallup River. After a flood in 1906, most of the White River flow was directed into the Stuck River, and engineering projects permanently diverted the north-flowing White River into the Stuck River, which was renamed the White River (Luzier, 1969). Some of these abandoned channels are shown on Plate 1.

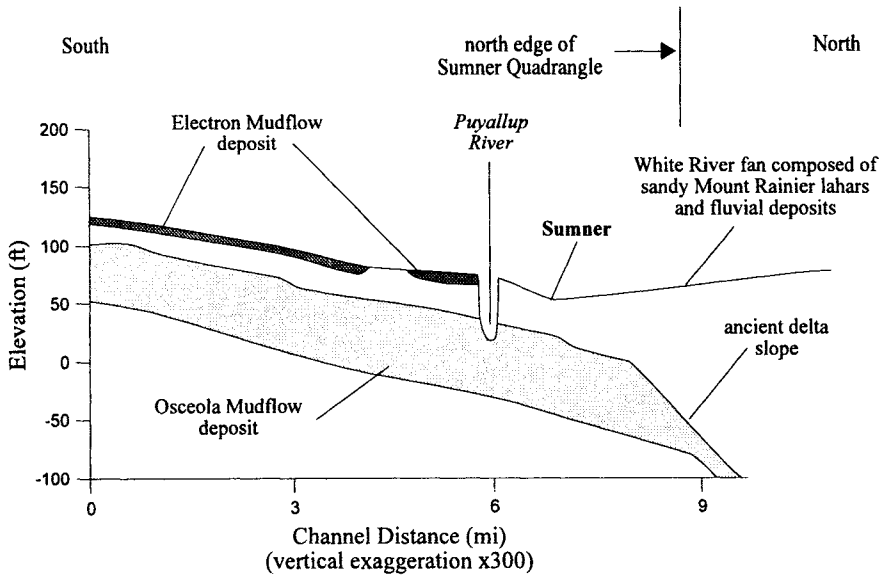


Figure 5. Diagrammatic profile of the Puyallup River valley in the Sumner quadrangle. The subsurface Osceola Mudflow is an important stratigraphic marker in the study area. In the Puyallup and Auburn quadrangles (Fig. 1), the mudflow traveled over ancient delta foreslopes (Fig. 3A) and flowed into former marine embayments of Puget Sound (Dragovich and others, 1994).

Mass-wasting deposits mapped by Crandell (1963) consist only of landslide debris, such as slump-earthflow or debris avalanche material. Colluvium that has accumulated in talus cones or piles as a result of surficial erosional processes, such as rilling or raveling, was not mapped. Hillslope toes are composed locally of a thick mantle of colluvial material resulting from upslope mass-wasting processes. Consequently, unmapped Category II low-density colluvial materials may overlie Category III high-density tills along the lowermost portions of many valley walls in the Sumner area.

Other post-Vashon deposits, such as Holocene lake sediments, also occur in the Sumner quadrangle. The lake deposits are chiefly thin peats, but they include some sand, silt, and clay formed in flood-plain depressions in the Duwamish valley. Many of the extensive peat deposits from low areas in the drift plain plateau or in valleys have been mined.

Modified land or fill is concentrated in valleys and includes fill adjacent to Lake Tapps and embankments for railroad lines, roadways, canals, and water impoundments.

FLUVIAL HISTORY OF THE VALLEY

Fluvial deposits of gravel, sand, silt, and clay are found in the Puyallup, White, and Duwamish valleys and in the valleys cut by South Prairie and Fennel Creeks. Flood plains are built by fluvial deposits in two fundamental ways, by lateral accretion during normal river meandering and migration of the river and by vertical accretion during flooding. Point bars at the apex of river channels are the most important lateral accretion deposit area. Here, sand and gravel deposits are accreted to the point bar as the channel migrates across the flood plain and undercuts the opposite bank. Flood-plain deposits are dominantly a result of vertical accretion whereby sediment-loaded flood waters deposit sand, silt, or clay due to flood current deceleration over flood plains. Peats form in oxygen-deficient swampy settings where vegetal decay is impeded. Channels migrate across flood plains slowly to rapidly, or may abandon portions of channels during migration, resulting in commonly complex fluvial stratigraphy. Discrimination between dominantly sandy channel deposits and dominantly fine or peaty flood-plain deposits is important for liquefaction susceptibility mapping. However, projections of alluvium to depth are complicated by complex facies changes caused by lateral channel shift or abandonment or bank collapse.

Other factors complicate any fluvial deposition model for the valley-fill sediments. Repeated deposition of lahars (mudflows) in a volcanogenic environment results in high sedimentation rates, and the history of 'normal' fluvial deposition is punctuated by catastrophic input of laharic sediments. Also, valley-fill sediments in the Puyallup and Duwamish embayments are composed of deltaic sediments formed as the ancient river deltas prograded down these valleys during the Holocene (Dragovich and others, 1994). Little is known about the distribution or characterization of valley-fill deltaic sediments in the Sumner quadrangle. The lack of detailed information highlights the need for site-specific liquefaction hazard characterization.

We reviewed several 1989 stereo aerial photographs (Washington Department of Natural Resources Flight Index Symbol SP-89; approximately 1:12,000 scale) to evaluate the previous geologic mapping, refine our geologic mapping, and map landslides, abandoned channels, and river bar and swale topography (Plate 1). In Plate 1, the hachured features mark the traces of clearly identifiable abandoned channels; these channels were abandoned by avulsion or by artificial channel adjustments such as those summarized by Palmer (1992, p. 4). The stippled pattern denotes the bar and swale topography formed by lateral accretion during channel migration when rivers undercut the cutbank opposite the point bar. The resulting collapsed sediment is carried downstream as bed load and is commonly deposited as a submerged bar on the same side of the river. The result is a cross-stratified deposit with a subdued

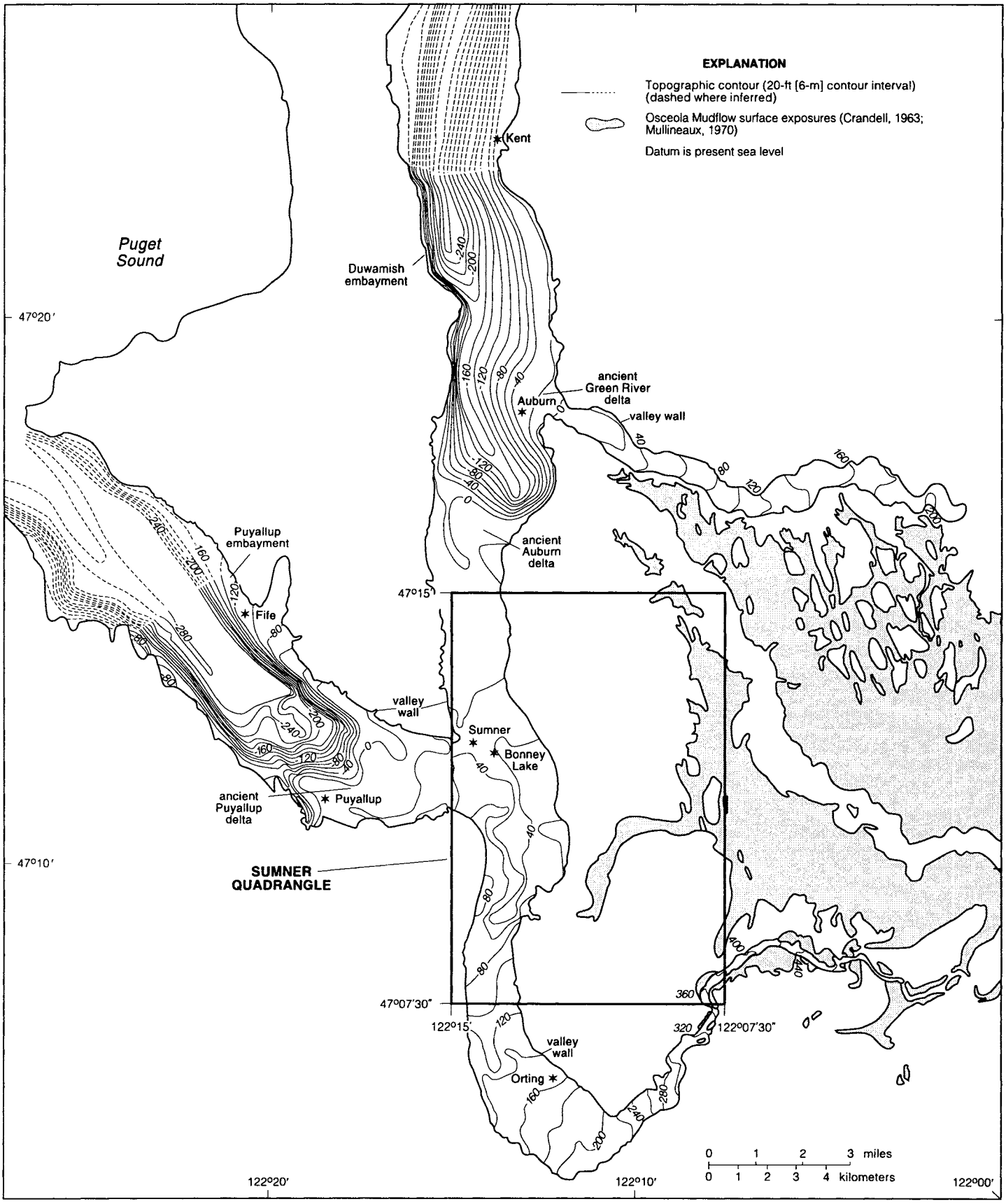


Figure 6. Contour map of the upper surface of the Osceola Mudflow deposit in and near the Sumner quadrangle. Rectangle shows the position of the Sumner quadrangle; stars indicate the approximate locations of the centers of various communities.

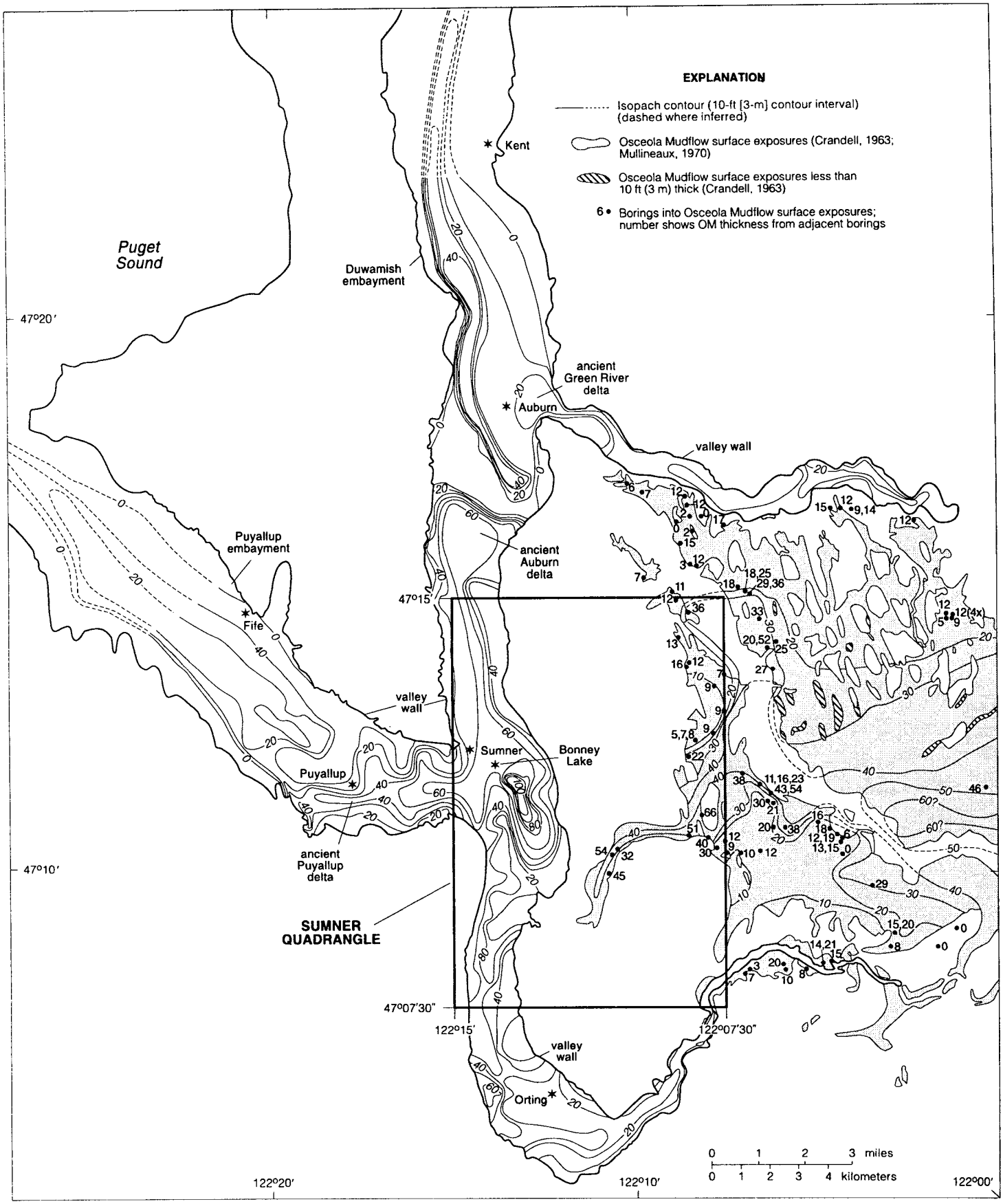


Figure 7. Isopach map showing the thickness of the Osceola Mudflow deposit in or near the Sumner quadrangle. Rectangle shows the position of the Sumner quadrangle; stars indicate the approximate locations of the centers of various communities.

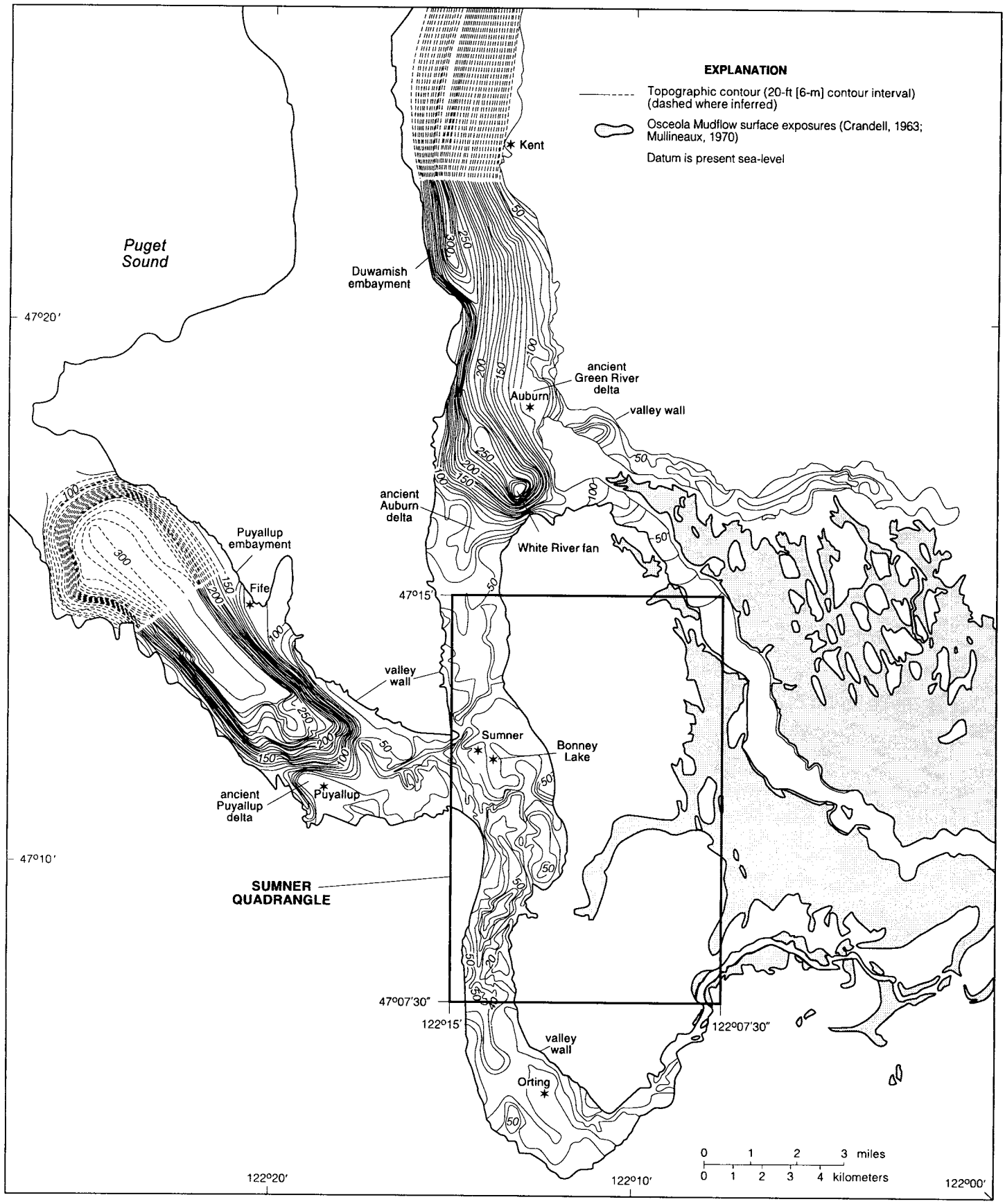


Figure 8. Isopach map showing the thickness of post-Osceola valley fill in or near the Sumner quadrangle. Rectangle shows the position of the Sumner quadrangle; stars indicate the approximate locations of the centers of various communities.

relief of low ridges and intervening swales that may record many episodes of channel migration. The overall pattern of these features the Sumner quadrangle suggests that the Puyallup River channel changes position both by avulsion of long segments or by channel abandonment and by slower meander migration forming the characteristic bar and swale topography.

LIQUEFACTION SUSCEPTIBILITY MAP OF THE SUMNER QUADRANGLE

Geological mapping of the Sumner 7.5-minute quadrangle is provided mainly by Crandell (1963). Some of the landslides were mapped by Fiksdal (1979). We have generalized Crandell's surficial geologic map units into three major categories of liquefaction susceptibility (discussed in detail below). These categories deposits are:

- *Category I:* artificial fill and modified land, Holocene alluvium, and areas of outcrop of the Electron Mudflow in the Puyallup valley.
- *Category II:* Holocene lacustrine and mass-wasting deposits, including landslides and late Pleistocene sandy glaciolacustrine sediments.
- *Category III:* All Pleistocene glacial (including deposits of Vashon proglacial and ice-contact stratified drift but excluding late Pleistocene sandy glaciolucustrine deposits) and nonglacial deposits, and the Osceola Mudflow.

Table 1 summarizes the three liquefaction categories and the corresponding geologic map units. Plate 1 shows the distribution of these categories in the Sumner quadrangle.

Table 1. The three liquefaction categories used in this study and the corresponding geologic map units of Crandell (1963) and Fiksdal (1979)

Category	Geologic description	Map units Crandell (1963)	Map units Fiksdal (1979)
I	artificial fill and modified land; Holocene alluvium; Electron Mudflow	af afm Qa Qem	
II	Holocene lacustrine sediments; Holocene mass-wasting deposits; late Pleistocene (Vashon Stade) ice-contact and proglacial lacustrine sand deposits	Qlp Qms Qil,Qpl	OL (plate 5)
III	Vashon Stade (late Pleistocene) glacial deposits: ice-contact stratified drift; proglacial stratified drift; glacial drift, chiefly till; advanced stratified drift; glacial drift, undifferentiated; older Pleistocene glacial and nonglacial deposits; Holocene Osceola Mudflow	 Qik,Qit Qpv,Qpo,Qpd,Qpa Qgt Qsa Qg Qss,Qpy,Qst,Qad, Qor, Qu Qom	

Liquefaction Analysis of Soil Deposits Found in the Sumner Quadrangle

by Stephen P. Palmer

METHODOLOGY USED TO EVALUATE LIQUEFACTION SUSCEPTIBILITY

My analysis of liquefaction susceptibility in the Sumner quadrangle closely follows the methodology of Grant and others (1992), Palmer (1992), Shannon & Wilson Inc. (1993), and Palmer and others (1994, 1995). I estimate the potential for soil liquefaction using the field evaluation methodology developed by Seed and Idriss (1971) and modified by Seed and others (1983, 1985). This field evaluation procedure uses Standard Penetration Test (SPT) N-values (ASTM D 1586-84)[1], sample descriptions, grain-size analyses, and measured ground-water depths obtained from geotechnical borings to estimate the factor of safety for a hypothetical earthquake with a specified magnitude and peak ground acceleration (PGA).

The SPT N-values and other data are obtained from sampled depths in a geotechnical boring so that the thicknesses and depths of individual liquefiable soil units and the total thickness of liquefiable material in that boring can be estimated. The procedure used in this study characterizes the liquefaction susceptibility of various Quaternary deposits through the cumulative frequency histogram of the aggregate thickness of liquefiable material penetrated in the borings. This is equivalent to the thickness criteria used by Grant and others (1992) and Shannon & Wilson, Inc. (1993).

The Quaternary units in the study area are grouped into three categories (Categories I, II, and III) on the basis of their geological and engineering characteristics (Table 1). The liquefaction susceptibility of each category is quantified from borings drilled only in geologic units that are included in that category. The liquefaction category contacts shown in Plate 1 are primarily taken from the geologic mapping of Crandell (1963) and Fiksdal (1979). A number of areas of landsliding have been identified using air photo analysis and ground investigation by Dragovich and Pringle as part of this study and are included in Figure 2 and Plate 1.

This study is primarily concerned with evaluating liquefaction that would have potential to cause noticeable effects at the ground surface. A relationship presented by Ishihara (1985) suggests that for PGAs of 0.30 g or less, liquefaction that occurs at depths greater than approximately 40 ft (12 m) will probably not cause noticeable effects or damage at the surface. Thus, this study limits the evaluation of liquefaction to only the upper 40 ft (12 m) of the borings. Many of the borings used in this study are less than 40 ft (12 m) deep—the average depth of all borings is 41.7 ft (12.6 m). Also, restricting the evaluation to these shallow depths allows a more direct comparison to historic reports of liquefaction.

Table 2. Conversion of Unified Soil Classification System (USCS) soil class to fines fraction used as input to the liquefaction susceptibility analysis

USCS soil class	Fines fraction (percent)
SP	5
SM	25
SP–SM	15
SW–SM	35

The field evaluation methodology requires an estimate of the fines fraction (the fraction of a sample that passes a 200-mesh sieve). I used measured grain-size distribution data to provide this parameter. If measured data were not available, I estimated the fines fraction from the soil category assigned using the Unified Soil Classification System (ASTM D 2487-90)[2] and the conversions given in Table 2. I restricted the liquefaction analysis to sandy soils containing 40 percent or less fines. This is less conservative than Seed and others' (1983, 1985) method, as they allow liquefaction of sandy soils with as much as 50 percent fines. I also did not investigate the possibility of liquefaction of soils classified as silts (greater than 50 percent fines content) even though liquefaction of native silt soils has been observed in past earthquakes (for example, at Ying Kou City [Arulanandan and others, 1984, 1986] and San Fernando Juvenile Hall [Bennett, 1989]).

Cumulative frequency histograms for Category I, II, and III deposits were made for a hypothetical earthquake of magnitude 7.3 (M_W 7.3) that produced a PGA of either 0.15 g or 0.30 g. This is consistent with the scenario earthquakes used by Grant and others (1992) and Shannon & Wilson, Inc., (1993) in evaluating liquefaction susceptibility in the Seattle and Tacoma areas. The scenario earthquake used in this study was intended to represent a major earthquake similar to the 1949 Olympia event. I consider the M_W 7.3 scenario earthquake to be at an intermediate depth (30 to 37 mi or 48 to 60 km) located within the subducting Juan de Fuca plate; this is termed an intraplate earthquake. The two values of PGA used in the scenario earthquake are expected to bracket the range of damaging ground motions that would arise from a M_W 7.3 intraplate event. The 0.30 g PGA corresponds closely to the PGA measured in downtown Olympia during the 1949 earthquake.

However, recent studies indicate that other earthquake sources have the potential to generate more severe ground motions than the scenario earthquake chosen for this study. The

[1] American Society for Testing and Materials (ASTM), 1991, D 1586-84, Standard method for penetration test and split-barrel sampling of soils. *In* Annual book of ASTM standards, v. 04.08, Soil and rock; dimension stone; geosynthetics, p. 232-236.

[2] American Society for Testing and Materials (ASTM), 1991, D 2487-90, Standard test method for classification of soils for engineering purposes. *In* Annual book of ASTM standards, v. 04.08, Soil and rock; dimension stone; geosynthetics, p. 309-319,

potential for great (M_w 8 or larger) thrust earthquakes to occur on the Cascadia subduction zone has been recognized (Atwater, 1987; Weaver and Shedlock, 1991; Atwater and others, 1995). Also, evidence for a major earthquake (M_w 7 to 7.5) on the Seattle fault about 1,000 years ago was recently presented (Bucknam and others, 1992; Atwater and Moore, 1992; Jacoby and others, 1992). The projected trace of this west-trending fault is located approximately 21 mi (34 km) north of the northern boundary of the study area. However, the Seattle fault is south-dipping, so that the main area of energy release during an earthquake on this fault could be closer to the study area.

Ground motion simulation studies for an M_w 8.0 to 8.5 subduction zone earthquake were presented by Cohee and others (1991) and Wong and others (1993). These studies suggest that the PGAs in the Puget Sound region resulting from such an earthquake would be reasonably bounded by the 0.15 g to 0.30 g range of the scenario earthquake used in this study. However, the duration of strong ground shaking for a subduction zone event would be significantly longer than for the M_w 7.3 event considered in this study. The longer duration of shaking would result in more numerous instances of liquefaction and more ground displacement and consequent damage. A major earthquake ($M_w > 7.0$) on the Seattle fault could result in PGAs that might exceed 0.30 g in the northern portion of the study area and that could produce more numerous and severe occurrences of liquefaction than would be expected for the scenario event used in this study.

The evaluation of liquefaction susceptibility presented in this study is nonconservative because I did not consider liquefaction of sandy or silty soils containing more than 40 percent fines. Also, my choice of scenario earthquakes does not necessarily represent the most severe ground motions that can occur in the study area. However, my methodology provides a quantitative basis for assessing the relative liquefaction susceptibility of each of the three liquefaction hazard categories distinguished in the study area that is applicable regardless of the choice of earthquake sources. Furthermore, my results can be compared to those of Grant and others (1992) and Shannon & Wilson, Inc. (1993) to obtain a perspective on the relative liquefaction hazard regionally.

Geotechnical Boring Data Used in Evaluation of Liquefaction Susceptibility

The geotechnical boring data used in this study were obtained primarily from the Washington State Department of Transportation (WSDOT). Some additional data were supplied by the Pierce County Department of Public Works, and the City of Sumner. A total of 153 borings were obtained from these agencies. The available borings are clustered around state highway and Pierce County road construction projects that required geotechnical evaluations.

Ninety-eight and 55 of the available borings were drilled in Category I and III deposits, respectively. There were no borings located in Category II deposits. Drilled total depths for these borings ranged from 9 to 161.5 ft (2.8 to 50 m), and the average depth of all borings used in this study is 53.9 ft (16.4 m). The average drilled depth in Category I deposits was 64.4 ft (19.8 m), and in Category III deposits the average was 35.1 ft (10.8 m). All boring logs included sample descriptions, SPT N-values, and a general description of drilling and sampling procedures; most boring logs or reports recorded measured depth to ground water, accessory geotechnical data (such as grain-size analyses), and a site plan showing boring locations.

Seed and others (1984) note that variation in drilling methods and sampling procedures used in geotechnical borings can significantly affect the measured SPT N-values. They suggest that the ideal drilling and sampling practice for obtaining SPT N-values for evaluating liquefaction susceptibility is as follows:

- 4- to 5-in.(10.2-12.7 cm) -diameter rotary boring drilled using an upward-directed flow of bentonite mud (typically a tri-cone bit configuration);
- a sampling tube with 2.00-in. (5.08 cm) O.D. and 1.38-in. (3.50 cm) I.D. without a liner;
- AW drill rods for depths less than 50 ft (15.2 m), and N, BW, or NW rods for greater depths;
- 30 to 40 blows per minute delivered to the sampler;
- SPT N-value measured between 6 in. (15.2 cm) and 18 in. (45.7 cm.) penetration of the sampler at the bottom of the hole; and
- 2,520 in.-lb (2903 kg-cm) energy delivered to the sampler (60% of theoretical maximum).

The energy delivered to the sampler is typically not measured, but it has been shown to depend on the type of hammer and size of the drill rods used in the penetration testing. In the United States, the most commonly used hammer configuration is a rope and pulley system using a safety hammer (Seed and others, 1984). AW drill rods are often used in shallow geotechnical borings drilled in the Puget Sound region. Consequently, SPT N-values obtained from these borings would follow this detail of the recommended practice of Seed and others (1984). Use of a rope and pulley safety hammer system with AW rods would ideally result in a 60 percent transfer of energy to the sampler at depths less than 50 ft (15.2 m) (Seed and others, 1984), which would satisfy their recommended parameters.

The N-values reported in many borings drilled since the mid-1980s by the Washington State Department of Transportation were obtained using a variety of automatic trip hammers. Recent measurements performed on two WSDOT trip hammers indicated approximately 70 percent efficiency in energy transfer to the drill rods (American Society of Civil Engineers Seattle Section Geotechnical Group, 1995). However, many of the boring logs obtained from WSDOT files predate the use of the automatic trip hammer, and many recent WSDOT boring logs do not document the type of hammer (rope and cathead versus trip hammer) used in the SPT testing. Measurements of hammer efficiency made as part of the 1995 ASCE Seattle Section Geotechnical Group spring seminar on in-situ testing for seismic evaluation demonstrated that an assumption of approximately 60 percent efficiency is only appropriate for carefully conducted SPT testing using a rope and cathead safety hammer or an automatic trip hammer (American Society of Civil Engineers Seattle Section Geotechnical Group, 1995). As a minimum criterion, measurement of the SPT-N value in all borings used in this study explicitly adhered to ASTM D1586-84. I have treated SPT blow counts from all data sources as if the hammer efficiency were 60 percent. This may lead to a biased estimate of the calculated fac-

tors of safety, but as I have treated all borings in the same manner, this bias should have little effect in my evaluation of the relative susceptibility of the various liquefaction categories.

The most significant departure from the recommended procedures of Seed and others (1984) is the regular use of hollow-stem augers instead of rotary methods in drilling geotechnical borings in the Puget Sound region. A standard auger has an 8-in. (20.4 cm) O.D. and a 4-in. (10.2 cm) I.D. and drills a hole larger than the 4- to 5-in. (10.2 to 12.7 cm) optimal size. Water, rather than bentonite mud, is often used as the drilling fluid, if fluid is used at all during drilling. However, Seed and others (1988) have shown that the type of fluid (drilling mud or water) does not affect the SPT blow counts.

Shannon & Wilson, Inc. (1990) suggested that SPT N-values measured in borings drilled using hollow-stem augers are consistently lower than those measured in rotary-drilled borings. The certainty of this observation is obscured by the mixed use of safety- and donut-type hammers in their study. Shannon & Wilson, Inc., (1993) drilled paired rotary and hollow-stem auger borings with the same drill rig at three sites in the Puyallup valley and reported no significant bias in measuring SPT N-values for the different drilling methods. Only a small number of borings in this study's data set are known to have been drilled using rotary methods. For the majority of the available borings either the method of drilling was not reported or they were drilled using hollow-stem augers. Thus, this study ignores any bias introduced into SPT N-values measured in hollow-stem auger borings on pragmatic grounds: it would not be possible to perform a defensible evaluation of liquefaction susceptibility using only the sparse data set provided by rotary-drilled borings.

Table 3. Descriptions of ground failures in the Sumner 7.5-minute quadrangle caused by the 1949 and 1965 Puget Sound earthquakes (modified from table 2 of Chleborad and Schuster, 1990; metric values and explanatory information in brackets). Location numbers correspond to ground-failure location numbers on Plate 1. All data have location accuracy A, indicating that available information allowed accurate relocation on the map

Loc. no.	Failure type (year of earthquake)	Reference municipality	Quotation and (or) comment
56	sand boils (1949)	Sumner, Wash.; Pierce County	Two sand boils, about 3 ft [0.9 m] in diameter and 5 or 6 in [13–15 cm] high, occurred at 8502 Riverside Rd. East in Sumner. Water from the sand boils had a salty taste (Francis Watson, personal commun., 1989).
57	sand boils (1949)	Sumner, Wash., Pierce County	Blows of water and sand occurred on my property about 1 mile [1.6 km] east of Sumner (Herman Nix, personal commun., 1989).
58	sand boils (1949)	Sumner, Wash., Pierce County	Many sand boils, about 6 in [15 cm] in diameter and 1 or 2 in [2.5–5 cm] high, were produced by the 1949 earthquake near the corner of Main and Van Tassle on the east side of Sumner. The sand was clean and black (Fred Weber, personal commun., 1989).
59	settlement (1965); misc. effects (1965); misc. effects (1949)	Sumner, Wash., Pierce County	"Broken water mains*** cement porch fell toward street*** school gymnasium walk sunk in and cracked. [In the 1949 earthquake] springs disappeared, water lowered" (Mrs. L. R. Bariekman, written commun., 1965).

Historic Liquefaction

The two largest earthquakes in recent historic times in the Puget Sound region are the 1949 surface wave magnitude (M_S) 7.1 Olympia and the 1965 M_S 6.5 Seattle–Tacoma earthquakes. The study area was exposed to Mercalli Modified Intensity VIII and VII shaking in the 1949 and 1965 events, respectively (Murphy and Ulrich, 1951; Roberts and Ulrich, 1951; von Hake and Cloud, 1967). Sites of ground failures caused by liquefaction in the study area have been reported by Hopper (1981) and Chleborad and Schuster (1990). Four sites where liquefaction occurred are identified by the reference number used in Chleborad and Schuster (1990) and are shown in Plate 1. Table 3 reproduces the information given for the sites identified in Chleborad and Schuster (1990).

All of the historic liquefaction sites are located in the Puyallup and upper Duwamish valleys in Holocene alluvium (Category I deposits). Sites 57, 58, and 59 are located near the confluence of the Puyallup and White Rivers, and site 56 is slightly farther to the south. The reports for sites 56, 57, and 58 all clearly describe sand blows caused by the 1949 earthquake. The description of the sand as "clean and black" at site 58 is similar to that given for many of the liquefaction reports in the Puyallup valley cited in Shulene (1990), Chleborad and Schuster (1990), and Palmer and others (1991). The phenomena observed at site 59 during the 1949 and 1965 earthquakes are somewhat equivocal evidence of liquefaction. The observed settlements could be the result of dynamic compaction of loose soils and not necessarily liquefaction-induced subsidence. Also, the report of the disappearance of springs and "lowering of water" is not a direct indication of soil liquefaction. The correspondence between the abandoned channels mapped on Plate 1 and three of the four liquefaction sites is noteworthy in that it suggests a higher susceptibility in the vicinity of these geomorphic features.

LIQUEFACTION SUSCEPTIBILITY OF THE OSCEOLA MUDFLOW

Recent studies of historic liquefaction in the Puyallup valley (Palmer and others, 1991; Pringle and Palmer, 1992; Shannon & Wilson, Inc., 1993; Dragovich and others, 1994) have suggested that Holocene sedimentation has been dominated by lahars originating from Mount Rainier and that these deposits can be extremely susceptible to liquefaction. The Osceola Mudflow crops out widely in the Sumner quadrangle and is found in the subsurface of the upper Duwamish and Puyallup valleys (Dragovich and others, 1994). Because of the great extent of this deposit in the study area, it is important to make some determination of its susceptibility to liquefaction.

A significant factor inhibiting liquefaction is the gravel, silt, and clay content of a susceptible sandy soil (National Re-

search Council Committee on Earthquake Engineering, 1985). Crandell (1963, p. A46) describes the Osceola Mudflow as "...an unsorted and unstratified mixture of subrounded to subangular stones in a purplish-gray plastic clayey-sand matrix." Crandell's description of the Osceola Mudflow as a clayey sandy gravel suggests that this deposit may not be capable of liquefying during an earthquake. However, a quantitative approach to evaluating the soil properties of the Osceola Mudflow is needed in order to fairly assess the liquefaction susceptibility of this deposit.

Evidence of Past Liquefaction

During a geotechnical investigation conducted by WSDOT for the State Route 167/32nd Street Interchange, several undisturbed samples of the upper contact of the Osceola Mudflow and the overlying alluvial soils were obtained. An undisturbed sample S-2 was obtained in boring BH-1-93 between 40 and 42 ft (12.2 and 13.3 m) depth; the boring log of BH-1-93 is presented in Figure 9. As sample S-2 was pushed from the Shelby tube, it separated along a number of vertical and horizontal sand-filled partings between 40.0 and 40.6 ft (12.2 and 12.4 m). These partings occurred along apparent sand injections into the silty alluvium that directly overlies the Osceola Mudflow. The contact between these two units was observed in the bottom of this undisturbed sample at a depth of 41.5 ft (13.1 m).

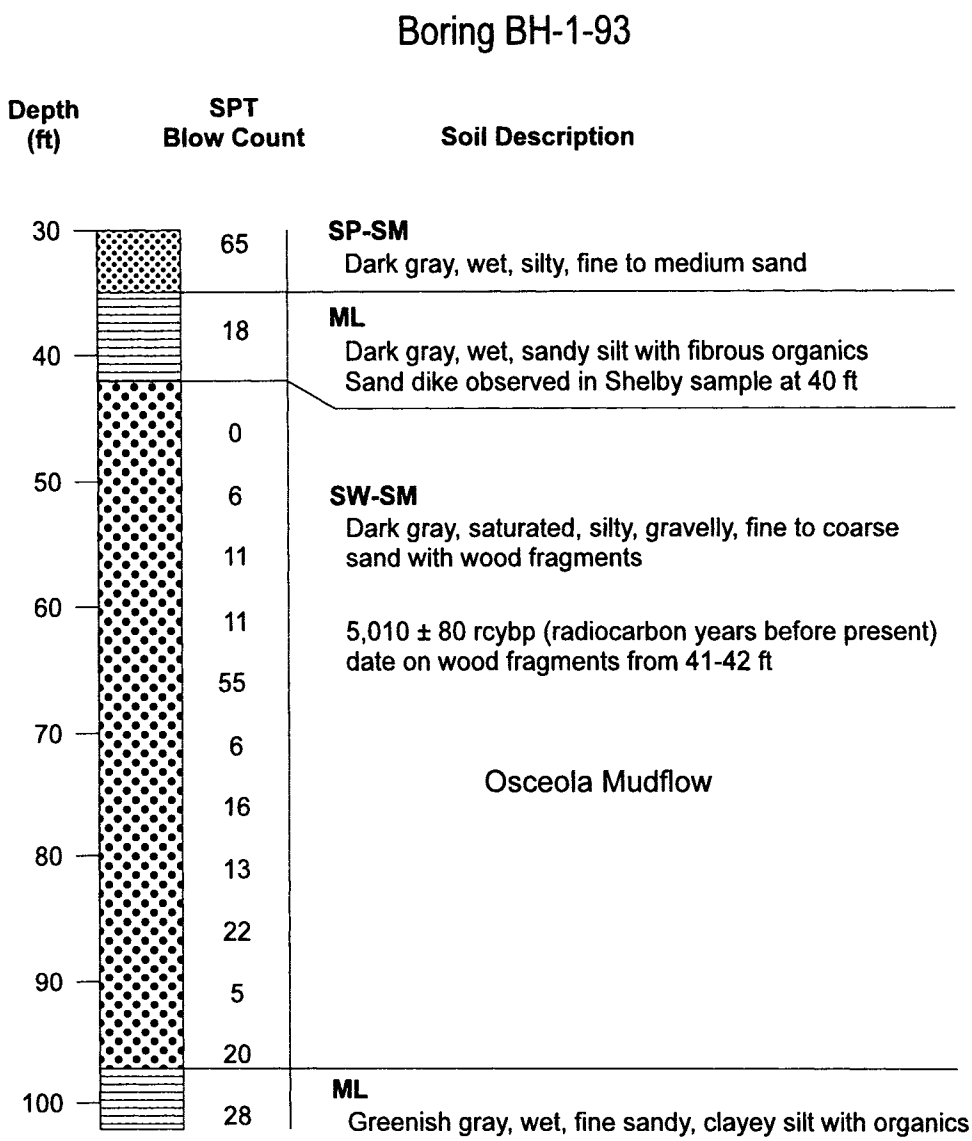


Figure 9. BH-1-93 boring log.

The Osceola Mudflow is 46 ft (14.1 m) thick in boring BH-1-93, so it is unlikely that the observed dikes originated in the loose sands underlying the Osceola. Thus, the source for the sand dikes is either within the Osceola or in proximate liquefiable sands interbedded with the silty alluvium. The latter source seems unlikely from a geometric standpoint; the liquefied sand would need to have been injected as sills and move laterally and (or) downward into the silty alluvium immediately adjacent to boring BH-1-93 to form the dikes and sills observed in sample S-2. However, downward-directed injected sand has been observed in liquefaction features resulting from the 1964 Good Friday earthquake in Alaska (T. J. Walsh, DGER, oral commun., 1995). These features resulted from liquefaction at depths less than 3 ft (0.9 m) below ground surface.

The sand in the dikes and sills in sample S-2 is predominantly fine grained and crystal rich and contains numerous pumice fragments with only a minor component of other lithic grains. The fine sand fraction in a sample of the Osceola Mudflow obtained at a depth of 50.0 to 51.5 ft (15.2 and 15.6 m) in boring BH-1-93 contains a higher percentage of lithic grains, but it also is primarily composed of crystals and pumice.

Crandell (1963) indicates that in its outcrop area the upper 10 to 12 ft (3.0 to 3.6 m) of the oxidized (weathered) zone of the Osceola Mudflow is cemented with iron oxides and perhaps with secondary silica. He notes that this oxidized and cemented zone may be "... largely the result of seasonal alternations of moisture conditions that promote excessive oxidation, hydration, and dehydration." The presence of this cemented zone results in a high bearing capacity at the surface. Crandell (1963) reports that the mudflow beneath this cemented layer has practically no bearing strength when near its liquid limit. He points to examples from a deep excavation for a sawmill southwest of Buckley and from construction of the footings for the Rainier State School east of Buckley, which extended below the cemented layer into the unoxidized mudflow material.

Chleborad and Schuster (1990) provide comprehensive documentation of failures caused by the 1949 and 1965 Puget Sound earthquakes. Their compilation shows that liquefaction was not observed in areas of Osceola Mudflow outcrop. Ishihara (1985) presents a series of curves that demonstrate the

effect of a nonliquefiable surface layer on the potential for level-ground disturbance during liquefaction of the underlying soil column. For a PGA of 0.2 g, Ishihara's relations would predict that the 10- to 12-ft (3.0 to 3.6 m) -thick cemented surface layer of the Osceola Mudflow would preclude the development of liquefaction-related effects at ground surface. Although these relations are based on a small number of case studies, they do suggest that the lack of liquefaction effects observed during the 1949 and 1965 earthquakes does not necessarily imply lack of liquefaction of the Osceola Mudflow below the zone of cementation.

Data on Relevant Soil Properties

Three considerations in evaluating the liquefaction susceptibility of the Osceola Mudflow in the subsurface of the Puyallup valley are:

- the relative density of the soils, as estimated from index measurements such as SPT blow counts and cone penetrometer tip (CPT) resistance;
- the amount of silt and gravel fraction present in this soil unit as estimated from gradation data;
- the plasticity of the silt and (or) clay fraction based on Atterberg limits.

Figure 4C plots both the average raw blow counts (N_1) and the corrected average blow counts ($(N_1)_{60}$) against depth below the top of the Osceola Mudflow. The effective stress and energy normalization corrections of the N_1 values are performed as suggested by Seed and others (1983, 1985) assuming a hammer efficiency of 60 percent. The average uncorrected blow counts show a general increase with depth, but average corrected blow counts are fairly constant with depth, and indicate that the mudflow deposit is a loose to medium dense soil. $(N_1)_{60}$ values of 11 or less would allow liquefaction of a silty sand containing 35 percent fines at a cyclic stress ratio of 0.2. This cyclic stress ratio is within the levels of ground motions characterized by the larger scenario earthquake used in this study and is likely within the range of ground motions expected at this site since the mid-Holocene.

Corrected tip resistances in CPT-1 (Fig. 10), located adjacent to boring BH-1-93, range from 5 to 30 bars (ignoring spikes), indicating loose soil conditions. Correction for excess pore pressure follows a method reviewed in Robertson and Campanella (1989) and uses a net area ratio of 0.6 for the Hoggentoggler piezo-cone used by WSDOT. Figure 11 is a cross-plot of the corrected tip resistance versus friction ratio for the Osceola Mudflow penetrated in CPT-1. Points that plot inside the outlined region (as shown in Robertson and Campanella, 1989) can be considered susceptible to liquefaction. As can be seen from the figure, a large proportion of the data points falls in the region that indicates susceptibility to liquefaction.

Figure 4A presents gradation data obtained from surface outcrops of the Osceola Mudflow (Crandell, 1971) and from subsurface samples of this deposit in the Puyallup and upper Duwamish valleys. The figure shows the envelopes of the two gradation data sets. Inherent in the subsurface data are problems with undersampling of the coarse gravel fraction due to the size of the split-spoon sampler (1⅜ in. I.D.) and the 'nugget' effect resulting from a single large clast dominating the weight percentage of a small volume of sample. The biases introduced from these two effects are opposing and may to an extent be self-canceling. However, it is not possible to accurately quantify these effects, and only some broad generalizations can be made from these gradation data:

- The particle-size distribution of the surface and subsurface samples are very similar.
- The fines content ranges between 5 and 30 percent and averages about 20 percent, and the gravel content ranges from 10 to 60 percent and averages about 25 percent.

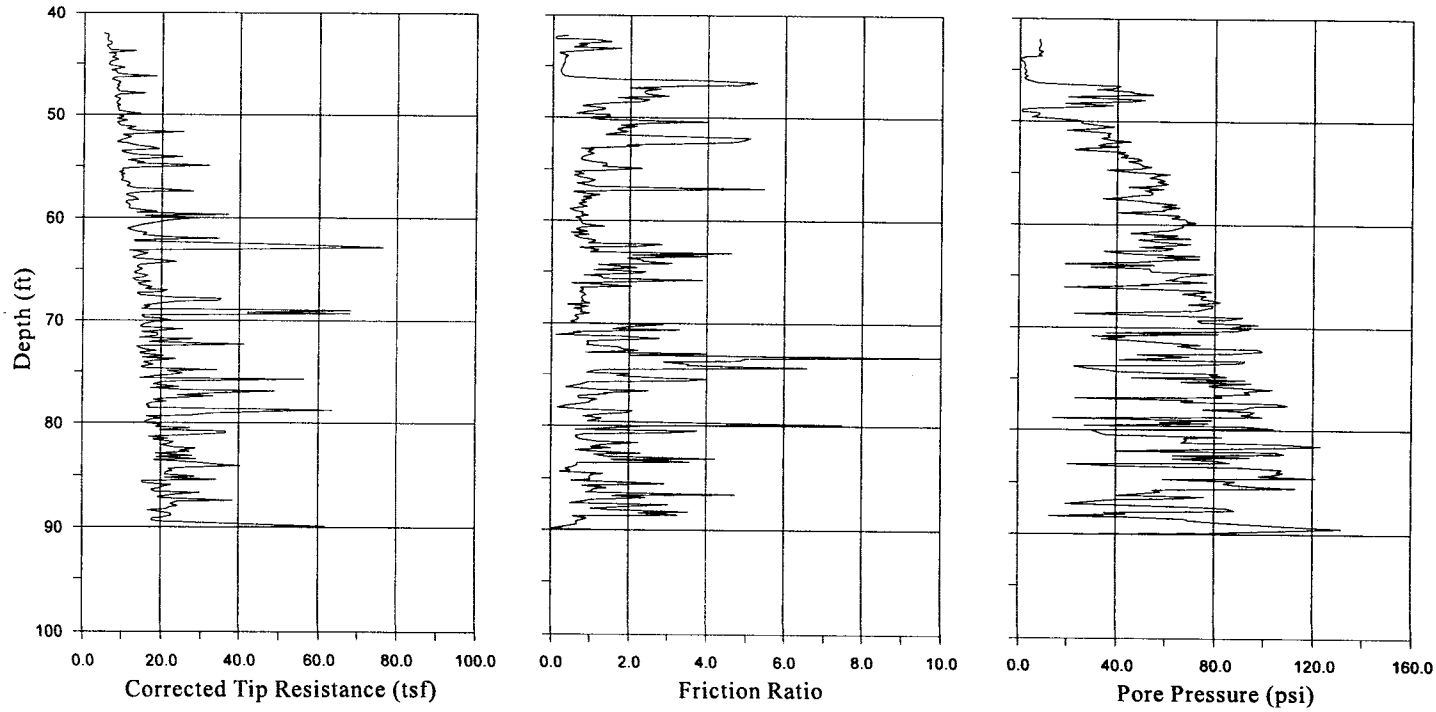


Figure 10. Display of tip resistance (corrected for pore pressure), friction ratio, and pore pressure for the section of CPT-1 penetrating the Osceola Mudflow. Depth range of the mudflow was determined from sample descriptions in the adjacent boring BH-1-93.

- The subsurface samples may contain a smaller percentage of fines and a larger percentage of sand fraction than the surface samples.

Crandell's (1977) gradation data for eight surface samples indicate that the clay-size fraction ranges from 7 to 13 percent by weight. Scott and others (1992, p. 23) describe the Osceola Mudflow as "remarkably clayey; the composite deposit (matrix and coarse phases) contains 2 to 15 percent clay, with a mean of 7 percent (13 samples)." Clay percentages referred to by Scott and others (1992) are particle-size measures, not mineralogical percentages. Crandell (1971, p. 28) states that "Clay minerals make up from 60 to 80 percent of the clay-sized fraction of each sample. Montmorillonite and kaolinite predominate in various proportions in every sample of the deposit...."

Crandell (1971) also reports the Atterberg limits on the 0.420 mm and smaller (clay-size) fraction of the eight samples of the Osceola Mudflow. Liquid limits range from 28 to 42 percent with an average of 33 percent, and plasticity indices range from 2 to 15 percent with an average of 8.4 percent. These results indicate that the clay-size fraction of the Osceola Mudflow has low plasticity, falling in the range of ML to CL soils. Only one Atterberg test was available for a subsurface sample of the Osceola Mudflow. This test was performed on material passing the No. 40 sieve and indicated a liquid limit of 27.3 percent and a plasticity index of 5.8 percent. This sample has a fines content of 28.2 percent and a gravel content of 13.4 percent.

Liquefaction of the 1980 Mount St. Helens Debris Avalanche Deposit

Jenkins and others (1994) report that geotechnical studies performed during construction of the Spirit Lake Memorial Highway (State Route 504) determined that the debris avalanche deposits from the 1980 eruption of Mount St. Helens are highly susceptible to liquefaction. To mitigate the liquefaction hazard, WSDOT found it necessary to densify the soils underlying the approach fill and bridge abutment footings at Bridge 12, which crosses South Coldwater Creek at the mouth of Coldwater Creek valley. Blast-induced densification was chosen on the basis of cost and feasibility of construction (Jenkins and others, 1994). Liquefaction resulting from the blasting was indicated from pore-pressure measurements and by the observation of sand boils and upward ground-water flow after detonation. A quarter-mile farther up Coldwater Creek valley from Bridge 12, vibrations from the passage of heavy construction equipment generated lateral spreading in debris avalanche deposits that had not been densified during the Bridge 12 project.

Fairchild (1985, 1987) discusses liquefaction of the debris avalanche deposits as a possible mode of generation of the North Fork Toutle River mudflow. This mudflow was initiated approximately 3 hours after the May 18, 1980, eruption in response to a long period of strong harmonic tremors. Fairchild (1985, 1987) reconstructed the timing and behavior of the debris flow and was able to determine its source area. Gradations from debris avalanche material collected from the source areas fell within the following ranges: gravel and coarser (26–36 percent), sand (44–59 percent), and fines (15–20 percent). These grain-size ranges are similar to those of subsurface samples of the Osceola Mudflow previously discussed. Grain-size data from Glicken (1986) show that the clay-size fraction of the debris avalanche deposit ranges from 0.09 to 3.39 percent and averages 1.07 percent, which is significantly less than the ranges and averages reported by Crandell (1971) and Scott and others (1992) for outcrop samples of the Osceola Mudflow.

The Mount St. Helens debris avalanche deposits are poorly sorted (well graded in soils engineering terminology) and are similar to the Osceola Mudflow in terms of the gradation ranges. Recent experience has demonstrated that these debris-avalanche deposits are susceptible to liquefaction, even though they may contain significant percentages of fines and gravel. Because these gravelly deposits are matrix supported rather than clast supported, their susceptibility to liquefaction is primarily determined by the behavior of the sand and fine fractions.

Case Studies of Liquefaction of Silty Soils

Liquefaction of fine-grained mine tailings (tailings slimes) is reviewed by Ishihara (1985). His review indicates that mine tailings susceptible to liquefaction exhibit the following characteristics:

- low relative density as a result of the method of emplacement;
- clay-size fractions ranging from 10 to 30 percent by weight, although this size fraction is essentially devoid of clay minerals;
- plasticity indices ranging from 1 to 11 percent—that is, these are low plasticity silts.

I reviewed two case studies of earthquake-induced liquefaction in native silty soils that are relevant to evaluation of the liquefaction susceptibility of the Osceola Mudflow. The first study is an analysis of lateral spreading at the San Fernando Valley Juvenile Hall during the 1971 Sylmar earthquake (Bennett, 1989). The second evaluates liquefaction in Ying Kou City, People's Republic of China, during the Haicheng earthquake of 1975 (Arulanandan and others, 1984, 1986).

The soils identified as having liquefied at the San Fernando Valley Juvenile Hall site are primarily silts with interbedded very silty sands (Unit B of Bennett, 1989). The fines content averages 62 percent and ranges from 38 to 83 percent; the clay-size fraction averages 10 percent and ranges from 3 to 20 percent. Uncorrected blow counts average 6.7 and range from 2 to 12; $(N_1)_{60}$ values range from 3.7 to 10.6 (Bennett, 1989). These silts have plasticity indices ranging from 2 to 11 percent and liquid limits ranging from 25 to 35 percent. Consequently these soils are classified as low plasticity silts (ML and ML-CL soils). Liquidity indices for these soils are less than unity, indicating that these soils are not sensitive.

Soils that were identified by Arulanandan and others (1986) to have liquefied during the Haicheng earthquake range from silty sands to sandy silts and from clayey silts to silty clays. Laboratory testing and field evaluation indicate that these fine soils have:

- liquid limits ranging from 24 to 35 percent, and plasticity indices ranging from 6 to 14 percent;
- liquidity indices nearly equal to or greater than one, with a maximum of 2.3, indicating that these are sensitive soils;
- fines contents ranging from 40 to 90 percent;

- uncorrected SPT blow counts ranging from 0 to 14 in the upper 33 ft (10 m) of the soil column.

Figure 12 is a cross-plot of corrected tip resistance versus friction ratio for CPT soundings at liquefaction sites in Ying Kou City (data from Arulanandan and others, 1986). The CPT data used in this plot did not have simultaneous pore-pressure measurements. Arulanandan and others (1986) present data from a single piezo-cone sounding at one of the liquefaction sites; this sounding shows that excess pore pressures are generated during tip advance and that correction of the tip resistance data is needed. The correction scheme that I adopted is based on the evaluation of this piezo-cone sounding and is as follows:

- A correction of 2.5 kg/cm^2 was used at intervals where the uncorrected tip resistance was less than 15 kg/cm^2;
- A correction of 1.0 kg/cm^2 was applied for tip resistances equal to or greater than 15 kg/cm^2.

The CPT cross-plot shows that many of the data points fall within the region defined in Robertson and Campanella (1989) as being susceptible to liquefaction. The CPT cross-plots for the Osceola Mudflow and the Ying Kou City liquefaction sites (Figs. 11 and 12, respectively) are in fact quite similar. This similarity supports the hypothesis that the Osceola Mudflow may be susceptible to liquefaction. Arulanandan and others (1984) estimate that cyclic stress ratios of 0.1 to 0.15 were generated in Ying Kou City during the Haicheng earthquake, which is in the range of cyclic stress ratios generated within the Osceola Mudflow under the earthquake scenarios used in this study.

Synthesis of Data and Interpretations for the Osceola Mudflow

The Osceola Mudflow found in the subsurface of the Puyallup and upper Duwamish valleys is typically a gravelly, silty sand having a USCS classification of SW-SM. Silt content typically ranges from 10 to 30 percent, and gravel content ranges from 10 to 60 percent. Atterberg limits on the clay-size fraction of the Osceola Mudflow indicate low plasticity, and a single test

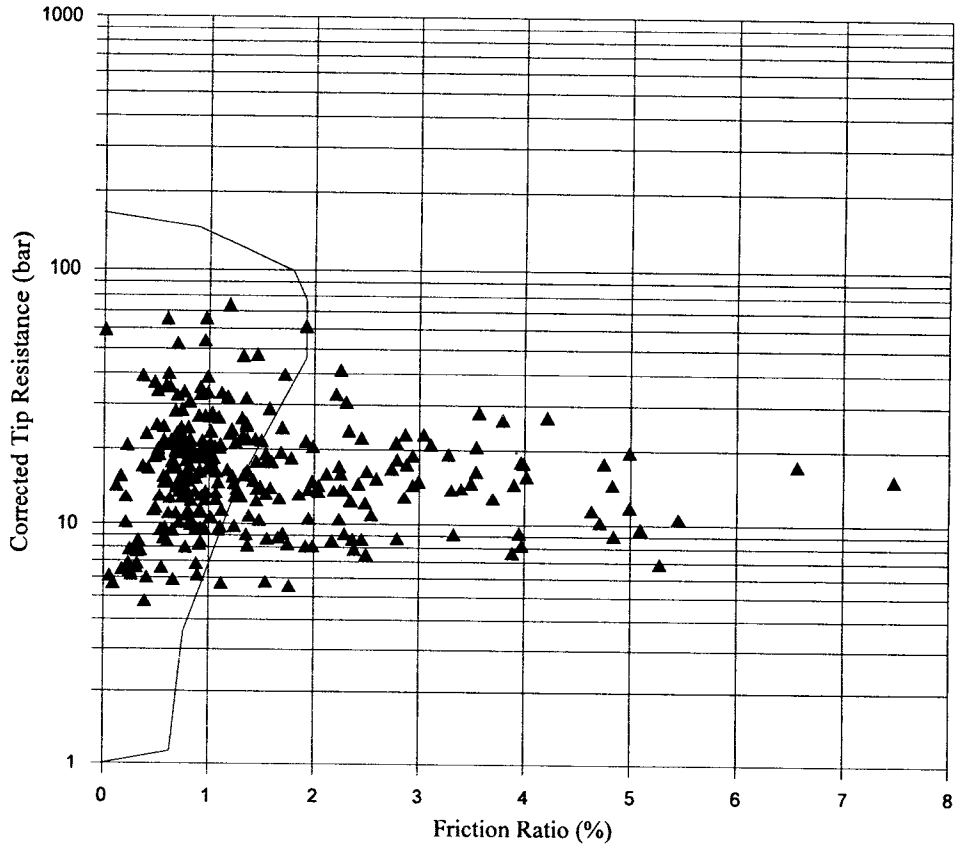


Figure 11. Cross-plot of corrected tip resistance versus friction ratio for the section of the Osceola Mudflow penetrated by CPT-1. Note that many of the data points fall within the outlined region (Robertson and Campanella, 1989) delineating soils that are susceptible to liquefaction.

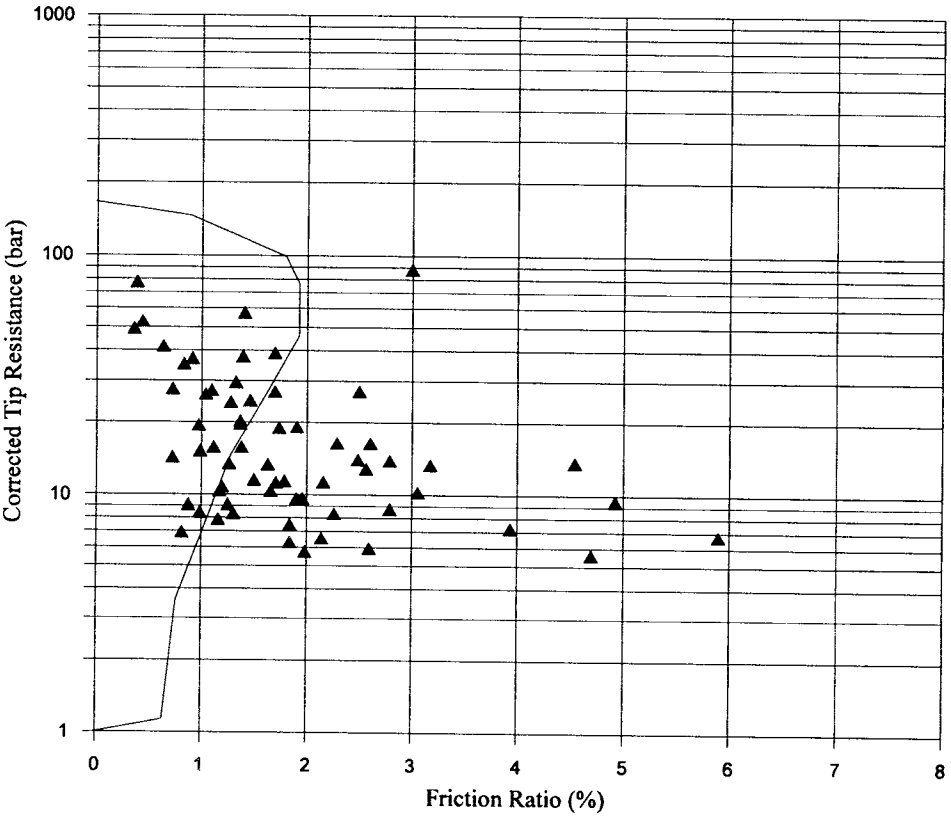


Figure 12. Cross-plot of tip resistance (corrected for pore pressure) versus friction ratio for sites in Ying Kou City where the Haicheng earthquake caused liquefaction. Data are from Arulanandan and others (1986). Many of the data points fall within the outlined region (Robertson and Campanella, 1989) delineating susceptibility to liquefaction. Note the similarity of this cross-plot to that for the Osceola Mudflow shown in Figure 11.

on material passing the No. 40 sieve likewise shows low plasticity. Corrected SPT blow counts and cone penetrometer tip resistance values indicate that the mudflow is a loose to medium dense soil where sampled in the sub-surface of the upper Duwamish and Puyallup valleys.

Vibration or blast-induced liquefaction of the debris avalanche deposits of the 1980 eruption of Mount St. Helens has been documented by Fairchild (1985, 1987) and Jenkins and others (1994). These deposits are typically poorly sorted silty gravelly sands and are similar to the Osceola Mudflow in terms of particle size and gradation. Both these deposits are matrix supported; consequently their liquefaction susceptibility is dominated by the sand and fines fractions. The Mount St. Helens debris avalanche deposits have a smaller clay-size fraction (average 1.07 percent) than the average for the Osceola Mudflow (7 percent). However, there is considerable range in clay content in the Osceola Mudflow samples (2 to 15 percent), and only about 75 percent of the clay-size fraction is actually composed of clay minerals. Thus it is necessary to examine the potential effects of the silt and clay fractions on liquefaction of the Osceola Mudflow.

I have reviewed two documented case histories of liquefaction occurring in silt soils. In both cases, the silt soils were of low plasticity, with plasticity indices and liquid limits falling in the same ranges as those documented for the clay-size fraction of the Osceola Mudflow. Based on the $(N_1)_{60}$ values reported in these case studies, the soils that liquefied were typically loose to medium dense. Cross-plots of CPT corrected tip resistance and friction ratio obtained at liquefaction sites in Ying Kou City and CPT data from the Osceola Mudflow in the upper Puyallup valley suggest that the mudflow may be liquefiable. Finally, the sand dikes observed in WSDOT boring BH-1 provide equivocal evidence of liquefaction of the Osceola Mudflow based on their proximity to the upper contact of this stratigraphic unit.

From these data and analyses I have concluded that the fines fraction of the Osceola Mudflow is not sufficiently plastic to impede the generation of high pore pressures that could result in liquefaction of these soils under suitable earthquake ground-motions. There is no significant difference in plasticity between the fines fraction of the Osceola Mudflow and the silty soils that liquefied at the San Fernando County Juvenile Hall and in Ying Kou City. Likewise, the gradation and Atterberg limits data for the mudflow fall within the range of criteria presented by Seed and Idriss (1982) for silt soils that may be vulnerable to significant dynamic strength loss. These criteria are:

- percent finer than 0.005 mm <15 percent;
- liquid limit <35 percent;
- water content > 0.9 times the liquid limit.

Experimental and field studies have tended to examine only noncohesive granular soils and rarely have evaluated the response of a well-graded deposit such as the Osceola Mudflow. Therefore, the existing field-performance methods are potentially unsatisfactory in assessing the pore-pressure behavior and residual strength of a silty, well-graded soil such as the mudflow. Consequently, the dynamic strength behavior and liquefaction susceptibility of the Osceola Mudflow should be the subject of further investigation. This investigation should involve acquisition of gradation and plasticity data from additional borings drilled both in the alluvial valleys and in outcrop areas, and laboratory and field measurement of dynamic strength properties.

Table 4. Criteria used by Shannon & Wilson, Inc., (1993) for rating the hazard due to liquefaction based on analysis of geotechnical boring data in the Tacoma area

Percentage of borings in a geographic location with thickness of liquefied sediment ≥: (a) 3.05 m (10 ft) for a 0.30 g event, and (b) 0.305 m (1 ft) for a 0.15 g event	Hazard rating
>50	High
25–50	Moderate
1–25	Low
<1	Very low

RESULTS OF LIQUEFACTION ANALYSIS FOR THE SUMNER QUADRANGLE

Figure 13 is a cumulative frequency histogram for each scenario earthquake showing the percentage of the total borings located in Category I deposits that equal or exceed an aggregate thickness of liquefiable soils expressed as a percentage of the total boring depth. The aggregate thickness is the sum of the thicknesses of all soil units that would liquefy at the magnitude and for PGA value chosen for the scenario earthquake. Figure 13 shows the histograms for the two scenario earthquakes used in this study (a M_W 7.3 earthquake that produces a PGA of 0.15 g or 0.30 g). The abscissa of the histograms measures the aggregate thickness of liquefiable material in a boring (expressed as a percentage of the depth of the boring). For borings drilled deeper than 40 ft (12.1 m), only the upper 40 ft (12.1 m) were analyzed for susceptibility to liquefaction. The ordinate delineates the percentage of the total number of borings that contain a percentage of liquefiable material greater than the abscissa value.

In constructing Figure 13, I have considered the Osceola Mudflow to be liquefiable and amenable to the factor of safety analysis of Seed and others (1983, 1985). In performing the factor of safety analysis, I assigned a 35 percent fines content to the soil unit (USCS soil class SW–SM), Table 1) composed of Osceola Mudflow. Figure 13 shows that 51 percent of the borings had at least 1 ft (0.3 m) of liquefiable material for the 0.15 g event and 36 percent had at least 10 ft (3.0 m) of liquefiable soils for the 0.30 g earthquake assuming a boring depth of 40 ft (13.2 m). Table 4 presents the thickness criteria used by Shannon & Wilson, Inc. (1993) to rank the relative liquefaction susceptibility of the various soil units in their study area. Using these criteria, Category I deposits have a moderate hazard rating as only 36 percent of the borings have 10 ft (3.0 m) of liquefied soils for the 0.30 g case.

Table 5. Relative liquefaction susceptibility and associated hazard rating from Youd and Perkins (1987)

Relative susceptibility	Hazard rating
1.0 to 10.0	High
0.1 to 1.0	Moderate
0.01 to 0.1	Low

A second method of ranking the liquefaction susceptibility of a soil deposit is presented by Youd and Perkins (1987). They calculate relative susceptibility to liquefaction using the following expression:

Relative susceptibility = [(A x B x C)/10] x 100 , where,

A = percent of sandy soils expressed as a decimal fraction;

B = percent of these soils that are liquefiable if saturated, expressed as a decimal fraction;

C = percent of these soils that are saturated, expressed as a decimal fraction.

Their hazard rating scheme is based on the relative susceptibility and is summarized in Table 5.

Youd and Perkins (1987) evaluated and mapped the liquefaction susceptibility of soil deposits found in San Mateo County, California, using the field evaluation methodology of Seed and others (1983, 1985). In their liquefaction analysis they used a scenario earthquake with a magnitude of 6.5 that produces a PGA of 0.20 g (Youd and others, 1975). I calculated factors of safety for a number of soil profiles using both the scenario earthquake of Youd and Perkins (1987) and the magnitude 7.3 earthquake producing a PGA of 0.15 g used in this study. I found that for a variety of subsurface conditions in which liquefaction is marginal (that is, the factor of safety is near unity), this study's scenario earthquakes yielded factors of safety from 10 to 15 percent higher (see footnote 4) than those calculated using Youd and Perkins' (1987) scenario event. Because I have used a less severe earthquake to evaluate liquefaction susceptibility in the study area than that used by Youd and Perkins (1987), my results are not directly comparable.

Inspection of Youd and Perkins expression for computing relative susceptibility shows that this value can be obtained by integrating the cumulative frequency histogram (after conversion of percentages to their equivalent decimal values) and multiplying the result by 10. This calculation yields a relative susceptibility of 2.01 for Category I deposits in the Sumner quadrangle for the 0.15 g cumulative frequency histogram. This relative susceptibility falls well within the high hazard using the Youd and Perkins (1987) ranking criteria (Table 5).

I did not rigorously account for the differences in calculated factors of safety resulting from the different scenario earthquakes used in this study and in Youd and Perkins (1987). However, it is clear that a more severe scenario earthquake will result in a greater amount of liquefaction (for example, compare the 0.15 g and 0.30 g cumulative frequency histograms shown in Fig. 13), and that Youd and Perkins (1987) used a more severe scenario event in their liquefaction susceptibility analysis. Consequently the relative susceptibility calculated from my analysis (2.01) somewhat underestimates the value I would have obtained if I had used earthquake magnitudes and PGAs comparable to those used by Youd and Perkins (1987).

Figure 14 is a cumulative frequency histogram constructed for Category I deposits, but in borings that penetrated the Osceola within the upper 40 ft (13.2 m), only the alluvial de-

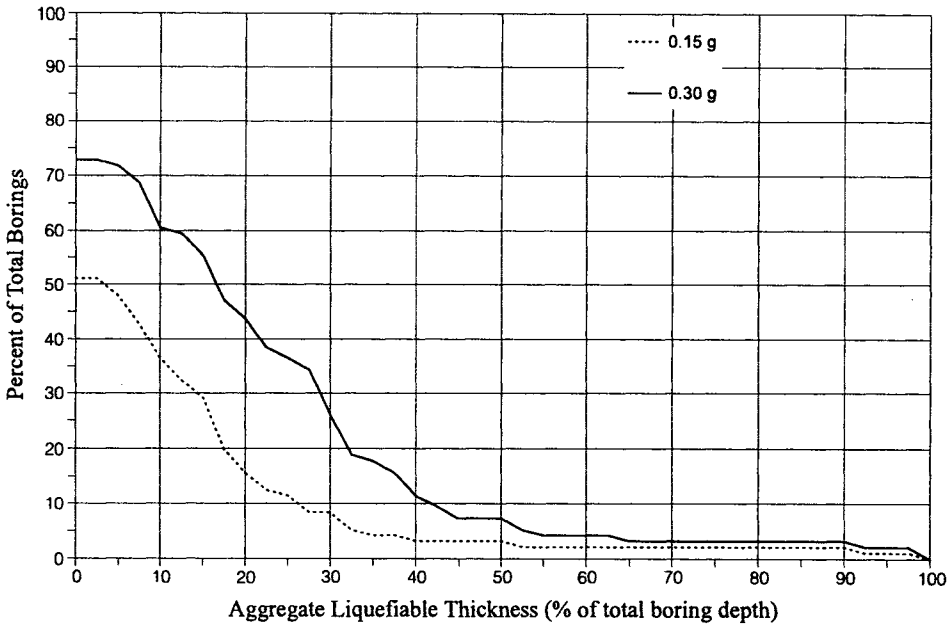


Figure 13. Cumulative frequency histogram for the upper 40 feet of Category I deposits in the Sumner quadrangle for a hypothetical M_w 7.3 event. The Osceola Mudflow was considered liquefiable and included in computation of the aggregate thicknesses.

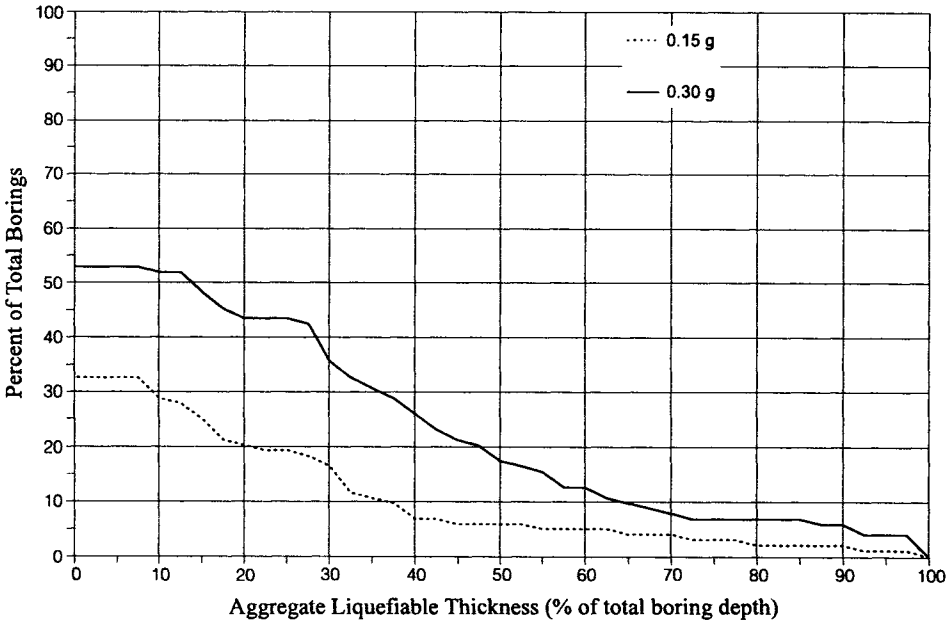


Figure 14. Cumulative frequency histogram for the upper 40 feet of Category I deposits in the Sumner quadrangle for a hypothetical M_w 7.3 event. The Osceola Mudflow deposits were excluded in the computation of aggregate thicknesses.

posits that overlie the Osceola were analyzed. In this case the upper contact of the Osceola Mudflow was treated as the final depth of the boring. Figure 14 shows that 33 percent of the borings had at least 1 ft (0.3 m) of liquefiable material for the 0.15 g event, and that 52 percent had at least 10 ft (3.0 m) of liquefiable soils for the 0.30 g earthquake. Again, a boring depth of 40 ft (13.2 m) was assumed in estimating the thickness of liquefiable soils. Using the criteria of Shannon & Wilson, Inc., (1993) shown in Table 4, this subset of the Category I data again indicates ranking in the moderate hazard category. The relative susceptibility calculated using the methodology of Youd and Perkins (1987) for *non-Osceola* Category I deposits is 1.12, which corresponds to a high rating. This relative susceptibility is likewise somewhat underestimated because of the difference in scenario earthquakes between this study and that of Youd and Perkins (1987).

The four historical liquefaction sites in the Sumner quadrangle are in Category I deposits. Two methods of ranking liquefaction susceptibility indicate that Category I deposits have a hazard rating ranging from moderate to high. Past liquefaction of the Osceola Mudflow may be indicated by the sand dikes observed in sample S-2 in boring BH-1-93. Analysis of SPT blow counts, CPT soundings, gradations, and Atterberg limits and comparison of these data to case histories in which silt soils have liquefied indicate that the Osceola Mudflow is likely to develop excess pore pressure during dynamic loading and may be capable of liquefying during an earthquake. All of these lines of reasoning led to my decision to rank Category I deposits as having a high liquefaction susceptibility. *This ranking does not indicate that any specific locality within a Category I deposit will be underlain by liquefiable soils; the presence or absence of liquefiable material can only be determined by a site specific geotechnical investigation performed by a qualified practitioner.*

The abandoned channels and areas of bar and swale topography mapped in Plate 1 may represent areas of locally higher liquefaction susceptibility. As noted above, three of the four historic liquefaction sites in the Sumner quadrangle are in areas mapped as abandoned channels, and a fourth site is adjacent to an abandoned channel and a large area of bar and swale topography. The abandoned channels typically are low points in the local topography, and consequently the ground-water table would be at a shallower depth beneath these channels than beneath the adjacent flood plain. Both the abandoned channels and bar and swale topography will likely have a high proportion of sand-size sediments as a result of alluvial processes. Finally, some of these abandoned channels may have been filled during the development of the town of Sumner.

The outcrop area of the Electron Mudflow in the Puyallup valley is shown on Plate 1 and is considered a Category I deposit. The Electron Mudflow is underlain by alluvial deposits similar to those exposed farther downvalley near Sumner, which I have shown to have a high liquefaction susceptibility. Crandell (1963) observed that weathered sections of the Electron Mudflow have been weakly cemented by iron oxides, although the amount of cementation is not nearly as great as that of the weathered Osceola Mudflow. This cementation may inhibit both liquefaction of the Electron Mudflow and the surface expression of liquefaction of the underlying alluvial soils. However, sand boils and other indications of liquefaction were observed in the upper Puyallup valley near Orting during the 1949 earthquake. These liquefaction features occurred where the Electron Mudflow is likewise exposed in the floor of the valley. If these reports are reliable, the mudflow may not completely inhibit the surface manifestation of liquefaction of the underlying alluvial soils and may in fact itself be liquefiable. No geotechnical data were available in the Sumner quadrangle for the Electron Mudflow, so no quantitative liquefaction analysis could be performed. I include the Electron Mudflow as a Category I deposit in the Sumner quadrangle because it is undoubtedly underlain by very liquefiable alluvial soils and because of the accounts of liquefaction in the vicinity of Orting where the mudflow covers the valley floor.

Category II deposits include Holocene lacustrine and mass-wasting deposits and Vashon recessional (ice-contact and proglacial) lacustrine sand. There were no borings in this quadrangle that were drilled in areas mapped as Category II. The Holocene lacustrine deposits are primarily composed of peat, clay, and silt. They locally contain sandy layers as thick as 4 ft (1.2 m) (Crandell, 1963, p. 52). Crandell speculates that the sand in a peaty depression in the valley of Fennel Creek (sec. 35, T. 20 N., R. 5 E.) "probably was derived from outcrops of Vashon sand on the east side of the depression." Considering the topography and gradient of Fennel Creek upstream of the depression, it is likely that fluvial processes deposited the sands on top of the peat layer (P. T. Pringle, DGER, oral commun., 1995). Crandell also describes thick sand layers in peat deposits in the adjacent Buckley quadrangle; their origin is more difficult to explain because no major streams feed into those depressions. Because these Holocene lacustrine deposits are primarily composed of peat and silt, they would typically be considered as having a low liquefaction susceptibility. However, there was one reported site in a Holocene lacustrine deposit in the Big Soos Creek drainage north of the study area where liquefaction might have occurred during the 1949 earthquake (Chleborad and Schuster, 1990; Palmer and others, 1994).

Chleborad and Schuster (1990) report a number of earthquake-induced landslides and associated ground cracks along steep slopes in the Puyallup and Duwamish valleys. It is not clear, however, if these failures were caused primarily by liquefaction. Liquefaction-induced soil failures on steep slopes would be difficult to distinguish from landslides induced by the imposed ground accelerations, although a failure mechanism might be inferred by a thorough post-earthquake geotechnical investigation.

The Vashon (late Pleistocene) ice-contact and proglacial sandy lacustrine sediments found in the study area are similar in description, age, and geologic origin to Vashon glaciolacustrine units found in the Poverty Bay quadrangle that are assigned a moderate liquefaction susceptibility based on the analysis of geotechnical boring data (Palmer and others, 1995). Vashon recessional lacustrine deposits in the Sumner quadrangle, they have been included in Category II because of their similarity to the sandy glaciolacustrine units found in Poverty Bay quadrangle.

Soil types occurring in Holocene lacustrine and mass-wasting deposits are quite varied, ranging from nonliquefiable peat and organic silt to potentially liquefiable clean sand. Late Pleistocene ice-contact and proglacial sandy lacustrine sediments are likely to have a moderate susceptibility to liquefaction based on their similarity to other deposits found in the

Poverty Bay quadrangle and in the Olympia area (Palmer and others, 1995). The historic record of earthquake-induced ground failures observed in Category II deposits suggests that seismically induced liquefaction of these deposits is possible. Consequently I rank Category II deposits as having a low to moderate liquefaction susceptibility in order to reflect the variability in the geological and engineering characteristics of these deposits.

Figure 15 presents the cumulative frequency plot for Category III deposits based on 48 borings drilled in Vashon and older glacial and nonglacial deposits that have been overridden by at least one continental ice sheet. These deposits are typically quite dense and provide excellent foundation stability (Mullineaux, 1970). The relative susceptibility for Category III deposits is 0.007, which falls below the low liquefaction hazard rating of Youd and Perkins (1987). This category also has a very low ranking using the thickness criteria of Shannon & Wilson, Inc. (1993).

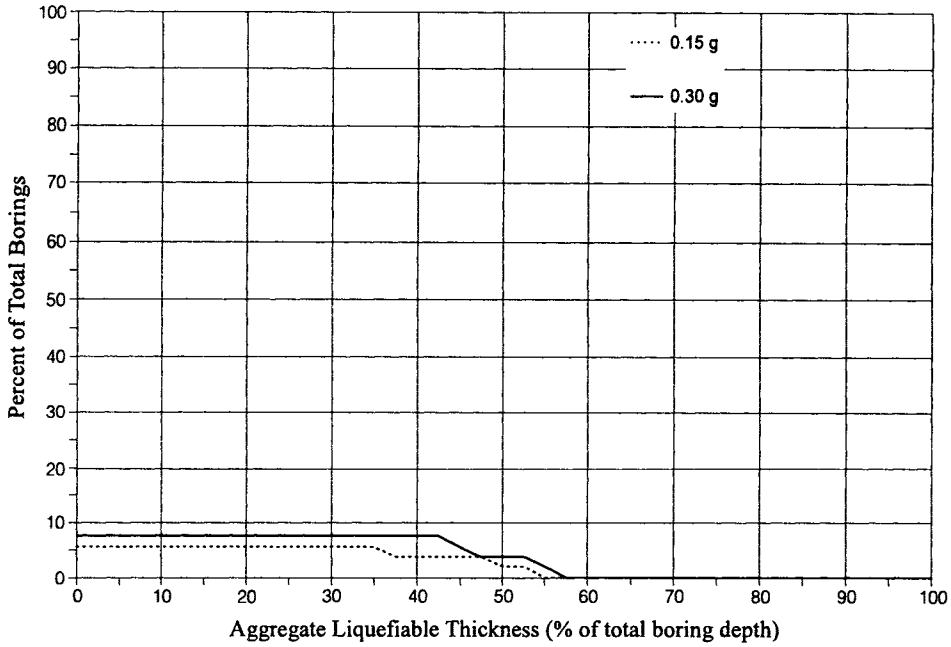


Figure 15. Cumulative frequency plot for the upper 40 feet of the Category III deposits (excluding Vashon recessional deposits) in the Sumner quadrangle for a hypothetical M_w 7.3 event.

Data from seven borings drilled in Vashon recessional deposits (units Qit and Qpv in Fig. 2) were not used in constructing this figure because these deposits have not been compacted under the weight of an overriding ice sheet. Units Qit and Qpv have average uncorrected blow counts of 32 and 24, respectively. If representative, these average blow counts are sufficiently high to preclude liquefaction of these deposits under the levels of shaking represented by the choice of scenario earthquakes used in this study. Crandell (1963) describes both Qit (kame-terrace gravel) and Qpv (valley-train deposits) as a sand and pebble to cobble gravel containing scattered boulders. Thus, the high blow counts measured in the seven borings drilled in these units could be biased by the high gravel component of these sediments and are not necessarily representative of the relative density of these soils. Exposures of these Vashon recessional deposits have been identified on Plate 1 as sandy sections within these deposits may have some susceptibility to liquefaction because they have not been glacially compacted.

No boring data were available for the Osceola Mudflow in its outcrop area, where it is described as having fair to good foundation stability (Mullineaux, 1970). Crandell (1963) indicates that the upper 10 to 12 ft (3–4 m) of the weathered mudflow is oxidized and cemented and that it provides sufficient bearing capacity for light construction. However, below this weathered zone the mudflow becomes highly unstable when disturbed and near its liquid limit. Geotechnical analyses of unweathered sections of the Osceola Mudflow found in the Puyallup and Duwamish valleys indicate that these deposits might be susceptible to liquefaction. I have assigned this unit to Category III lacking more detailed information on the dynamic behavior of the unweathered portion of the Osceola Mudflow in its outcrop area.

No instances of liquefaction were observed in Category III deposits during the 1949 and 1965 Puget Sound earthquakes. The geologic descriptions, geotechnical analyses, and historical record indicate that Category III deposits have little susceptibility to liquefaction, and I have assigned them a low rating. However, unmapped areas of fill located within areas shown as Category III deposits could have a significantly higher liquefaction susceptibility. Thus, the presence or absence of liquefiable soils at a given location within the Category III map area can only be determined by a site-specific geotechnical investigation performed by a qualified practitioner.

CONCLUSIONS

Table 6 summarizes this study's ranking of the liquefaction susceptibility in the Sumner quadrangle. In the study area, Holocene alluvial deposits in the Puyallup and White River valleys and Prairie Creek (Category I) are ranked as having a high liquefaction susceptibility and represent the areas with the greatest liquefaction hazard. Although the Electron Mudflow may not be a liquefiable soil, it is included as a Category I deposits because in the Sumner quadrangle it is undoubtedly underlain by very liquefiable Holocene alluvium. The lack of geotechnical borings penetrating Category II deposits (Holocene mass-wasting and lacustrine sediments and Vashon recessional lacustrine sand) precludes quantitative analysis of liquefaction susceptibility. The general description of the

Table 6. Ranking of the liquefaction susceptibility of the three liquefaction categories in the Sumner quadrangle

Category	Liquefaction susceptibility rating
I	High
II	Low to Moderate
III	Low

Holocene lacustrine sediments (Crandell, 1963) indicates that they are typically composed of silty and peaty soils having a low susceptibility to liquefaction. However, sand interbeds as much as 4 ft (1.2 m) thick have been observed in some lacustrine deposits. The presence of sand beds in these deposits and the possible occurrence of liquefaction in a Holocene lacustrine unit in the Big Soos Creek drainage to the north suggests that liquefaction of these sediments is possible. Some of the numerous ground failures (cracking, slumping, etc.) in mass-wasting deposits observed during the 1949 and 1965 earthquakes may have been the result of liquefaction, but no definitive evidence supporting liquefaction as the primary cause of these failures is available. Late Pleistocene sandy glaciolacustrine deposits in the Sumner quadrangle are quite similar to potentially liquefiable glaciolacustrine sediments found in the Poverty Bay quadrangle. I rank Category II deposits as having a low to moderate liquefaction susceptibility to reflect the variability in the engineering characteristics of the lacustrine and mass-wasting deposits and the historic reports of earthquake-induced liquefaction and other ground failures.

I have ranked Category III deposits, which include Vashon and older glacial and nonglacial deposits (except for Vashon recessional lacustrine sand) as having a low liquefaction susceptibility. Except for Vashon recessional deposits, Category III soils have been overridden by at least one continental ice sheet and are consequently quite dense. The liquefaction susceptibility for these glacially overridden deposits is ranked as low using the criterion of Youd and Perkins (1987) or very low using the thickness criteria of Shannon & Wilson, Inc. (1993). Vashon recessional deposits (other than lacustrine sands) are typically coarse gravel soils that would consequently have a low liquefaction susceptibility. However, more sandy sections of these recessional deposits might be more susceptible to liquefaction. Areas covered by the Vashon recessional deposits are delineated on Plate 1.

The mid-Holocene Osceola Mudflow is also included as a Category III deposit having a low liquefaction susceptibility. In outcrop, the Osceola Mudflow typically has a weathered, cemented surface layer not susceptible to liquefaction. Osceola Mudflow deposits found in the subsurface of the Puyallup and Duwamish valleys have not been exposed to the weathering processes that result in iron and silica cementation, and may in fact be susceptible to liquefaction. At question is the potential seismic behavior of the unweathered portion of the mudflow in its outcrop area. This area has been included in Category III because of the presence of the cemented surface layer and the lack of observed historic liquefaction and has been delineated on Plate 1. Further investigation of the dynamic behavior of the unweathered Osceola Mudflow is warranted.

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WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES
Raymond Lasmanis, State Geologist

GM-44

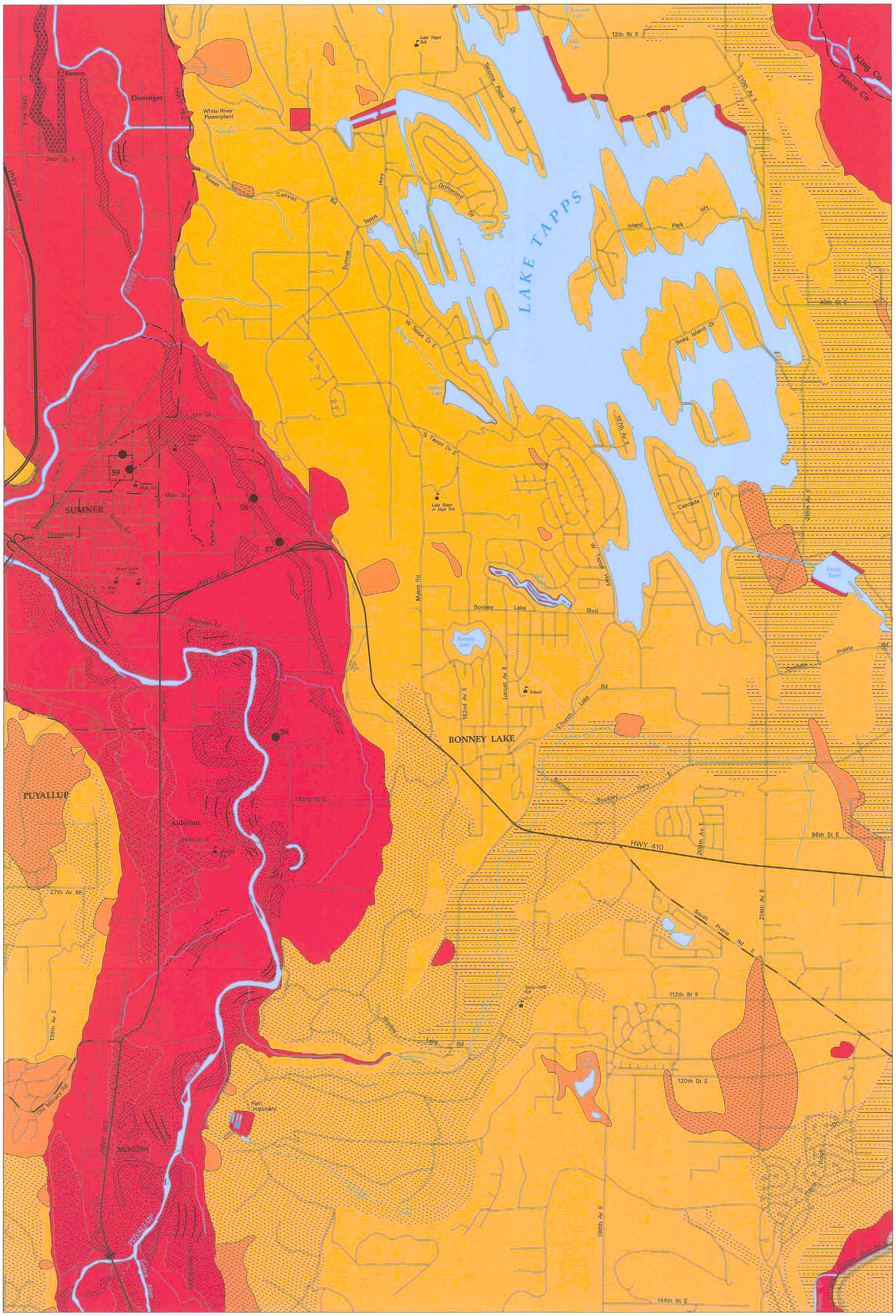
LIQUEFACTION SUSCEPTIBILITY FOR THE
SUMNER 7.5-MINUTE QUADRANGLE, WASHINGTON
PLATE 1 OF 1

LIQUEFACTION SUSCEPTIBILITY FOR THE SUMNER QUADRANGLE, WASHINGTON

by

Joe D. Dragovich and Patrick T. Pringle
with a section on liquefaction analysis by Stephen P. Palmer

1995



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EXPLANATION

CATEGORY I includes artificial fill and modified land and Holocene alluvium and the Electron Mudflow.
LIQUEFACTION SUSCEPTIBILITY: HIGH

CATEGORY II includes Holocene lacustrine and mass-wasting deposits and late Pleistocene sandy glaciolacustine sediments.
LIQUEFACTION SUSCEPTIBILITY: LOW TO MODERATE

CATEGORY III includes all other Pleistocene glacial and nonglacial deposits and the Osceola Mudflow.
LIQUEFACTION SUSCEPTIBILITY: LOW

Major open water features.

Contacts between liquefaction susceptibility categories. Geologic map units derived from Crandell (1963), Fiksdal (1979), and interpretation of aerial photographs.

Historic liquefaction sites identified by the corresponding reference number in Chleborad and Schuster (1990). Table 3 reproduces the quotations and comments given for the sites in Table 2 of Chleborad and Schuster (1990).

Pre-1906 course of the White River as mapped by Willis and Smith (1899).

Osceola Mudflow deposits.

Electron Mudflow deposits.

Proglacial and ice-contact stratified drift deposits.

Abandoned channels of the Puyallup, White or Stuck Rivers that generally do not appear to contain intermittent streams or support riparian vegetation. Features are dashed where inferred or approximately located.

Bar and swale topography, lines show bar crest lineaments.

This map is meant only as a general guide to delineate areas prone to liquefaction. This map is not a substitute for site-specific investigation to assess the potential for liquefaction for any development project. Because the data used in the liquefaction susceptibility assessment have been subdivided on the basis of regional geologic mapping, this map cannot be used to determine the presence or absence of liquifiable soils beneath any specific locality. This determination requires a site-specific geotechnical investigation performed by qualified practitioners.

This project was partially supported by the Federal Emergency Management Agency, and the Washington Division of Emergency Management.

SCALE 1:24,000

0 0.5 1 1.5 2
MILES

Lambert Conformal projection
1927 North American Datum
Washington coordinate system, south zone
Base map information from the Washington Department of Natural Resources, Geographic Information System - 1995
Cartographic design and production by Carl F. T. Harris
Washington Division of Geology and Earth Resources