

GROUND FAILURE ASSOCIATED WITH THE PUGET SOUND REGION EARTHQUAKES OF APRIL 13, 1949, AND APRIL 29, 1965

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ABSTRACT

Landslides, ground settlement, and surface cracks generated during earthquakes have been a major cause of property damage and casualties in earthquake-prone regions of the world. The historical record suggests that during future large earthquakes, such ground failures will most likely occur at the same or geologically similar locations as those of previous earthquakes. At many of these locations, the potential for losses has increased due to rapid population growth and extensive urban development. Consequently, detailed information on historical earthquake-induced ground failures, including location, topography, hydrology, and geologic materials, is essential for understanding the nature and extent of the hazard and for responsible land-use planning.

The Puget Sound region earthquakes of April 13, 1949 (magnitude 7.1), and April 29, 1965 (magnitude 6.5), the two largest historical Puget Sound earthquakes, produced ground failures over a large area that includes most of western Washington and part of northwestern Oregon. Because information on the locations and nature of ground failures associated with earthquakes prior to the 1949 event is meager, the many reports on the 1949 and 1965 occurrences are an important source of data for predicting ground-failure hazards from future earthquakes. Our investigation of ground failures produced by the 1949 and 1965 earthquakes consisted of a review of published information, interviews with residents and local officials having information on the ground failures, and a field study of selected ground-failure sites. This collection of new data and the verification and refinement of reported data have resulted in a substantial increase in the quantity and quality of ground-failure information for the region.

Many of the 1949 and 1965 ground failures involved artificial fill underlain by alluvial, deltaic, lacustrine, or glacial deposits. Landslides, including slumps, slides, and flow failures, were common on bluffs overlooking Puget Sound, along roads and railroads, and along the banks of rivers and lakes. Rock falls, rock slides, and rock avalanches occurred almost exclusively in the Cascade Range and along the western Columbia River Valley. Reports of sand boils and other evidence that suggests liquefaction of sediments as the probable cause of ground failure are associated principally with failures in the lowlands involving Holocene fluvial deposits, deltaic deposits, beach deposits, tidal-flat muds, or artificial fill. In a few cases, evidence of possible liquefaction was reported for failures in poorly consolidated Pleistocene glacial deposits.

In this report, we provide topographic maps of the region showing the locations of all known landslides, ground cracks, liquefaction features, and miscellaneous effects related to ground failure from the 1949 and 1965 earthquakes. These maps allow quick visual comparison of the 1949 and 1965 data regarding types of ground failures and their distribution. In addition, we provide tables of information on selected ground failures keyed by number to locations on the maps. These tables include information on ground failure type, geographic location, estimates of location accuracy, and descriptive information from reports and field studies. Also included are numerous photos of ground failures, some published here for the first time.

INTRODUCTION

Many of the losses from a future large earthquake in the western Washington–northwestern Oregon region would likely be caused by ground failure. This prediction is supported by the local historical record and by studies of the effects of past earthquakes in other earthquake-prone regions of the world. The great Alaskan earthquake of 1964, for

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This process results in large soil deformations under load, allowing buildings or other structures to founder and sink into the ground. The previously cited instance involving multistory apartment houses that tilted during the 1964 earthquake in Niigata, Japan, is a classic example of bearing-capacity failure due to liquefaction.

Sand boils are formed by water venting to the ground surface from zones of high pore pressure generated at shallow depth by the consolidation of saturated granular soils during seismic shaking. The ejected or vented water usually carries suspended sediment to the surface; this sediment is deposited in a conical shape around the vent. Sand boils are not strictly a form of ground failure because alone they do not cause ground deformation; they are, however, diagnostic evidence that liquefaction has occurred.

GROUND FAILURE CAUSED BY HISTORICAL EARTHQUAKES IN THE WESTERN WASHINGTON-NORTHWESTERN OREGON REGION

It is estimated that a magnitude 4 earthquake is the smallest event likely to cause landsliding (Keefer, 1984). Magnitude 5 earthquakes are considered the minimum for soil liquefaction and liquefaction-generated lateral spreads and flows (Kuribayashi and Tatsuoka, 1975, 1977; Youd, 1977; Keefer, 1984). The western Washington-northwestern Oregon region has experienced many historical earthquakes capable of causing ground failures. Nason and others (1988) listed the 23 known earthquakes felt in Washington having magnitudes greater than 4.7. Of those, 16 occurred in the Puget Sound region between Olympia and the Canadian border, in the Cascade Range, and along the Washington-Oregon border.

Nason and others (1988) noted 14 earthquakes from 1872 to 1980 that are known to have triggered landslides in Washington. However, information on the distribution and nature of landslides and other ground failures related to historical western Washington earthquakes prior to the 1949 Olympia earthquake is meager. For example, credible accounts of landslides generated by the 1872 North Cascades earthquake, the largest known seismic event in Washington or Oregon (magnitude 7.0-7.5), are limited to the few reports along the Columbia River east of the Cascades, along the shores of Lake Chelan north of Wenatchee, Wash., and in southern British Columbia in the vicinity of Fort Shepard and at Lake Okanagan (Coombs and others, 1977). An assertion, based on contemporaneous and later accounts, that the 13,000,000 m³ Ribbon Cliffs rock slide along the Columbia River north of Wenatchee was triggered by the 1872 event (Coombs and others, 1977) is presently disputed. Kienle and others (1978) concluded, on the basis of tree and tree-stump

dating, that the slide did not occur during the 1872 earthquake and that any significant movement of the landslide debris took place more than 215 years ago. In comparison to the few reports of ground failure due to the 1872 earthquake, several hundred to many thousands of landslides have been reported for earthquakes of similar magnitude in other areas of the world (Keefer, 1984), suggesting that few of the landslides triggered by the 1872 North Cascades earthquake were reported. Sparse population and difficult travel and communication at the time may account for the apparent lack of reported ground failures.

Landslides on Mount Rainier were attributed to earthquakes in 1894, 1903, and 1917 (Townley and Allen, 1939); however, few details are known about the extent and nature of those ground failures. A well-known and well-documented rock slide/debris avalanche, the world's largest historical landslide (volume of 2.7 km³), was triggered by a magnitude 5 earthquake associated with the 1980 eruption of Mount St. Helens. The landslide swept about 22.5 km down the valley of the North Fork Toutle River, destroying public and private buildings, State Highway 504, U.S. Forest Service and logging company roads, and several bridges (Schuster, 1983).

During the period from 1872 to 1989, the greatest number of recorded earthquake-induced ground failures occurred as a result of the magnitude 7.1 Olympia earthquake of April 13, 1949, and the magnitude 6.5 Seattle-Tacoma earthquake of April 29, 1965. Consequently, ground failures associated with those two events were chosen for detailed study and are discussed in the following sections.

PREVIOUS STUDIES

Previous investigators (Hopper, 1981; Keefer, 1983) have identified types of ground failures associated with the 1949 and 1965 Puget Sound earthquakes, described their distribution, and defined geologic environments in the Puget Sound region that have high susceptibility to earthquake-induced ground failure. Their studies were based on published and unpublished data including extensive information derived from written responses to University of Washington intensity-survey questionnaires by local inhabitants of the damaged areas. Hopper (1981) noted that liquefaction phenomena were confined primarily to areas that experienced a Modified Mercalli intensity (MMI) of VIII (with a few occurrences in intensity VII areas) and that reports of landslides and settlement came from areas with shaking intensities as low as MMI V (isoseismal maps for the 1949 and 1965 earthquakes are shown in fig. 186). Keefer (1983) identified the following geologic environments in the Puget Sound region as having high susceptibility to earthquake-induced ground failure: areas of poorly compacted artificial fill; areas of Holocene alluvium, lacustrine sediments, and beach sediments; deltas of rivers emptying into Puget Sound; and rock or soil slopes steeper than 35° in the Puget Sound lowland or adjacent mountains.

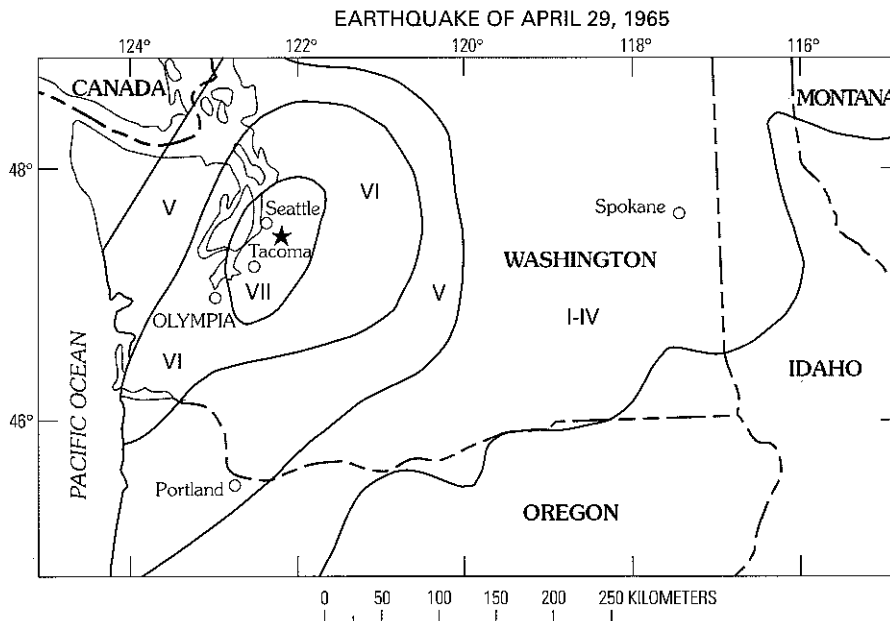
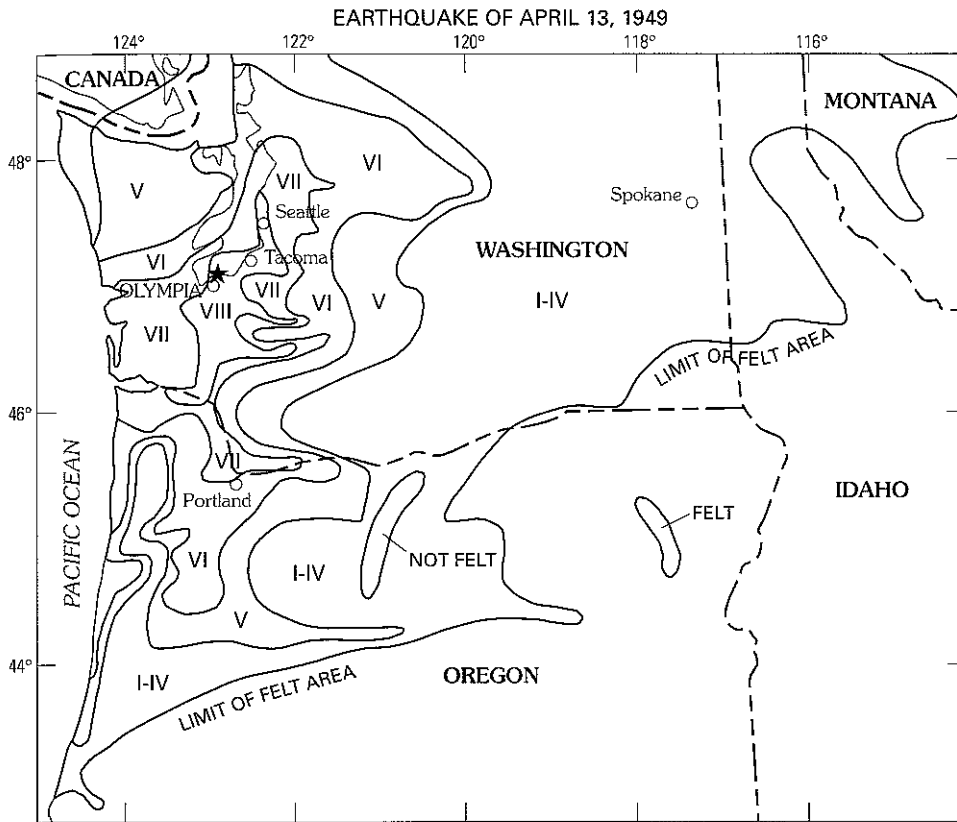


Figure 186. Modified Mercalli intensity maps for the Puget Sound earthquakes of April 13, 1949 (modified from Ulrich, 1949), and April 29, 1965 (modified from Algermissen and Harding, 1965). Stars indicate the earthquake epicenters.

DATA LIMITATIONS

The quality and completeness of available information on 1949 and 1965 ground failures are highly variable. Youd and Hoose (1978), in a similar study, cited several reasons for limited and incomplete data, two of which apply here: (1) most postearthquake investigations have been designed to assess the damage to structures; hence, ground failures not affecting constructed works often have been neglected; and (2) the areal coverage of postearthquake investigations has been uneven—areas in and near centers of population and along major transportation routes have received much more attention than less developed or remote areas. In addition, location information is sometimes vague or of questionable accuracy. In other cases, damage descriptions lack sufficient information to determine whether damage to structures resulted from ground failure or solely from some other cause such as ground shaking. An obvious disadvantage in a study such as this is the inability to examine reported ground failures immediately after their occurrence. Many years have passed since the 1949 and 1965 earthquakes, and field evidence of many of the ground failures is obscure or nonexistent. Despite these limitations, much reliable data on the location and characteristics of ground failures was obtained, which can be used to help delineate areas and geologic environments susceptible to earthquake-induced ground failure.

CHARACTERISTICS OF THE STUDY AREA

Ground failures associated with the 1949 earthquake were scattered over an area of about 28,500 km² and those of the 1965 earthquake over an area of about 20,700 km². The total area considered in this study encompasses these two areas from near the Canadian border on the north to just beyond Portland, Oreg., on the south and from the Cascade Range on the east to the Pacific Ocean on the west (fig. 187).

The physiography and geology of the total area affected by 1949 and 1965 ground failures are highly varied. A broad lowland, bordered on the east by the Cascade Range and on the west by the Coast Range, is underlain predominantly by Pleistocene glacial sediments associated with advances of the Puget Lobe of the Cordilleran ice sheet. These sediments include glacial till, outwash sand and gravel, and glacial lake deposits of sand, silt, and clay. Nonglacial sediments interbedded with the glacial deposits provide a record of repeated advances of the Puget Lobe into the Puget Sound region (Mullineaux, 1970). In some areas of the lowland, the thickness of unconsolidated sediments exceeds 900 m (Hall and Othberg, 1974). The Pleistocene sediments cover Tertiary sedimentary and volcanic bedrock in all but a few areas where the bedrock is covered by younger sediments or is exposed at the surface. Continental glacial sediments extend

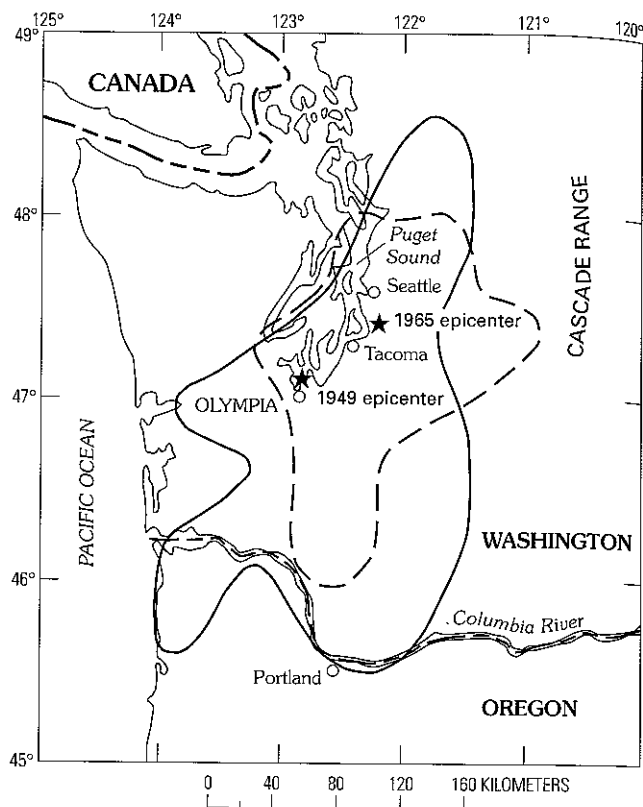


Figure 187. Areas of reported ground failures related to the Puget Sound earthquakes of April 13, 1949 (solid line), and April 29, 1965 (dashed line). Modified from Keefer (1983).

from north of the study area to a hilly area between Olympia and Centralia, Wash., on the south and from the Olympic Mountains on the west to the Cascade Range on the east. These glacial deposits are generally unconsolidated but vary in degree of compactness. Deposits overridden by the thick glacial ice are more highly consolidated than other glacial and postglacial sediments, resulting in varying physical properties. Compared to bedrock and postglacial deposits, glacial sediments overridden by glacial ice are intermediate in both density and water content (Mullineaux and others, 1967). The erosive action of rivers and glaciers has sculpted the glacial fill, leaving the troughs of Puget Sound, lake basins, broad valleys, and intervening land areas that stand as high as a few hundred meters above sea level. In many places, erosion of the glacial sediments has produced steep slopes that are susceptible to landsliding.

Numerous areas underlain by deltaic sediments, tidal-flat muds, or beach deposits border the many kilometers of Puget Sound shoreline. Also, local to fairly extensive deposits of artificial fill are common along transportation corridors and in residential, business, and industrial areas.

Valley floors in the lowland are underlain chiefly by postglacial alluvial deposits of unconsolidated sand, silt,

clay, and gravel up to a few hundred meters thick. Prehistoric mud/debris flows that originated on the flanks of Mount Rainier deposited sediment beyond the mountain front onto nearby valley floors and other lowland areas. One of these, the Osceola "Mudflow," spread material over an area of about 170 km² to depths as great as 23 m (Crandell, 1963).

The rugged Cascade Range, in the eastern part of the study area, rises from about 200 m above sea level on its western border with lowland areas to as high as 4,389 m at the summit of Mount Rainier. In many areas, the terrain of the Cascade Range is characterized by steep slopes and sheer cliffs that are prone to various types of landsliding.

In northern Washington, the Cascade Range is composed of a variety of rock types including metamorphic rocks of Paleozoic age, Paleozoic and Mesozoic sedimentary and volcanic rocks of marine origin, and volcanic and plutonic rocks of various ages including those of the Mount Baker and Glacier Peak volcanoes. The northern Cascades were extensively glaciated during the Pleistocene; as a result, glacial till is ubiquitous, and outwash and glacial-margin deposits are common in the river valleys and along the mountain front (Fiksdal and Brunengo, 1981).

Most of the Cascades south of the Skykomish River, within the study area, are composed of Tertiary and Quaternary volcanic rocks. Smaller areas are underlain by intrusive rocks such as granodiorite, rhyolite, and granite, most of which are interspersed among widespread volcanic deposits (Walsh and others, 1987). In a few scattered areas, metamorphic rocks and marine and continental sedimentary rocks of various ages are present.

Towering, snowclad volcanoes such as Mount Rainier dominate the landscape with their steep rock faces and precipitous cliffs formed by the action of glaciers and other erosive agents. Jointed volcanic strata on the sides of the volcanoes typically dip downslope, which adds to other factors that can cause instability.

Alpine glaciers, fed by extensive ice fields, moved down major valleys in the Cascades at various times during the Pleistocene. Many valleys were glaciated in the central part of the Washington Cascades, including those of the Lewis, Kalama, Toutle, Cowlitz, Nisqually, Puyallup, White, Green, and Cedar Rivers. Alpine glacial drift, including till, and glaciofluvial and glaciolacustrine sediment are widespread in several of the mountain valleys occupied by those rivers. In some places on the west side of the range, the drift extends onto the adjoining lowland (Crandell, 1965; Fiksdal and Brunengo, 1981; Walsh and others, 1987). Artificial fill is present locally in developed areas, along transportation routes, and where it has been used in the construction of earthfill dams or other engineered structures.

Other lowlands within the study area are situated south or southwest of the Puget Sound lowlands in southwestern Washington and northwestern Oregon. These include the valleys of the Chehalis, Cowlitz, Columbia, and Willamette Rivers. Valley floors in these lowland areas are underlain

chiefly by unconsolidated Quaternary alluvium composed of silt, sand, gravel, and clay (Trimble, 1963; Walsh and others, 1987). Local areas of artificial fill are common in some towns and urban areas, along railroads and highways, and at the sites of engineered structures such as earthfill dams.

Hills and mountains rise from valley bottoms and coastal areas in southwestern Washington and northwestern Oregon to form the upland areas of the remaining part of the study area. Most of the upland areas range in elevation from a few hundred to more than a thousand meters above sea level. The Coast Range of southwesternmost Washington and northwesternmost Oregon is composed predominantly of marine and nonmarine sedimentary rocks, various types of volcanic deposits, and basic intrusive rocks, all of Tertiary age (Warren and others, 1945; Walsh and others, 1987). Unlike many glaciated areas of the Cascades, the Coast Range of southwestern Washington and northwestern Oregon typically has a very thick weathering profile related to millions of years of exposure.

Upland areas between the Coast Range and the Cascades in southwestern Washington and northwestern Oregon are also underlain by a variety of rock types including volcanic rocks, continental sedimentary rocks, alpine glacial outwash deposits, and periglacial flood deposits. As in other parts of the study area, artificial fill is present locally in developed areas and along transportation corridors. Also, beach deposits that include fine to coarse beach sands and gravels, dune sands, and estuarine muds and sands are common in the coastal areas of the region.

The study region includes large areas that are particularly susceptible to landsliding due to a number of causes. The general character, distribution, and causes of landslides in the various physiographic regions of Washington and Oregon, including the area of this study, have been reviewed by the authors in a previous report (Schuster and Chleborad, 1989).

PRECIPITATION AND GROUND WATER

Precipitation is an important factor affecting the susceptibility of a given area to earthquake-induced ground failure. This is particularly true for areas underlain by sediment types susceptible to liquefaction because saturation or near saturation of sediments is required before liquefaction can occur. In addition, elevated pore pressures associated with saturated slope conditions can reduce slope stability, thus increasing the probability of slope failure during earthquakes.

Western Washington and northwestern Oregon are areas of relatively high precipitation (fig. 188), with the wet season extending from September through April. In the area of study, annual precipitation means range from approximately 122 cm/yr in the area of the Puget-Willamette lowland to more than 254 cm/yr in the high, snowy parts of the Cascade Range. Precipitation records for the Seattle-

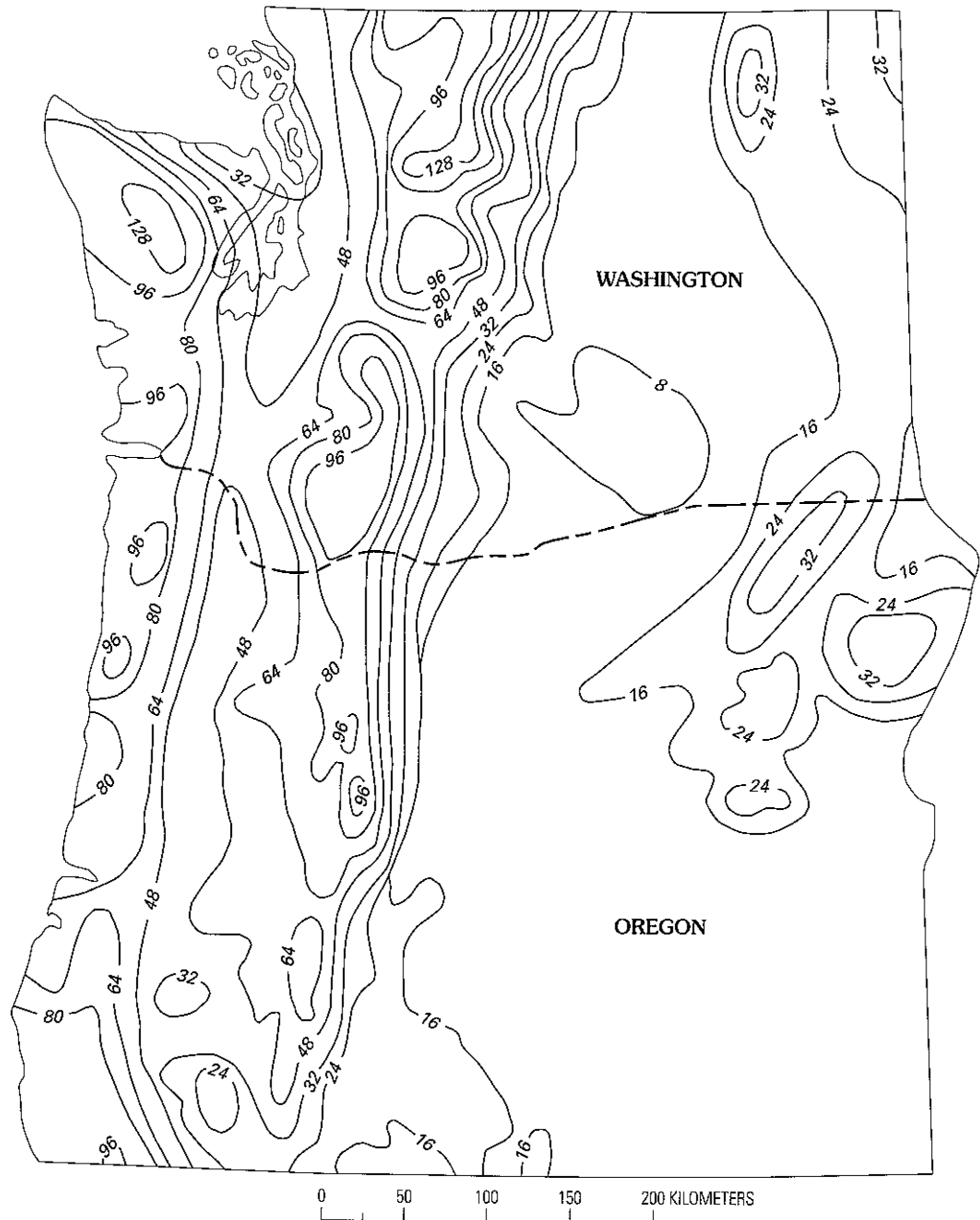


Figure 188. Contour map showing mean annual precipitation (1 inch equals 2.54 cm) in Washington and Oregon for the period 1931–1960 (modified from U.S. Geological Survey, 1970).

Tacoma area for the water years 1948–1949 and 1964–1965 (those associated with the 1949 and 1965 earthquakes) are shown in figure 189. These water years were slightly below normal; 8.66 cm below normal in 1948–1949 and 6.60 cm below normal in 1964–1965. For the purpose of comparison, precipitation records from the Seattle-Tacoma area for the water year 1971–1972 (an unusually wet year) are also shown in figure 189. Precipitation during that year was 40.6 cm above normal. High precipitation was a major cause of

numerous damaging landslides that occurred in the Seattle area during the spring of 1972 (Tubbs, 1974). Because the 1949 and 1965 earthquakes occurred well into the wet seasons, water tables were probably at or near their yearly highs, increasing the probability of some types of ground failure; however, had amounts of precipitation been similar to those in the 1971–1972 water year, it is likely that many more ground failures would have been triggered by the two earthquakes.

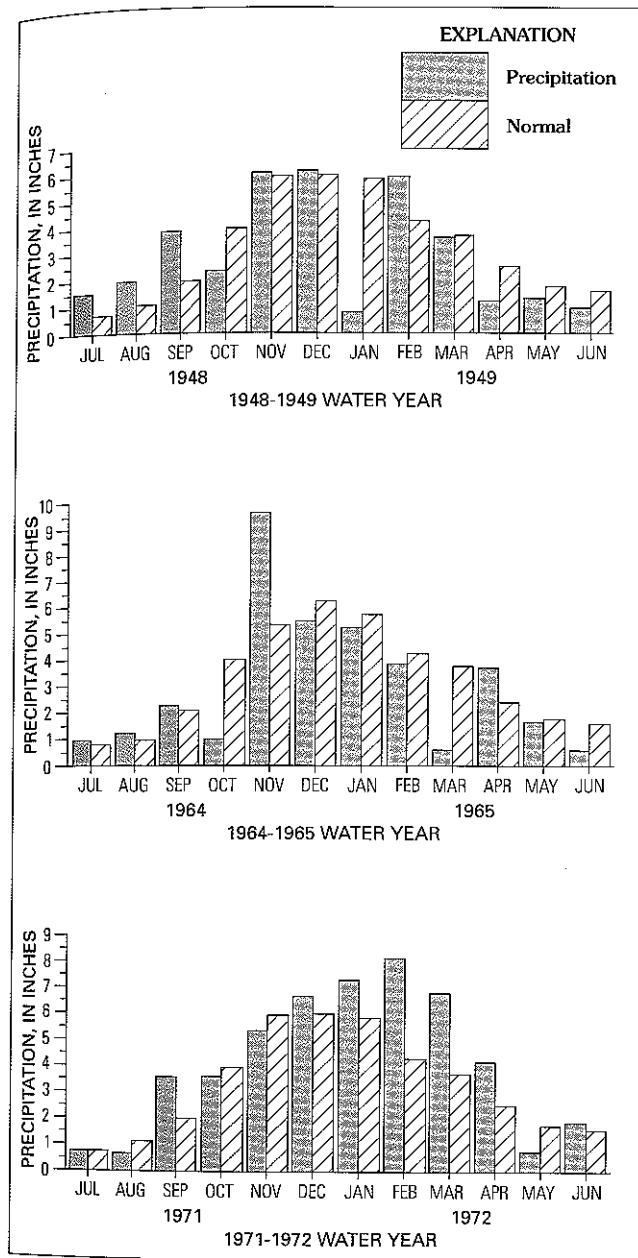


Figure 189. Graphs showing precipitation (1 inch equals 2.54 cm) in the Seattle-Tacoma area for the water years 1948-1949, 1964-1965, and 1971-1972 (U.S. Department of Commerce, 1948, 1949, 1964, 1965, 1971, and 1972).

DISTRIBUTION AND CHARACTER OF GROUND FAILURES TRIGGERED BY THE PUGET SOUND EARTHQUAKES

Data compiled on individual ground failures are presented in plates 4-8, which show ground-failure locations (1949, closed symbols; 1965, open symbols), and in tables 29-33, which provide descriptions of selected ground

failures. Entries in the tables include the following: (1) relatively extensive ground failures and ground failures exhibiting relatively large displacements, (2) all known landslides, (3) all known sand boils and other ground failures that appear related to liquefaction of sediments, (4) significant ground failures at locations affected by both the 1949 and 1965 earthquakes, (5) significant ground failures at locations showing concentrations or trends of ground failure, and (6) ground failures that have affected engineered structures such as dams and bridges. Excluded from the tables are the numerous minor settlements and ground cracks that are not clearly related to landsliding or liquefaction phenomena. However, these smaller ground failures are included on the plates in order to show the overall distribution of ground effects and to help identify significant trends or concentrations of ground failures that may be present. Copies of published and unpublished information used in the development of tables 29-33 and plates 4-8 are on file in the offices of the U.S. Geological Survey in Golden, Colorado.

For the purpose of showing ground-failure distributions and for ease of discussion, the study area was divided into four regions. The regions were selected on the basis of the number or density of ground-failure locations in a given area, the availability of base maps at appropriate scales, and, as much as possible, on similarities in topography and geology. The following discussion considers the distribution and character of ground failures in each of the four regions.

CENTRAL AND SOUTHERN PUGET LOWLAND REGION

The central and southern Puget lowland region (pls. 4 and 5) includes much of the Puget Sound lowland. About 85 percent of the reported ground failures in the 1965 earthquake and 50 percent in the 1949 earthquake occurred in this region. Some areas experienced Modified Mercalli intensities as high as MMI VIII during both earthquakes (Ulrich, 1949; Algermissen and Harding, 1965; Hake and Cloud, 1967) (fig. 186). Ground cracks and settlement were the most numerous and widespread of the reported ground failures. Most were isolated occurrences of limited extent that caused only minor damage to roads, buildings, foundations, driveways, utilities, and so forth. Some, however, contributed to the considerable structural damage that occurred in areas of relatively intense ground shaking. Landslides in the region were most common on hillsides and coastal bluffs and along the banks of rivers, lakes, and other bodies of water. Many caused damage to roads, railroads, buildings, waterfront facilities, utility lines, and recreational facilities. One large debris avalanche, with an estimated volume of 500,000 m³, occurred along the eastern bluff of the Tacoma Narrows 3 days after the April 13, 1949, earthquake. A few flow failures related to the 1965 event also occurred in the region. A significant number of ground failures developed in

environments thought to be conducive to liquefaction failures, as suggested by the presence of sediment types susceptible to liquefaction, high water tables, and in some cases the occurrence of sand boils in the immediate vicinity.

NORTHERN HALF OF THE CENTRAL AND SOUTHERN PUGET LOWLAND REGION

The northern half of the central and southern Puget lowland region (pl. 4) includes the parts of King, Snohomish, Kitsap, Island, Jefferson, Mason, and Clallam Counties bounded by lat 48°00' N. and lat 47°30' N. and by long 122°00' W. and long 123°00' W.; this area includes Seattle. Plate 4 shows a conspicuous concentration of ground failures related to both the 1949 and 1965 earthquakes in West Seattle (locs. 7–13) and the adjacent Duwamish River–Harbor Island–Elliott Bay waterfront area (locs. 14–25, and 28).

In West Seattle, the number of reported ground failures for the 1965 earthquake far exceeded those of the 1949 event. One of the most destructive 1949 ground failures was a slump that occurred on moderately sloping ground in artificial fill overlying the Esperance Sand Member of the Vashon

Drift (loc. 10; fig. 190). The failure reportedly damaged six homes, including four that were under construction (see damage description, table 29). Hillside residential property (loc. 13) in West Seattle was the site of minor ground cracking in 1949 and ground cracking and settlement in 1965. The proximity of that site to a steep bluff located near the head of a large mapped landslide (Waldron and others, 1962) suggests an incipient slope failure, apparently initiated by the 1949 quake and reactivated in 1965. Minor sliding also occurred in 1965 at a few other locations on steep to moderately sloping bluff areas on the east and west sides of West Seattle (locs. 8, 9, 11, and 12). Two of the 1965 slope failures were wholly or partly in artificial fill (locs. 8 and 11); the other three (locs. 9, 12, and 13) apparently involved the Esperance Sand Member and (or) overlying surficial debris. Most of the bluff areas that border West Seattle have been categorized as unstable with regard to slope stability (Washington Department of Ecology, 1979a). A common slope-failure process that occurs on the bluffs in West Seattle and in other parts of the city, especially during wet periods, involves the Esperance Sand Member and the underlying Lawton Clay Member of the Vashon Drift (Tubbs, 1974; Tubbs and Dunne, 1977). Ground water percolates downward through the Esperance Sand Member until it reaches relatively



Figure 190. Slumping and settlement in West Seattle (pl. 4, loc. 10) induced by the April 13, 1949, earthquake. The slumping exposed artificial fill (lower left) that underlies the site. Photograph from the Seattle Post-Intelligencer Collection, courtesy of the Museum of History and Industry, Seattle, Wash.

impermeable alternating sand and clay layers at the top of the Lawton Clay Member; the water then changes direction and moves laterally until it reaches the hillside, where it saturates surface debris and seeps out onto the ground surface. Slumping of the Esperance Sand Member occurs near the Esperance-Lawton contact, usually due to the development of pore-water pressure in the sand (Tubbs, 1974). Other slides develop as slide debris accumulates and seepage undermines the toes of slopes (Tubbs and Dunne, 1977; fig. 191). Yount (1983) suggested that the water-saturated condition along the Esperance-Lawton contact may be a contributing factor to intensified ground shaking during earthquakes, particularly in the vicinity of Tertiary bedrock at Alki Point, a short distance from the bluffs (Waldron and others, 1962).

Ejection of ground water (a form of sand boil) in the Alki Point beach area (closed and open circles at loc. 7) that occurred during both the 1949 and 1965 earthquakes is a probable indication of liquefaction. The area is underlain chiefly by postglacial beach deposits (Waldron and others, 1962; Mullineaux and others, 1967). Similar deposits in other areas have been found to have moderate to high susceptibility to liquefaction and liquefaction ground failure (Yound and Perkins, 1978; Keefer, 1984). Closer to Alki Point, in the vicinity of Alki Monument (loc. 7, open-square symbol), about 15 cm of settlement occurred in the 1965 earthquake along an extensive stretch of promenade located behind a seawall. Many waterline breaks, some of which may have been caused by unreported or undetected ground failure, also occurred in the Alki Point area in 1965.

According to Mullineaux and others (1967), waterline breaks were more numerous at Alki Point than anywhere else in Seattle.

Other 1965 reports of ground failures in the West Seattle area consist of numerous instances of minor ground cracking and settlement that often resulted in damage to foundations, basement floors, sidewalks, driveways, bulkheads, and so on, or jamming and sticking of windows and doors. Some of those failures probably were related to consolidation of sediments caused by vibration, although Hopper (1981) found little or no correlation between damage related to settling reports and reports of chimney damage caused by vibration. Hopper (1981) also noted that nearly the entire cluster of 1965 settling reports for West Seattle is located on the Esperance Sand Member (called the older sand by Waldron and others, 1962) but concluded that the relationship may be coincidental because the same geologic unit appears at other places in the city without any concentrations of reported ground settlement. In addition, a study of the distribution of chimney damage in the 1965 earthquake with respect to the various Pleistocene deposits in West Seattle demonstrated that the damage pattern is not related to recognizable differences in the underlying deposits (Mullineaux and others, 1967). Some incidents of minor settling and ground cracking may have been caused by incipient sliding, particularly those on the steep bluff areas that partly surround West Seattle. The occurrence of ground failures in West Seattle during both the 1965 and 1949 earthquakes indicates that the area is highly susceptible to ground failure caused by intense seismic shaking.

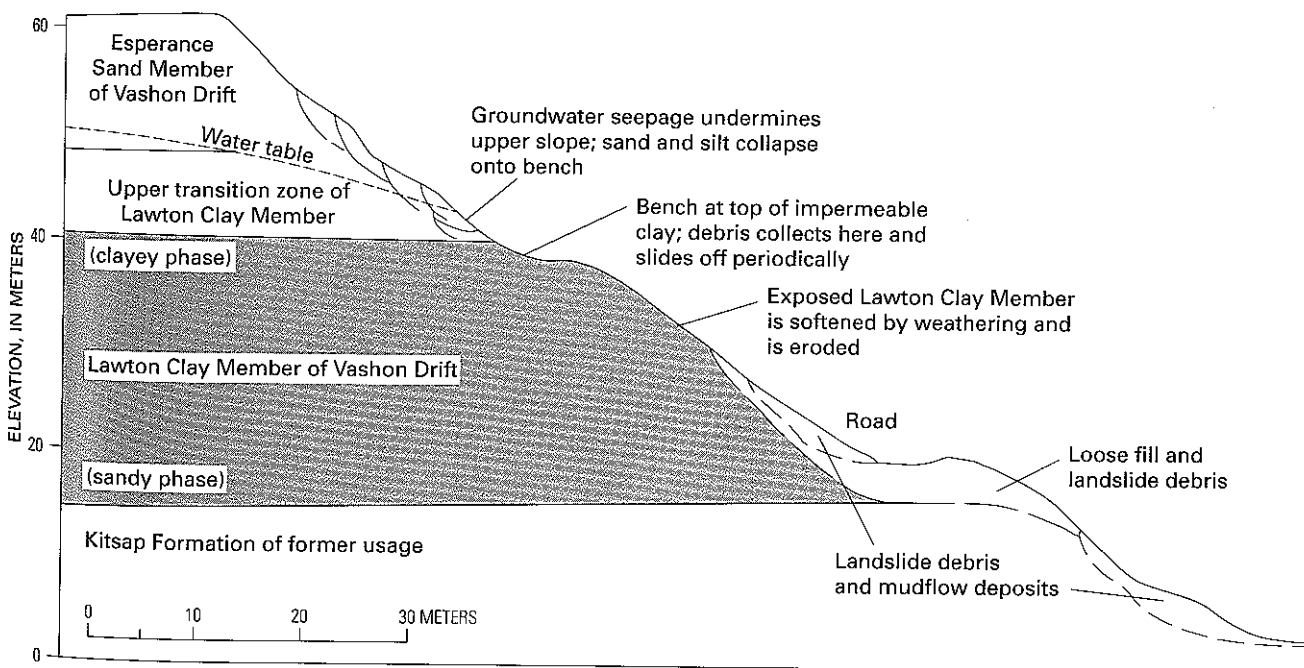
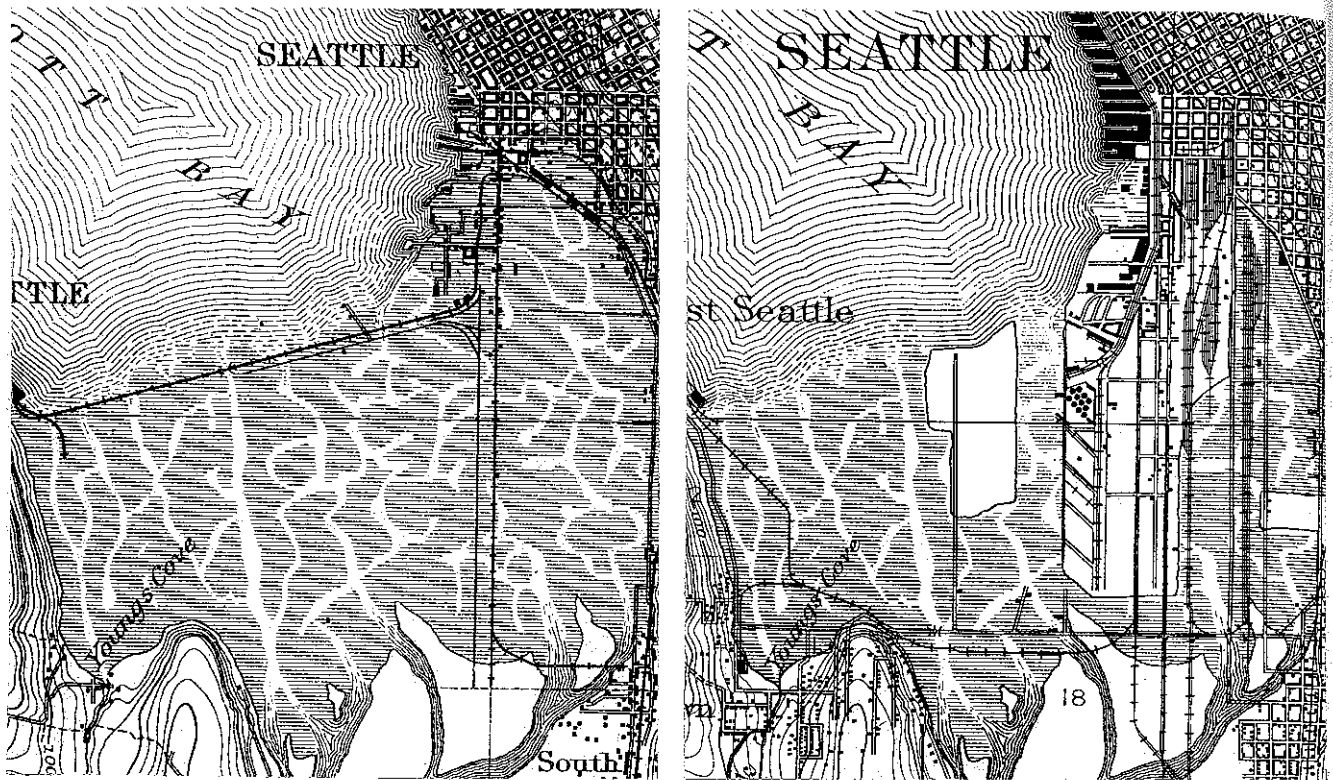


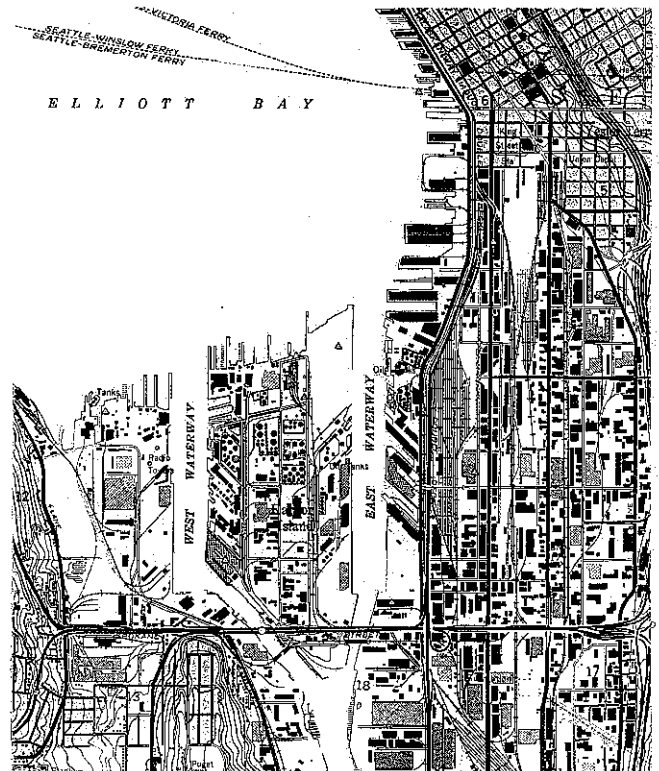
Figure 191. Cross section of a West Seattle bluff showing conditions associated with slope failure (from Tubbs and Dunne, 1977).



1893

1908

Figure 192. Maps showing the sequence of development of the former tidal flats area at the mouth of the Duwamish River, Seattle, between the years 1893 and 1973. Since 1893, the tidal flats have been extensively covered by artificial fill to allow waterfront development. The area was the site of many earthquake-induced ground failures and considerable property damage in both 1949 and 1965. From U.S. Geological Survey (1894, 1909, and 1949 (photorevised 1968, 1973)).



1973

The Duwamish River–Harbor Island–Elliott Bay waterfront area lies just to the east of West Seattle (pl. 4). The area, much of which is a former tidal flat (fig. 192), was extensively artificially filled (Waldron and others, 1962) to provide real estate for industrial and commercial interests along the waterfront. Structural damage was substantial in this area in both the 1949 and 1965 earthquakes (Edwards, 1951; Mullineaux and others, 1967). The heaviest building damage in Seattle related to the 1965 earthquake occurred in this area, from the lower downtown business district south to about Spokane Street (Mullineaux and others, 1967). A considerable amount of the 1949 and 1965 damage was related to ground failure (table 29, locs. 14–25 and 28). Ground-failure displacements ranged from a few centimeters to about a meter, but most were less than 30 cm. Direct evidence of liquefaction of sediments is provided by reports of sand boils produced by the 1949 earthquake on the west side of the West Waterway (loc. 19), on Harbor Island (loc. 21), and adjacent to the Elliott Bay waterfront (loc. 25), and by the 1965 earthquake at locations 24 and 25 adjacent to Elliott Bay. Incipient lateral spreading or slumping, indicated by lateral as well as vertical displacements, occurred at locations 15–17 north and south of Spokane Street (fig. 193) in

1949 and north of Spokane Street (locs. 18 and 22) in 1965. There were many reports of settlement in the waterfront area in both 1949 and 1965 (pl. 4; table 29) that may have resulted from consolidation of sediments, incipient landsliding, or both. All this evidence indicates that many locations within the Duwamish River–Harbor Island–Elliott Bay waterfront area are highly susceptible to damaging ground failure during intense seismic shaking and that there is a high susceptibility to liquefaction of artificial fill and (or) underlying postglacial sediments in the former tidal flats area. Similar types of ground failure causing equal or greater damage can be expected in the event of future large earthquakes that cause intense ground shaking in the area.

Other locations in Seattle experiencing ground failure in both the 1949 and 1965 earthquakes include the University of Washington practice field area just west of Union Bay at Lake Washington (pl. 4, loc. 31), the area just south of Green Lake (loc. 33), and two locations along the west shore of Lake Washington (locs. 4 and 27). Similar to ground failures in the Duwamish River–Harbor Island–Elliott Bay waterfront area, locations 4, 31, and 33 are also in areas of artificial fill underlain by postglacial lacustrine or alluvial sediments (Waldron and others, 1962;

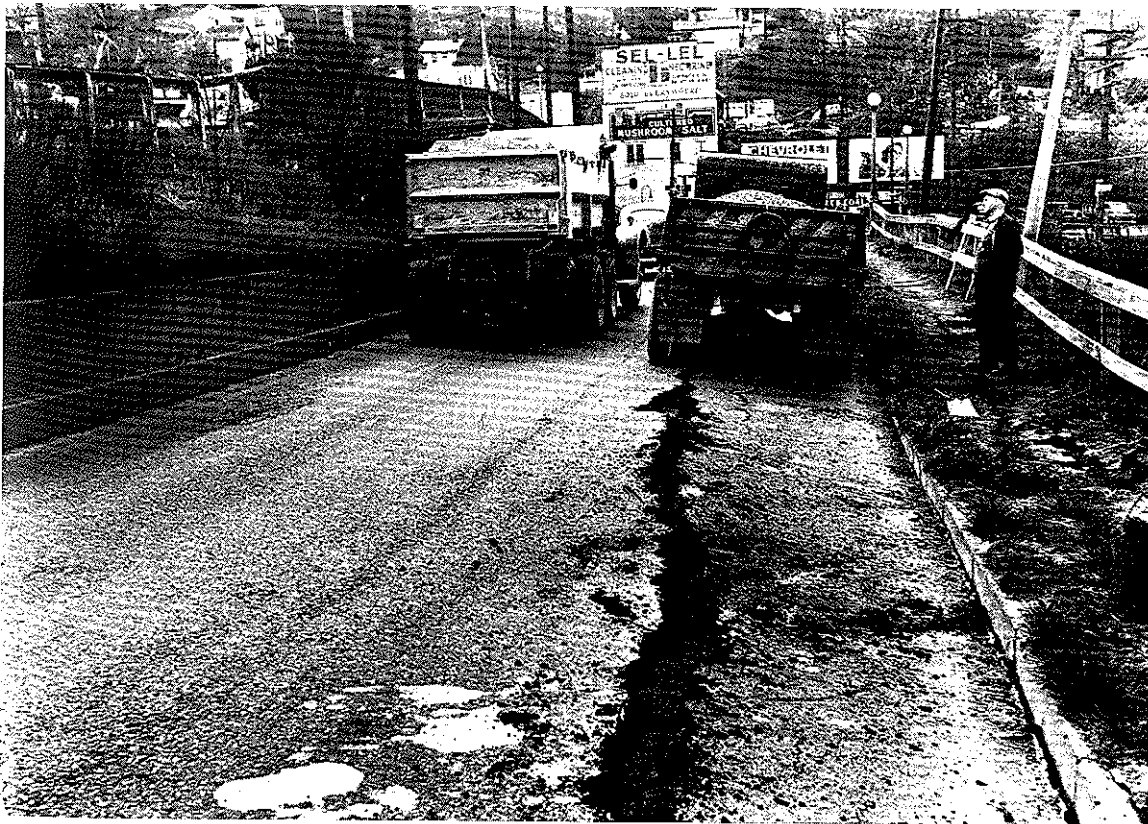


Figure 193. Ground failure along Spokane Street approach to West Seattle (pl. 4, loc. 16) triggered by the April 13, 1949, earthquake. Pavement cracks and slight slump are in a road embankment composed of artificial fill. Note arcuate scarp and tilted light pole at right. Photograph from the Seattle-Post Intelligencer Collection, courtesy of the Museum of History and Industry, Seattle, Wash.



Figure 194. Slump along the shore of Green Lake, north of downtown Seattle. This 1949 earthquake-induced ground failure occurred near the south end of the lake (pl. 4, loc. 33) in an area that subsequently experienced ground failure during the April 29, 1965, earthquake. Photograph from the Seattle Post-Intelligencer Collection, courtesy of the Museum of History and Industry, Seattle, Wash.



Figure 195. Ground cracks on the southeast side of Green Lake in north Seattle (pl. 4, loc. 33). The cracks opened during or shortly after the April 13, 1949, earthquake and probably resulted from subsidence and lateral movement of ground downslope toward the lake (out of sight to the left of view). Photograph from the Seattle Post-Intelligencer Collection, courtesy of the Museum of History and Industry, Seattle, Wash.

Mullineaux and others, 1967; Hale Lowry, oral commun., 1988). Ground-failure location 27 is locally underlain by artificial fill (Steele Lindsay, written commun., 1965).

In the Union Bay area of Lake Washington (locs. 31 and 32), vertical and horizontal displacements as great as 0.3 m were reported in both 1949 and 1965; damage caused by these ground failures was minor, however. As in the waterfront areas, the occurrence of sand boils and associated ground cracking during the 1965 earthquake is evidence of the susceptibility of the artificial fill and (or) underlying alluvial and lacustrine sediments to liquefaction and liquefaction-related ground failure.

Slumping and possible lateral spreading along the south shore of Green Lake (loc. 33; figs. 194 and 195) in 1949 apparently did little damage. Ground failure in the same area in 1965 damaged a small building, fractured walks and paving, and broke utility lines (Mullineaux and others, 1967). Possible liquefaction of sediments at the south end of Green Lake is suggested by the presence of loose granular sediments, the probability of a high water table in sediments at or below lake level, and the characteristics of some of the 1949 and 1965 ground failures that suggest incipient lateral spreading.

A hillside failure in north Seattle, triggered by the 1965 earthquake, evolved into a debris flow that covered a road in Carkeek Park (loc. 36, fig. 196). The flow originated in a

large ravine north of Piper Creek. The sides of the ravine are underlain by the Esperance Sand Member and undifferentiated nonglacial sediments (Washington Department of Ecology, 1979a). The *Seattle Times* (1965c) stated that the slide "opened a pool of ground water that roared down the creek," flooding the road with debris. Water from a small creek that flows down the ravine may also have mixed with the slide debris, adding to its mobility. The slide resulted in only minor damage to the park road.

Another 1965 flow failure occurred in the city of Edmonds, north of Seattle (loc. 40; fig. 197). The failure, which took place at the head of a small ravine on moderately sloping ground, left a cavity tens of meters across and 3–5 m deep. Slide debris flowed downslope for several hundred meters. The site of the failure is within an area underlain by advance outwash deposits of the Vashon Drift, mostly clean sand and gravel (Minard, 1983). According to local residents, the site is also directly underlain by artificial fill. An eyewitness to the event reported that the slide uncovered a stream that mixed with the slide material, transforming the slide "into a muck the consistency of wet cement." The earth flow destroyed an abandoned artesian well and watershed located on the property.

At Port Orchard, on the Kitsap Peninsula west of Seattle (loc. 1), ground failure triggered by the 1965 earthquake badly damaged an asphalt-covered parking lot in a business



Figure 196. Mudflow covering Carkeek Park Road in northwest Seattle (pl. 4, loc. 36). This mudflow developed as material from an earth slide triggered by the April 29, 1965, earthquake mixed with water and flowed down a Piper Creek tributary ravine. Photograph used by permission of the *Seattle Times* Co.



Figure 197. Earth flow in Edmonds, Wash. (pl. 4, loc. 40), induced by the April 29, 1965, earthquake. The landslide began at the head of a small ravine and flowed downslope about 180 m, destroying an abandoned city water-well shed in its path. Photograph from the Seattle Post-Intelligencer Collection, courtesy of the Museum of History and Industry, Seattle, Wash.



Figure 198. Damage to Country Club Road, southwest of Port Orchard, Wash. (pl. 4, loc. 2), due to slumping induced by the April 29, 1965, earthquake. This slump occurred in granular fill underlain by glacial deposits of the Vashon Drift. Photograph used by permission of the Bremerton Sun.

area adjacent to Sinclair Inlet. The failure occurred in a waterfront area of artificial fill (Washington Department of Ecology, 1979b). Spatial relationships with adjacent geologic units (Washington Department of Ecology, 1979b) suggest that the artificial fill is underlain by the Esperance Sand Member. A newspaper photo of part of the damaged area (Bremerton Sun, 1965a) shows vertical displacements of the asphalt and underlying fill as great as 0.6 m. A slight lateral displacement was indicated in the direction of the inlet.

Another small slide in artificial fill during the 1965 earthquake extensively damaged a paved road south of Port Orchard (loc. 2; fig. 198). Movement was downslope in the direction of a small ravine adjacent to the road embankment. Glacial deposits of the Vashon Drift underlie the artificial fill at this location.

Location 39 (pl. 4) at Suquamish was the site of a 1965 coastal-bluff landslide that badly damaged a house and uprooted trees. According to a press report, the shoreline heaved as much as 4.6 m in some places (Hake and Cloud, 1967). The 15-m-high bluff is underlain by the Vashon Drift (till and outwash sand and gravel) (Washington Department of Ecology, 1979b). Field studies in 1988 revealed zones of seepage near midslope in the reported area of sliding. The ground failure resulted in a 30-m-long cracked and raised area on the beach, parallel to the shoreline.

A 10 m section of highway fill, 5 km west of Kingston (loc. 41), slumped about 1 m as a result of the 1965 tremor. At that location, the highway crosses a low, wet area (a ravine and small creek). Geologic mapping by Garling and others (1965) indicates that the failure site is part of an area underlain by recessional outwash deposits of the Vashon Drift. Damage caused by the slide closed one lane to traffic until repairs could be made.

SOUTHERN HALF OF THE CENTRAL AND SOUTHERN PUGET LOWLAND REGION

The southern half of the central and southern Puget lowland region (pl. 5) includes parts of King, Pierce, Kitsap, Mason, and Thurston Counties bounded by lat 47°30' N. and lat 47°00' N., and by long 122°00' W. and long 123°00' W. In this area, reported landslides, ground cracks, and settlement related to the 1949 and 1965 earthquakes were numerous and widespread (pl. 5; table 30).

Sand boils and other ground-failure effects indicating liquefaction were common on broad valley floors extending from the former tidal flat area at Tacoma (area of locs. 77-79) southeast to Puyallup (locs. 60-71), and from Sumner (locs. 57-59) to just north of Kent (locs. 106 and 107). The valley floors are underlain generally by postglacial alluvial sediments and locally by artificial fill (Mullineaux, 1965a, 1965b; Walsh and others, 1987).

On the former Tacoma tidal flat (area of locs. 77-79), sand boils, ground cracks, and settlement occurred as a result of both the 1949 and 1965 earthquakes. Reported displacements were less than 0.3 m, but ground cracks developed that were as long as 300 m. In one instance in 1949, displacement (indicated by a ground crack) in the direction of the waterfront suggests incipient lateral spreading or slumping (loc. 77). Many waterline breaks occurred in the area in 1949, and streets and other paved areas were damaged by ground cracks and settlement in both 1949 and 1965. The area of the former tidal flat is underlain mostly by fine sand and silt that are extensively covered by artificial fill.

Reports of sand boils produced by the 1949 earthquake were most numerous in and near the city of Puyallup. Much of our data comes from Shulene (1990), who presented information on the location and nature of sand-boil occurrences in the Puyallup area. In northwest Puyallup, sand-boil activity was concentrated in areas north and south of Stewart Avenue (locs. 63-69), such as the 20-square-block area north of Stewart Avenue running west from 5th Street NW to 9th Street NW and from Stewart Avenue north to 8th Avenue NW (loc. 66). Sand boils reportedly pushed through the concrete basement floor of one home and forced timber foundation through the flooring of another, which caused considerable damage. Also, liquefied sand came up through a basement floor and floated a furnace that was apparently unsecured. In addition, city water mains were broken and ground cracks opened across some streets and walks. In one case, vertical displacement associated with a ground crack that crossed a street was great enough to cause a drop that was noticeable when driven over by a car. In general, reports of sand boils in this area did not include detailed descriptions of the amounts and types of sediment involved; however, at two of the sites, several small mounds (maximum dimension less than 0.6 m) of black sand were reported. Damage to the basements described above, however, suggests considerably larger volumes of ejected material at those locations.

Another concentration of sand-boil activity occurred in an area just south of Stewart Avenue and west of 12th Street NW (loc. 68). Ground cracks several meters long and several centimeters wide developed, and some reported "geysers" (sand boils) deposited many yards of sediment on the surface and caused flooding (figs. 199-201). At one location, as many as 20 sand boils appeared that left "cone shaped" piles of light-colored sand as much as 18 cm in diameter and 20 cm high; at another "sand pile," diameters were estimated as 0.6-0.9 m. At yet another location, sand boils producing a blue-gray sand were reported. The only sand-boil activity reported for the 1965 earthquake in or near Puyallup occurred within this same area (loc. 68). The 1965 occurrence took place on the Ayles Junior High School playfield and reportedly produced a "considerable amount of water."

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Figure 199. Sand boil in Puyallup, Wash. (pl. 5, loc. 68), produced by the April 13, 1949, earthquake. The earthquake generated many sand boils in northwest Puyallup. Some, such as this one, deposited considerable volumes of sediment on the surface; others were associated with damage to homes in the area. The sand boil vent (collapsed area in the center) is 2–3 m long. Photograph by Richard Six, Puyallup, Wash.



Figure 200. Ground crack and ejected sediment (sand boil) produced by the April 13, 1949, earthquake. This ground failure in northwest Puyallup, Wash. (pl. 5, loc. 68), may indicate incipient lateral spreading due to liquefaction of sediments. Shadow of individual (lower left) shows scale. Photograph by Richard Six, Puyallup, Wash.

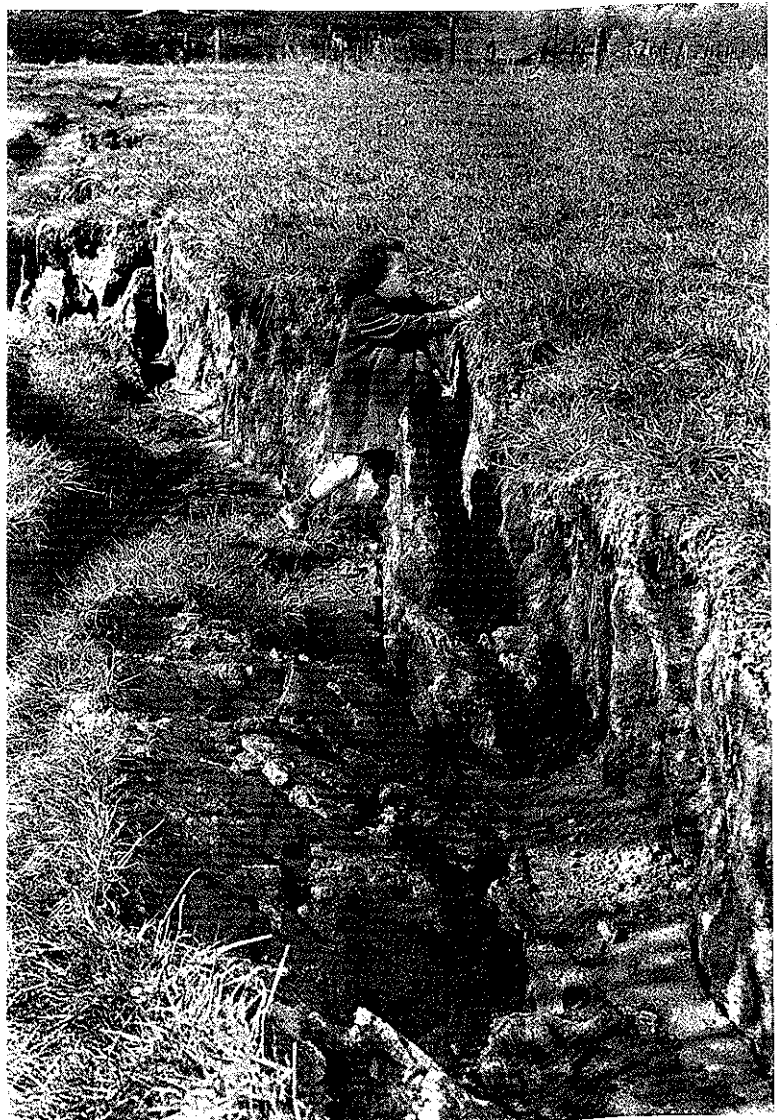


Figure 201. Flooding in northwest Puyallup, Wash. (pl. 5, loc. 68), at the time of the April 13, 1949, earthquake. According to local residents, the flooding could not be attributed to broken water mains and may have resulted from the ejection of ground water from the many sand boils that occurred in the area. Photograph by Richard Six, Puyallup, Wash.

high at a location along West Main Street (loc. 63) presently occupied by the Puyallup High School Gymnasium. To the west (loc. 69), a basement was "pushed up" on one end so that the house teetered, and liquefied sand ejected into a basement attained a depth of approximately 1.2 m. Also at this location, 0.3-m-high sand mounds developed "all over" a cultivated field. In addition, a report of ground cracks and a "shift" in a road adjacent to the Puyallup River in Puyallup (loc. 67) suggests slumping or lateral spreading at that location.

Northwest of Puyallup, along the west side of Clarks Creek (loc. 71), a 60- to 100-m-long crack developed during the 1949 earthquake and exhibited as much as a few meters of horizontal and vertical displacement (fig. 202). Lateral movement was in the direction of the creek, indicating lateral spreading or slumping of the alluvial soil. The foundation of a nearby house on the east side of Clarks Creek was reportedly destroyed, probably as a result of ground failure.

Figure 202. Ground crack along Clarks Creek, northwest of Puyallup, Wash., associated with slumping or lateral spreading of alluvial sediments (pl. 5, loc. 71). This 1949 earthquake-induced ground failure extended along 60–90 m of the west bank of Clarks Creek; lateral movement was in the direction of the creek (out of sight to the left of view). Photograph from the Richards Photographic Studio Photo Collection, courtesy of the Tacoma Public Library, Tacoma, Wash.



Sand boils occurred at several locations north of the Puyallup River. Included among these were the reports of a sand-boil deposit as great as 5 m in diameter (loc. 72), "dozens" of sand boils composed of light-colored sand (loc. 74), and sand boils 0.3–0.5 m in diameter and 9–12 m apart made up of black, clean sand (loc. 75).

The 1949 earthquake generated many small sand boils with clean, black sand at one location just east of Sumner (loc. 58); detailed descriptions of sediment type were not reported for two other locations to the southeast (locs. 56 and 57).

Farther north, near the King-Pierce County line (loc. 100), sand boils in 1949 reportedly deposited fine sand at various points along a long fissure and at various locations in a cultivated field; in 1965, ejected sand formed many piles over two fields. In this same area in 1949, a fissure reported to be about 30 m long, 0.3 m wide, and as much as 2 m deep developed in a cultivated field. Immediately after the event, water was observed covering the bottom of the fissure. The



Figure 204. Damage to Deschutes Parkway, Olympia, Wash., resulting from a 1965 earthquake-induced ground failure (pl. 5, loc. 48). The parkway was constructed on granular fill placed on tidal flat muds that are now within the limits of Capitol Lake; failure was probably due to liquefaction. Photograph by Gerald W. Thorsen, Division of Geology and Earth Resources, Washington Department of Natural Resources, Olympia, Wash.

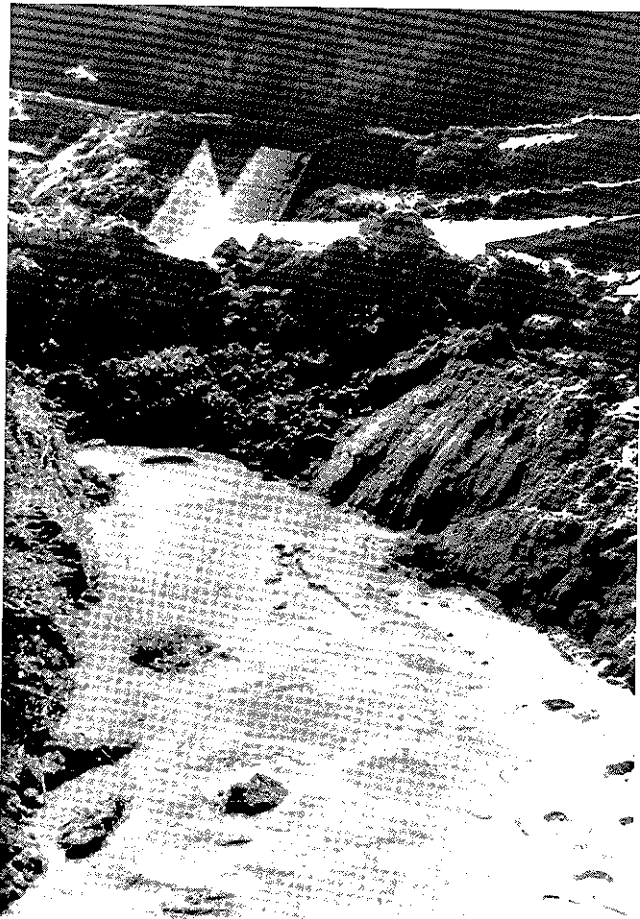


Figure 205. Sand boils near Capitol Lake in Olympia, Wash., related to the earthquake of April 29, 1965 (pl. 5, loc. 48). The sand boils are evidence of soil liquefaction at this ground failure location. Sidewalk slab in background shows scale. Photograph by Gerald W. Thorsen, Division of Geology and Earth Resources, Washington Department of Natural Resources, Olympia, Wash.

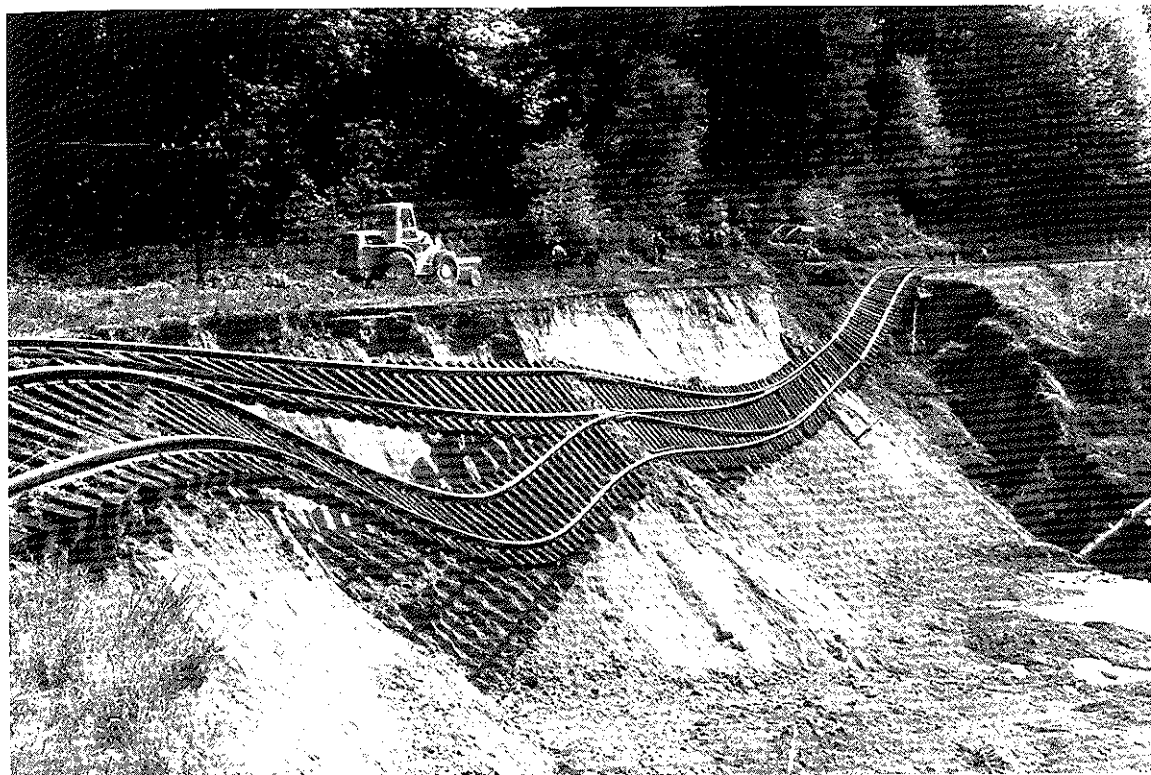


Figure 206. Damage to Union Pacific Railroad tracks near Tumwater, Wash. (pl. 5, loc. 45), due to a 1965 earthquake-induced slope failure in artificial fill. Photograph by Gerald W. Thorsen, Division of Geology and Earth Resources, Washington Department of Natural Resources, Olympia, Wash.



Figure 207. Damage to Black Lake Road south of Olympia, Wash. (pl. 5, loc. 44), caused by failure of a steep lake bank during the earthquake of April 13, 1949. Photograph used by permission of Jack Goldsby, Tumwater, Wash.

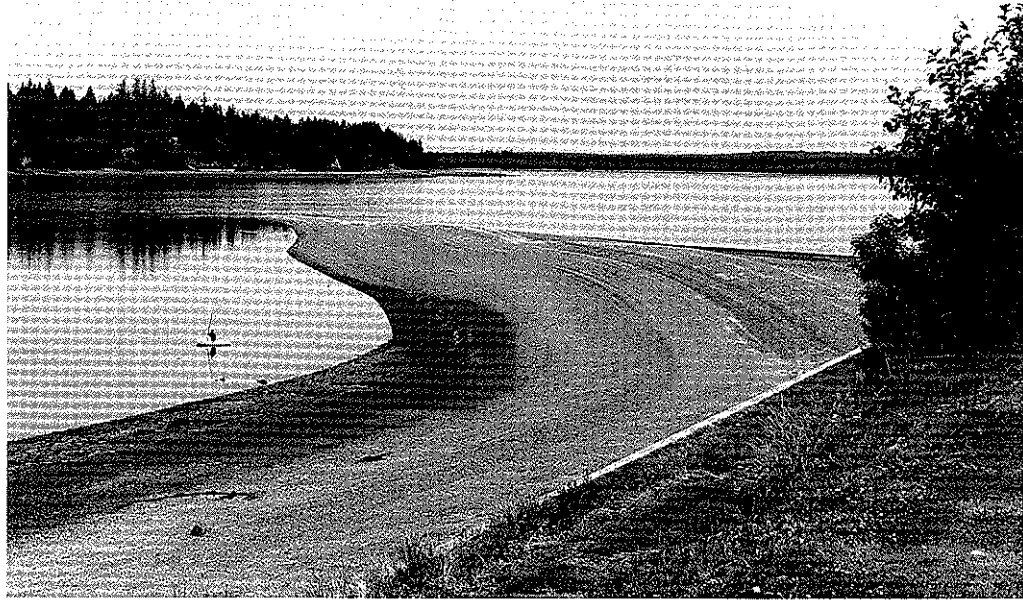


Figure 208. View of Cooper's Point, located 11 km north of Olympia, Wash. (pl. 5, loc. 51). About 45 m of the end of the sand spit failed and disappeared into Puget Sound during the April 13, 1949, earthquake. Photograph was taken in 1988.

Southwest of Olympia (pl. 5, loc. 44; fig. 207), about 30 m of one lane of Black Lake Road was damaged in 1949 by slumping. The failure occurred on a steep 8-m-high lake bank underlain by Vashon outwash sand and possibly some artificial fill.

About 45 m of the sandspit at Cooper's Point, north of Olympia (pl. 5, loc. 51, fig. 208), slid into Puget Sound during the 1949 earthquake. An eyewitness reported seeing the mass of land sinking beneath the waves. Soundings taken afterward at high tide indicated water depths of 15 m in an area where formerly the spit was 1.5 m above water at high tide. The sandspit is a Holocene beach deposit (Washington Department of Ecology, 1980b) that includes medium to coarse sand and minor gravel.

In Olympia, extensive settling was reported in 1949 in the Port of Olympia area (loc. 50) and in a residential area three to eight blocks east of the State Capitol (loc. 46). The entire port area, underlain by artificial fill, was reported to have settled 13 cm. Pipelines were broken and asphalt was bulged up over pilings. Settlement east of the State Capitol, which reportedly occurred in an area underlain by a peat soil, damaged several residences.

CASCADE RANGE, WASHINGTON, REGION

The Cascade Range of Washington (pl. 6) includes the area bounded by lat 49°00' N. and lat 46°00' N. and by long

121°00' W. and long 122°00' W. The region includes central and eastern parts of King, Skagit, Snohomish, and Whatcom Counties; eastern parts of Lewis and Pierce Counties; north-central and northeastern Skamania County; and far western parts of Chelan, Kittitas, and Yakima Counties. Nearly all of the reported 1949 and 1965 ground failures are located on the western side of the Cascade Range (pl. 6, table 31). Ground failures produced by the 1949 and 1965 earthquakes in this mostly mountainous region include (in order of abundance) rock falls and rock slides on steep cliffs and rock faces, slumps and other slides in alluvial valleys along roads and river banks, and minor ground cracks and (or) settlement in alluvial areas on valley floors and in embankment areas of dams.

A cluster of ground-failure activity was generated by the 1949 earthquake along the Cowlitz River Valley near Randle (locs. 117–122). Blocks of volcanic rocks fell from steep cliffs east of Randle onto Cline Road (locs. 120 and 121) and onto the old Randle-Packwood Highway (loc. 122). The blocks were reported to be as large as 6 m on a side. On the valley floor, southwest of Randle (loc. 117), a road embankment composed of artificial fill underlain by loose, liquefiable sand slumped into a nearby field. Road damage caused by the slump is shown in figure 209. Simultaneously on the same property (loc. 118), numerous sand boils erupted. To the east and closer to the Cowlitz River (loc. 119), small slumps were triggered along the bank of an abandoned river channel.



Figure 209. Slump in a 1- to 1.2-m-high road embankment in the Cowlitz River Valley, about 1.6 km southwest of Randle, Wash. (pl. 6, loc. 118). This April 13, 1949, earthquake-induced ground failure occurred in artificial fill underlain by loose liquefiable sand. The earthquake also produced sand boils in an adjacent field. Photograph by Alice Peters, Randle, Wash.

Rock slides on Mount Rainier were reported for both the 1949 and 1965 earthquakes. In 1949, a "major" rock slide occurred on the slopes above Nisqually Glacier and, in 1965, large amounts of rock and soil reportedly fell or slid in the vicinity of Kautz Glacier (pl. 6, loc. 126). Closer to the community of Longmire, the 1949 tremor induced rock falls and (or) rock slides of undetermined size on the cliffs of Eagle Peak (loc. 123) and Rampart Ridge (loc. 124). Also, incipient sliding of flood debris in the Kautz Creek drainage was reported (loc. 125). Numerous instances of ground failure on and near Mount Rainier, related to the 1949 and 1965 earthquakes and to several other historical earthquakes prior to the 1949 event (Noson and others, 1988), strongly indicate a high susceptibility to earthquake-induced landsliding. Jointing and layering of the volcanic rocks that underlie the steep slopes of Mount Rainier probably contribute to their seismic instability.

Mount Si (fig. 210; pl. 6, loc. 130) was the site of earthquake-triggered rock slides in 1945, 1949, and 1965. On April 29, 1945, an earthquake with a felt magnitude of 5.9 (Noson and others, 1988) triggered landsliding on Mount Si that was described by Bodle and Murphy (1947), as follows: "At the Mount Si Ranger Station, near North Bend, the earth buckled and heaved and tons of rock and earth cascaded down the 4,000 ft [1,220 m] cliffs of Mount Si." In 1949, a

large dust cloud caused by a rock slide was observed rising from the west side of the mountain at about the 600 m level and, in 1965, a slide on the southwest slope of Mount Si was described as "extensive." The 1945, 1949, and 1965 ground failures demonstrate the high susceptibility of steep rock slopes on Mount Si to earthquake-induced rock falls, rock slides, and rock avalanches. Metavolcanic rocks (metamorphosed basic lavas), some of which are foliated, form the bedrock surface over much of the western part of Mount Si (Kremer, 1959). The rocks on the western part of the mountain dip very steeply to the west, and much of the rock is fractured. Fractures and bedding planes with unfavorable orientations commonly contribute to the instability of rock slopes. As stated by Piteau and Peckover (1978), "The stability of rock slopes depends largely on the presence and nature of defective planes or discontinuities within the rock mass."

Minor ground cracking was reported on Mud Mountain Dam (loc. 127) in 1949 and 1965 and on Howard Hanson Dam (loc. 128) in 1965. In both instances, the dams were not endangered. Small slides in the vicinity of Mud Mountain Dam were also reported for both the 1949 and 1965 earthquakes. In 1949, sliding occurred in an old slide area downstream from the dam and, in 1965, a slope near the Vista House was affected by small slides.

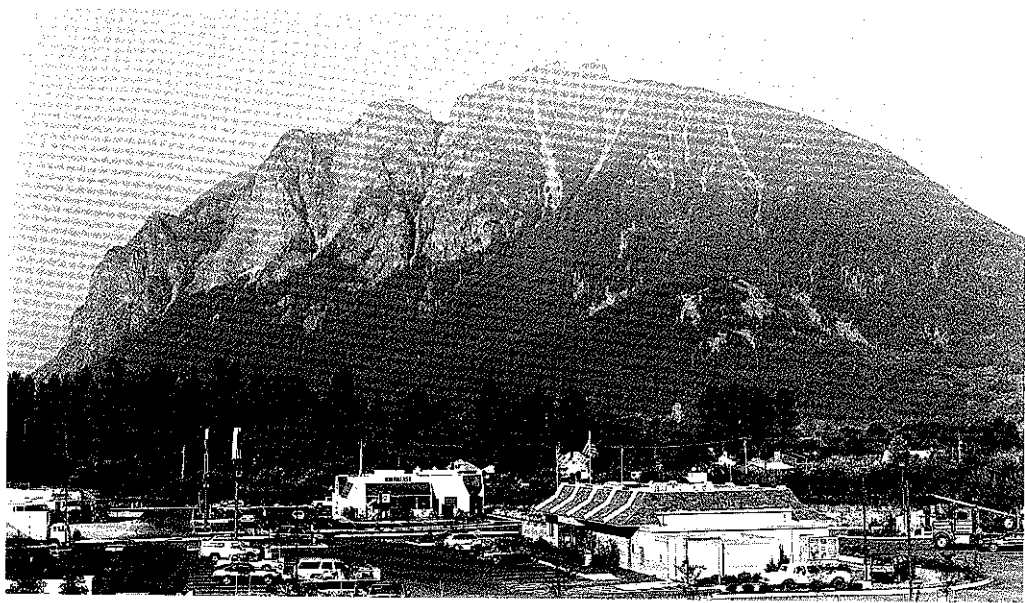


Figure 210. Mount Si near North Bend, Wash. (pl. 6, loc. 130). "Rockslides" on Mount Si were reported for the Puget Sound area earthquakes of April 29, 1945, April 13, 1949, and April 29, 1965. Photograph was taken in 1988.

CENTRAL-SOUTHWESTERN WASHINGTON REGION

The central-southwestern Washington region (pl. 7) extends from lat 47°30' N. to lat 46°22' N. and from long 122°00' W. to the Pacific Ocean (excluding the area of pl. 4). Included in the region is all of Lewis County west of long 122°00' W., the area of southwestern Pierce County south of lat 47°00' N. and west of long 122°00' W., all of Thurston County south of lat 47°00' N., Mason County south of lat 47°30' N. and west of long 123°00' W., all of Grays Harbor County south of lat 47°30' N., and all but the southwesternmost part of Pacific County. In this region, nearly all of the reported ground failures were produced by the 1949 earthquake; most occurred in lowlands, including the valley bottoms of major rivers and adjacent hillsides, and in glaciated areas bordering the southern terminus of Puget Sound. Ground-failure locations in this region are shown on plate 7; reports describing selected ground failures are listed in table 32.

Reports of sand boils and related ground cracking produced by the 1949 earthquake came from several locations in the central part of the region (locs. 141 and 146-149). As many as 12 sand boils deposited "patches" of sand in a swampy pasture near Deep Lake, east of Maytown (loc. 141). An eyewitness reported that mud was ejected first, followed by clean, white sand. The ejected sediment erupted along a north-south-trending line over a zone 3 m wide, forming "patches" on the ground as wide as 3 m. The area is underlain by glacial deposits of the Vashon Drift (Walsh and others, 1987); a gravel pit at the south end of

the property, a short distance from the sand boils, exposes poorly sorted sand.

On a low terrace of the Chehalis River, just south of Centralia (loc. 146), about 20 ground cracks appeared in a farmer's field; from some of these (figs. 211 and 212), geysers of water and sediment spouted as much as 45 cm above the ground. It was reported that the geysers brought up what appeared to be "clean ocean sand." It was also reported that water continued to run slowly from the fissures for about a week.

On the flood plain of the Chehalis River northwest of Centralia (loc. 149), sand boils erupted from a ground crack approximately 2.5 cm wide and 5 m long. In the process, "several buckets full" of pure white sand were deposited on the ground. A 1949 sand boil south of Chehalis (loc. 147) is reported to have "heaved some ground" 0.6 m in the vicinity of a spring, forming a mound from which "muddy water" poured. Available information was not sufficient to determine the exact location of the sand boil or the type of sediment involved.

One other sand-boil occurrence in the region is suggested by the report of a fissure on a road near Ceres (loc. 148) that produced a "wet and soft spot in the roadbed where it was previously dry." Artificial fill underlies the road at that location.

Ground settlement related to the 1949 earthquake caused extensive damage to several buildings in Centralia (loc. 145), including a church that had to be condemned. Water mains in the city also were damaged. Foundation damage and broken water pipes in the Hanaford Valley area (loc. 142) were probably related to ground failure. Both



Figure 211. Alignment of sand boils in a field 1.6 km southwest of Centralia, Wash. (pl. 7, loc. 146), is related to linear ground crack from which the water and sand were emitted during a 1949 liquefaction incident. Photograph by Ted Dorn, Centralia, Wash.

areas are underlain by alluvial sediments that are locally covered by artificial fill.

In the areas adjoining the central Puget Sound lowland, landslides were triggered on hillsides, along roads and railroads, and on lake and river banks. In the LaGrande-Eatonville-Kapowsin area (locs. 136–139), landslides and ground cracks were associated with both the 1949 and 1965 earthquakes. Although little information is available regarding the exact locations and nature of ground failures in the vicinity of LaGrande (pl. 7, loc. 136), it was reported that the 1949 earthquake generated ground cracks on “side hills” in the area and, in 1965, that “slides went into rivers and onto roads.”

A landslide triggered by the 1949 earthquake at Ohop Lake (loc. 138) is particularly interesting because, like the Tacoma Narrows landslide (pl. 5, loc. 81), it demonstrates the continuing hazard of some earthquake-induced ground failures beyond the time of the earthquake. At the time of the April 13, 1949, tremor, a 200-m-long and 8- to 10-cm-wide

crack appeared on a county road located several feet above lake level on the northwest side of the lake. One month later, on May 13, complete failure occurred as the unstable mass suddenly slumped and (or) flowed about 30.5 m into the lake. The failure, which involved artificial fill underlain by alluvial sediments, left a scarp on the roadway about 1.5 m high (fig. 213). Summer cottages and supports for telephone and power lines were damaged by the slide.

In 1949, a smaller slide damaged about 30 m of an approach to a railroad overpass southeast of Eatonville (loc. 137). Artificial fill was also involved in that failure.

The 1949 earthquake induced a slump along about 30 m of county road adjacent to the Cowlitz River southeast of Morton (loc. 134). The slide material (glacial sand and gravel) dammed the river for a short time. Closer to Morton, the same event triggered a rock fall (loc. 135) from a near-vertical exposure of Tertiary-age sedimentary rocks. It was reported that a block of bedrock 8 m high fell from the cliff, frightening homeowners below.

Reported landslides in the vicinity of Centralia and Chehalis (locs. 143 and 144) were later determined to be small slumps with displacements of 0.6 m or less. One of the slides occurred on the side of an old gravel pit north of Centralia (loc. 143) in a glacial outwash deposit of sand and gravel; the other, located on the north shore of Plummer Lake (loc. 144), probably involved Quaternary alluvial sediments. Small slumps in 1949 also damaged roads near Rochester (loc. 150) and Oakville (loc. 151); both involved artificial fill on poor alluvial foundations. Horizontal and vertical displacements of 0.6 m or less were noted.

An 85-m-long section of a railroad embankment slumped into Patterson Lake south of Lacey (loc. 140) during or shortly after the 1949 earthquake. The slide is reported to have caused a wave surge that rose 25–30 cm over a nearby dock. About 19,000 m³ of material was required to repair the damage (U.S. Army Corps of Engineers, 1949). The failure involved artificial fill over glacial sediments of the Vashon Drift.

Near Shelton (pl. 7, loc. 156), one lane of U.S. Highway 101 was damaged by a minor slump triggered by the 1965 earthquake. The slump, which was in artificial fill underlain by glacial sediments, dropped a part of the road approximately 0.3 m for a distance of about 46 m. Also, slides generated by the 1965 event were reported along the west side of Oakland Bay near Shelton (loc. 155). However, available information was insufficient to determine the exact locations and characteristics of those ground failures.

Numerous broken water mains and sidewalk cracks in Hoquiam and Aberdeen (locs. 152 and 153) associated with the 1949 earthquake may have resulted from minor settlement or incipient landsliding. Much of the Hoquiam-Aberdeen area adjacent to Grays Harbor is underlain by Quaternary alluvium (Walsh and others, 1987), and artificial fill is present locally. Ground failure induced by the 1949



Figure 212. Sand boils on the floodplain of the Chehalis River, about 1.6 km southwest of Centralia, Wash. (pl. 7, loc 146). Water and sand spouted from several ground cracks at this location at the time of the April 13, 1949, earthquake. Photograph by Ted Dorn, Centralia, Wash.



Figure 213. Scarp created by a landslide on the west side of Ohop Lake, Pierce County, Wash. (pl. 7, loc. 138). Incipient failure induced by the April 13, 1949, earthquake resulted in the development of a large ground crack. On May 13, complete failure occurred as the unstable mass suddenly slumped into the lake, damaging the roadway, utility lines, and cottages near the shore. Photograph used by permission of the Tacoma News Tribune.

and 1965 earthquakes has produced similar effects in other areas with similar geologic settings.

WESTERN COLUMBIA RIVER REGION, OREGON AND WASHINGTON

Included in the western Columbia River region (pl. 8) are the following Washington counties: Cowlitz and Wahkiakum Counties, western and southern parts of Skamania County west of long 121°00' W. and south of lat 46°00' N., part of western Klickitat County west of long 121°00' W. and south of lat 46°00' N., and southwestern Pacific County south of lat 46°23' N. Included in Oregon are Clatsop, Columbia, Washington, Multnomah, and Hood River Counties; the northwestern part of Wasco County west of long 121°00' W. and north of lat 45°14' N.; the northern parts of Clackamas and Yamhill Counties north of lat 45°14' N.; and all of Tillamook County except the southwest corner south of lat 45°14' N.

In this region, the 1949 earthquake spawned numerous ground failures along and near the Columbia River; these included rock falls, rock slides, or rock falls/rock avalanches on steep cliffs and rock faces, and ground cracks, settlement, and sliding probably related to liquefaction in alluvial areas on the valley floor.

A landslide (probably a rock fall/rock avalanche) that originated on a steep head scarp of the 36 km² Bonneville landslide west of Stevenson, Wash. (loc. 160), reportedly created a dust cloud that was seen for miles along the Columbia Gorge. Rock falls on the steep scarps are a common, ongoing mass-wasting process that is probably easily accelerated by seismic activity. According to Palmer (1977), "The head scarps are actively raveling, with large blocks more than 15 ft [4.6 m] in diameter crashing down from time to time, so that it is unsafe at the base of the cliffs." The head scarp of the Bonneville slide (fig. 214) exposes about 370 m of the Eagle Creek Formation (conglomerate, sandstone, and minor tuff) overlain by basalt (Korosec, 1987). It was reported that a "considerable" area of fresh surface on the rock cliff was exposed by the 1949 landslide and that abandoned buildings, including a small school house, were damaged or destroyed. Post-1949 airphotos reveal an area of slide debris, possibly related to the 1949 earthquake, as much as several tens of meters wide and a few hundred meters long at the base of a steep cliff on the south side of Table Mountain (loc. 160).

At Blue Lake, east of Portland, Oreg. (loc. 158), a 1949 rock fall from a near-vertical rockface on the south side of the lake reportedly endangered a boathouse. A 9- to 15-m-high cliff at that location exposes part of the Troutdale Formation (conglomerate and sandstone) (Trimble, 1963).

Rock falls involving highly jointed volcanic rocks occurred along the Spokane-Portland-Seattle railway about 1.6 km east of Mayger, Oreg. (loc. 166), and along the Ocean

Beach Highway just west of Stella, Wash. (loc. 168). The rock fall east of Mayger damaged the railroad, but it was reported that only a few hours were required to clear the slide and repair the damage. The rock fall at location 168 originated on the near-vertical face of a 15- to 25-m-high bluff that extends for about 0.8 km along the highway west of Stella. Part of the rock fall reportedly crossed the highway and spilled into the Columbia River. According to an eyewitness, the Washington State Department of Highways had to "shoot" (use explosives) to remove a block of rock "as large as a house."

Sand boils and associated ground cracks indicating liquefaction of sediments occurred at Longview, Wash., in 1949 near the junction of N.W. Nichols Street and Ocean Beach Highway (pl. 8, loc. 163) and near 40th Avenue (loc. 164). Geysers of water and sand 1-1.2 m high developed in a yard and, nearby, sand boils and settlement caused considerable structural damage to a local residence. The area is part of a flat, low-lying terrace or flood plain of the Columbia River underlain by Quaternary alluvium. Artificial fill is present locally. The 1949 ground failure near 40th Avenue took the form of a 6-m-long ground crack from which "black, fine sand bubbled." The site is part of a sandy flood plain; Quaternary alluvial sediments underlie the area (Walsh and others, 1987). Local residents who lived in the vicinity in 1949 say the ground-water table was almost at the surface at the time of the earthquake.

Other effects of the 1949 earthquake, possibly related to liquefaction of Columbia River sediments, include the following: a slide involving artificial fill overlying alluvium that damaged 100 m of the Longview dike road (loc. 165); damage to a building at Mayger, Oreg. (loc. 167), related to shifting of pilings toward the Washington side of the river; sliding or flowing of sediments on Puget Island in the Columbia River (loc. 170), indicated by well pipes all bent in the same direction; and settling, ground cracks, and bent pipes in a flat-lying, swampy alluvial area at Skamokawa, Wash. (loc. 171).

OBSERVATIONS AND CONCLUSIONS

In this study, data on ground failures generated by the April 13, 1949, and April 29, 1965, Puget Sound earthquakes were obtained by (1) review of published and unpublished information, (2) interviews with local residents and State and local officials, and (3) field study of selected ground-failure sites. These data include new and previously unpublished ground-failure information, particularly on landslides, related to the 1949 and 1965 events. The data support conclusions by Hopper (1981) and Keefer (1984) regarding the general distribution and character of the 1949 and 1965 ground failures and the relative susceptibility of geologic environments in the Puget Sound region to earthquake-induced ground failure. The following observations and

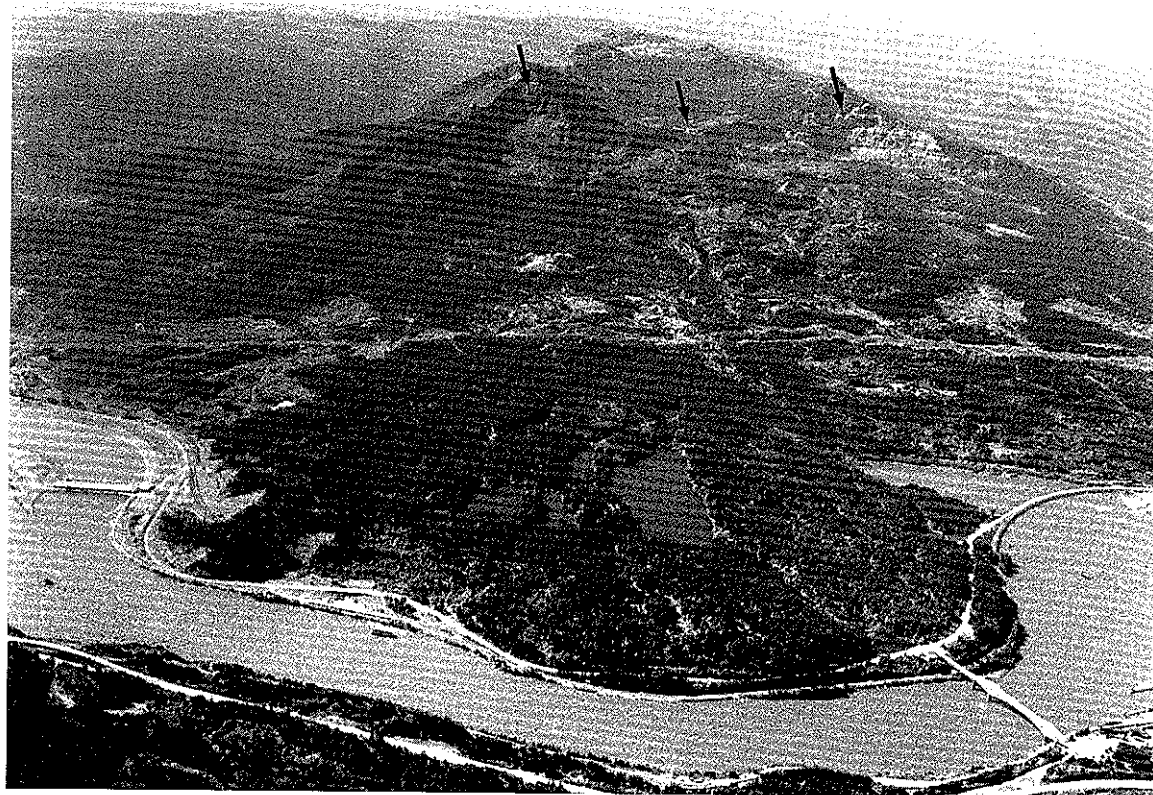


Figure 214. Bonneville landslide area along the Columbia River west of Stevenson, Wash. (pl. 8, loc. 160). Rock fall/rock avalanche activity triggered by the April 13, 1949, earthquake occurred along the steep head scarp (arrows), creating a dust cloud visible for many kilometers along the Columbia River Gorge. Photograph by Derek Cornforth, Landslide Technology, Portland, Oreg.

conclusions are based, in large part, on the perspective gained by the compilation of new and existing information on ground-failure characteristics and by study and comparison of ground-failure distributions made possible by the plotting of 1949 and 1965 ground failures on regional topographic maps (pls. 4-8).

Ground failures triggered by the 1949 and 1965 earthquakes were scattered over areas of about 28,500 km² and 20,700 km², respectively (fig. 187). Ground failures in areas affected by both earthquakes were similar, taking the form of landslides, settlement, and ground cracks. Although most of the reported ground failures were small settlements and ground cracks that resulted in only minor damage to roads, sidewalks, buildings, utility lines, and other structures, many caused significant damage in areas of intense ground shaking. Many damaging ground failures occurred in environments thought to be conducive to liquefaction failures, as suggested by the presence of sediment types susceptible to liquefaction, high water tables, and in some cases the occurrence of sand boils in the immediate vicinity.

Liquefaction of sediments, indicated by sand boils, was most common on flood plains or low terraces of valley floors extensively underlain by Quaternary alluvium and

locally by artificial fill and at the mouths of rivers where deltaic sediments and tidal flat muds are extensively overlain by artificial fill. Many slides, mostly small slumps with estimated volumes of less than 1,500 m³ (Chleborad and Schuster, 1989), involved artificial fill underlain by granular alluvial, deltaic, lacustrine, or glacial deposits. Most of these occurred in embankments along primary and secondary roads and railroads and along the banks of rivers, lakes, and other bodies of water. Also, slumps and other slides of undetermined type were common on steep bluffs along Puget Sound. Many of the slides along these bluffs occurred within a stratigraphic sequence composed of glacial sediments of the Vashon Drift that included its Esperance Sand Member or its lithologic equivalent underlain by impermeable silts and clays. Such conditions often give rise to naturally unstable slopes because of high groundwater conditions. The importance of local groundwater conditions in the development of earthquake-induced flows, slumps, and other slides is suggested by the proximity of many of the slope failures to rivers, lakes, streams, or other bodies of water and by reports of associated springs, swampy areas, and "opened pools of ground water," all of which indicate a probable high water table and saturated

ground conditions. Coupled with the presence of loose granular sediments, such conditions often indicate a high susceptibility to liquefaction-induced ground failure.

Rock falls, rock slides, and rock avalanches reported for the 1949 and 1965 earthquakes occurred almost exclusively in the mountainous terrain of the Cascade Range and along the western Columbia River valley. Typically, these failures originated on very steep slopes (slopes of 45° or more) in areas of highly jointed volcanic, metamorphic, or sedimentary rocks and in areas where such failures occur naturally even under nonseismic conditions.

Examination of ground-failure distributions in each of the four regions discussed reveals that a high percentage of the reported failures occurred in and near the more populated and heavily traveled areas, which suggests that many ground failures that occurred in less populated and inaccessible areas were not reported. This notion is supported, to some extent, by the paucity of reports of landsliding in several large areas of landslide-susceptible terrain in western Washington and northwestern Oregon, such as the Cascade and Coast Ranges (Radbruch-Hall and others, 1982; Schuster and Chleborad, 1989), where intense ground shaking (MMI V or greater) might be expected to generate such failures.

Future large earthquakes in the western Washington-northwestern Oregon region can be expected to generate similar types of ground failures in the same or geologically similar environments as those that occurred in the 1949 and 1965 earthquakes. The location and extent of losses caused by future earthquake-induced ground failures will depend on many factors, including the magnitude and location of the earthquake, ground-water conditions at the time of the earthquake, and the susceptibility of populated and developed areas to damaging ground failure during intense seismic shaking. Recognition of geologic environments susceptible to earthquake-induced ground failure is an important step in efforts to reduce the earthquake hazard faced by residents of the western Washington-northwestern Oregon region.

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TABLES 29-33

Descriptions of ground failures in the Puget Sound region caused by the April 13, 1949, and April 29, 1965, earthquakes

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Table 29. Descriptions of selected ground failures in the northern half of the central and southern Puget lowland region.

[Location numbers correspond to ground-failure location numbers on plate 4. do., ditto. Location accuracy: A, available information allows accurate location; B, available information allows location to within a kilometer; C, available information allows location to within a few kilometers. Quotations referenced as "written commun., 1949" or "written commun., 1965" are responses to University of Washington intensity surveys. Copies of the questionnaire responses are on file in the offices of the U.S. Geological Survey in Golden, Colo. Metric values and explanatory information in brackets have been added to the quotations by the authors. Comments following quotations are those of the authors and are based on field observations, information from cited references, and interviews with local residents]

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
1	Slump or lateral spread (1965)	Port Orchard, Wash.; Kitsap County	A	[Photo caption] "HMM, HMM AND WOW!—Two people nonchalantly talk at the Thriftway Supermarket parking lot near the rumpled edge of the northeastern part of the lot. The store building itself suffered some damage but, as in the case of other locations in the county, blackout on fill material was damaged the most by the tremor." (Bremerton Sun, 1965a). Photo shows part of a badly broken asphalt-covered parking area adjacent to Sinclair Inlet in Port Orchard. Vertical displacements of approximately 0.6 m are apparent in the photo.
2	Slump (1965)	Port Orchard, Wash.; Kitsap County	A	A slide caused by the 1965 earthquake damaged Country Club Road southeast of Port Orchard (Blair Seymour, Bremerton Sun, oral commun., 1988). Slump in artificial fill underlain by Vashon Drift damaged 15–30 m of pavement along Country Club Road. Movement was downslope in the direction of a small ravine adjacent to the road embankment (see fig. 198).
3	Settlement (1965)	Seattle, Wash. (Boeing Field); King County	B	"About a mile still farther south [of the Georgetown District], * * * property loss at the Boeing Company was reported to be high. Much destruction there resulted from subsidence" (Mullineaux and others, 1967).
4	Settlement (1949)	Seattle, Wash.; King County	A	"Quake opens 6 inch [15 cm] cracks in yard * * * house sank 4 inches [10 cm]." (Seattle Post-Intelligencer, 1949e).
	Settlement (1965)	do.	A	"Similar damage [to that in the 1949 earthquake] occurred as a result of the 1965 earthquake. Cracks appeared in the basement and the dock separated. House next door had settling and yard cracks in the 1949 and 1965 quakes. The area was once the site of the old Taylor Sawmill." (Hale Lowry, oral commun., 1988).
5	Slide(s) (1965)	Maple Valley, Wash. (Renton); King County	B	"Slides were reported in the * * * Devil's Elbow Road near Maple Valley." (Seattle Times, 1965a). The location of "Devil's Elbow Road" is believed to be a 0.8-km-long section of paved road that joins SE 95th Way and NE 27th Street just north of Renton (12.5 km northwest of Maple Valley). The road, which is presently abandoned due to extensive landsliding, is situated on the steep sides of a ravine in the May Creek drainage. Slumping has dropped parts of the paved road as much as 0.3 m vertically along sections 30 m in length on both sides of the ravine. The exact location of the earthquake-induced landsliding is undetermined.

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| 6 | Slump (1965) | Mercer Island, Wash.;
King County | C | <p>[Photo caption] "The shoulders of the road cracked along East Mercer Way." (Mercer Island Reporter, 1965).</p> <p>This Mercer Island photo shows arcuate crack, about 6 m long and 2.5-7.6 cm wide, along shoulder of road and steep embankment. Vertical and horizontal displacements appear slight.</p> |
| 7 | Ejection of ground water (1949); ejection of ground water (1965) | Seattle, Wash. (West Seattle; Alki); King County | A | <p>"Basement floor [damage] and fresh water came in [at the time of the 1965 earthquake] * * * after the 1949 earthquake the professor and some students came out and took samples of the water in our basement. It was fresh water and we are only about 100 feet [30 m] from the bay." (Mrs. J.W. Woodhouse, written commun., 1965).</p> <p>"Almost a third of the long promenade behind the seawall at Alki sank some 6 inches [15.2 cm] in the vicinity of the Alki Monument." (Seattle Times, 1965c).</p> <p>"At Alki Point, * * * waterline breaks were more numerous than anywhere else in the city." (Mullineaux and others, 1967).</p> |
| 8 | Slide (1965) | Seattle, Wash. (West Seattle); King County | A | <p>"Cracks in swimming pool * * * shifting and sliding of dirt under pool." (John E. Smith, written commun., 1965).</p> |
| 9 | Slide (1965) | Seattle, Wash. (West Seattle); King County | B | <p>"There was some sliding on steep bluffs at the south end of Schmidt Park." (Harold Borden, oral commun., 1988).</p> |
| 10 | Slump (1949) | Seattle, Wash (West Seattle); King County | A | <p>"Six houses were ripped apart on the 5100 block of Admiral Way by Wednesday's earthquake. Two families were forced to move out of their shattered homes. The other four houses were new homes, under construction and nearly completed. All four were splintered. * * * Ground on the block shifted and pulled open in the quake. The home, * * * at 5127 Admiral Way, dropped three feet and slid a foot and a half off its foundation." (Seattle Post-Intelligencer, 1949g).</p> <p>[Photo caption] "A small residence on unconsolidated fill lost its foundation when settlement dropped the concrete wall and the horizontal movement added to the damage." (Edwards, 1950).</p> <p>[Photo caption] "LONG WAY DOWN—* * * deep crevasse * * * another graphic example of damage wrought by quake showed up at 5135 Admiral Way." (Seattle Post Intelligencer, 1949a). See figure 190.</p> |
| 11 | Slump (1965) | Seattle, Wash. (West Seattle); King County | A | <p>"Fill soil settled and cracked, 5 x 40 foot [1.5x12.3 m] concrete bulkhead twisted and dropped on north end. Fill area slid down hill." (E.J. Carlson, written commun., 1965).</p> |
| 12 | Slump (1965) | Seattle, Wash. (West Seattle); King County | B | <p>"Cracked cement steps. * * * Some breaking off of cliff." (A.R. Munson, written commun., 1965).</p> <p>"Slumping was observed along a steep slope adjacent to 36th Avenue S.W., near Admiral Way." (Hake and Cloud, 1967).</p> |

Table 29. Descriptions of selected ground failures in the northern half of the central and southern Puget lowland region—Continued.

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
13	Slump (1965)	Seattle, Wash. (West Seattle); King County	A	"In 1949 we had a * * * crack in the backyard along the same path as from this last quake, only less severe and no yard drop then like we have now * * * We live on a hillside." (G.F. Kok, written commun., 1965). Apparent slight slump triggered by the 1965 earthquake. Original, incipient sliding may have been triggered previously by the 1949 earthquake. The site is located at or near the head of a large landslide mapped by Waldron and others (1962).
14	Ground crack (1949)	Seattle, Wash. (Delridge Way); King County	A	"The Seattle Housing Authority will remove two buildings in the temporary Delridge Homes project, 4545 Delridge Way, as a result of Wednesday's earthquake, Charles W. Ross, executive director, said Thursday. Ross said no damage was done to the structures themselves, * * * but that a break in the earth underlying them might cause serious slippage later in case of heavy rainfall. [Ross also said] the area is partly a fill" (Seattle Post-Intelligencer, 1949c).
15	Lateral spread or slump (1965)	Seattle, Wash. (Spokane Street); King County	A	"The Bethlehem Steel Seattle Mill Depot No. 92, Spokane Street, Seattle, was observed by a competent engineer during the quake. The building is single story concrete posts with brick curtain walls on a concrete footing with a concrete floor resting on filled ground. The rear of the building is 9 feet [2.7 m] from the top of a 1 on 2 slope 7-1/2 feet [2.2 m] above adjacent tide land. After the perceptible ground motion of the quake had ceased, cracks started developing in the 20-foot [6 m] bay next to the tide land. A triangular section of the brick wall moved vertically downward from 1-3/16 inches to 1-3/4 inches [3.0-4.4 cm]. The ground at the rear of the building pulled away from the wall 2-1/2 inches [6.3 cm] and settled vertically 3 inches [7.6 cm] and 4 inches [10.2 cm] below the marks left on the wall by the soil surface." (U.S. Army Corps of Engineers, 1949).
16	Slump (1949)	Seattle, Wash. (Spokane Street); King County	A	[Photo caption] "QUAKE CRACKED STREET" (Seattle Post-Intelligencer, 1949d). Crack and slight slump on Spokane Street approach to West Seattle (see fig. 193). Failure occurred in embankment of artificial fill a few tens of meters high.
	Settlements (1949)	do.	B	[Spokane St. between 23d Ave. S.W. and Harbor Ave. S.W.] "Settlements of 1" to 4" [2.5-10.2 cm] at several points. Longitudinal joint separation." (City of Seattle earthquake damage report, 1949, unpublished, on file in the offices of the City of Seattle Engineering Department).
17	Lateral spread or slump (1949)	Seattle, Wash. (Duwamish Waterway); King County	C	"A concrete wall around a tank farm adjacent to the Duwamish waterway indicated considerable earth movement. One east-west wall about 100 feet [30 m] long and 12 feet [4 m] high reveals three vertical construction joints opened 1-5/8, 2, and 1-3/4 inches [4.1, 5.1, and 4.4 cm], or a total of 6 inches [15 cm] during or since the quake. The joint filler in a north-south wall was squeezed out a maximum of 3 inches [7.6 cm] at the bottom of one joint. The wall nearest to the Duwamish waterway and parallel to it has settled 2 inches [5.1 cm] below adjacent walls and is out of plumb. Lateral and vertical movement of the ground is evident." (U.S. Army Corps of Engineers, 1949).

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| 18 | Lateral spread or slump (1965) | Seattle, Wash. (Duwamish Waterway; West Waterway); King County | A | "Pier 5, where construction projects were underway, was hardest hit. The bulkhead and the fill behind it settled, the fill dropping 6 inches to 2 feet [0.15-0.61 m] for a width of 5 to 40 feet [7.6-12.2 m]. The bulkhead was reported to be 6 to 8 inches [15.2-20.3 cm] out of line." (Hake and Cloud, 1967).
"*** subsidence of the material along the west side of the pier [Pier 5]. *** north end wall is exposed *** wall has displaced downward from the dock a distance of 8 inches [20.3 cm]. The soil in this area for a 20-foot [6.1 m] width has subsided. The ground has displaced to approximately 1-1/2 feet [0.5 m] below the level of the existing dock. This subsidence decreases to approximately 8 inches [20.3 cm] at the southern end of the pier." (Seattle Fire Department, 1965).
"Pier 6, located directly south of Pier 5. This pier has had similar problems to those of Pier 5. There is subsidence of from 6" to 12" [15-30 cm] at the land face of the pier." (Seattle Fire Department, 1965). |
| 19 | Settlement (1965) | do. | A | "The KJR Radio transmitting tower suffered structural damage but the ground apparently settled around the footings 1 inch [2.5 cm] below the former level. Cracking of soil and sand boils occur in the area between the tower and the Duwamish waterway." (U.S. Army Corps of Engineers, 1949). |
| 20 | Settlement (1949); sand boils (1949) | Seattle, Wash. (Duwamish Waterway); King County | A | "The Fisher Flouring Mills in Seattle constructed a new brick restaurant building adjoining an older brick office building. There is little evidence of movement on the exterior ***. Inside the old office, the floor is badly out of level, in one place bulged up 7 inches [17.8 cm] above the adjacent floor of the new building" (U.S. Army Corps of Engineers, 1949).
"The Fisher Flouring Mills had extensive damage ***. Underground piping around the plant also broke" (Hake and Cloud, 1967). |
| 21 | Miscellaneous effects (1965) | do. | A | [Photo caption] "Water flowed and spurted from sand during the earthquake consolidation of ground on Harbor Island, Seattle." (Edwards, 1950). |
| 22 | Sand boils (1949) | Seattle, Wash. (Harbor Island); King County | B | "Piers 15 and 16 on Harbor Island shifted toward the water by about 1 foot [0.3 m] due to the soil losing much or all of its strength, or partially liquefying and pushing the dock toward the water. An exception was the northern extension of the pier which was under construction and did not yet have its soil backfill." (Hake and Cloud, 1967).
"Todd Shipyard Corporation: 3 breaks in underground mains" (Seattle Fire Department, 1965). |
| 23 | Lateral spread or slump (1965) | Seattle, Wash. (Harbor Island); King County | A | |
| | Miscellaneous effects (1965) | do. | B | "The Northern Pacific Railway Company's bridge (single bascule) crossing Duwamish Waterway near West Spokane Street was reported to have permanently shifted from 4 to 7 inches [10.2-17.8 cm]. The bridge was open at the time of the earthquake. *** The city double bascule bridges *** crossing Duwamish Waterway at Spokane Street were closed at the time of the quake. The main bridge piers shifted, reducing the horizontal distance between the piers several inches and jamming forward edges of the bascule leaves together." (U.S. Army Corps of Engineers, 1949).
"Both of the Southwest Spokane Street bridges were jammed shut when the shock threw them out of line." (Hake and Cloud, 1967). |
| | Miscellaneous effects (1949) | Seattle, Wash. (Duwamish Waterway); King County | B | |
| | Miscellaneous effects (1965) | do. | B | |

Table 29. Descriptions of selected ground failures in the northern half of the central and southern Puget lowland region—Continued.

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
24	Settlement (1965); ejection of groundwater (1965)	Seattle, Wash. (Elliott Bay; 1st Ave. S.); King County	A	"The building [Millwork Supply, 2229 First Ave. S.] is located on dredged fill material and is believed to be on piling. During the earthquake approximately 8 inches [20 cm] maximum downward settlement of footings occurred. * * * basement floor slabs on grade were severely cracked and displaced due to the action of footing settlement combined with upward pressure of ground water against the bottom of the slabs." (Seattle Fire Department, 1965).
	Settlement (1949)	do.	B	[Road damage to 1st Ave. S. between Lander and Holgate Streets] "Settlements to extent of 3" [7.6 cm] vertically—2" [5 cm] horizontal separation." (City of Seattle Survey of Pavement Damage, etc.—Earthquake of April 13, 1949; unpublished report on file in the offices of the City of Seattle Engineering Department).
25	Sand boils (1949); settlement (1949)	Seattle, Wash. (Elliott Bay; 1st Ave. S. and Massachusetts Ave.); King County	A	"Examination of the ground around Albers Brothers Elevators shows no evidence of settlement except that a number of sand boils developed from 5 to 15 feet [1.5–4.5 m] away from the elevators on the northeast side. The ground around a large fuel tank has settled differentially from zero to 1/2 inch [1.3 cm] as evidenced by the soil contact mark." (U.S. Army Corps of Engineers, 1949).
	Settlement (1949); sand boils (1965)	do.	A	"The building [Queen City Sheet Metal Shop, 1730 1st Ave. S.] * * * is supported on posts and blocks. The building has settled very badly throughout the years. This settling has been exaggerated during the present earthquake. The floor has been shored up in different places during the recent years but all the old existing posts are leaning in various directions and the floor is very badly out of level. * * * During the winter months, the area has standing water and has to be pumped by means of a sump pump. During the present earthquake a considerable amount of water came in. This apparently was from consolidation of the earth below, which forced the water in this lower stratum into the area. This water was also followed by the characteristic fine silt which now covers most of the underneath area." (Seattle Fire Department, 1965).
26	Slump (1949)	Seattle, Wash. (19th and Holgate); King County	A	"We thought a sewer broke when water started coming in our basement but when the wooden floor down there splintered and a big bump of earth came up we didn't know what happened.' That's how Esther Kempton, bookkeeper at Washington Glass Co., 23 S. Massachusetts St., described early reactions to the earthquake at her place of work. Firemen were called when 'gasses and water continued to bubble from it' (the hump of earth), she said." (Seattle Post-Intelligencer, 1965b).
27	Settlement (1965); ground cracks (1949)	Seattle, Wash. (Mount Baker District); King County	A	"The April 13, 1949, earthquake caused a slide at 19th and Holgate that took out a driveway." (Jim Brazil, U.S. Forest Service, oral commun., 1988). " * * * we are on waterfront filled land * * * foundation cracked, also concrete * * * one arm of dock broken in two, fell into water, other parallel arm had second of five piles from shore settle, putting swayback in walkway. * * * Basement concrete floor cracked in 1949 [earthquake], opened wider and heaved to different levels." (Steele Lindsay, written commun., 1965).

- 28 Slide (1949) A Seattle, Wash. (4th Ave. S. at Dearborn St.); King County
"Lateral movement to west of west half of pavement." (City of Seattle earthquake damage report, 1949; unpublished report on file in the offices of the City of Seattle Engineering Department).
- 29 Slide (1965) A Seattle, Wash. (Queen Anne); King County
"Hillside backyard sank 2 ft [0.6 m]—seems to have settled on one side more" (Mrs. Jack A. Hanover, written commun., 1965).
- 30 Miscellaneous effects (1965) C Seattle, Wash. (Lake Washington Ship Canal); King County
"The gas distribution system was broken at about 60 different points. The major break was in a 16-inch [40 cm] main in a tunnel under the Lake Washington Ship Canal. All breaks were on filled ground. Many breaks were caused by lateral displacement of the mains pulling the service connections free" (U.S. Army Corps of Engineers, 1949).
- 31 Ground crack (1949) A Seattle, Wash. (Union Bay, University of Washington); King County
[Photo caption] "NEW 50-YARD LINE?—** The crack, about 100 yards [90 m] from the open end of Stadium, is about 50 feet [15 m] long by a foot [0.3 m] wide, and about 3 feet [1 m] deep." (Seattle Post-Intelligencer, 1949b)
" ** a fissure opened in the practice field at the University. Underground pressure from the shock sent sand spurting in a 100-foot-long [30 m] zig-zag stretch on the lower football field." (Hake and Cloud, 1967).
"Behind the men's pool, areas of the ground dropped as much as a foot [0.3 m]. Dirt floor sections in the Hec Edmondson Pavilion also sank slightly." (Hake and Cloud, 1967).
- 32 Settlement (1965); sand boils (1965) B Seattle, Wash. (Union Bay); King County
"North of Union Bay, a broad fill over alluvial and lacustrine sediments subsided and exhibited ground cracks and sand mounds. Subsidence caused minor damage to paving and walks, and an estimated 10 to 30 percent of shelf goods were shaken down in two stores in the shopping center there." (Mullineaux and others, 1967).
- 33 Shump (1949); slide (1949) A Seattle, Wash. (Green Lake); King County
"A 60-foot [18 m] section of the south shore of Green Lake dropped four feet into the lake during the earthquake Wednesday. Cracks three or four inches [8–10 cm] wide also appeared on the bicycle path a short distance from the slide. The ground was broken up and parts of the path appeared to have dropped from four to six inches [10–15 cm] into the lake." (Seattle Post-Intelligencer, 1949f). See figure 194.
[Photo caption] "PAVEMENT CRACKED OPEN: These men ** * inspected the pavement in East Green Lake Way near North 63rd which split as a result of today's earthquake." (Seattle Times, 1949a). See figure 195.
"Just south of Green Lake ** * lacustrine sediments overlain by thin fill subsided, apparently as a result of both compaction and lateral movement downslope toward the lake. Here, ground cracks opened as much as 2 inches [5 cm] breaking the foundation of a small building, fracturing walks and paving, and breaking utility lines." (Mullineaux and others, 1967).
"The earthquake [of 1965] produced bizarre results at Green Lake, John W. Sandusky, park-department engineer reported. [The earthquake] buckled blacktop paving around the Aqua Theater and opened large fissures in the ground on the south and west banks of the lake. ** * [the earthquake] put two waves in West Green Lake Way between the Aqua Theater and Lower Woodland Park. At the Lower Woodland baseball fields, water spurting 10 to 15 feet [3–5 m] high around the lighting standards. ** * A four inch [10 cm] water main serving Evans Pool at Green Lake was ruptured" (Seattle Times, 1965c).
- Settlement (1965); slide (1965); ground cracks (1965); miscellaneous effects (1965) A do.

Table 29. Descriptions of selected ground failures in the northern half of the central and southern Puget lowland region—Continued.

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
34	Slide (1965); settlement (1965)	Seattle, Wash. (Phinney Ridge); King County	A	"Bulkhead [slid] down. [Settling of] front yard by walk at stairs to front porch. * * * 35 feet [1.1 m] of west bulkhead fell. Doors jammed and would not close. Front door will not open—tubs on floor. Sewer pipe broken in middle from toilet outlet. Foundation shows open places and broken away from rockery." (Mrs. S.G. Tudor, written commun., 1965).
35	Slide (1949)	Kirkland, Wash. (Champaign Point); King County	B	"Point moved toward lake; * * * moved rail fence west; dock dropped * * * earthquake felt strongly over an area of 3 lots located on Champaign Point. Other residents in the neighborhood recorded no damage. * * * The cracks in cement have become wider since the shock, and we have noticed occasional creakings in the house * * *. In the front of the house deep cracks in the earth appeared next to the basement walls, and water pipes were broken in the sprinkler system from the lake. The basement floor was cracked and two small cement retaining walls dropped several inches." (B.J. Dalton, written commun., 1949).
36	Slide/mud flow (1965)	Seattle, Wash. (Carkeek Park); King County	B	"An earthquake opened a pool of ground water that roated down the creek in historic Carkeek Park. Debris flooded the road, blocking it until at least next week." (Seattle Times, 1965c). The mud flow (fig. 196) originated in a large ravine on the north side of Piper Creek in Carkeek Park. The exact point of origin of the ground failure is undetermined. Water in a small creek that flows down the ravine may have mixed with the slide debris, adding to its mobility.
37	Slide (1965)	Seattle, Wash. (Sheridan Beach); King County	A	"Rock bulkhead on Lake Washington lowered six (6) inches [15 cm]. Large rocks fell away—ground cracked in flower beds." (Mrs. K.J. Emery, written commun., 1965).
38	Slide (1965)	Seattle, Wash. (Lake City); King County	A	"Slide in lawn area where sand fill had been used for septic tank area (7 years ago). Area fell and slid about 8–12 inches [21–30 cm]." (Leon M. Pool, written commun., 1965).
39	Slump (1965)	Suquamish, Wash.; Kitsap County	A	"The press reported the shoreline of Suquamish, in northeast Kitsap County heaved up 15 feet [4.5 m] in places. A 2-story beach house was demolished and trees were uprooted." (Hake and Cloud, 1967). "A house was badly damaged and there was a crack about 100 ft [30 m] long on the beach parallel to the shoreline. The beach was uplifted as if by a hydraulic lift. The damage occurred along the bluff near the end of 8th Street." (Leroy Todd, oral commun., 1988). The slope failure is located within a 1.2-km-long coastal bluff area identified as "unstable" in the Coastal Zone Atlas of Washington (Washington Department of Ecology, 1979b). Seepage occurs near midslope on the 15.2-m-high bluff. A 1.0- to 1.5-m-high stone bulkhead, emplaced to prevent further erosion, extends about 100 m along the shoreline at the base of the slope.

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| 40 | Slide/earthflow (1965) | Edmonds, Wash.;
Snohomish County | A | [Photo caption] "A CHURNING MASS of mud, rocks and other debris in Edmonds is investigated by curious visitors. The slide occurred during yesterday's quake, sucking in an abandoned shack and several trees and tapping an underground stream. First a big hole occurred, then earth and debris sloughed into it. The stream rapidly covered the bottom of the hole with the thick muck. The slide area was 50 feet [15 m] wide, 15 feet [5 m] deep, a block long." (Seattle Post-Intelligencer, 1965a). |
| 41 | Slump (1965) | Kingston, Wash.;
Kitsap County | A | [Photo caption] "NORTH END ROAD DAMAGE—A 30 ft [9 m] section of Highway 104, three miles [5 km] west of Kingston, was torn away by the force of this morning's earthquake. The crevice, estimated at three feet [0.9 m] deep, was being repaired." (Bremerton Sun, 1965b). |
| 42 | Ground cracks (1965) | Port Ludlow, Wash.;
Jefferson County | C | "Beach at Port Ludlow cracked—then filled in by next day. Area 100×500 ft [30×150 m] on east side of bay (all sand)." (Mrs. John G. Jackowski, written commun., 1965). |
| 43 | Miscellaneous effects (1965) | Everett, Wash.;
Snohomish County | C | "In Everett, two of the three 48-inch [1.2 m] main supply conduits to the city failed. These occurred where the lines are carried on trestles over Ebey Slough" (excerpt from a preliminary report by the Washington Surveying and Rating Bureau; Hake and Cloud, 1967). |

Table 30. Descriptions of selected ground failures in the southern half of the central and southern Puget lowland region.

[Location numbers correspond to ground-failure location numbers on plate 5. do., ditto. Location accuracy: A, available information allows location to within a kilometer; B, available information allows location to within a few kilometers. Quotations referenced as "written comment, 1949" or "written comment, 1965" are responses to University of Washington intensity surveys. Copies of the questionnaire responses are on file in the offices of the U.S. Geological Survey in Golden, Colo. Metric values and explanatory information in brackets have been added to the quotations by the authors. Comments following quotations are those of the authors and are based on field observations, information from cited references, and interviews with local residents]

Location No.	Failure type (Year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
44	Slump (1949)	Olympia, Wash. (Black Lake); Thurston County	A	"* * * about 75 feet [23 m] of one lane of the Black Lake Road slipped into the lake about a half mile [0.8 km] north of Columbus Park." (Daily Olympian, 1949a). Failure involved steep lake bank and roadway on west side of Black Lake. Lake bank is about 8 m high. Cracks in pavement indicate continued instability at this location. Location on plate 5 is based on information given to Steve Palmer of the Washington Division of Geology and Earth Resources by local resident Jack Goldsby in 1992. See figure 207.
45	Slump (1965)	Tumwater, Wash. (Capitol Lake); Thurston County	A	"Thursday morning's seismic shock shook loose part of a Capitol Lake hillside snapping off 40 yards [37 m] of the City of Tumwater's main sewer line and diverting sewage into the lake. Tons of hillside opposite Wildwood Center in the 2800 block of Capitol Boulevard tumbled a hundred yards [91.4 m] downhill, covering a railroad spur and leaving behind another 50 yards [45 m] of Union Pacific freight line track dangling naked but unbroken." (Anderson, 1965). See figure 206.
46	Settlement (1949)	Olympia, Wash.; Thurston County	A	"A residential area three to eight blocks east of the capitol is founded on a peat soil and appears to be undergoing delayed settlement. The major portion of the residential damages are centered in this area." (U.S. Army Corps of Engineers, 1949).
47	Slide (1949)	Olympia, Wash.; Thurston County	B	"[Northern Pacific Railway, Grays Harbor Line] Mile Post 10+1/2—Embankment slipped out for 45 feet [14 m]." (U.S. Army Corps of Engineers, 1949).
48	Slump(s) (1965); sand boils (1965)	Olympia, Wash. (Capitol Lake, Deschutes Parkway); Thurston County	A	[Photo caption] "Shifting earth sent the edge of this highway at Olympia into Capitol Lake behind the state capitol. A half-mile [0.8 km] section was damaged." (Tacoma News Tribune, 1965c). See figure 204. [Photo caption] "Sand boils or 'mud volcanoes' along Capitol Lake in Olympia indicate local soil liquefaction during the 1965 quake. Such features are formed by geysers of muddy water escaping from saturated sediments." (Washington Division of Geology and Earth Resources, 1984). See figure 205.
49	Miscellaneous effects (1949)	Olympia, Wash.; Thurston County	B	"Breaks in water mains occurred during the 3 days following the earthquake. In all, 24 breaks were reported. The most serious drop in pressure (from 90 p.s.i. to 20 p.s.i.) resulted in the temporary closing of the business district" (U.S. Army Corps of Engineers, 1949). "* * * water and gas mains were broken [in Olympia]." (Murphy and Ulrich, 1951).

50	Settlement (1949)	Olympia, Wash. (port area); Thurston County	A	"The entire port area, a man-made fill, settled 5 inches [13 cm]. * * * Evidence of differential settlement around the Port of Olympia Cold Storage Warehouses of 2 inches [5 cm] was seen." (U.S. Army Corps of Engineers, 1949).
51	Slump (1949)	Olympia, Wash. (Coopers Point); Thurston County	A	"Clifford Kyllonen, Olympia tug boat skipper, reported that 150 feet [45 m] of the sandspit of Cooper's Point, seven miles [11 km] north of Olympia crumpled and disappeared into Puget Sound during the shock. Kyllonen said he was standing off the spit when the shock occurred, and took color pictures of the mass of land sinking beneath the waves. He said geodetic survey maps showed the spit being five feet [1.5 m] above water at high tide. At high tide yesterday, Kyllonen took soundings and found the spit was now 50 ft [15 m] below the surface." (Bremerton Sun, 1949). "It normally extends 300 yds [275 m] and at high tide is partially covered by water. After the quake the middle portion of the point no longer was visible at low tide. Between 100 and 150 feet [30-45 m] of the spit had sunk into the bay. About 25 feet [8 m] of the north end of the point remained as an island." (Daily Olympian, 1949c). See figure 208.
52	Slides (1965)	Hartstene Island, Wash.; Mason County	B	"We visited the hole in the wall settlement (Hartstene Estates) at the south end [of the island] * * *. Parts of the road had given way in that area, and the County Road crew was on the spot putting up barricades and making repairs." (Shelton-Mason County Journal, 1965).
53	Settlement (1949)	Lacey, Wash. (McAllister Springs); Thurston County	A	"The McAllister Springs project withstood the earthquake well. The only damage was done when the tumbler caused an earth fill dam at the springs to drop." (Daily Olympian, 1949b).
54	Slump (1965)	Orting, Wash.; Pierce County	A	A crack 120-150 m long and 15 cm wide opened up along the brow of the hill and across the road (Emmett Chase, oral commun., 1988).
55	Sand boils (1949); ground crack (1949)	Orting, Wash.; Pierce County	B	Sand boils occurred on a farm about 3 km south of Orting. Fine, blue-gray sediment was ejected from a zigzag crack in the ground. It happened in a field on the west side of the [Orting-Electron] highway near a small creek. The sand was somewhat "oily" and the children got very dirty playing in it (Charlotte Rogich, oral commun., 1990). ¹
56	Sand boils (1949)	Sumner, Wash.; Pierce County	A	Two sand boils, about 0.9 m in diameter and 13-15 cm high, occurred at 8502 Riverside Road East in Sumner. Water from the sand boils had a salty taste (Francis Watson, oral commun., 1989). ¹
57	Sand boils (1949)	Sumner, Wash.; Pierce County	A	Blows of water and sand occurred on my property about 1.6 km east of Sumner (Herman Nix, oral commun., 1989).
58	Sand boils (1949)	Sumner, Wash.; Pierce County	A	The 1949 earthquake produced many sand boils, about 15 cm in diameter and 2.5-5.0 cm high, near the corner of Main and Van Tassle on the east side of Sumner. The sand was clean and black (Fred Weber, oral commun., 1989). ¹

Table 30. Descriptions of selected ground failures in the southern half of the central and southern Puget lowland region—Continued.

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
59	Settlement (1965); miscellaneous effects (1965); miscellaneous effects (1949)	Sumner, Wash.; Pierce County	A	"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. Bartekman, written commun., 1965).
60	Miscellaneous effects (1949)	Puyallup, Wash.; Pierce County	B	"An opening in the earth, 1 foot [0.3 m] in diameter was reported just outside the East City limits towards Sumner on Linden Drive." (Puyallup Valley Tribune, 1949).
61	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	Approximately 20 sand boils erupted as a result of the 1949 earthquake at 1100 7th Ave. SE. The spurts of water were about 15 cm high. The mounds of sediment were composed of clean, bluish sand and were less than 0.3 m in diameter. An artesian well is nearby (William McAlister, oral commun., 1989). ¹
62	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	There were six sand blows at 1224 5th St. SW. The sand was bluish gray and more water came from the holes after the earthquake. (Bill Morris, oral commun., 1989). ¹
63	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	Five or six geysers spurted about 1.5 m high on West Main under where the Puyallup High School gym stands today. They came after the earthquake and lasted a few minutes. The mounds were less than 0.3 m wide and less than 0.3 m high. (Mrs. Hoganson, oral commun., 1989). ¹
64	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	There were sand blows at 811 2d Ave. NW in Puyallup. They came a little after the earthquake, were about 0.6 m high, and ejected black sand. (Erlvne Eklund, oral commun., 1989). ¹
65	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	There were many sand blows in the backyard at 113 16th St. SW and also across the alley from that location. (Mrs. Carstens, oral commun., 1989). ¹
66	Ground crack (1949); miscellaneous effects (1949)	Puyallup, Wash.; Pierce County	A	[716 7th Ave. N.W.] " * * * water pipe, from house to city main, running north and south was broken—also a crack opened running north and south across cement walk and across the street. Water was forced up out of the ground near the water main." (J. Stackhouse, written commun., 1949).
	Sand boils (1949)	do.	A	"Many of the geysers spurted up beneath homes. The Darrell Wilson home on 9th St. N.W. was damaged considerably when a geyser pushed up the basement's cement floor, leaving large chunks standing on end. Another home's timber foundation was pushed through the flooring on the first floor. * * * Residents at first believed the geysers were caused by breaks in the water mains * * * but the line of spurting water was far from any main." (Tacoma News Tribune, 1949c).
	Settlement (1949)	do.	A	At the time of the 1949 earthquake, a crack occurred across 9th St. and a car would drop when driven over it; the basement floor of the house at 407 N. 9th St. was pushed up to the ceiling, that is, to the floor joists (Warren Picha, oral commun., 1989).

Sand boils (1949) miscellaneous effects (1949)	do.	A	Sand boils developed in the alley west of 7th St. NW and north of 5th Ave. NW and the basement floor buckled up at 714 7th St. NW. Also, liquefied sand came up through a basement floor and floated a furnace that was evidently not bolted to the floor at 407 8th St. NW (Merle McMullen, oral commun., 1989). ¹
Sand boils (1949)	do.	A	Sand boils occurred at 702 5th Ave. NW, 616 5th Ave. NW, 609 7th Ave. NW, 802 5th Ave. NW, and at a brick house on the corner at 9th St. NW and 5th Ave. NW (Irwin Connell, oral commun., 1989). ¹
Sand boils (1949)	do.	A	There were sand boils in the 800 block of 8th St. NW. There were maybe six black sand gushers. They came a little after the earthquake and were about 0.6 m high (Erlayne Eklund, oral commun., 1989). ¹
Sand boils (1949)	do.	A	There were sand boils at 5th Ave. NW and 6th St. NW, and the basement at 406 6th St. was pushed up (Earle Shoupe, oral commun., 1989). ¹
Ground cracks (1949); settlement (1949)	Puyallup, Wash.; Pierce County	A	"Breaks in the earth surface on the Zilke pasture, beyond 7th NW and River Road have been reported. A shift in the River Road is noticeable." (Puyallup Valley Tribune, 1949).
67 Sand boils (1949); ground cracks (1949)	Puyallup, Wash.; Pierce County	A	[1215 3d Ave. NW] "There were many openings in soil; some merely round holes, others were cracks several yards long through which water spouted—some reported five feet [1.5 m] high. Many of these were seen by me, however, none more than a few inches. This locality was badly flooded, but soon subsided, leaving many yards of silt on the surface." (F.J. Plattenberger, written commun., 1949).
Sand boils (1949)	do.	A	There were possibly 20 sand boils at 1301 4th Ave. NW. These were rather cone shaped, 13-18 cm in diameter and 13-20 cm high. The sand was light colored and holes in the cones were maybe as much as 1.2 cm in diameter. This was the site of much water and sand all over the front lawn and driveway (Richard Six, oral commun., 1989). ¹ See figures 199-201.
Sand boils (1949) Sand boils (1949)	do. do.	A A	There were sand boils at 1515 4th Ave. NW (Mrs. Carstens, oral commun., 1989). ¹ A blue-gray sand came up in gushers among the daffodil rows between 12th St. NW and 13th St. NW and between 2d Ave. NW and 3d Ave. NW (unidentified respondent, oral commun., 1989). ¹
Sand boils (1949)	do.	A	Sand piles, 0.6-0.9 m in diameter, appeared on the north side of Stewart Avenue between 11th St. NW and 13th St. NW (Fred Richey, oral commun., 1989). ¹
Sand boils (1965)	do.	A	There was sand boil activity [related to the 1965 earthquake] on the Aylene Junior High School playground. There was a considerable amount of water and the long jump pit had to be moved (Lloyd Freuderstein, oral commun., 1989; George Willfong, oral commun., 1989). ¹

Table 30. Descriptions of selected ground failures in the southern half of the central and southern Puget lowland region—Continued.

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location, county	Location accuracy	Quotation and (or) comment
69	Settlement (1949) Sand boils (1949) Sand boils (1949)	Puyallup, Wash.; Pierce County do. do.	A A A	Basement was pushed up on one end so house teetered [18th St. at 4th Ave.] (Warren Picha, oral commun., 1989). The house on the NE corner of 4th Ave. NW and 18th St. NW had about 1.2 m of liquefied sand in the basement (Earle Shoupe, oral commun., 1989). ¹ There were sand boils at 4th Ave. NW and 18th St. NW (Dorothy McCleary, oral commun., 1989). ¹ There were sand boils "all over" cultivated farm property at 2001 4th Ave. NW. The geysers were about 0.3 m high (Mr. and Mrs. Elmer Johnston, oral commun., 1989). ¹
70	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	There were sand boils at 2612 Tacoma Road [at the time of the 1949 earthquake] (Marie Biehn, oral commun., 1989). ¹
71	Slump or lateral spread (1949); ground crack (1949) Settlement (1949) Miscellaneous effects (1949) Ground crack (1949)	Puyallup, Wash.; Pierce County do. do. do.	A A A A A	"Cracks and destruction at the Pat Fox Farm." (anonymous, written commun., 1949). Crack along the west bank of Clarks Creek was 60–90 m long and about 0.9 m high. Photograph in 1949 issue of Life Magazine shows the ground crack. House across [Clarks] creek was tilted and concrete foundation destroyed (Warren Picha, oral commun., 1949). See figure 202. At 5720 66th Ave. East, the basement floor came up and the well became cloudy but cleared up (Fred Richen, oral commun., 1989). ¹ There was an east-west crack down Stewart Avenue that extended past the Clarks Creek bridge (Richard Six, oral commun., 1989). ¹
72	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	Sand boil activity just east of Freeman Road and about 2 blocks from the Puyallup River resulted in a deposit of sand as much as 4.6 m in diameter. The spurts of water and sand were 1.5–1.8 m high (Mrs. Eggiman, oral commun., 1989). ¹
73	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	Sand boils occurred in back of the house and a little to the left of the driveway. The house is located north of the Puyallup River along Freeman Road and is between the railroad tracks and a small creek (Sylvia Veal, oral commun., 1989). ¹
74	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	There were dozens of sand boils from Freeman Road to the base of the North Hill. They were composed of light-colored sand (Ted Maloney, oral commun., 1989). ¹
75	Sand boils (1949)	Puyallup, Wash.; Pierce County	A	Sand boils at 5820 44th St. East ejected blackish, clean sand. The sand deposits were 0.3–0.5 m in diameter and 9–12 m apart. They looked like mole hills; the wider hills were flatter (George Richen, oral commun., 1989). ¹

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| 76 | Sand boils (1949) | Puyallup, Wash.;
Pierce County | A | Sand boils appeared along the North Levee Road about 45 m from the river. The gushers were 2.4-3.0 m high (Marie Bingasser, oral commun., 1989). |
| 77 | Settlement (1949);
ground crack (1949) | Puyallup, Wash.;
Pierce County | A | "Although survey data are not available, settlement in the tide flat area is known to have taken place. In one instance, a ground fissure approximately 1,000 feet [305 m] in length, opened along a line paralleling 11th Street. One black-topped side street entered 11th Street in this stretch. The black-top surface of this street was ruptured, the opening being approximately 4 inches [10 cm] wide and having a vertical displacement of 6 inches [15 cm], the low side was toward the waterfront." (U.S. Army Corps of Engineers, 1949). |
| | Sand boils (1965) | do. | A | "Sand boils appeared in the tide flats area at Alexander Avenue between 11th Street and Lincoln Avenue at the time of the 1965 earthquake." (R.M. Button, Chief, Building Department, Tacoma City Engineers Office, oral commun., 1988). |
| 78 | Settlement (1949);
sand boils (1949) | Puyallup, Wash. (tidal flat
area); Pierce County | B | "Settlement in the tide flats area was accompanied by boils of water, mud and debris at several points. The flow of material from these boils continued for about 20 minutes after the quake." (U.S. Army Corps of Engineers, 1949). |
| | Miscellaneous effects
(1949) | do. | B | "The Superintendent of Water reports a total of 19 line breaks during the quake, the majority occurring in the tide flats area." (U.S. Army Corps of Engineers, 1949). |
| | Ground crack (1965) | do. | A | "City Public Works Director G.M. Schuster * * * said a crack a few inches wide and about 500 feet [152.4 m] long opened up alongside Thorne Road, in the port industrial area." (Tacoma News Tribune, 1965a). |
| 79 | Sand boils (1949);
ground cracks (1949) | Tacoma, Wash. (tidal flat
area); Pierce County | A | "Northern Pacific roundhouse and repair tracks crews gaped in astonishment just after the quake Wednesday. They saw an unadvertised "geyser" in their midst, apparently stemming from the long ago bed of the Puyallup River, near East 23rd and G Sts. Long jagged cracks, 60 to 70 feet [18.3-21.3 m] appeared at the edge of the repair track space where water shot upward, bringing with it deposits of fine, white sand. Quick investigation disclosed no water pipes or city mains were near the spot. The water spout, witnesses said, lasted a considerable time after the tremor subsided." (Tacoma News Tribune, 1949a). |
| 80 | Slide (1949) | Tacoma, Wash. (Mason
Gulch); Pierce County | A | "Two of the 12-inch [0.3 m] diameter cast iron pipes were sheared by a landslide in Mason Gulch in the north end of the city." (U.S. Army Corps of Engineers, 1949). |
| | Slide (1965) | do. | A | "The 1949 quake caused sliding along Mason Gulch, and sliding occurred again at the same location due to the 1965 earthquake. The sidewalk and chainlink fence at top of slope have been moved back several times due to slide activity." (Unidentified resident, oral commun., 1988). |

Table 30. Descriptions of selected ground failures in the southern half of the central and southern Puget lowland region—Continued.

Location no.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
81	Slide (1949); ground cracks (1949)	Tacoma, Wash.; Pierce County	A	"The only major landslide known to have occurred as a result of the quake tremors was at Salmon Beach, 6 miles [10 km] northwest of downtown Tacoma at the Narrows. The slide occurred at 2:55 am on 16 April, 3 days after the quake. The top of the bluff is approximately 400 feet [120 m] above the waters of Puget Sound. Original estimates placed the quantity of earth moved at 11,000,000 cubic yards [$8.4 \times 10^6 \text{ m}^3$], although this is thought to be excessive. One million cubic yards [$7.6 \times 10^5 \text{ m}^3$] is believed to be a more reasonable figure. Geologists who have visited the site report the sand and gravel bluff to be resting on a clay base. Although the slide came within 20 yards [18.3 m] of the nearest of 108 beach residences, no property damage or loss of life was reported from the slide. However, a wave front estimated to be 8 feet [2.4 m] high was created by the slide. This wave did minor damage to small docks and boats moored nearby. Fissures are exposed along the bluff crest extending away from the present slide and paralleling the bluff brow for a distance of several hundred feet." (U.S. Army Corps of Engineers, 1949). See figure 203.
	Sand boil (1949)	do.	A	"The crack in the cliff could send more tons of earth plunging down. * * * Though the split is but two inches [5 cm] wide, it is deep. White sand boiled up through it to the surface during Wednesday's quake." (Vogel, 1949).
82	Slump (1949, 1965)	Tacoma, Wash.; Pierce County	A	"* * * there is a bank about twenty feet [6 m] high that drops down to the lower pasture, which slopes down the hill to the railroad tracks and the water. Part way down this bank the ground split and the whole lower area dropped about one and one-half feet [0.5 m]. This lower area is about 400 feet [120 m] east and west and 600 feet [183 m] north and south. This dropping also occurred during the 1949 earthquake." (Mr. and Mrs. Sydney Selden, Jr., written commun., 1965).
	Slide (1949)	do.	A	Failure occurred along same failure surface in both the 1949 and 1965 earthquakes, but was much worse in 1949. In 1949, the scarp developed for about 183 m and the slump dropped about 0.6 m. In 1965, movement along the scarp was probably somewhat shorter (maybe about 137–140 m), and slump dropped about 0.5 m in 1980 due to heavy rain (Sydney Selden, Sr., oral commun., 1988).
83	Slides (1965)	Tacoma, Wash. (Day Island Bridge); Pierce County	A	"City Public Works Director G.M. Schuster said * * * city crews Friday were placing fill in a portion of the road under the Day Island Bridge, where about 1,000 yards [900 m] of material slipped away." (Tacoma News Tribune, 1965a). "Slides reported on Lemons Beach Road and on a cliff near Day Island Bridge. Fill on mainland side of approach to Day Island Bridge gave way during the quake sending earth and trees cascading into a gully. The slide undermined the roadbed of the Lemons Beach Road under the bridge and that road was closed to traffic. Trees were uprooted and scattered like matchsticks by the slide." (Tacoma News Tribune, 1965b).

- 84 Slide (1949) Fox Island, Wash. (west of Tacoma); Pierce County A
 [Photo caption] "QUAKE TOPPLES HOUSE INTO PUGET SOUND: This aerial photograph shows the roof of a house which the Coast Guard said toppled into Puget Sound from Fox Island, just south of Tacoma, during yesterday's earthquake. The Coast Guard did not learn whether anyone was in the house when the quake shook the small island." (Seattle Times, 1949b).
 "I visited the site a couple of months after the earthquake. The owner had excavated a small shelf 50 to 100 feet [15-30 m] above the beach, and the shelf and house had slid into the water. I saw wires, plastic pipe, etc., severed by the slide." (Jay Bower, oral commun., 1988).
- 85 Slump/debris flow (1965) Grapeview, Wash.; Mason County A
 "** * quake caused a slide in a section of the Grapeview road that necessitated closing the road the day of the quake." (Shelton-Mason County Journal, 1965).
 "Fill split down the middle and the slide material moved 150 yards [137.2 m] out along the cove as a kind of flow." (Kent Hansen, oral commun., 1988).
 Failure occurred in a 9.1-m-high road embankment where the road crosses a small arm of McLane Cove.
- 86 Slump (1949, 1965) Allyn, Wash. (Rocky Point); Mason County A
 "The highway here was cracked in several places and portions of it settled about six inches [15 cm]." (G.H. Allyn, written commun., 1949).
 "The slide also moved in the quake of April 29, 1965." (Mrs. Gaetana, oral commun., 1988).
 The failure, which involved artificial fill, occurred along the highway adjacent to Case Inlet. The failed embankment is about 6 m high. Slumping caused a vertical displacement of approximately 15 cm along 30 m of highway.
- 87 Slump (1949) Port Orchard, Wash. (south on old Gig Harbor highway); Kitsap County A
 "The road bed that went out [at the time of the April 13, 1949, earthquake] on the Gig Harbor highway about 1/2 mile [0.8 km] south of our place, also caved in the quake of '39 [November 13, 1939]." (Mrs. C.L. Werner, written commun., 1949).
 [Photo caption] "Break in State Highway No. 14, near Port Orchard, Washington. SE 1/4 of SE 1/4 of Section 23, Township 23 N, Range 1 E, W.M." (Coombs and Barksdale, 1942).
 Ground failure at this location triggered by the Puget Sound earthquake of November 12, 1939 ($M=6.2$, Nason and others, 1988) is described by Coombs and Barksdale (1942) as follows: "Investigation of this crack showed it to be on the surface of a fill approximately 260 yards [237 m] in length and 4 yards [3.7 m] thick in the center. A bed of quicksand fed continuously by many springs a short distance away on the uphill side underlies the sand and gravel of the fill. So unstable a foundation might well be expected to give way under the effects of the earthquake motion."
- 88 Slump (1965) Gig Harbor, Wash. (highway near Crescent Lake); Pierce County A
 [Photo caption] "A narrow but deep fissure opened up on the Purdy Road near its intersection with the Crescent Lake Road near Gig Harbor during Thursday's tremor. * * * [the crack] was more than a foot [0.3 m] wide and at least four feet [1.2 m] deep in spots." (Tacoma News Tribune, 1965a).
 The highway crosses a flat, swampy area at this location. The highway was less than 0.3 m above the lake originally, and underlying soil was probably saturated.

Table 30. Descriptions of selected ground failures in the southern half of the central and southern Puget lowland region—Continued.

Location no.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
89	Slump (1965)	Gig Harbor, Wash. (north side of town); Pierce County	A	[Photo caption] "A 20-foot [6 m] section of the road by Gig Harbor's town park slid into a small creek and tidal pool Thursday during the quake." (Tacoma News Tribune, 1965a). Slump occurred in road embankment (artificial fill) founded on tidal-flat mud. Road embankment is about 2 m high.
90	Slide (1965); miscellaneous effects (1965)	Vashon Island, Wash. (west side); King County	A	"On road going down to the beach which is cut out of the side of a bank a crack approximately 1/2 to 3/4 inches [1-2 cm] wide and about 50 ft [1.5 m] long appeared. This road had been graded out in 1947 and has shown only very minor settling since then during heavy winter rains. The crack looked as though it developed along the line where the fill part of the road is. * * * Water in wells was murky for about 6 weeks afterward * * * they are only 10 ft [3 m] deep." (Norman A. Benson, written commun., 1965).
91	Ground cracks (1965)	Vashon Island, Wash. (west side, Reddings Beach); King County	B	"Cracked foundation. Two hundred feet [60 m] of roadway blacktopped, opened up one inch [2.5 cm]." (Harold J. Raymond, written commun., 1965).
92	Slide (1965)	Vashon Island, Wash. (west side, Reddings Beach); King County	B	"Tons of sand broke off a 120 foot [37 m] bank north of us." (Harold J. Raymond, written commun., 1965).
93	Slide (1965)	Vashon Island, Wash. (west side, Jod Creek); King County	A	"50 feet [15 m] east of Jod Creek, crack in damp soil, 60 ft [18 m] long, 3 ft [0.9 m] deep x 1 ft [0.3 m] wide at center (crack runs N-S)." (M.C. Ball, written commun., 1965).
94	Slumps (1965)	Vashon Island, Wash. (east side, Klahanie Beach); King County	A	"Waterfront cottage sitting on wooden supports behind bulkhead, at bottom of hill, was pushed forward several inches. Concrete behind cottage cracked and buckled. Trail on hill behind community developed crack with some settling. Wood retaining wall behind cottage pushed forward." (Mark D. Hafermann, written commun., 1965). Crack on hill was about 60 m long. Downhill side dropped a few centimeters. There were also slides on side hill behind second and third houses from south end. Those slides moved about a meter but did no damage (Jan Weir, oral commun., 1988).
95	Slide (1965)	Vashon Island, Wash. (Shawnee Beach); King County	A	"Also there was a slide across the road about 1/2 mile [0.8 km] south from Burton." (Mrs. F.M. Urschel, written commun., 1965).

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|-----|--|--|---|--|
| 96 | Settlement (1965) | Vashon Island, Wash. (Shawnee Beach); Mason County | A | "Two cracks formed in a small swimming pool in our yard. Cement patio around pool pulled away from pool—each section cracking away. Either the pool raised or the patio sunk because it sets up a little higher now." (Mrs. F.M. Urschel, written commun., 1965). |
| | Slide (1965) | do. | A | "* * * a large crack formed at the side of the road in the shoulder just behind our place—the main road between Burton and the Tahlequah Ferry. [The crack] was 2' [5.1 cm] wide in places with a drop about the same and was about 30' to 40' [9-12 m] long." (Mrs. F.M. Urschel, written commun., 1965). |
| 97 | Slide (1965) | Vashon Island, Wash. (Magnolia Beach); King County | A | Concrete bulkhead on beach settled. Bulkhead was built on fill that was placed on hard clay. There was approximately a 15 cm drop, and the bulkhead cracked (Robert Gordon, oral commun., 1988). |
| 98 | Ground crack (1965) | Maury Island, Wash. (south end); King County | A | "The private road into our property sustained a crack about 3 inches [8 cm] wide at the highest point of road and about 100 yards [90 m] down road crack continued." (Donald Boot, written commun., 1965). |
| 99 | Slide (1965) | Tacoma, Wash. (Paisades); King County | B | "30 ft [9 m] long crack in earth parallel to bank and running in north-south direction. Some sliding of bank." (J.C. Peaslie, written commun., 1965). |
| 100 | Ground crack (1949); sand boils (1949); miscellaneous effects (1965) | Pacific, Wash. (south, near county line); King and Pierce Counties | A | "Beginning in the south side of Pacific (Pacific City) and running almost straight south for a 1/2 mile [0.8 km] into Pierce County, a fissure opened up, out of which at various points water boiled out (according to one observer) * * * to a height of 2 feet [0.6 m]. Several inches of water were on the surface before the action stopped. The water carried with it a considerable amount of very fine sand." (Ralph Pommert, written commun., 1949).
"The ground out here is peat and sand, and very pliable. The water bubbled in one place * * * approximately 1 ft [0.3 m] out of ground. Bubbled on all of our land out here and pushed up various types of soil. A very large crack on place next to ours * * * crack runs NW to SW. Imagine it was much deeper than it is now for soil and silt washed in. On next place to above a large crack * * * in berry patch. Their strawberries sank several inches. At trunks of trees fence posts, all bubbled and soil washed up. Water lines broke." (Margaret E. Farr, written commun., 1949).
"Among the strange things that came along with the earthquake Thursday was one out of Roy Road, on the way to Auburn, when a housewife saw a field near her home develop its own sprinkler irrigation system. * * * As it spouted out it brought with it a foamy sand which was in piles all over the two fields." (Summer News-Index, 1965).
"The sand boils occurred just SW of the intersection of 2nd Street East and Valentine Road (Mrs. Palmer Johnson, oral commun., 1988). |
| | Sand boils (1965) | do. | A | |

Table 30. Descriptions of selected ground failures in the southern half of the central and southern Puget lowland region—Continued.

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
101	Sand boils (1949)	Auburn, Wash.; King County	A	Coworkers reported seeing numerous water-sand geysers in fields adjacent to the shop at the north end of the Auburn General Depot [at the time of the 1949 earthquake] (Larry Lundberg, oral commun., 1988).
102	Slide (1949, 1965)	Auburn, Wash. (east of Auburn on Lake Holm Road); King County	A	"Slides were reported in the Lake Holm Road east of Auburn." (Seattle Times, 1965a). "In the 1949 quake, a crack about 3 inches [7.6 cm] wide and several feet deep opened between the house and the garage. I think it went down to the [Big Soos] creek and reappeared at about the Auburn-Black Diamond Road. In the 1965 quake the crack did not reopen on our place, but did cause a small slide on 148th St. where it comes down the hill." (Mr. and Mrs. Larry Lundberg, oral commun., 1988).
103	Ejection of ground water (1965)	Auburn, Wash. (north side); King County	B	[Photo caption] "GROUND SEEPAGE—Jerry Keese, city sewage plant superintendent, *** checks seriousness of seepage around manhole on line leading into plant in North Auburn. Keese said later it appeared to be relief point for ground water—not sewage—and that there was no apparent break in the line." (Auburn Globe-News, 1965).
104	Slump (1965)	Kent, Wash. (Kent-Des Moines Road); King County	A	[Photo caption] "ROAD COLLAPSE—Damage caused when a water main broke alongside the Kent-Des Moines Highway just west of the Green River bridge during Thursday's earthquake ***. The road shoulder collapsed as a result of the quake damage." (Kent News-Journal, 1965b).
105	Slump (1949); sand boils (1949); miscellaneous effects (1949)	Kent, Wash. (NE on Big Soos Creek); King County	A	"Water system is gravity line taken from springs east side of creek, 2 and 3 inch [5.1 and 7.6 cm] wooden pipe—about 950 feet [298.6 m]. Went to inspect pipelines 1 hour after quake, nearly all were leaking where line crosses creek and swamp, emitting white water (water mixed with clay). Water reservoir (earth constructed) all white and all springs giving more water. Above reservoir crack in earth about 100 feet [30.5 m] long north and south. At that time lower, or west side of crack, had slipped about 3 inches [8 cm] but after 24 hrs it was about 8 inches [20 cm] and appeared to be slowly settling. At one spot that was dry I could slip my hand into the crack. I went to inspect other springs, one on adjoining property about 1000 ft [300 m] north of my reservoir was emitting white water with about 4 times the volume as before the quake and brought up considerable fine sand and clay. Between this spring and mine there were numerous spots where seepage of new water occurred in spots that were dry." (John Haverinen, written commun., 1949). The reservoir mentioned in the letter above was located on hillside just east of Big Soos Creek and below the power lines that cross the upper part of the hillside. The reservoir was very small, not more than a few tens of feet across (John Haverinen, Jr., oral commun., 1988).

106	Sand boil (1965); ground crack (1965)	Kent, Wash. (208th St. near O'Brien); King County	A	"Cracked cement driveway * * * water and sand spurted through cement driveway—several ground cracks and erosions of water and sand." (Mrs. Milton Botts, written commun., 1965).
107	Sand boils (1965)	Kent, Wash. (212th St. just west of Green River); King County	A	[Photo caption] "BOIL AND BUBBLE—Thursday morning's earthquake created an odd phenomena in a field near O'Brien being worked by Albert Dreisow. * * * [Dreisow] found numerous 'mud pots' [sand boils] in the field, similar to the fissure he is examining here." (Kent News-Journal, 1965a). "Two sand boils appeared in the fields; one on each side of 212th Street." (Albert Dreisow, oral commun., 1988).
108	Slide (1965)	Kent, Wash. (42d Avenue S.); King County	B	[Photo caption] "ROAD DAMAGED—Last Thursday's earthquake caused the side of 42nd Avenue South, near St. Patrick's Cemetery, to cave in and county road crews placed one-way signs along the damaged roadway." (Kent News-Journal, 1965c).
109	Slide (1965)	Seattle, Wash. (Burien, Three Tree Point area, 172d Street S.W.); King County	A	"Home located above [Puget] sound water 300' [90 m] on hillside. Sandy soil, facing south. * * * cracks of 2" to 3" [5-8 cm] were discovered across bank running east to west. Concrete sidewalk along edge of bank, cracked and upheaved—sand shaken away from underneath the concrete. Place next door had same damage." (Larry Lemmel, written commun., 1965). "Buckled [concrete]; [cracks] approximately 4 inches [10 cm]; [settling] at hilltop." (Mrs. John Maass, written commun., 1965). Sketch map shows a continuous crack 8-10 cm wide on hillside overlooking Puget Sound. The crack (in the drawing) extends across the hillside parallel to 172d Street S.W. the length of 3 or 4 residential properties. "Broken [concrete walkway]. The hill pushed down on the retaining walls and pushed them out about three inches [8 cm]." (Mrs. Henry A. Roche, written commun., 1965).
110	Slide (1965)	do.	A	
111	Slide (1965)	Seattle, Wash. (Tukwila); King County	B	The 1965 earthquake triggered a landslide on the Foster golf course along the Duwamish. The slide involved fluvial sands and silts and was probably induced by liquefaction (Seed, 1968).
111	Settlement (1965)	Renton, Wash. (Burnett Street and Seventh Avenue); King County	B	"Mayor Custer said filling and paving to repair settling of the entire length of Burnett Street and Seventh Avenue would cost an estimated \$15,000 to \$20,000. Custer said the settling was along the route of the Metro sewer line, but Robert Hillis of Metro reported there was no damage to the line. * * * City Engineer Jack Wilson said Burnett and Seventh had dropped as much as two feet [0.6 m] in some places." (The Record Chronicle, 1965).
111	Settlement (1965)	Renton, Wash. (Shafruck Street between S. 6th and S. 7th Streets); King County	A	"Foundation cracked open under house. Cement walk from street to house cracked open. House settled about 2-1/2 inches [6 cm]. Front and backyard upheaved and sunken in spots." (A.F. Salisbury, written commun., 1965).

Table 30. Descriptions of selected ground failures in the southern half of the central and southern Puget lowland region—Continued.

Location no.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
112	Slide (1965)	Renton, Wash. (Highlands); King County	C	"Cement block retaining wall holding back sand bank collapsed completely—wall was free standing, 5'x34' [1.5x10.4 m]. Wall runs north and south." (Edith Look, written commun., 1965).
113	Slides (1965)	Renton, Wash. (Jones Road); King County	C	"There was a lot of damage to Jones Road—slide, cracks, and settling (broke water pipes)." (Mrs. A.F. Savoya, written commun., 1965). "Slides were reported in the Lake Holm Road east of Auburn, the Jones Road near Maple Valley and the Devil's Elbow Road near Maple Valley." (Seattle Times, 1965a).
114	Ground crack (1965)	do.	A	"A narrow crack less than 2.5 cm wide and 45.7 m long opened up across Jones Road at the time of the 1965 quake. The crack ran across Jones Road from the south side of the street, and continued across our yard to the front of the house, where it damaged some brick-work" (Bill Niemi, oral commun., 1988). Crack developed on alluvial floodplain or low terrace of the Cedar River.

¹Information originally gathered by Dr. John A. Shulene of Puyallup, Wash. This information is based on telephone conversations or personal interviews with residents who responded to a request for information on sand boils related to the April 13, 1949, or April 29, 1965, earthquakes. Dr. Shulene's request for information was placed in the Pierce County Herald in May of 1989.

Table 31. Descriptions of selected ground failures in the Cascade Range of Washington region.

[Location numbers correspond to ground-failure location numbers on plate 6. do., ditto. Location accuracy: A, available information allows accurate location; B, available information allows location to within a kilometer, C, available information allows location to within a few kilometers; D, information insufficient to locate accurately. Quotations referenced as "written commun., 1949" or "written commun., 1965" are responses to University of Washington intensity surveys. Copies of the questionnaire responses are on file in the offices of the U.S. Geological Survey in Golden, Colo. Metric values and explanatory information in brackets have been added to the quotations by the authors. Comments following quotations are those of the authors and are based on field observations, information from cited references, and interviews with local residents]

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
115	Miscellaneous effects (1949)	Mount Adams, Wash.; Yakima County	C	"Clyde Sword and a passenger, Babe Forsyth, flew over the mountain [Mount Adams] and reported that there was a large opening on the southeast side and steam was rising from it." (Chehalis Advocate, 1949). "*** strange cloud formation which appeared from behind Mt. Adams after the quake and continued until darkness fell. This cloud formation looked stranger yet when viewed through high powered glasses. It looked like steam or smoke which rose from a certain point and drifted with the wind. No other clouds were in the clear sky and this one remained just like smoke would, except for its drifting with the wind ***." (Chehalis Advocate Correspondence Service respondent [anonymous], written commun., 1949).
116	Slump (1949)	Randle, Wash. (just north of Cispus River bridge on old road); Lewis County	A	Slump of road on sidehill slope. Road slumped about 0.6 m vertically for a length of about 18 m (Lawrence E. Panco, oral commun., 1988).
117	Slump (1949)	Randle, Wash.; Lewis County	A	Road embankment failed about 1.6 km southwest of Randle during the 1949 earthquake (Hubert Derosett, oral commun., 1988). The slump occurred on a 0.9- to 1.2-m-high road embankment in artificial fill underlain by loose, liquefiable sand. The failure extensively damaged several meters of roadway (see fig. 209). Numerous sand boils simultaneously erupted in a nearby field (loc. 118).
118	Sand boils (1949)	Randle, Wash.; Lewis County	A	"Sand boils dumped wheelbarrow loads of sand in our pasture in the 1949 quake." (Lawrence Peters, oral commun., 1988).
119	Slumps (1949)	Randle, Wash.; Lewis County	A	"There were small slides along the west bank of the oxbow lake on my property southeast of Randle at the time of the 1949 quake." (Norm McMahon, oral commun., 1988).
120	Rockfall (1949)	Randle, Wash.; Lewis County	A	"Several blocks of rock 4-6 ft [1.2-1.8 m] across came down [during the 1949 earthquake] and blocked Cline Road about 1 mile [1.6 km] southeast of Randle." (Hubert Derosett, oral commun., 1988).

Table 31. Descriptions of selected ground failures in the Cascade Range of Washington region—Continued.

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
121	Rockfall (1949)	Randle, Wash.; Lewis County	A	"A large block about 20 ft [6 m] on a side dropped from a steep cliff onto Cline Road at a point about 2-1/2 miles [4 km] southeast of Randle. This happened as a result of the 1949 earthquake." (Hubert Derosett, oral commun., 1988).
122	Rockfall (1949)	Randle, Wash.; Lewis County	A	"A rockfall occurred along the old Randle-Packwood Highway, about 5 miles [8 km] east of Randle. Rocks up to 3 ft [0.9 m] in diameter came down and some trees toppled." (Hubert Derosett, oral commun., 1988).
123	Rockfall (1949)	Longmire, Wash. (Mount Rainier National Park); Lewis County	C	"* * * rocks were observed falling from the cliffs of * * * Eagle Peak." (National Park Service, 1949).
124	Rockfall (1949)	Longmire, Wash. (Mount Rainier National Park); Lewis County	B	"* * * rocks were observed falling from the cliffs of Rampart Ridge" (National Park Service, 1949).
125	Slide (1949)	Longmire, Wash. (Mount Rainier National Park); Lewis County	C	"On the Kautz Creek drainage the 1947 flood debris showed an assortment of parallel cracks in the snow, indicating a shifting of the unconsolidated fill beneath." (National Park Service, 1949). "Of interest was the fact that the material deposited by the 1947 Kautz Creek flood shifted somewhat during the quake. In the snow overlying the flood deposits, a series of en echelon cracks showed up, with the direction of movement of the deposits downward toward lower elevations." (John C. Preston, National Park Service, written commun., 1949).
126	Rocklide (1949)	Longmire, Wash. (Mount Rainier National Park); Lewis County	B	"One major rock slide on the slopes above the Nisqually Glacier was reported." (John C. Preston, National Park Service, written commun., 1949).
	Rockfall/rockslide (1965)	do.	B	"Some rock, snow and icefall occurred on the mountain. * * * A helicopter flying near the glacier observed large pieces of ice (glacier) breaking and falling away, and in turn creating avalanches. Large amounts of rock and soil adjacent to the Kautz Glacier were observed by Chief Park Ranger Ruben Hart from a helicopter, although none of this was large enough to form a barrier in the river." (National Park Service, 1965).

127	Ground cracks (1949)	A	Buckley, Wash. (Mud Mountain Dam); King and Pierce Counties	<p>"At Mud Mountain Dam old longitudinal cracks in the fill in the zone of juncture between the core and the rock fill reopened to a width of about 1 inch [2.5 cm]. The dam is not endangered." (U.S. Army Corps of Engineers, 1949).</p> <p>"Some additional material in an old slide area on the right bank downstream from the dam loosened and slid into the stream. A crack near the left side of the spillway was apparently unaffected." (U.S. Army Corps of Engineers, 1949).</p> <p>"Small cracks from 1/2 to 1-1/2 inches [1.3-2.8 cm] wide were found parallel to the axis of the dam between the impervious core and rockfill zones. These cracks are of an intermittent nature but extend generally along the entire length of the embankment. This cracking is similar to the cracking at Howard Hanson Dam. * * * The shock caused small earth slides adjacent to the Vista House and minor cracking of the concrete slab around the Vista House." (Steinborn, 1965).</p>
	Slide (1949)	B	do.	
	Ground cracks (1965); slides (1965)	A	do.	
128	Ground cracks (1965)	A	Palmer, Wash. (Howard Hanson Dam); King County	<p>"Cracking was found along the crest of the embankment parallel to the axis of the dam and upstream of the centerline in the sand and gravel zone or between this zone and the drain. These cracks were intermittent but they extended in one line or two parallel lines throughout the length of the embankment. Where two lines of cracks occurred they were from 6 inches to 24 inches [15-61 cm] apart. The widest opening was 1/2 inch [1.3 cm]. Maximum differential settlement along the crack did not exceed 1/2 inch [1.3 cm]. There was no measurable settlement of the dam." (Steinborn, 1965).</p>
129	Slide (1965)	C	Ronald, Wash. Kittitas County	<p>"Large rock dump started to slide and cave." (Hake and Cloud, 1967).</p>
130	Rockslides (1949)	B	North Bend, Wash. (Mount Si); King County	<p>"Rockslides on Mt. Si [triggered by the 1949 earthquake]." (Murphy and Ulrich, 1951).</p>
	Rockslides (1965)	A	do.	<p>"Press reported an extensive slide occurred on the southwest slope of Mount Si near North Bend [at the time of the 1965 earthquake]." (Hake and Cloud, 1967).</p> <p>"Dust cloud rose from near the bottom of the rock face on the west side of Mt. Si during the 1965 earthquake [near the 670-m-elevation level]." (Jack Ferrell, U.S. Forest Service [retired], oral commun., 1988).</p> <p>Prior to 1949, the earthquake of April 1945 also triggered rockslides on Mount Si. According to Bodle and Murphy (1947), "At the Mount Si Ranger Station, near North Bend the earth buckled and heaved and tons of rock and earth cascaded down the 4,000-foot [1,200 m] cliffs of Mount Si." See figure 210.</p>
131	Rockfall (1965)	C	Index, Wash. (Mount Persis); Snohomish County	<p>"Mrs. Spencer White of the Mt. Index Service Station reported that the quake sent huge boulders rolling down the side of Mt. Persis, near the Stevens Pass Highway." (Everett Herald, 1965).</p> <p>"Boulders came rolling down onto the Stevens Pass Highway from Mt. Persis east of Everett, causing some damage." (Wenatchee Daily World, 1965).</p>
132	Snow and rock avalanches (1949)	D	Darrington, Wash.; Snohomish County	<p>"Snow and rock avalanches in the mountains [in the vicinity of Darrington]." (Murphy and Ulrich, 1951).</p>

Table 32. Descriptions of selected ground failures in the central-southwestern Washington region.

[Location numbers correspond to ground-failure location numbers on plate 7. do., ditto. Location accuracy: A, available information allows accurate location; B, available information allows location to within a kilometer; C, available information allows location to within a few kilometers. Quotations referenced as "written commun., 1949" or "written commun., 1965" are responses to University of Washington intensity surveys. Copies of the questionnaire responses are on file in the offices of the U.S. Geological Survey in Golden, Colo. Metric values and explanatory information in brackets have been added to the quotations by the authors. Comments following quotations are those of the authors and are based on field observations, information from cited references, and interviews with local residents.]

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
133	Slump (1949)	Mossyrock, Wash.; Lewis County	A	"Quake left a 25-foot [8 m] long crack in the ground in the backyard. * * * Crack runs north and south." (Mrs. V.C. Holsted, written commun., 1949). Crack resulted from a slight slump near the base of the slope adjacent to the Wmston Creek flood plain.
134	Slump (1949)	Kosmos, Wash.; Lewis County	A	Road slumped into the Cowitz River, damming it for a short time. Failure occurred along 90 m of river bank on the north side of the river. The failed slope was 15-21 m high and near vertical in its upper part. The material involved was sand and gravel, but mostly medium sand (Hubert Derosett, oral commun., 1988).
135	Rockfall (1949)	Morton, Wash.; Lewis County	A	"A rock cliff across the valley had huge boulders shaken down." (Mrs. Clifford Butts, written commun., 1965). A block of bedrock about 8 m high fell from the face of a near vertical cliff, frightening homeowners below (Ivy Beck and Lena Hall, oral commun., 1988).
136	Slides (1949)	La Grande, Wash.; Pierce County	C	"Ground cracks on side hills 1 inch [2.5 cm] wide 25-30 ft [8-9 m] long. Landslides [in the vicinity of La Grande]." (Murphy and Ulrich, 1951). "Earth cracks along canyon of the Nisqually River; slides into rivers and onto roads." (Hake and Cloud, 1967).
137	Slump (1949)	Eatonville, Wash.; Pierce County	A	"The quake opened a crack about 100 ft [30 m] in length on the Alder * * * cutoff, about 6 inches [15 cm] wide." (Eatonville Dispatch, 1949). About 1.6 km south of Eatonville, a 30-m-long road crack appeared as a result of a slump on an approach to a railway overpass. The slump, which occurred in an embankment of artificial fill, had a vertical displacement of approximately 0.6 m (Percy Williams, oral commun., 1987).
138	Slump (1949)	Eatonville, Wash. (Ohop Lake); Pierce County	A	"On the Lake road the crack is three to four inches [8-10 cm] wide and extends about 700 feet [210 m] from Point Ohop on towards Kapowsin." (Eatonville Dispatch, 1949). "Quake Slide Makes Isle—Reverberations from the April 13 earthquake continue to be felt throughout Pierce County. Witness the creation of a new island in Ohop Lake Friday noon when thousands of tons of earth from an 800-foot [250 m] stretch of the Ohop-Kapowsin road sheared off the hillside and plunged into the water. The road cave-in was a direct result of the quake occurring just a month ago. The quake had left a crack in the highway * * *. Efforts of county road crews to fill up the crevice had proved unavailing. * * * summer cottages were thrown off plumb as much as two feet [0.6 m] * * *. Communication lines, including telephone and power lines, were intact, but hanging on by slender threads." (Tacoma Sunday Ledger-News Tribune, 1949). The surface of the road along the west side of Ohop Lake originally developed a 215- to 250-m-long crack due to incipient slumping triggered by the 1949 earthquake. One month later, on May 13, complete failure occurred as the unstable mass slid and (or) flowed as far as 30.5 m into the lake, leaving a 1.5 m scarp along the roadway (see fig. 213). The slide involved artificial fill overlying well-consolidated alluvial sediments.

139	Soil fall (1965)	Electron, Wash.; Pierce County do.	A	Sand and gravel fell from a 15-m-high vertical face onto the road to the powerhouse. About 38 m ³ of material blocked the road (Emmett Chase, oral commun., 1988). "Ground cracked [near Electron]." (Hake and Cloud, 1967).
140	Ground crack (1965) Slump (1949)	Lacey, Wash. (Patterson Lake); Thurston County	A	"We really felt it bad on S.E. side of Lake Patterson. As I sat up after the shaking ground threw me, I saw the last cars of a freight train go over the trestle across the lake, then the land slid from under the tracks and at the same time the water rose over the dock (10 or 12 inches [25 or 30 cm])" (Mrs. Harry A. Esborg, written commun., 1949). "Bridge 31—East Approach: Embankment for 275 ft [84 m] slid into Patterson Lake. Repairs by contractor—25,000 CY [19.1×10 ⁴ m ³] mt" (U.S. Army Corps of Engineers, 1949).
141	Sand boils (1949)	Maytown, Wash. (just east of Deep Lake); Thurston County	A	"In one of our pastures we found a dozen patches of mud and sand which had apparently been forced up from under the ground. The largest patch was about ten feet [3 m] across; the smaller ones were only three to four feet [0.9–1.2 m]. The largest patch seemed to have come out of a crack in the earth; the others, from holes. Mud—quite liquid—came out first, and then sand flowed out to form a layer several inches thick. When we plowed the field recently we had to plow under a couple of these spots, but the rest are on swampy ground and can still be seen." (Mrs. W.N. Winslow, written commun., 1949). Ejected sand was clean and white and glistened like glass. It was extruded along a line spread over a zone about 3 m wide. The fissure was oriented north-south and lay east of Deep Lake (Mr. and Mrs. Conrad Newman, oral commun., 1988). Farming practices mixed sand with other soil, and features were obliterated in a relatively short time. For a year or so afterward, the sand boils were visible indirectly because they were drier and less fertile. The area is underlain by glacial drift; gravel exposed in gravel pit at the south end of the property has poorly sorted sand. The key control in the formation of the sand boils was probably a high water table and a lens of well sorted, sandy stratified drift in the glacial deposits.
142	Ground cracks (1949)	Centralia, Wash. (Hanaford Valley); Lewis County	C	"We are on a quicksand base, mostly at a depth of 7 ft [2.1 m] * * * most water pipes were broken and * * * 70 percent foundation damage." (Mrs. Paul Quay, written commun., 1949).
143	Slump (1949)	Centralia, Wash. (Pacific Sand and Gravel Pit); Lewis County	A	[Photo caption] "This fissure and others extended about 100 ft [30 m] in an old gravel pit near Centralia." (Edwards, 1951). Slight slump (vertical displacement of several centimeters) at edge of old gravel pit. Failure probably occurred in Vashon glacial outwash deposits (sand and gravel) present at the site.
144	Slump (1949)	Centralia, Wash. (north shore of Plummer Lake); Lewis County	A	Cracks 8–15 m long and several centimeters wide developed on the north shore of Plummer Lake during the 1949 earthquake (Don Swanson, oral commun., 1988).

Table 32. Descriptions of selected ground failures in the central-southwestern Washington region—Continued.

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
145	Settlement (1949); miscellaneous effects (1949)	Centralia, Wash.; Lewis County	A	"* * * 1 church condemned, continued settling of ground caused extensive damage. Water mains broken, and 5,000 feet [1,520 m] of concrete pipe city intake water supply damaged." (Murphy and Ulrich, 1951). "In Centralia, Washington, the Field and Lease Building, constructed in 1890 of Tenino sandstone, is apparently settling after the quake. A plate glass window broke 5 days after the quake. Horizontal and diagonal lines drawn across plaster cracks show minute displacement after a week. * * * Dust and scratches on two adjoining masonry buildings, Warren Brothers Garage and the Panorium Cleaners on West Main, Centralia, indicate differential vertical movement between the buildings." (U.S. Army Corps of Engineers, 1949).
146	Sand boils (1949); ground cracks (1949)	Centralia, Wash. (Chehalis River Valley); Lewis County	A	"Also reported yesterday was the opening of about 20 crevasses on the farm of Mrs. Ted Dorn on the old Military road between Centralia and Chehalis, some of them 25 feet [8 m] long. From some of them water spouted, followed by an upheaval of sand and mud." (Tacoma News Tribune, 1949b). "Clear water spouted 18 inches [45 cm] in the air and in a few moments brought up huge quantities of what appears to be clean ocean sand." (Daily Chronicle [Centralia], 1949). "Four miles [6.4 km] southwest of town, water spouted 18 inches [45 cm] high in middle of field, leaving a very fine sand formation for a considerable space around each hole, the holes varying from 1 to 3 inches [2.5–8.0 cm] in diameter. Water spouted from inch wide crack 8 or 10 feet [2.4 or 3.0 m] long." (Murphy and Ulrich, 1951). Water spouted about 3.0–3.7 m high and continued spouting (at lesser heights) for an hour or so. The water ran slowly for about a week (Ted Dorn, oral commun., 1988). See figures 211 and 212.
147	Sand boil (1949); miscellaneous effects (1949)	Chehalis, Wash.; Lewis County	B	"Our water supply is about half of what it was from a spring. It seems to have changed the spring some; heaved some ground near the spring up 2 feet [0.6 m] and poured muddy water out of top of mound." (Mrs. Frank O. Miller, written commun., 1949).
148	Ground crack (1949); ejection of ground water (1949)	Adna, Wash.; Lewis County	A	"* * * the carrier on Route 1 [Chehalis] observed that following the quake a fissure appeared in the county road on the hill above Ceres. This fissure appears to have produced a wet and soft spot in a roadbed which was previously dry." (Lloyd Sullivan, Postmaster, Chehalis, written commun., 1949). Apparently, this crack developed at the contact between artificial fill and the original slope. The road was cut from a steep slope, north of the railroad, about 6 m above the Chehalis River flood plain.
149	Sand boil (1949); ground crack (1949)	Rochester, Wash.; Thurston County	A	"Our farm borders on the Chehalis River nine miles [14.5 km] west of Centralia. Within one and one half blocks of the river bank the earth cracked about fifteen feet [4.5 m] in length and there was quite a deposit of pure white sand (several buckets full and moisture around it). The crack was about an inch [2.5 cm] wide." (Mrs. Wilbert Brewer, written commun., 1949).

150	Slump (1949)	Rochester, Wash.; Thurston County	A	<p>A crack and slight slump occurred about 5 km northeast of Rochester on the Rochester Little Rock Road. The slump occurred along a section of road adjacent to a swampy alluvial flat near the Black River (Alan Schwiesow, City Engineer, Centralia, oral commun., 1988).</p> <p>Examination of a photograph of this 1949 ground failure (Hopper, 1981, p. 93) indicates that the shoulder of the road failed along several meters of roadway. Vertical and horizontal displacements appear to be less than 0.3 m and 0.6 m, respectively. The slide occurred in artificial fill on a very poor alluvial foundation.</p>
151	Slump (1949)	Oakville, Wash.; Grays Harbor County	A	<p>The 1949 earthquake caused a crack and slump on a county road along the Chehalis River, about 1.6 km southwest of Oakville. The crack was about 60 m long and there was about 0.3 m of vertical displacement (Alan Schwiesow, City Engineer, Centralia, oral commun., 1988).</p> <p>Failure probably occurred at the contact between the artificial fill and original ground surface. New cracks are apparent that indicate continued instability.</p>
152	Miscellaneous effects (1949); ground cracks (1949)	Hoquiam, Wash.; Grays Harbor County	C	<p>"At least a dozen water mains and pipes broken. Several sidewalks cracked." (Murphy and Ulrich, 1951).</p>
153	Miscellaneous effects (1949)	Aberdeen, Wash.; Grays Harbor County	B	<p>"Breaks and leaks in water mains were numerous and in widely scattered sections of the city * * *. A major break, with pipes broken in nearly a half-dozen places, occurred near Second and Grant Streets." (Aberdeen World, 1949).</p>
154	Settlement (1949)	McCleary, Wash.; Grays Harbor County	B	<p>"Simpson Logging Company in McCleary, Washington, reported a water reservoir, constructed originally in cut was enlarged later by 12 feet [3.7 m] of fill on about 1 on 1 slope and paved with reinforced concrete. The southeast and northwest corners opened about 2 inches [5 cm] at the top and about 6 feet [1.8 m] of water ran out rapidly. The fill was constructed by D8 caterpillar with no specified compaction. Settlement of the fill was clearly indicated." (U.S. Army Corps of Engineers, 1949).</p>
155	Slides (1965)	Shelton, Wash. (west side of Oakland Bay); Mason County	C	<p>"Some slides noticed along Oakland Bay closer to town." (Business Manager, Washington Corrections Center, written commun., 1965).</p>
156	Slump (1965)	Shelton, Wash.; Mason County	B	<p>"One lane of U.S. Highway 101, four miles [6.4 km] north of Shelton, sank about a foot [0.3 m] for a distance of about 150 feet [45 m]." (Washington Highways, 1965).</p> <p>Slump occurred on Highway 101 along the east side of Purdy Creek near Purdy Canyon. The failure took place wholly or partly in artificial fill underlain by granular sediments.</p>

Table 33. Descriptions of selected ground failures in the western Columbia River region, Washington and Oregon.

[Location numbers correspond to ground-failure location numbers on plate 8. do., ditto. Location accuracy: A, available information allows accurate location; B, available information allows location to within a kilometer; C, available information allows location to within a few kilometers; D, information insufficient to locate accurately. Quotations referenced as "written commun., 1949" or "written commun., 1965" are responses to University of Washington intensity surveys. Copies of the questionnaire responses are on file in the offices of the U.S. Geological Survey in Golden, Colo. Metric values and explanatory information in brackets have been added to the quotations by the authors. Comments following quotations are those of the authors and are based on field observations, information from cited references, and interviews with local residents.]

Location no.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
157	Slump (1949)	Twin Rocks, Oreg.; Tillamook County	A	"Just south of the Twin Rocks Welding works several large cracks appeared in the earth causing part of the bank to drop and almost slide into the small lake. The cracks extend almost to the hard surface of the highway." (Headlight-Herald, 1949). Slight slump of highway embankment that crosses a low, wet area on the west side of Spring Lake in Twin Rocks. The existing embankment is about 1.2 m high and is composed of artificial fill founded on unconsolidated granular sediments.
158	Rockfall (1949)	Portland, Oreg.; Multnomah County	A	"Ray E. Wenger, 1283 SW Cardinell Drive, reported that a rock measuring 15 by 20 by 5 feet [4.6 m×6.1 m×1.5 m] had fallen within a few feet of his boathouse at Blue Lake. Wenger said the rock rolled to its present position during the earthquake, but now it is balancing on one end. He fears it may cause serious damage to the boathouse if not moved." (Oregon Journal, 1949b). The rockfall occurred along the south shore of Blue Lake where part of the Troutdale Formation (conglomerate and sandstone) (Trimble, 1963) is exposed in a near-vertical, 9- to 15-m-high cliff.
159	Miscellaneous effects (1949)	Government Camp, Oreg. (Mount Hood); Clackamas County	C	"This mountain village experienced a sharp earthquake just before noon today and startled residents, looking up at Mount Hood, saw several puffs of what appeared to be black smoke rise from behind Crater Rock. Crater Rock is below the summit on the south side. * * * The smoke—if smoke it was—subsided quickly, and experienced mountaineers believe it may have been dust clouds rising from a landslide that the tumbler could have started. The steep area back of Crater Rock is an area of frequent slides, and often in the past great dust clouds have risen as the ice, snow and rock masses hurtled down the gullies." (Oregon Journal, 1949a).
160	Rockfall/rock avalanche (1949)	Stevenson, Wash.; Skamania County	B	"A two-mile [3.2 km] slide on the Washington side of the Columbia across from Cascade Locks swept away the face of a south cliff on Table Mountain. The avalanche of rocks and dirt threw up a cloud of dust that lasted more than 10 minutes and was observed for miles along the Columbia Gorge." (Oregonian, 1949a). "Hundreds of yards of Red Bluff, west of Stevenson, crashed to the bottom of a ravine along its base * * *. The most spectacular result of the quake was the collapse of Red Mountain. A heavy rumble from that direction focused hundreds of eyes on the sheer dirt and rock cliff above which a cloud of dust several hundred feet in height rose and swirled. The noise continued for two minutes or more and considerable fresh surface was exposed when the dust storm cleared. Smaller amounts of earth and rock continued to fall for several minutes after the quake had subsided." (Skamania County Pioneer, 1949).

The rockfall-rock avalanche ground failure(s) originated along part of a 5-km-long, steep head scarp of the Cascades (Bonneville) landslide. The headscarp of the Cascades landslide exposes 370 m of the Eagle Creek Formation (conglomerate, sandstone, and minor tuff) overlain by basalt (Korosec, 1987).

Air photo studies indicate that rockfalls and other slides are common along the scarp. Debris from slide activity, possibly related to the 1949 event, extends a few hundred meters downslope from the scarp on the south side of Table Mountain. See figure 214.

"C.H. Girardot, depot agent, said trainman told him there was a crack in the earth north of the Toutle River bridge; the crack opened about 4 inches [10 cm] wide and is 25 to 30 feet [8-9 m] long." (Cowlitz County Advocate, 1949).

The "crack" apparently occurred on the flood plain of the Cowlitz River just north of its confluence with the Toutle River. The gently sloping to nearly flat terrain is underlain by a sandy alluvial soil. Probable slump or lateral spread.

"Many cracks up to 6 inches [15 cm] wide in fields and on river dikes. Landslides." (Murphy and Ulrich, 1951).

"Here what appears to have been a subterranean eruption occurred and fissures or long splits over an extended area opened up. It was apparent that while the earth was in motion water and sand had erupted in the form of geysers. The severest damage was in the basement where the concrete floor literally bulged and cracked in every direction permitting water and sand to seep in. The force of the upheaval apparently lifted the house off its foundation and when it settled back its position was distorted as much plaster was cracked loose and hardly a door would close." (Longview Daily News, 1949b).

"My brother said he saw 2 to 3 foot [0.6-0.9 m] high spurts of water and sand in the backyard." (Allen Windus, oral commun., 1988).

The above quotations represent two separate ground-failure locations, about 180 m apart, near the junction of N.W. Nichols and Ocean Beach Highway in Longview. The area is part of a flat, low-lying terrace or flood plain of the Columbia River underlain by Quaternary alluvium (Walsh and others, 1987). Artificial fill may be present locally.

"A crack about 20 feet [6 m] in length opened on the five acre farm of Charles Wilson, 2103 40th Avenue Longview, during the quake. Black, fine sand bubbled up out of the crack for a time it was reported." (Longview Daily News, 1949b).

The ground-failure site was (in 1949) part of a swampy, sandy flood plain. The area is now a residential neighborhood. Local residents who lived in the vicinity at the time say the water table was almost at the surface. There is an open slough on the SW edge of the property. The area is underlain by Quaternary alluvium (Walsh and others, 1987).

Artificial fill may be present locally.

161 Slump (1949)

Castle Rock, Wash.;
Cowlitz County

B

162 Ground cracks (1949);
slides (1949)Castle Rock, Wash.;
Cowlitz County

D

163 Sand boils (1949);
ground cracks (1949)Longview, Wash.;
Cowlitz County

A

164 Sand boils (1949);
ground crack (1949)Longview, Wash.;
Cowlitz County

A

Table 33. Descriptions of selected ground failures in the western Columbia River region, Washington and Oregon—Continued.

Location No.	Failure type (year of earthquake)	Reference municipality or geographic location; county	Location accuracy	Quotation and (or) comment
165	Slump (1949)	Longview, Wash.; Cowlitz County	A	<p>"Earthquake cracks * * * extend for more than 300 feet [90 m] along the Longview dike road near Willow Grove. * * * At another point along the road, the cracks extend in the soil at an angle to right of way, and cross through the dike." (Longview Daily News, 1949a).</p> <p>[Photo caption] "Earthquake cracks as deep as can be seen * * * range up to nine inches [22.9 cm] wide." (Longview Daily News, 1949a).</p> <p>Cracks and a slump in a dike road in a flat swampy area adjacent to the Columbia River. The cracks developed in an embankment of artificial fill underlain by alluvial sediments of the Columbia River. The road surface is 3.0–3.7 m above the river and approximately 1.8 m above a swamp on the opposite side.</p>
166	Rockfall (1949)	Mayger, Oreg.; Columbia County	B	<p>"The quake did start rock slides and bend rails on the Spokane, Portland and Seattle Railway that closed the line from Portland to Seaside at a point near Mayger, west of Rainier. Repairs were completed in a few hours, however." (Oregonian, 1949b).</p> <p>A steep face of the Wanapum Basalt and (or) Grays River volcanic rocks (Walsh and others, 1987), about 1.6 km east of Mayger, is the likely origin of the "rock slide" reported in the above newspaper quote. About 60 m of highly jointed volcanic rocks are exposed in the steep face.</p>
167	Miscellaneous effects (1949)	Mayger, Oreg.; Columbia County	A	<p>"Heaviest damage reported was at Mayger where the Point Adams Fish Co. station reports a loss of approximately \$4,000 when several pilings were taken out by the quake and the building itself was moved about five feet [1.5 m] toward the Washington side of the river." (Clatskanie Chief, 1949b).</p>
168	Rockfall (1949)	Stella, Wash.; Cowlitz County	B	<p>"5 Narrowly Miss Highway Rock Slide—Five rural Longview residents narrowly escaped being in the path of a rock slide that came down across the Ocean Beach Highway, west of Stella, during Wednesday's earthquake. Traveling to Longview, Mr. and Mrs. Frank Jackson, Mr. and Mrs. Donald Jackson and their infant, stopped their car on the highway—without feeling the tremor—when they saw rocks suddenly start dropping from a towering bluff onto the highway. As they sat in their car, a large section of the bluff toppled across the highway, spilling over into the Columbia River." (Longview Daily News, 1949c).</p> <p>One block of rock that came down in the slide west of Stella was as big as a house. The Highway Department had to "shoot" it to get it off the road (Emmett Williams, oral commun., 1988).</p> <p>This rockfall originated on a 15- to 25-m-high face of highly jointed basalt (Wanapum Basalt, according to Walsh and others, 1987). The rock face is near vertical and extends from 0.4 to 1.2 km west of Stella on the north side of the Ocean Beach Highway.</p>

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|-----|------------------------------|--|---|--|
| 169 | Slide (1949) | Clatskanie, Oreg.;
Columbia County | A | <p>"Three were injured in Clatskanie Wednesday indirectly as a result of the earthquake. Andrew Rantala was buried in a slide at the new Clatskanie high school site * * *. After the workmen resumed work in the afternoon, Mr. Rantala was digging a footing for new forms next to a bank about eight feet [2.4 m] high when suddenly the bank gave way, covering him a foot or so. * * * It is surmised that the quake had loosened the dirt bank, causing the slide." (Clatskanie Chief, 1949a).</p> <p>"Three or four water mains were broken in Clatskanie" (Clatskanie Chief, 1949b).</p> |
| 170 | Miscellaneous effects (1949) | do. | B | <p>"I understand from the commercial fisheries warden in this area, that on Puget Island in the Columbia near Cathlamet, a number of well pipes were all bent in the same direction, indicating a definite movement between strata there." (George C. Oldham, written commun., 1949).</p> |
| 171 | Miscellaneous effects (1949) | Cathlamet, Wash. (Puget Island, Columbia River);
Wahkiakum County | B | <p>"The town of Skamokawa is situated partly on an island and partly on the mainland, connected by a bridge. The structures on the island are built on high underpinnings, or piling, because the tide of the Columbia River inundates the portion of the island outside the dike. Our Post Office is one of these. * * * The parsonage behind the Church [adjacent to the Post Office] divided by a six inch [15.2 cm] crack, and the underpinning split to the extent that it was unsafe for occupancy. The severest damage seems to have occurred to another dwelling a few hundred feet from our office. An outer storehouse crumpled and fell into the tide-land, and two women of the house who rushed to the sidewalk at the first tremor, were thrown through the air about ten feet [3 m], while the sidewalk collapsed. * * * oil and water lines were broken." (Barbara H. Eggman, written commun., 1949).</p> <p>Ground failure, probably caused by liquefaction of sandy alluvial sediments, occurred in a flat-lying swamp area on a point between Brooks Slough and Steamboat Slough. There were foundation failures of wooden buildings built on sand (and possibly on a surface layer of sawdust from sawmills that existed on the point at that time).</p> |
| 172 | Miscellaneous effects (1949) | Skamokawa, Wash.;
Wahkiakum County | B | <p>"Several water mains broke and flooded basements." (Murphy and Ulrich, 1949).</p> |
| | | Astoria, Oreg.;
Clatsop County | C | |