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Ground Failure Associated with the Puget Sound Region Earthquakes of April 13, 1949, and April 29, 1965

by

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INTRODUCTION

Much of the loss inflicted by a future large earthquake in the western Washington-northwestern Oregon region would likely be caused by earthquake-induced ground failure. This prediction is supported by the 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 example, spawned major landslides and other ground failures that accounted for 60 percent of the estimated $300 million in total damage--in addition to causing several tens of fatalities (Youd, 1978; Keefer, 1984). Ground shaking during the Alaskan quake caused water-saturated sediment beneath roads, railroads, bridges, and port facilities to liquefy and lose strength; resulting ground failures destroyed waterfronts at three coastal communities and buckled or compressed more than 250 bridges (Committee on Earthquake Engineering, 1985). In the same year, a magnitude 7.5 earthquake in Niigata, Japan, produced spectacular ground-failure damage. During that earthquake, saturated sand beneath a large apartment complex liquefied causing multi-story apartment buildings to sink and tilt as much as 60 degrees (Youd, 1978).

Occasionally, earthquakes generate ground failures that result in catastrophic loss of life. Since the year 1700, at least 250,000 people have been killed by earthquake-induced landslides in China (Li, in press). In a single event in 1920, in Gansu Province, China, massive earthquake-triggered landslides in loess resulted in as many as 100,000 fatalities (Close and McCormick, 1922, Varnes, 1978). Yet another example is the devastating earthquake-induced rock and ice avalanche that occurred in 1970 on the highest mountain in Peru (Nevados Huascaran). In that disaster, the failed mass evolved into a high-velocity debris avalanche that swept downvalley burying the town of Yungay and part of Ranrahirca, killing at least 18,000 people (Plafker and others, 1971).

Fortunately, ground failures generated by historic earthquakes in the western Washington-northwestern Oregon region have not resulted in catastrophic losses. The potential for greater losses in future earthquakes, however, has increased due to increased population and extensive urban development. It is estimated that approximately 2.6 million people and about $93 billion in property are now exposed to the earthquake hazard in the Seattle-Portland region alone (Hays and others, 1988). In addition, some studies suggest that an earthquake of magnitude 8 or greater, larger than any historic Washington or Oregon earthquake, is possible along the Cascadia subduction zone (Heaton and Hartzell, 1986). Such an earthquake would be expected to cause relatively strong shaking and numerous damaging ground failures over a large area that would probably include the heavily populated Puget Sound and Willamette Valley regions.

The historical record suggests that ground failures generated during future large earthquakes will most likely occur at the same or geologically similar locations as those generated during previous earthquakes (Youd and Hoose, 1978). This was recently demonstrated by ground failure occurrences in the magnitude 7.1 Loma Prieta, northern California earthquake of October 17, 1989 (Youd and Hoose, 1978; U.S. Geological Survey Staff, 1990; Earthquake Spectra, 1990). In the area of San Francisco Bay, damaging ground failures occurred in zones of artificial fill located along the waterfront, as did some major ground failures during the 1906 San Francisco earthquake. In the Salinas-Santa Cruz area, many catalogued 1906 failures in flood-plain deposits were reactivated by the 1989 earthquake. In addition, some areas in the Santa Cruz Mountains that developed landslides during the 1906 earthquake were hard hit by landslides triggered by the 1989 event. It is thus apparent that studies to determine the distribution, nature, and geologic environments of historic earthquake-induced ground failures are essential to efforts aimed at reducing earthquake hazards.

PURPOSE AND METHOD OF STUDY

The purpose of this study is to better define the distribution and characteristics of ground failures generated by two large, Pacific Northwest earthquakes--the Puget Sound earthquakes of April 13, 1949, and April 29, 1965. This information is intended to further develop an understanding of the probable location and nature of future earthquake-induced ground failure needed for earthquake-hazard reduction and effective land-use planning in the western Washington-northwestern Oregon region. In order to verify and refine reported data and to expand the existing ground-failure data base, a study was undertaken consisting of: (1) review of published information (newspaper and technical journal articles, and governmental agency accounts), (2) interviews with residents and local officials having information on ground failures related to the 1949 and 1965 earthquakes, and (3) field study of selected earthquake-induced ground-failure sites.

Locations of all known ground failures triggered by the 1949 and 1965 events were plotted as accurately as possible on topographic base maps (pls. 1-5), allowing quick visual comparison of regional ground-failure distributions of the two earthquakes. Descriptions of selected ground failures, keyed to ground-failure location numbers (pls. 1-5), are provided in tables presented in the appendix (tables 1-5). Estimates of the accuracy with which selected ground failures can be relocated, given available information, are also provided in the tables.

ACKNOWLEDGMENTS

The authors are particularly indebted to Margaret Hopper of the U.S. Geological Survey for her willingness to provide data files on ground failures compiled during her study of earthquake effects in the Puget Sound region, and to Gerald Thorsen, Geological Consultant (formerly with the Washington Division of Geology and Earth Resources), who generously contributed much helpful information including photographs of ground failures that occurred in the vicinity of Olympia, Washington. Steve Palmer, Washington Division of Geology and Earth Resources, and Gerald Thorsen reviewed the manuscript and provided valuable suggestions and comments. We gratefully acknowledge the cooperation and technical assistance of personnel of the Washington Division of Geology and Earth Resources, the Oregon Department of Geology and Mineral Industries, and of the City and County governments in western Washington and northwestern Oregon who supplied helpful information on ground-failure locations. Newspaper organizations in the region (referenced in the tables) were especially helpful in supplying photographs of ground failures. In addition, we thank the many individuals referenced in the tables on ground-failure descriptions, and in photo credits given in the figure captions, who supplied detailed information and (or) photographs of ground failures essential to the success of this study.

TYPES OF EARTHQUAKE-INDUCED GROUND FAILURE

Ground failure is movement of an earth mass (soil, rock, or debris) that results in permanent displacement or disruption of the ground surface. For the purpose of this report, earthquake-induced ground failure is defined as ground failure triggered by seismic shaking. Landslides, ground settlement, and ground cracks are the major types of earthquake-induced ground failure.

Landslides include rotational slides (slumps); translational slides; rock falls; soil falls; lateral spreads; mud, earth, and debris flows; and rock, soil, and debris avalanches (landslide nomenclature after Varnes, 1978). Three principal effects of earthquake wave propagation trigger landslides (Crozier, 1987): (1) the direct mechanical effect of horizontal acceleration, which, at high shaking intensity, may exceed acceleration due to gravity; (2) cyclic loading in clays, sands, and silts with weak interparticle bonding; and (3) reduction, by sudden shock, of intergranular bonding afforded by cohesion and internal friction, irrespective of the degree of saturation.

Ground settlement is herein defined as vertical displacement of the ground surface related to consolidation of sediments, subsurface sediment flow, landsliding, or to a combination of those processes.

Ground cracks include fissures or openings in the ground produced by seismic shaking. Ground cracks are often related to other forms of ground failure, such as landsliding and settlement.

Sand boils or sand blows, though not technically a form of ground failure, are considered because of their relation to some occurrences of landsliding, settlement, and ground cracking. Sand boils are discussed in more detail in a following section on liquefaction and related ground failure.

Miscellaneous effects that often are related to earthquake-induced ground failure, but are not in themselves conclusive evidence of ground failure, include broken or damaged underground utility lines, permanent bridge and piling displacements, bent or broken well pipe, disruption or change in water well or spring flow, and formation of clouds of airborne sediment (dust clouds) in areas susceptible to rockfalls, rockslides, or rock avalanches.

Types of earthquake-induced ground failure that have occurred in association with earthquakes in other areas, but have not been identified with the 1949 or 1965 Puget Sound earthquakes, include ground cracking directly related to tectonic faulting and regional tectonic subsidence or settlement. Although these forms of ground failure have not been identified among those produced by the 1949 and 1965 earthquakes, and thus are not discussed in this report, they are possible sources of loss in future earthquakes.

LIQUEFACTION AND RELATED GROUND FAILURE

Damaging earthquake-induced ground failure is often the result of liquefaction within a deposit of loose, saturated sand or other granular material. Liquefaction is defined as "the transformation of a granular material from a solid state into a liquefied state as a consequence of increased pore-pressures" (Youd, 1973). Ground shaking or cyclic loading during an earthquake initiates liquefaction in a loose, saturated granular soil by disrupting grain-to-grain contacts; ensuing soil consolidation and transference of overlying load from the grains to the pore water between the grains result in increased pore pressure and nearly complete loss of shear strength. The strength loss can result in lateral displacement of large surficial blocks of soil on gently sloping or nearly level ground (lateral spreads), flow failures on moderate to steep slopes (mud, earth, and debris flows), settlements, loss of bearing capacity, and sand boils. The following descriptions of liquefaction-related ground failure are excerpted, in large part, from a report by the Committee on Earthquake Engineering (1985).

Lateral spreads generally develop on very gentle slopes (most commonly between 0.3° and 3°) and move toward a free face, such as an incised stream channel. Lateral displacements range up to several feet, and, in particularly susceptible conditions, to several tens of feet, accompanied by ground cracking and differential vertical displacement (Youd, 1978). Lateral spreads often disrupt the foundations of buildings or other structures, rupture pipelines and other utilities in the failure mass, and compress engineering structures crossing the toes of the failures.

Flow failures develop in loose saturated sands or silts on natural or man-made slopes greater than 3°. Flows may consist of completely liquefied soils, or of blocks of intact material riding on layers of liquefied soil. They often displace large masses of material for many tens of feet at velocities ranging up to tens of miles per hour.

Consolidation and settlement of saturated sediments are commonly associated with and enhanced by liquefaction. Settlement of the ground surface at Portage, Alaska, due to the 1964 earthquake, lowered the ground sufficiently so that houses and highway and railroad grades were inundated at high tide.

Loss of bearing capacity occurs when the soil supporting a building or other structure liquefies and loses strength. This process results in large soil deformations under load, allowing buildings or other structures to founder and sink into the ground. A 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 FAILURES DUE TO HISTORIC EARTHQUAKES IN THE WESTERN WASHINGTON-NORTHWEST OREGON REGION

It is estimated that a magnitude 4 earthquake is the smallest earthquake 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 historic earthquakes capable of causing ground failures. Noson and others (1988) list 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 mountains, and along the Washington-Oregon border.

As was noted by Noson and others (1988), 14 earthquakes, occurring from 1872 to 1980, are known to have triggered landslides in Washington. However, information on the distribution and nature of landslides and other ground failures related to historic 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 (M 7.0-7.5), are limited to the few reports of landslides along the Columbia River east of the Cascades, along the shores of Lake Chelan north of Wenatchee, 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-million-m^3 Ribbon Cliffs rockslide 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 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 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); apparently few details are known about the extent and nature of those ground failures. A well-known and well-documented rockslide/debris avalanche, the world's largest historic landslide (volume = 0.62 mi^3 (2.7 km^3)), was triggered by a magnitude 5 earthquake associated with the 1980 eruption of Mount St. Helens. The landslide swept some 14 mi (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).

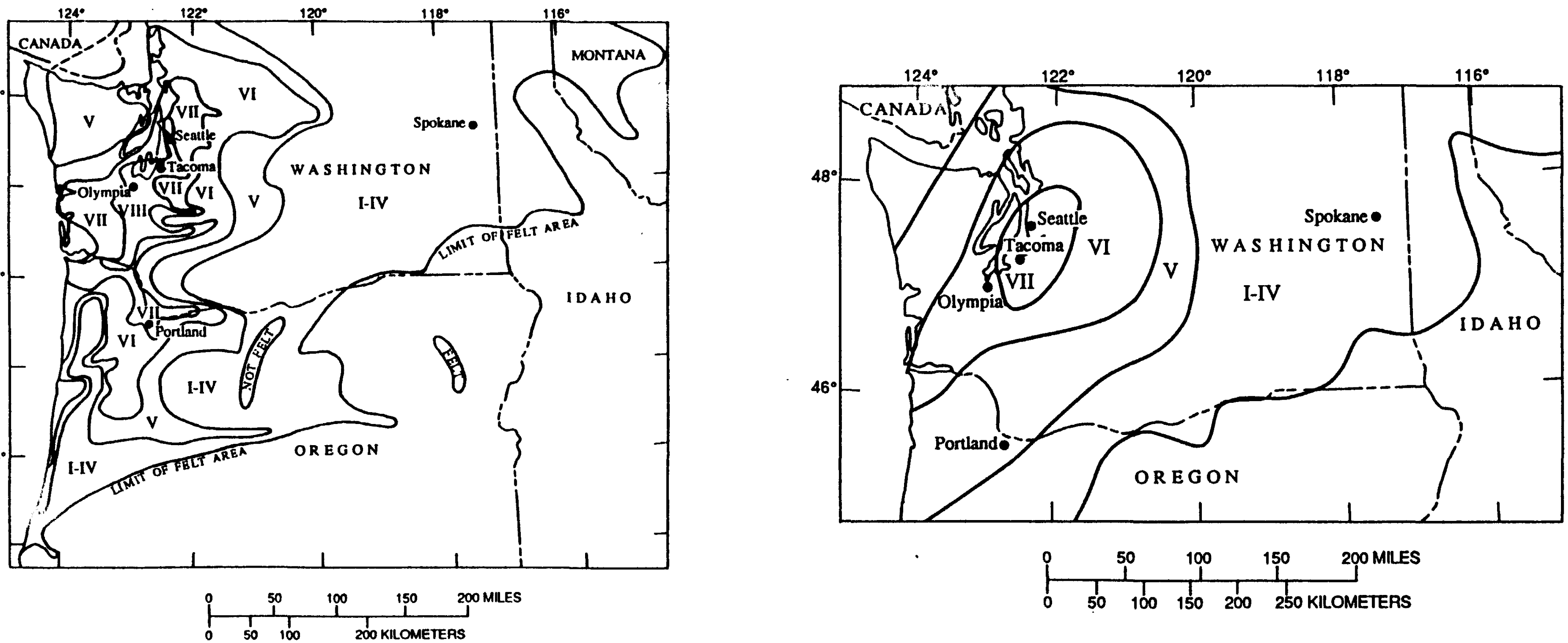
During the period from 1872 to 1989, the greatest number of recorded earthquake-induced ground failures occurred as a result of the magnitude 7.1 Olympia earthquake of April 13, 1949, and the magnitude 6.5 Seattle-Tacoma earthquake of April, 29, 1965. Consequently, ground failures associated with those 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 data 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 of intensity VIII MMI 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. 1). 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, or beach sediments; deltas of rivers emptying into Puget Sound; and rock or soil slopes steeper that 35° in the Puget Sound lowland or adjacent mountains.

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 post-earthquake 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 post-earthquake 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.



A

B

Figure 1.--Intensity maps for the Puget Sound earthquakes of, A, April 13, 1949 (modified from Ulrich, 1949), and B, April 29, 1965 (modified from Algermissen and Harding, 1965).

CHARACTERISTICS OF THE STUDY AREA

Ground failures associated with the 1949 earthquake were scattered over an area of approximately 11,000 mi^2 (28,490 km^2) and those of the 1965 earthquake over an area of approximately 8,000 mi^2 (20,720 km^2). The total area considered in this study encompasses the two areas of reported ground failure extending from near the Canadian border on the north to just beyond Portland, Oregon, on the south and from the Cascade Mountains on the east to the Pacific Ocean on the west (fig. 2).

The physiography and geology of the total area affected by 1949 and 1965 ground failures (fig. 2) is highly varied. A broad lowland, bordered on the east by the Cascade Mountains 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, thickness of unconsolidated sediments exceeds 3,000 ft (900 m) (Hall and Othberg, 1974). The Pleistocene sediments cover Tertiary sedimentary and volcanic bedrock in all but a few areas, where bedrock is covered by younger sediments or is exposed at the surface. Continental glacial sediments extend from beyond the study area on the north to a hilly area between Olympia and Chehalis on the south, and from the Olympic Mountains on the west to the Cascade Mountains 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 and engineering properties. Compared to bedrock and postglacial deposits, glacial sediments overriden by glacial ice are intermediate in both density and water content (Mullineaux, 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 several hundred feet above sea level. In many places, erosion of the glacial sediments has produced steep slopes that are susceptible to landsliding.

Areas underlain by deltaic sediments, tidal flat muds, or beach deposits are found at numerous locations bordering the many miles 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.

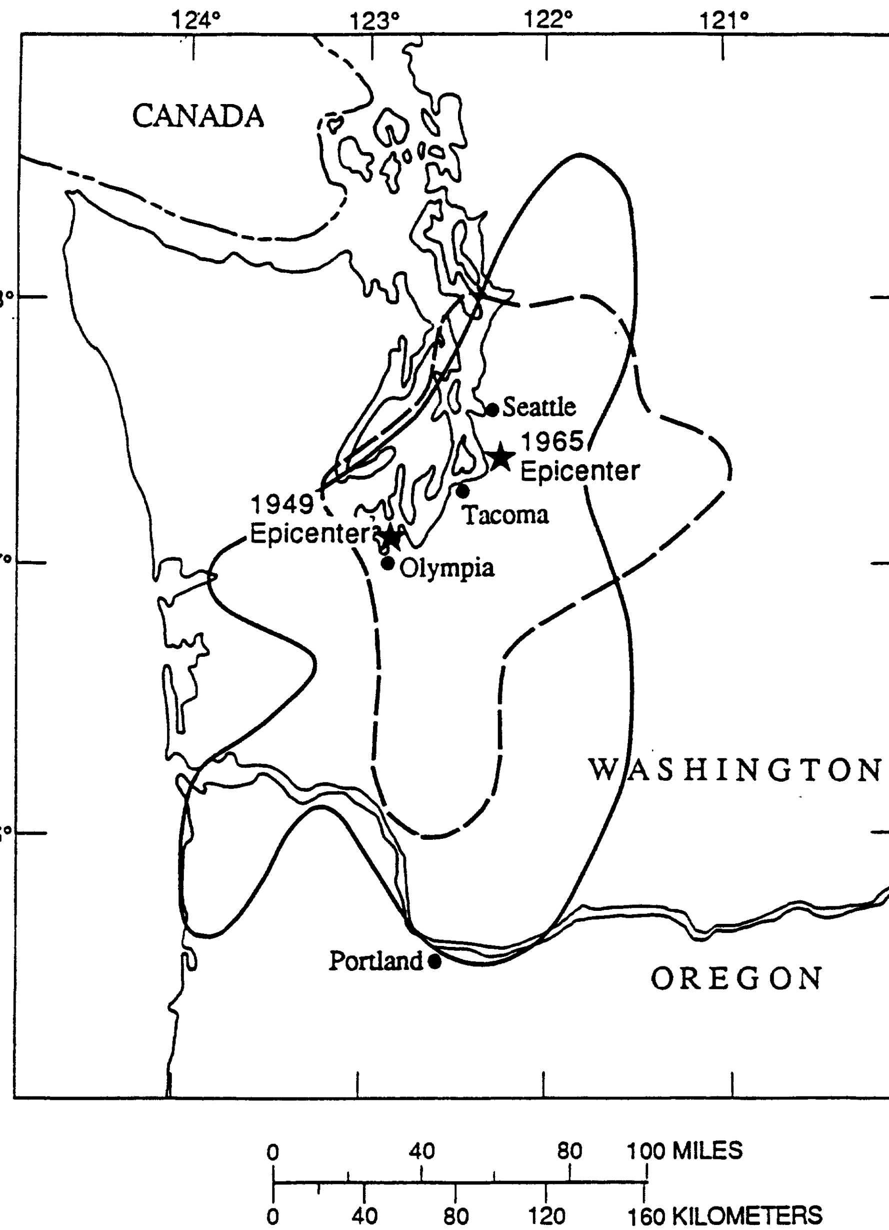


Figure 2.--Approximate areas of reported ground failures related to the Puget Sound earthquakes of April 13, 1949 (solid line) and April 29, 1965 (dashed line) (modified from Keefer, 1983).

Valley floors in the lowland are underlain chiefly by postglacial alluvial deposits of unconsolidated sand, silt, clay, and gravel up to several hundred feet 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 approximately 65 mi^2 (170 km^2) to depths as great as 75 ft (23 m) (Crandell, 1963).

The rugged Cascade Mountains, in the eastern part of the study area, rise from a few hundred feet above sea level on their western border with lowland areas to as high as 14,400 ft (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 the Cascade Mountains of northern Washington, a variety of rock types are present, 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 that comprise 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 volcanics (Walsh and others, 1987). In a few scattered areas, metamorphics and marine and continental sedimentary rocks of various ages, are present.

Towering, snowclad volcanoes, such as Mount Rainier, dominate the landscapes of their regions. At many locations on the volcanoes, steep rock faces and precipitous cliffs have been formed by the action of glaciers and other erosive agents. Jointed volcanic strata, comprising the sides of the volcanoes, typically dip downslope, adding to other factors that often 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 the valleys of the Lewis, Kalama, Toutle, Cowlitz, Nisqually, Puyallup, White, Green, and Cedar Rivers. Alpine glacial drift, including till, and glaciofluvial and glaciolacustrine sediment, is 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 lie south or southwest of the Puget Sound lowlands in parts of 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 (silt, sand, gravel, and clay) (Trimble, 1963; Walsh and others, 1987). Local areas of artifical fill are common in some towns and urban areas, along railroads and highways, and at the site 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 those upland areas range in elevation from several hundred to a few thousand feet above sea level. The Coast Range of far southwestern Washington and far northwestern Oregon is composed predominantly of marine and non-marine sedimentary rocks, various types of volcanics, 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. Major geologic materials that underlie those areas include volcanics, continental sedimentary rocks, alpine glacial outwash deposits, and periglacial flood deposits.

Similar to other parts of the study area, artificial fill is present locally in developed areas and along transportation corridors in southwestern Washington and northwestern Oregon. Also, beach deposits that include fine- to coarse-grained beach sands and gravels, dune sands, and estuarine muds and sands are common in the Pacific coastal areas of the region.

The regions discussed above include large areas of western Washington and northwestern Oregon 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. 3). The winter-spring wet season in western Washington and northwestern Oregon extends from the month of September through April. In the area of study, annual precipitation means range from approximately 48 in./yr (122 cm/yr) in the area of the Puget-Willamette lowland to more than 100 in./yr (254 cm/yr) in the high, snowy parts of the Cascade Mountains. Precipitation records for the Seattle-Tacoma area for the water years 1948-1949 and 1964-1965 (the water years associated with the 1949 and 1965 earthquakes) are shown in figure 4. As shown in figure 4, the 1948-1949 and 1964-1965 water years were slightly below normal; 3.41 in. (8.66 cm) below normal in 1948-1949 and 2.60 in. (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 4. Precipitation during that year was 16 in. (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 fallen similar to that in the 1971-1972 water year it is likely that many more ground failures would have have been triggered by the two earthquakes.

DISTRIBUTION AND CHARACTER OF GROUND FAILURE TRIGGERED BY THE APRIL 13, 1949, AND APRIL 29, 1965, PUGET SOUND EARTHQUAKES

Data compiled on individual ground failures are presented in plates 1-5, which show ground-failure locations (1949, closed symbols; 1965, open symbols), and in appendix tables 1-5, which provide descriptions of selected ground failures keyed to location numbers found on the respective location maps (pls. 1-5). Ground failures selected for inclusion in tables 1-5 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

Figure 3.--Contour map showing mean annual precipitation (in inches) in Washington and Oregon for the period 1931-1960 (modified from U.S. Geological Survey, 1970).

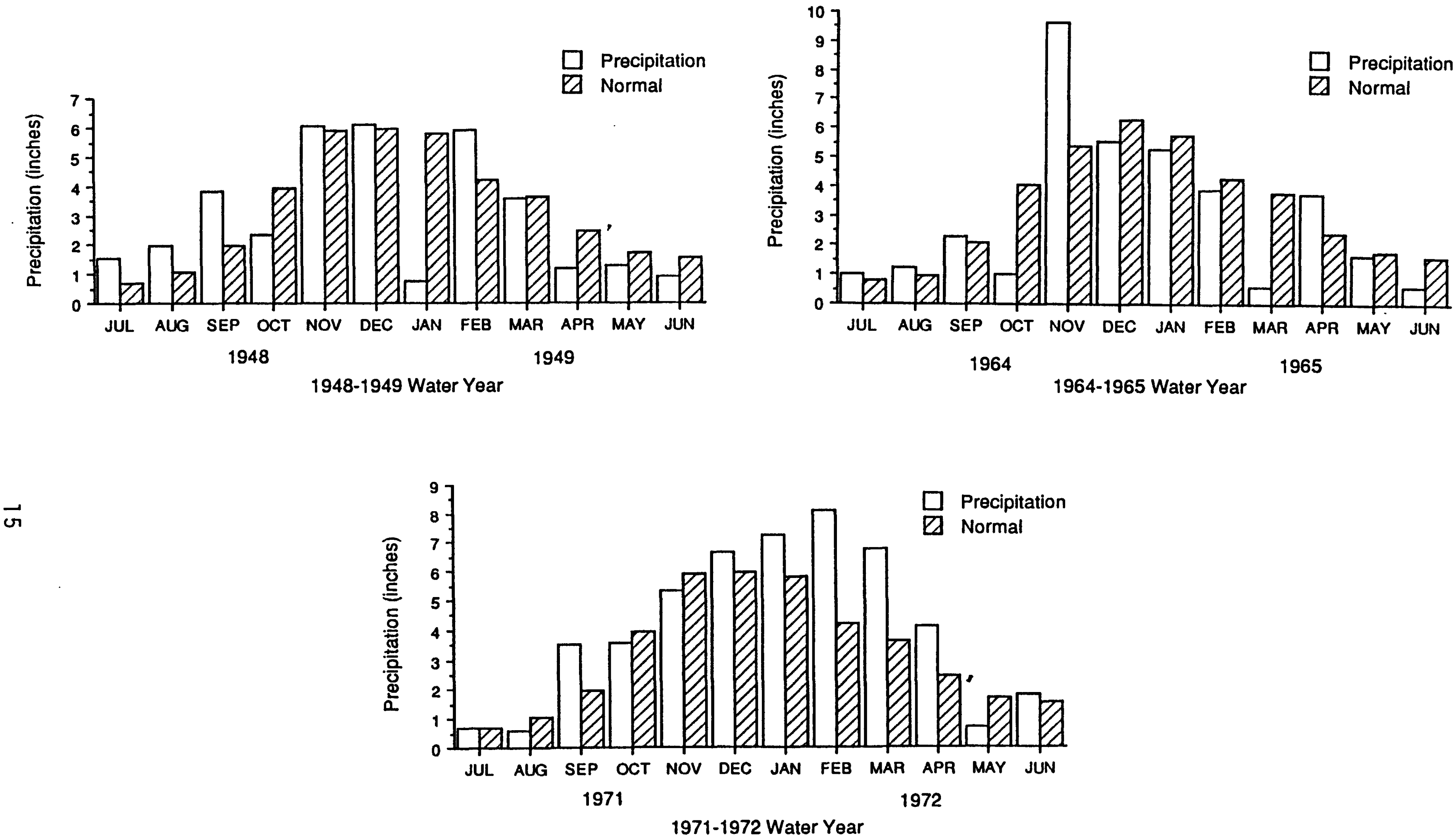


Figure 4.--Graphs showing precipitation in the Seattle-Tacoma area for the water years 1948-1949, 1964-1965, and 1971-1972 (U.S. Department of Commerce).

showing concentrations or trends of ground failure, and (6) ground failures that have affected engineering 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. These ground failures are included on the location maps (pls. 1-5) 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 1-5 and plates 1-5 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 (fig. 5, pls. 1-5). 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, insofar as possible, on similarities and differences 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. 1 and 2, fig. 5) includes much of the Puget Sound lowland. Approximately 85 percent of the reported ground failures in the 1965 earthquake and 50 percent in the 1949 quake occurred in this region. Some areas of the region experienced Modified Mercalli intensities (MMI) as high as VIII during the 1949 and 1965 earthquakes (Ulrich, 1949; Algermissen and Harding, 1965, von Hake and Cloud, 1967) (figs. 1 and 5). 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, etc. 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 structures, including roads, railroads, buildings, waterfront facilities, utility lines, and recreational facilities. One large debris avalanche, with an estimated volume of approximately 650 x 10^3 yds^3 (500 x 10^3 m^3), 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 an environment 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. These and other of the region's ground failures are considered in greater detail in the following discussion.

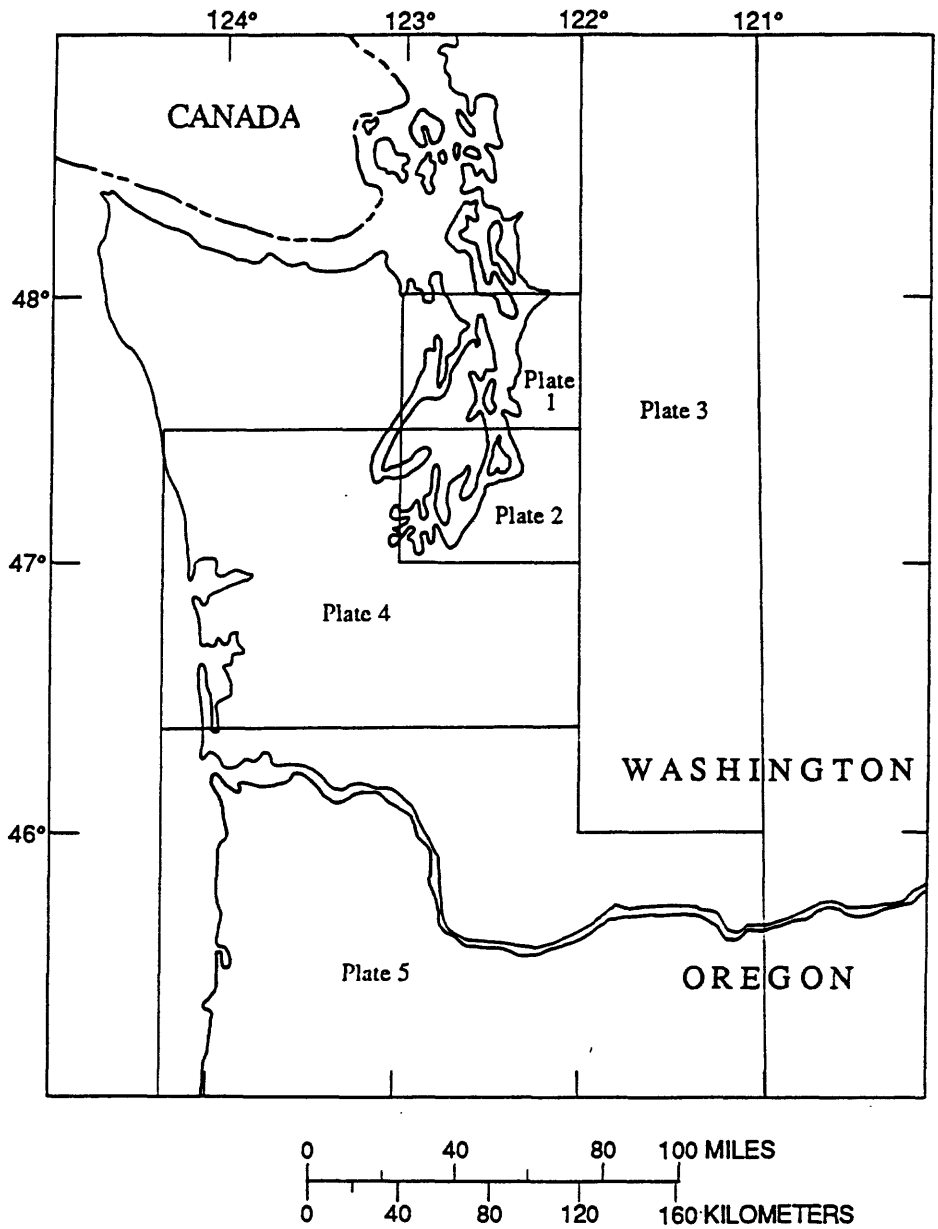


Figure 5.--Map of the western Washington-northwestern Oregon region showing areas covered by ground-failure location maps (plates 1-5).

NORTHERN HALF OF THE CENTRAL AND SOUTHERN PUGET LOWLAND REGION

The northern half of the Central and Southern Puget Lowland region (fig. 5, pl. 1) includes parts of King, Snohomish, Kitsap, Island, Jefferson, Mason, and Clallam Counties bounded by lat 48°00' on the north and 47°30' on the south, and by long 122°00' on the east and 123°00' on the west. Ground-failure locations in the northern half of the region, which includes the city of Seattle, are shown on plate 1; descriptions of selected ground failures are found in table 1 (appendix).

Plate 1 shows a conspicuous concentration of ground failure, related to both the 1949 and 1965 earthquakes, in West Seattle (area of locs. 7-13) and the adjacent Duwamish River-Harbor Island-Elliott Bay waterfront area (including locs. 14-25, and loc. 28).

In West Seattle, the number of reported ground failures for the 1965 quake far exceeded those of the 1949 event. One of the most destructive 1949 ground failures in West Seattle was a slump that occurred on moderately sloping ground in artificial fill overlying Esperance Sand (loc. 10; fig. 6). The failure reportedly damaged six homes, including four that were under construction (see damage description in the appendix, table 1). 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 Esperance Sand 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 and underlying Lawton Clay (Tubbs, 1974; Tubbs and Dunne, 1977). Ground water percolates downward through the Esperance Sand until it reaches relatively impermeable alternating sand and clay layers at the top of the Lawton Clay; 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 occurs near the Esperance Sand-Lawton Clay 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. 7). Yount (1983) suggested that the water-saturated condition along the Esperance-Lawton contact may be a contributing factor to intensified ground shaking during

Figure 6.--Slumping and settlement induced by the April 13, 1949 earthquake, damaged several houses in West Seattle. Photo shows slump scarp exposing artificial fill near Admiral Way (pl. 1, loc. 10). (Photograph from Seattle Post-Intelligencer Collection, courtesy of the Museum of History and Industry Seattle.)

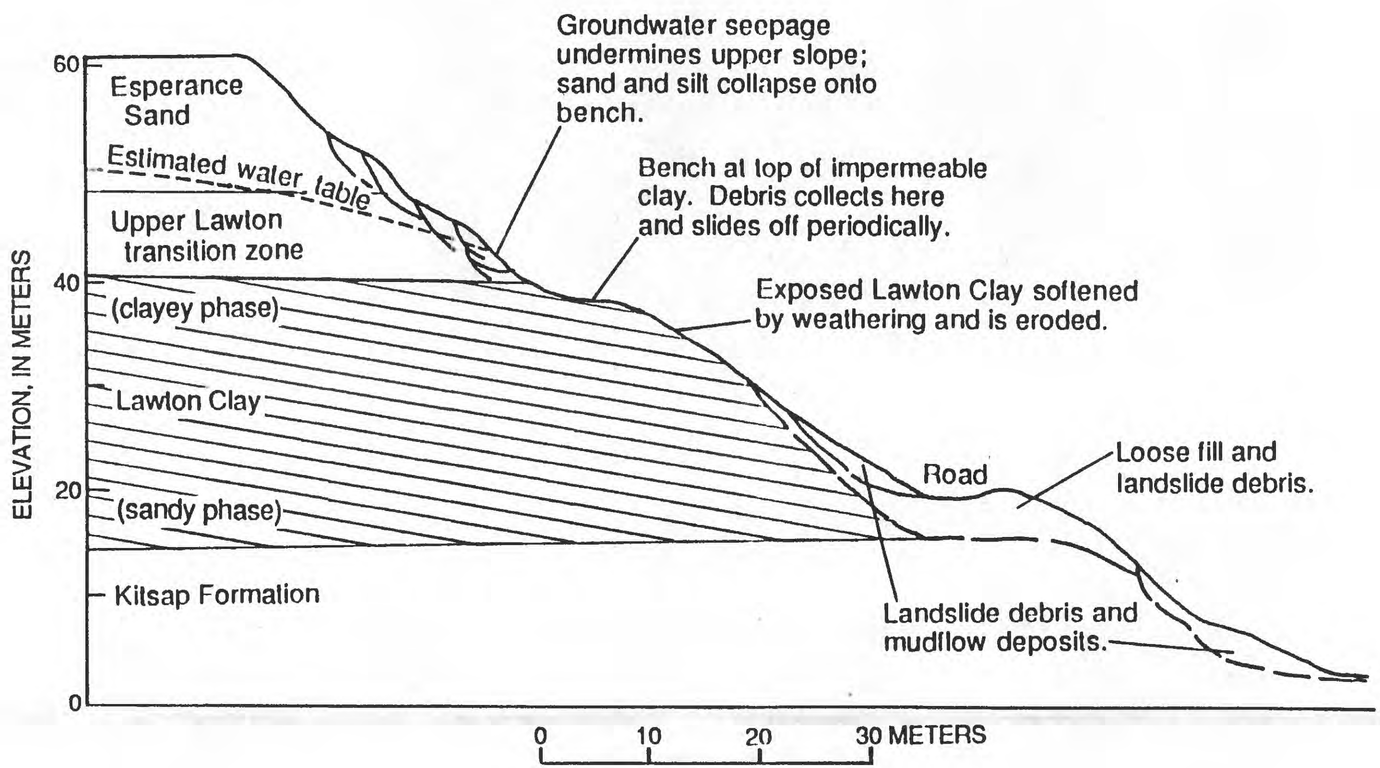


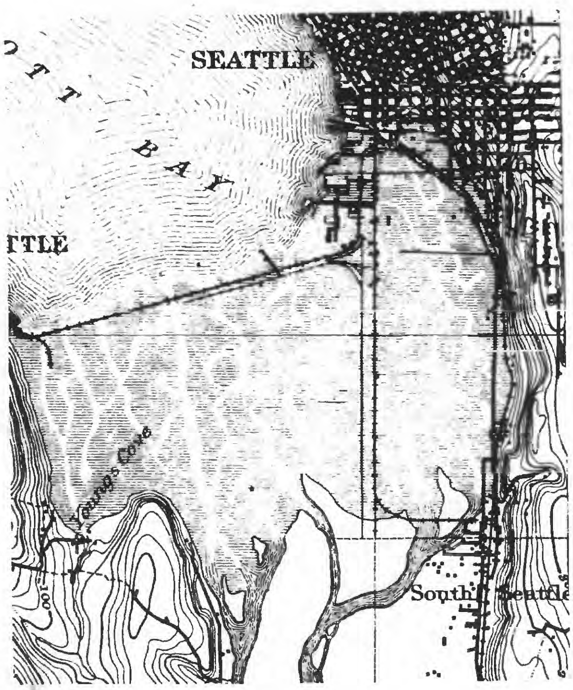
Figure 7.--Crossection of a West Seattle bluff showing stratigraphy and locations of slope failure (figure taken from Tubbs and Dunne, 1977).

earthquakes, particularly in the vicinity of Tertiary bedrock. Tertiary bedrock is exposed in West Seattle 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 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 Alki area in that vicinity 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 (Youd and Perkins, 1978; Keefer, 1984). Closer to Alki Point, in the vicinity of Alki Monument (loc. 7, open-square symbol), some 6 in. of settlement occurred in the 1965 quake 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, occurred in the Alki Point area in 1965. According to Mullineaux (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, etc., 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 all of the cluster of 1965 settling reports in west Seattle are located on Esperance Sand (called "older sand" by Waldron and others, 1962), but concluded that the relationship may be coincidental since the same geologic unit appears at other places in the city without a concentration of reported ground settlement. In addition, a study of the distribution of chimney damage related to the 1965 quake, with respect to that of various Pleistocene deposits in West Seattle, demonstrated that the damage pattern is not related to recognizable differences in the underlying Pleistocene 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 occurence 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.

The mouth of the Duwamish River-Harbor Island-Elliott Bay waterfront area lies just to the east of the West Seattle area (pl. 1). The area, much of which is a former tide flat (fig. 8), is extensively underlain by artificial fill (Waldron and others, 1962) emplaced to provide usable real estate for industrial and commercial interests in the waterfront areas. Structural damage was substantial in this area in both the 1949 and the 1965 earthquakes (Edwards, 1951; Mullineaux, 1967). The heaviest building damage in Seattle



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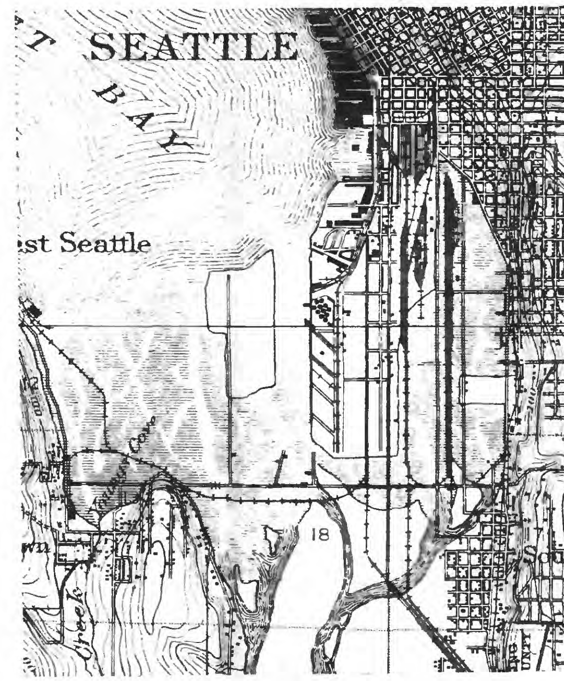

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Figure 8.--Maps showing a sequence of development of the former tidal flats area, at and near the mouth of the Duwamish River, Seattle, between the years 1893 and 1973. A, shows the area as it existed in 1893, B, in 1908, and C, in 1973. Since 1893, the tidal flats have been extensively covered by artificial fill to allow development. The area was the site of many earthquake-induced ground failures and considerable property damage in both 1949 and 1965. Map scales are approximately 1:62,500 (from U.S. Geological Survey 1:62,500 Seattle, 1894; 1:62,500 Seattle, 1909 (reprinted in 1942); 1:24,000 Seattle South, 1949 (photorevised 1968 and 1973)).

C

(related to the 1965 earthquake) occurred in this area from the lower downtown business district south to about Spokane Street and in West Seattle (Mullineaux, 1967). A considerable amount of the 1949 and 1965 damage in this area was related to ground failure (table 1, locs. 14-25 and 28). Ground-failure displacements ranged from a few inches to a few feet in both the 1949 and 1965 earthquakes, but most were less than a foot. 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 quake 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 north and south of Spokane Street (locs. 15-17 and fig. 9) in 1949, and north of Spokane Street (locs. 18 and 22) in 1965. There were many reports of settlement in the Duwamish-Harbor Island-Elliott Bay waterfront area in both 1949 and 1965 (pl. 1; table 1). Individual settlements may have resulted from consolidation of sediments, incipient landsliding, or both. The Duwamish-Harbor Island-Elliott Bay waterfront area is highly susceptible to damaging ground failure during intense seismic shaking as indicated by the numerous ground failures triggered by both the 1949 and 1965 earthquakes. High liquefaction susceptibility of artificial fill and (or) underlying postglacial sediments in the former tidal flats area is indicated by the occurrence of sand boils and incipient lateral spreads. 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 (Lake Washington) (pl. 1, loc. 31), the area just south of Green Lake (loc. 33), and two localities along the west shore of Lake Washington (locs. 4 and 27). Similar to ground failures in the Duwamish-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; Mullineaux, 1967; Hale Lowry, personal commun., 1988). Ground failure location 27 (pl. 1) 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 1 ft (0.3 m) were reported in both 1949 and 1965; damage caused by these ground failures was minor, however. The occurrence of sand boils and associated ground cracking during the April 29, 1965, earthquake (locs. 31 and 32) is evidence of the susceptibility of the artificial fill and (or) underlying alluvial and lacustrine sediments to liquefaction and liquefaction-related ground failure.

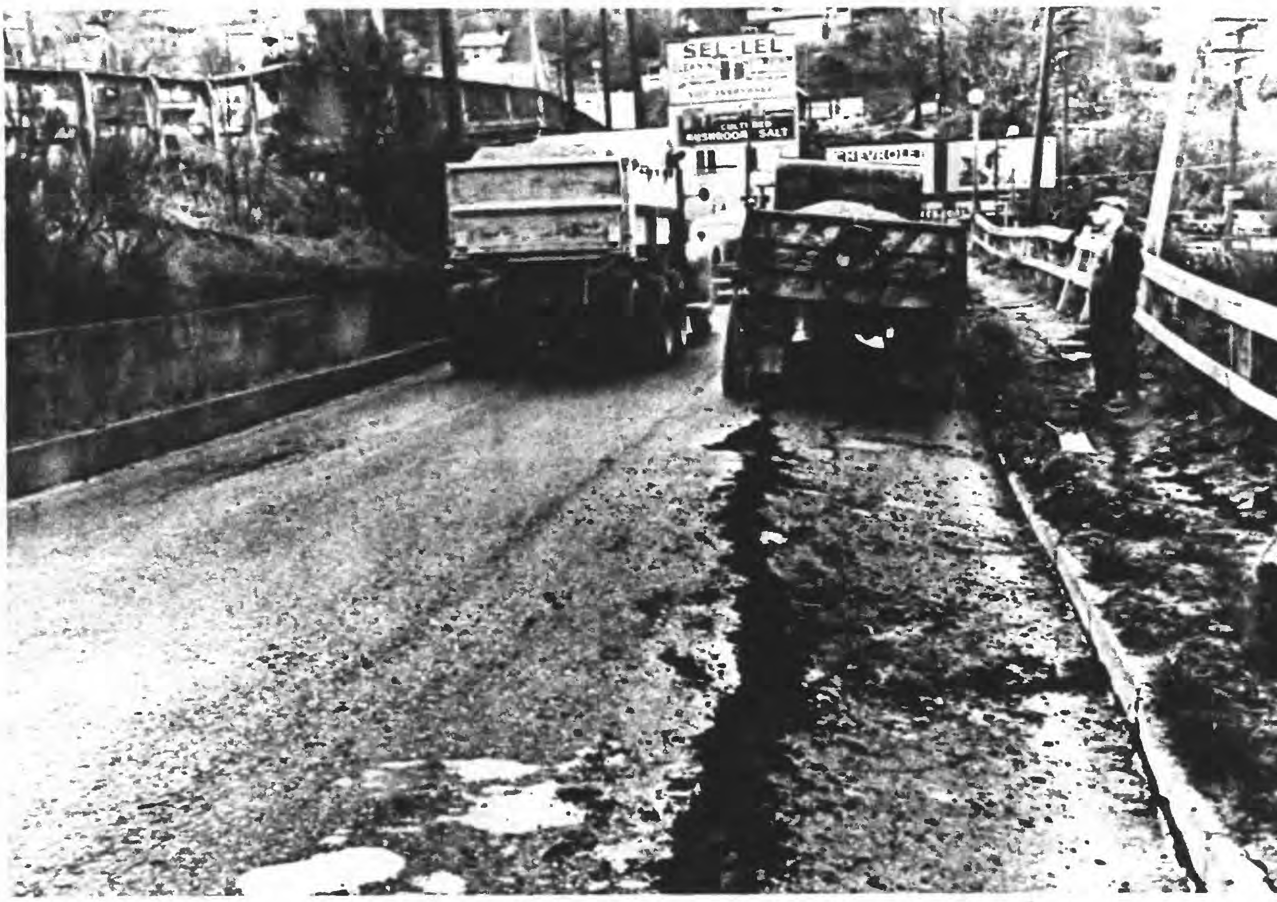

Figure 9.--View along Spokane Street approach to West Seattle (pl. 1, loc. 16). Photo shows pavement cracks and slight slump in road embankment composed of artificial fill. Note arcuate scarp and tilted light pole (right side of photo). The ground failure was triggered by the April 13, 1949, earthquake. (Seattle Post-Intelligencer Photo Collection, Museum of History and Industry, Seattle.)

Slumping and possible lateral spreading along the south shore of Green Lake (loc. 33, figs. 10 and 11) 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, 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 by 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. 12). The flow originated in a large ravine north of Piper Creek. The sides of the ravine are underlain by Esperance Sand and undifferentiated nonglacial sediments (Washington Department of Ecology, 1979a). A newspaper report (Seattle Times, 1965) states 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. 13). The failure, which took place at the head of a small drainage on moderately sloping ground, left a cavity several tens of feet across and 10 to 15 ft (3-5 m) deep. Slide debris flowed downslope for several hundred feet. The site of the failure is within an area underlain by Vashon advance outwash deposits (mostly clean sand and gravel) (Minard, 1983). According to local residents, the site is underlain locally 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 1965 earthquake badly damaged an asphalt covered parking lot in a business area adjacent to Sinclair Inlet. The failure occurred in a waterfront area of artificial fill (Washington Department of Ecology, 1979c). Spatial relationships with adjacent geologic units (Washington Department of Ecology, 1979c) suggest that the artificial fill is underlain by Esperance Sand. A newspaper photo of part of the damaged area (Bremerton Sun, 4/30/65) shows vertical displacements of the asphalt and underlying fill as great as 2 ft. Slight lateral movement was apparently in the direction of the Inlet.

Figure 10.--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. 1, loc. 33) in an area that subsequently experienced ground failure during the April 29, 1965 earthquake. (Photograph from Seattle Post-Intelligencer Collection, courtesy of the Museum of History and Industry, Seattle.)

Figure 11.--Ground cracks on the southeast side of Green Lake in north Seattle (pl. 1, loc. 33). The cracks opened during or shortly after the April 13, 1949, earthquake and probably resulted from subsidence and lateral movement of the ground downslope toward the lake (out of sight to the left of view in photo). (Photograph from Seattle Post-Intelligencer Collection, courtesy of the Museum of History and Industry, Seattle.)

Figure 12.--Mud flow covering Carkeek Park Road in Carkeek Park, northwest Seattle (pl. 1, loc. 36). This mud flow 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 by permission of the Seattle Times Co.)

Figure 13.--Earthflow in Edmonds, Wash. (pl. 1, loc. 40) induced by the April 29, 1965, Seattle-Tacoma earthquake. The landslide mobilized at the head of a small ravine and flowed downslope approximately 200 yds (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.)

A small slide in artificial fill, induced by the April 29, 1965, earthquake, extensively damaged a paved road south of Port Orchard (loc. 2, fig. 14). Movement was downslope in the direction of a small ravine adjacent to the road embankment. Vashon glacial drift underlies the artificial fill at this location.

Location no. 39 (pl. 1) 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 up to 15 ft (4.57 m) in places (von Hake and Cloud, 1967). The 50-ft (15.2 m)-high bluff is underlain by Vashon glacial drift (till and outwash sand and gravel) (Washington Department of Ecology, 1979c). Field studies in 1988 revealed zones of seepage near midslope in the reported area of sliding. The ground failure resulted in a crack and raised area on the beach, parallel to the shoreline, that was approximately 100 ft (30.5) long.

A 30 ft (9.1 m) section of highway fill, 3 mi (4.8 km) west of Kingston (loc. 41), slumped approximately 3 ft (0.91 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 (1962) indicates that the failure site is part of an area underlain by Vashon recessional outwash. 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 (fig. 5, pl. 2) includes parts of King, Pierce, Kitsap, Mason, and Thurston Counties, bounded by lat 47°30' on the north and 47°00' on the south and by long 122°00' on the east and 123°00' on the west. In this area, reported landslides, ground cracks, and settlement related to the 1949 and 1965 earthquakes were numerous and widespread (pl. 2 and table 2).

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 chiefly 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 1 ft (0.3 m), but ground cracks developed that were as long as 1,000 ft (300 m). In one instance in 1949, displacement 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

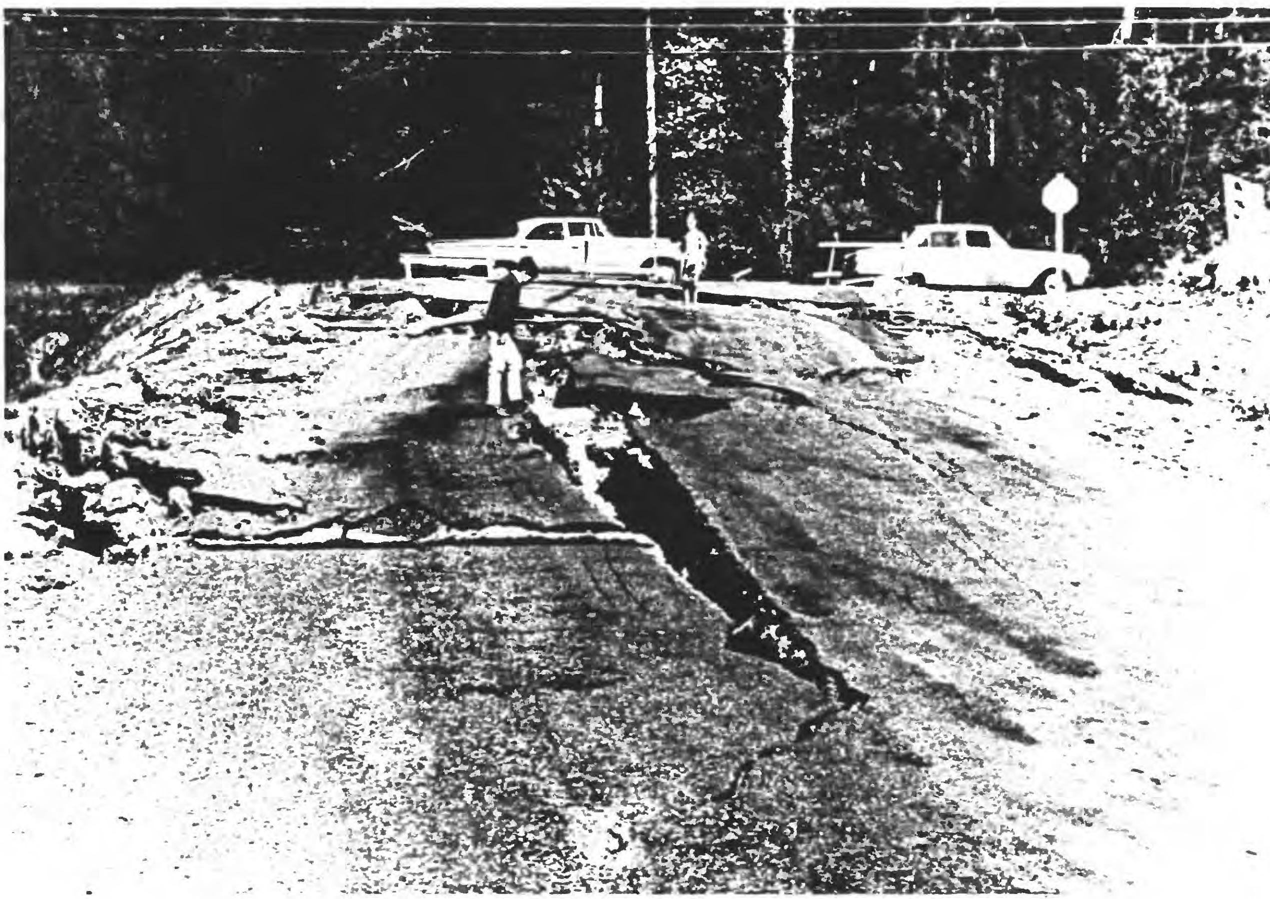

Figure 14.--Damage to Country Club Road southwest of Port Orchard, Wash., (pl. 1, loc. 2) due to slumping induced by the April 29, 1965 Seattle-Tacoma earthquake. This slump occurred in granular fill underlain by Vashon glacial drift. (Photograph by permission of the Bremerton Sun.)

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. Shulene (1989) presented information on the location and nature of sand boil occurrences in the Puyallup area. Much of the information that follows was obtained from that report. In northwest Puyallup, sand-boil activity occurred at many locations north and south of Stewart Avenue (locs. 63-69). A concentration of sand-boil activity developed at various places over a four by five city-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). Geysers (sand boils) reportedly pushed through the concrete basement floor of one home and forced timber foundation through the flooring of another, causing considerable damage. Also, it was reported that 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 2 ft (0.6 m)) of black sand were reported. Damage to basements (described above) 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 yards long and several inches wide developed, and some "geysers" reportedly deposited many yards of sediment on the surface and caused flooding (figs. 15-17). At one location, as many as 20 sand boils appeared that left "cone shaped" piles of light-colored sand as much as 7 in. (18 cm) in diameter and 8 in. (20 cm) high; at another "sand pile", diameters were estimated at 2 to 3 ft (0.6 to 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 area (loc. 68) as well. The 1965 occurrence took place on the Aylen Junior High School playfield and reportedly produced a "considerable amount of water."

It was reported that five or six "geysers" (produced by the 1949 earthquake) deposited mounds as much as 1 ft (0.3 m) high at a location along West Main Street (loc. 63), presently occupied by the Puyallup High School Gymnasium.

Figure 15.--Sand boil in Puyallup Wash., (pl. 2, loc. 68) produced by the April 13, 1949, earthquake. The 1949 earthquake generated many sand boils in the area of 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. (Photograph by Richard Six, Puyallup, Wash.)

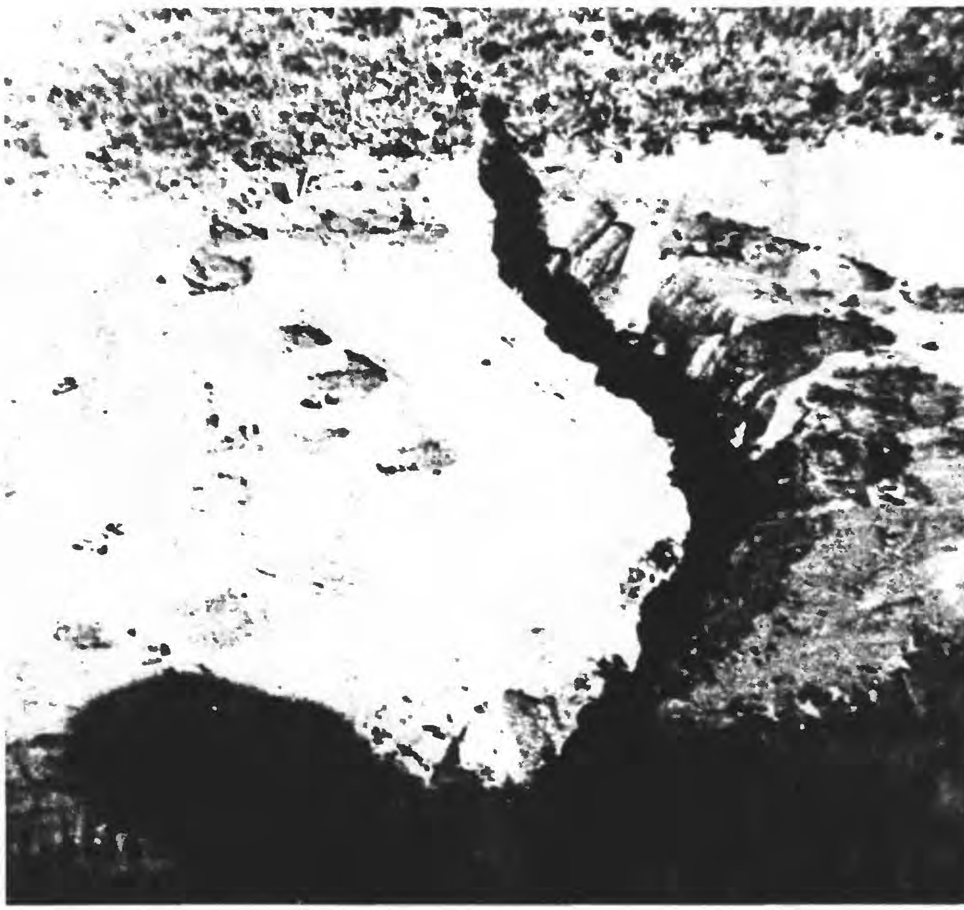

Figure 16.--Ground crack and ejected sediment (sand boil) produced by the April 13, 1949, earthquake. This open ground crack and sand boil in northwest Puyallup (pl. 2, loc. 68) may indicate incipient lateral spreading due to liquefaction of sediments. (Photograph by Richard Six, Puyallup, Wash.)

Figure 17.--Flooding in northwest Puyallup (pl. 1, 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.)

To the west (loc. 69), a basement was "pushed up" on one end so that the house teetered, and approximately 4 ft (1.2 m) of liquefied sand was ejected into a basement. Also in this area (loc. 69), 1-ft (0.3 m)-high sand mounds developed "all over" a cultivated field.

A report of ground cracks and a "shift" in a road adjacent to the Puyallup River in Puyallup (loc. 67) suggest slumping or lateral spreading at that location.

Northwest of Puyallup, along the west side of Clarks Creek (loc. 71), a crack developed during the 1949 earthquake that was 200-300 ft (60-100 m) long and exhibited as much as several feet of horizontal and vertical displacement (fig. 18). Lateral movement was in the direction of the creek, indicating lateral spreading or slumping of the alluvial soil. The foundation of a house located nearby on the east side of Clarks Creek was reportedly destroyed, probably as a result of ground failure.

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 15 ft (5 m) in diameter (loc. 72), "dozens" of sand boils composed of light-colored sand (loc. 74), and sand boils 12 to 18 in. (0.3 to 0.5 m) in diameter and 30 to 40 ft (9 to 12 m) apart, made up of black, clean sand (loc. 75).

The 1949 quake generated sand boils east and southeast of Sumner (locs. 56-58). Many small sand boils with clean, black sand were reported for one location just east of Sumner (pl. 2, loc. 58); detailed descriptions of sediment type were not reported for the other two locations (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; and in 1965, geysers ejected sand that formed many piles over two fields. In this same area, in 1949, a fissure reported to be approximately 100 ft (30 m) long, 1 ft (0.3 m) wide, and as much 6 ft (2 m) deep developed in a cultivated field. Immediately after the quake, water was observed covering the bottom of the fissure. The fissure was located near a swale immediately to the west, suggesting possible lateral movement in that direction. A well in the area revealed a sequence of 9-11 ft (3.0-3.5 m) of clean sand overlying 12-14 in. (30-35 cm) of peat, followed by more clean sand (R. Madole, U.S. Geological Survey, personal commun., 1989).

Two sand boils appeared in a cultivated field on the valley floor north of Kent near the Green River (loc. 107). A newspaper photograph of one of the sand boils (Kent News-Journal, 5/5/65) shows an open vent, approximately 1 ft (0.3 m) in diameter, surrounded by a circular apron of ejected sediment several inches deep and several feet in diameter.

Figure 18.--Ground crack along Clarks Creek northwest of Puyallup associated with slumping or lateral spreading of alluvial sediments (pl. 2, loc. 71). This 1949 earthquake-induced ground failure extended along 200-300 ft (60-90 m) of the west bank of Clarks Creek; lateral movement was in the direction of the creek (out of sight to left of view in photo). (Richards Photographic Studio Photo Collection, Tacoma Public Library, Tacoma, Wash.)

Landslides were generated along the bluffs overlooking Puget Sound, on hillsides, in road embankments, and along the banks of rivers, lakes, and other bodies of water. Landslides were triggered on the bluffs overlooking Puget Sound at Tacoma (locs. 80-83), on the east and west sides of Vashon Island (locs. 92, 94 and 95), on Fox Island (loc. 84), and west of the Seattle-Tacoma Airport near Three Tree Point (loc. 109). The largest reported landslide triggered by either of the Puget Sound earthquakes occurred on a steep, 300-ft (90 m)-high bluff on the eastern shore of the Tacoma Narrows, 3 days after the April 13, 1949, quake (loc. 81, fig. 19). The bluff failed catastrophically, sending approximately 65 x 10^4 yds^3 (50 x 10^4 m^3) of sand, gravel, trees, and other debris plunging into the waters of Puget Sound. The slide narrowly missed nearby beach homes and created an 8-ft (2.5 m) wave front that did minor damage to small docks and boats moored nearby. At the site, thick layers of unconsolidated sand, and sand and gravel overlie a firm silty clay base. Seepage occurs near the bottom of the slope at the gradational contact between the clay base and overlying sand. Geologic mapping indicates that the bluff area is underlain (from top to bottom) by Vashon glacial outwash, Esperance Sand, and undifferentiated Pleistocene sediments (Washington Department of Ecology, 1979b). A report of white sand boiling up through a deep crack a short distance from the cliff's edge (Vogel, 1949) suggests that liquefaction of sediments within the hillside may have weakened the slope at the time of the 1949 earthquake, 3 days prior to the failure (Chleborad and Schuster, 1989). Also in 1949, in a similar geologic setting (pl. 2, loc. 84 on Fox Island), a 50- to 100-ft (15.2-30.5 m)-high bluff failed, dumping a small house into Puget Sound. The bluff at that location is composed of Esperance Sand and underlying undifferentiated Pleistocene sediments (Washington Department of Ecology, 1979b). Two slumps that caused minor damage along the bluffs in Tacoma (locs. 80 and 82) showed activity in 1949 and 1965; both are in areas underlain by a sequence of Pleistocene sediments that includes the Esperance Sand.

A landslide (triggered by the 1965 earthquake) on a steep bluff on the west side of Vashon Island near Sanford Point (pl. 2, loc. 92) reportedly involved "tons of sand". Pleistocene sand deposits older than Vashon till underlie the bluffs of that area (Washington Department of Ecology, 1979a). In 1965, at Klahanie on the east side of the island (loc. 94), slumping occurred along approximately 200 ft (60 m) of hillside underlain by Vashon advance outwash and Esperance Sand. The slope failure resulted in minor damage to a waterfront cottage and retaining wall. Farther south on the island, near Burton (loc. 95), a slide that originated on a steep bluff covered the main highway between Burton and Tahlequah. Vashon till and Esperance Sand are the mapped geologic units that underlie that area (Washington Department of Ecology, 1979a). East of Vashon Island near Three Tree Point (pl. 2, loc. 109), an incipient slope failure, related to the 1965 seismic event, is suggested by the report of a ground crack 3-4 in. (8-10 cm) wide and at least 200 ft (60 m) long. The ground crack was located in the upper part of a steep 300-ft (100 m)-high bluff overlooking Puget Sound. The

Figure 19.--Tacoma Narrows landslide, April 16, 1949 (pl. 2, loc. 81). This landslide was probably triggered by the 1949 Olympia earthquake which occurred 3 days before the slide. The large mass narrowly missed homes to the south on Salmon Beach as it plunged into the waters of the Tacoma Narrows. The resulting 8-ft (2.5-m) tidal wave damaged small boats and nearby dock facilities. (Photograph by permission of Associated Press).

crack was oriented parallel to the strike of the slope. A short distance to the north, at location 109, the 1965 earthquake triggered a slope failure that damaged a retaining wall. Both ground failures (loc. 109) are in an area underlain by a large landslide deposit in Vashon glacial sediments (Waldron and others, 1962; Washington Department of Ecology, 1979a).

Hillside landslides involving glacial materials also occurred at locations inland from the bluffs of Puget Sound. East of Auburn, along the Big Soos Creek drainage (loc. 102), a hillside underlain by deposits of mass wasting, including relatively large block slides (Mullineaux, 1965b), showed evidence of earthquake-induced slope movement in 1949 and 1965. Several miles to the north, along the Big Soos Creek drainage (loc. 105), approximately 100 ft (30 m) of hillside above a small reservoir slumped slightly during and immediately after the 1949 quake. Ejection of sediment and additional water from a spring on the hillside indicate possible liquefaction of sediments.

To the south, near Orting (pl. 2, loc. 54), a 1965 ground crack reported to be 400-500 ft (120-150 m) long and 6 in. (15 cm) wide, and probably related to incipient sliding, opened along the brow of a hill overlooking Kapowsin Creek. Geologic mapping by Crandell (1963) indicated that the hillside is underlain by proglacial lacustrine sand.

The 1949 and 1965 earthquakes generated a number of slumps in road embankments composed of artificial fill. A 1949 road failure south of Port Orchard (loc. 87) occurred at the same location as a previous ground failure triggered by an earlier seismic event, the magnitude 6.2 Puget Sound earthquake of November 12, 1939. The 1939 ground failure was 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 [240 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 earthquake motion." Geologic mapping by Garling and others (1965) indicated that the area is underlain by Colvos Sand. It is thought that the upper part of the Colvos Sand can probably be correlated with the Esperance Sand in some areas (Washington Department of Ecology, 1979c).

A slump in a 20-ft (6 m)-high embankment of artificial fill adjacent to Case Inlet (pl 1, loc. 86) in 1949 resulted in ground cracks and as much as 6 in. (15 cm) of vertical displacement along 100 ft (30 m) of highway; the slump was reactivated by the 1965 earthquake. The site is part of an area underlain by Pleistocene sand older than Vashon till (Washington Department of Ecology, 1980b).

Failures involving artificial fill founded on postglacial alluvial sediments damaged roads in the Duwamish valley in the vicinity of Kent (locs. 104 and 108) in 1965. Small slumps at those locations resulted in displacements of a few inches (loc. 104) to a few feet (loc. 108); damage was minor.

A 1965 failure (loc. 83) in artificial fill undermined the roadway on the mainland side of the approach to Day Island bridge on the east side of the Tacoma Narrows. It was reported by the press that the slide sent trees and earth cascading into a gully.

As a result of the 1965 tremor, road-embankment failures in artificial fill founded on tidal-flat muds occurred at Gig Harbor (loc. 89), west of Grapeview at McLane Cove (loc. 85), and in Olympia (loc. 48). At location 72 west of Grapeview, a 30-ft (9 m)-high road embankment crossing a small arm of McClane Cove reportedly split down the middle and moved out along the cove as "a kind of flow". At Gig Harbor (loc. 89), a slump along 20 ft (6.1 m) of roadway caused fill material to move into a small creek and tidal pool.

Extensive slumping of artificial fill founded on tidal flat muds occurred along a 0.5-mi (0.8 km) stretch of the Deschutes Parkway on the west side of Capitol Lake in Olympia (pl. 2, loc. 48; fig. 20). Sand boils in the immediate vicinity (fig. 21) suggested that the ground failure was liquefaction induced.

The 1965 earthquake also generated a slump in artificial fill on a steep slope on the east side of Capitol Lake in Tumwater (loc. 45). The failure badly damaged 150 ft (45.7 m) of Union Pacific freight-line track (fig. 22) and broke the City of Tumwater's main sewerline, causing sewage to spill into Capitol Lake. The hillside is underlain by Vashon outwash sand (Walsh and others, 1987).

South of Olympia (loc. 44), approximately 75 ft (30 m) of one lane of Black Lake road was damaged in 1949 by slumping. The failure occurred on a steep, 25-ft (8 m)-high lake bank underlain by Vashon outwash sand and possibly some artificial fill.

Approximately 150 ft (45 m) of the sandspit at Cooper's Point north of Olympia (loc. 51, fig. 23) 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 approximately 50 ft (15 m) in an area where formerly the spit was 5 ft (1.5 m) above water at high tide. The sandspit is a Holocene age beach deposit (Washington Department of Ecology, 1980a) that includes medium to coarse sand and minor gravel.

Figure 20.--Damage to Deschutes Parkway, Olympia, Wash., resulting from 1965 earthquake-induced ground failure (pl. 2, loc. 48). The Parkway was constructed on granular fill placed on tidal-flat muds which are now within the limits of Capitol Lake; failure was probably due to liquefaction. (Photograph by G.W. Thorsen, Division of Geology, Washington Department of Natural Resources, Olympia.)

Figure 21.--Sand boils (near Capitol Lake in Olympia, Wash.) related to the earthquake of April 29, 1965 (pl. 2, loc. 48). The sand boils are evidence of soil liquefaction at this ground failure location. Sidewalk slab in background shows scale. (Photograph by G.W. Thorsen, Division of Geology, Washington Department of Natural Resources, Olympia.)

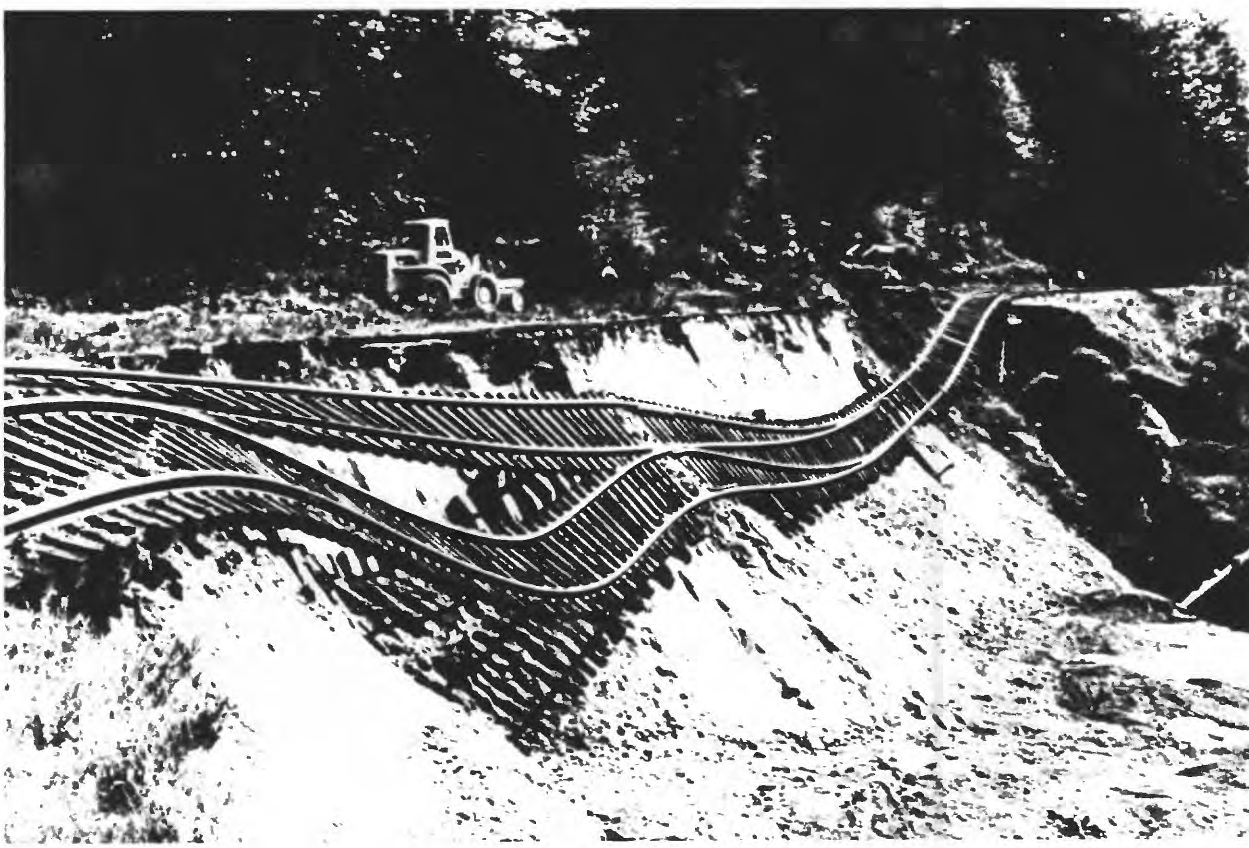

Figure 22.--Damage to Union Pacific Railroad tracks near Olympia, Wash. (pl. 2, loc. 45) due to a 1965 earthquake-induced slope failure in artificial fill. It was reported by the press that the slide severed the city of Tumwater's main sewage line causing sewage to flow into Capitol Lake. (Photograph by G.W. Thorsen, Division of Geology, Washington Department of Natural Resources, Olympia.)

Figure 23.--View of Cooper's Point located 7 mi (11 km) north of Olympia (pl. 2, loc. 51). Approximately 150 ft (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).

In Olympia, extensive settling was reported in 1949 in the Port of Olympia area (loc. 50) and in a residential area three to eight city blocks east of the State Capitol (loc. 46). The entire port area, underlain by artificial fill, was reported to have settled 5 in. (13 cm). Pipelines were broken and asphalt was bulged up over pilings. Settlement east of the State Capitol (loc. 46), which reportedly occurred in an area underlain by a peat soil, damaged several residences.

CASCADE MOUNTAINS OF WASHINGTON REGION

The Cascade Mountains of Washington Region (fig. 5, pl. 3) includes the area bounded by lat 49°00' on the north and 46°00' on the south, and by long 121°00' on the east and 122°00' on the west. 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. 3, table 3). Ground failures produced by the 1949 and 1965 earthquakes in this mostly mountainous region include (in order of abundance): rockfalls and rockslides 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 alluviated 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 rock fell from steep cliffs east of Randall onto Cline Road (locs. 120 and 121) and onto the old Randle-Packwood Highway (loc. 122). The blocks of rock were reported to be as large as 20 ft (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. Simultaneously, on the same property (loc. 118), numerous sand boils erupted. Road damage caused by the slump is shown in figure 24. A mile to the east and closer to the Cowlitz River (loc. 119), small slumps were triggered along the bank of an abandoned river channel.

Rockslides on Mount Rainier were reported for both the 1949 and 1965 earthquakes. In 1949, a "major" rockslide 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.3, locs. 126). Closer to the community of Longmire, the 1949 tremor induced rockfalls and (or) rockslides, 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). Landsliding on and near Mount Rainier, related to the 1949 and 1965 earthquakes and to several other historic earthquakes prior to the 1949 event (Noson and others, 1988), strongly

Figure 24.--Slump of 3-4 ft (1-1.2 m)-high road embankment in the Cowlitz River Valley, approximately 1 mi (1.6 km) southwest of Randle, Wash. (pl. 3, 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.)

indicates 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 (loc. 130, fig. 25) was the site of earthquake-triggered rockslides in 1945, 1949, and 1965. On April 29, 1945, an earthquake with a felt magnitude of 5.9 (Noson and others, 1988) occurred in the Mount Si area. Landsliding on Mount Si, related to the 1945 event, 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 rockslide, was observed rising from the west side of the mountain at about the 2,000 ft (610 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 rockfalls, rockslides, and (or) rock avalanches. Metavolcanics (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. It was also reported that the dams were not endangered. Small slides in the vicinity of Mud Mountain Dam (loc. 127) were 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.

CENTRAL-SOUTHWEST WASHINGTON REGION

The Central-Southwest Washington Region (fig. 5, pl. 4) extends from lat 47°30' on the north to lat 46°22' on the south, and from long 122°00' on the east to the Pacific Ocean on the west (excluding the area of plate 1, fig. 5). Included in the region is all of Lewis County west of long 122°00', the area of southwestern Pierce County south of lat 47°00' and west of long 122°00', all of Thurston County south of lat 47°00', Mason County south of lat 47°30' and west of long 123°00', all of Grays Harbor County south of lat 47°30', and all but the far southwestern 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 4;

Figure 25.--Mount Si near North Bend, Wash. (pl. 3, 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).

quotations and comments describing selected ground failures (numbered locations on plate 4) are found in table 4 in the appendix.

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. 42). 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 10 ft (3 m) wide, forming "patches" on the ground as wide as 10 ft (3 m). The area is underlain by Vashon Glacial 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), approximately 20 ground cracks appeared in a farmer's field; from some of these (figs. 26 and 27), geysers of water and sediment spouted as much as much as 18 in. (50 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), a sand boil(s) erupted from a ground crack approximately 1 in. (2.5 cm) wide and 15 ft (5 m) in length. 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" 2 ft (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, nor the type of sediments 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.

Settlement of the ground, 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 areas are underlain by alluvial sediments that are locally covered by artificial fill.

Figure 26.--Alignment of sand boils in field 1 mi (1.6 km) southwest of Centralia (pl. 4, loc. 146) is related to linear ground crack from which the water and sand were emitted. Geysers of water and sand spouted as much as 18 in (45 cm) above the ground surface and water continued to flow slowly for about a week according to an eyewitness account of this April 13, 1949, liquefaction phenomenon. (Photograph by Ted Dorn, Centralia, Wash.)

Figure 27.--Sand boils on floodplain of the Chehalis River approximately 1 mi (1.6 km) southwest of Centralia (pl. 4, loc. 146). Water and sand spouted from several ground cracks at this location at the time of the 1949 Olympia earthquake. (Photograph by Ted Dorn, Centralia, Wash.)

In the region of plate 1, 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 quakes. Although little information is available regarding the exact locations and nature of ground failures in the vicinity of LaGrande (pl. 4, 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 Lake Ohop (loc. 138) is particularly interesting because, like the Tacoma Narrows landslide (pl. 2, 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 700-ft (200 m)-long crack, 3-4 in. (8-10 cm) wide, appeared on a county road located several feet above lake level on the northwest side of the lake (loc. 138). One month later, on May 13th, complete failure occurred as the unstable mass suddenly slumped and (or) flowed about 100 ft (30.5 m) out into the lake. The failure, which involved artificial fill underlain by alluvial sediments, left a scarp on the roadway approximately 5 ft (1.5 m) high (fig. 28). Summer cottages and supports for telephone and power lines were damaged by the slide.

In 1949, a smaller slide damaged approximately 100 ft (30 m) of an approach to a railroad overpass southeast of Eatonville (loc. 137). Artificial fill was involved in that failure as well.

The 1949 quake induced a slump along approximately 100 yd (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 quake triggered a rockfall (loc. 135) from a near-vertical exposure of Tertiary age sedimentary rocks. It was reported that a block of bedrock 25 ft (8 m) high fell from the cliff, frightening homeowners below.

Reported landslides in the vicinity of Centralia and Chehalis (locs. 143 and 144) were determined to be small slumps with displacements of 2 ft (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 near Oakville (loc. 151); both involved artificial fill on poor alluvial foundations. Horizontal and vertical displacements of 2 ft (0.6 m) or less were noted.

Figure 28.--Photo of scarp created by May 13, 1949, landslide on the west side of Ohop Lake, Pierce County (pl. 3, loc. 138). Incipient failure, induced by the April 13, 1949, earthquake one month before, resulted in the development of a 700-ft (210 m)-long and 8-in. (20 cm)-wide ground crack. On May 13th, complete failure occurred as the unstable mass suddenly slumped and(or) flowed approximately 100 ft (30 m) into the lake, damaging the roadway, utility lines, and cottages near the shore. (Photograph by permission of Tacoma News Tribune.)

Part of a railroad embankment, for 275 ft (85 m), 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 10-12 in. (25-30 cm) over a nearby dock. Approximately 25,000 yds^3 (19,000 m^3) of material was required to repair the damage (U.S. Army Corps of Engineers, 1949). The failure involved artificial fill over Vashon glacial sediments.

Near Shelton (pl. 4, loc. 156), one lane of U.S. Highway 101 was damaged by a minor slump triggered by the April 29, 1965, earthquake. The slump, which was in artificial fill underlain by glacial sediments, dropped a part of the road approximately 1 ft (0.3 m) for a distance of about 150 ft (45.7 m). Also, slides generated by the 1965 quake were reported along the west side of Oakland Bay near Shelton (loc. 155). However, available information was insufficient to determine the exact location and characteristics of those ground failures.

Numerous broken water mains and sidewalk cracks in Hoquiam and Aberdeen (loc. 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 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, Oregon and Washington (fig. 5, pl. 5), are the following areas in the State of Washington: Cowlitz and Wahkiakum Counties, western and southern parts of Skamania County west of long 121°00' and south of lat 46°00', part of western Klickitat County west of long 121°00' and south of lat 46°00', and southwestern Pacific County south of lat 46°23'. Included in the State of Oregon are Clatsop, Columbia, Washington, Multnomah, and Hood River Counties; the northwestern part of Wasco County west of long 121°00' and north of lat 45°14'; northern parts of Clackamas and Yamhill Counties north of 45°14'; and all of Tillamook County, except the southwestern corner south of lat 45°14'.

In this region, the April 13, 1949, earthquake spawned numerous ground failures along and near the Columbia River; these included rockfalls, rockslides, or rockfall-rock avalanches on steep cliffs and rock faces, and ground cracks, settlement, and sliding, probably related to liquefaction, in alluviated areas on the valley floor.

A landslide (probably a rockfall-rock avalanche) that originated on a steep headscarp of the 14 mi^2 (36 km^2) Bonneville landslide west of Stevenson, Wash. (loc. 160), reportedly created a dust cloud that was seen for miles along the Columbia Gorge. Rockfalls on the steep scarps are a common, ongoing mass-wasting process that is probably easily accelerated by seismic activity. According to Palmer (1977), "The headscarps 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 headscarp of the Bonneville slide (fig. 29) exposes approximately 1,200 ft (370 m) of the Eagle Creek Formation (conglomerates, sandstones, 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 slide, 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 hundred feet wide and several hundred yards long at the base of a steep cliff on the south side of Table Mountain (loc. 160).

At Blue Lake east of Portland, Oregon (loc. 158), a 1949 rockfall from a near-vertical rockface on the south side of the lake reportedly endangered a boathouse. A 30- to 50-ft (9 to 15 m)-high cliff at that location exposes part of the Troutdale Formation (conglomerate and sandstone)(Trimble, 1963).

Rockfalls involving highly jointed volcanic rocks occurred along the Spokane-Portland-Seattle railway approximately 1 mi (1.6 km) east of Mayger, Oregon (loc. 166), and along the Ocean Beach Highway just west of Stella, Wa. (loc. 168). The rockfall east of Mayger (loc. 166) damaged the railroad, but it was reported that only a few hours were required to clear the slide and repair the damage. The rockfall occurrence on the Washington side of the Columbia (loc. 168) originated on the near-vertical face of a 50- to 80-ft (15-25 m)-high bluff that extends for approximately 0.5 mi (0.8 km) along the highway west of Stella. Part of the rockfall 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. 5, loc. 163) and near 40th Avenue (loc. 164). At the N.W. Nichols-Ocean Beach Highway location (loc. 163), geysers of water and sand 3-4 ft (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 ground crack, 20 ft (6 m) in length, from which "black, fine sand bubbled." The site is part of a sandy flood plain; Quaternary alluvial sediments

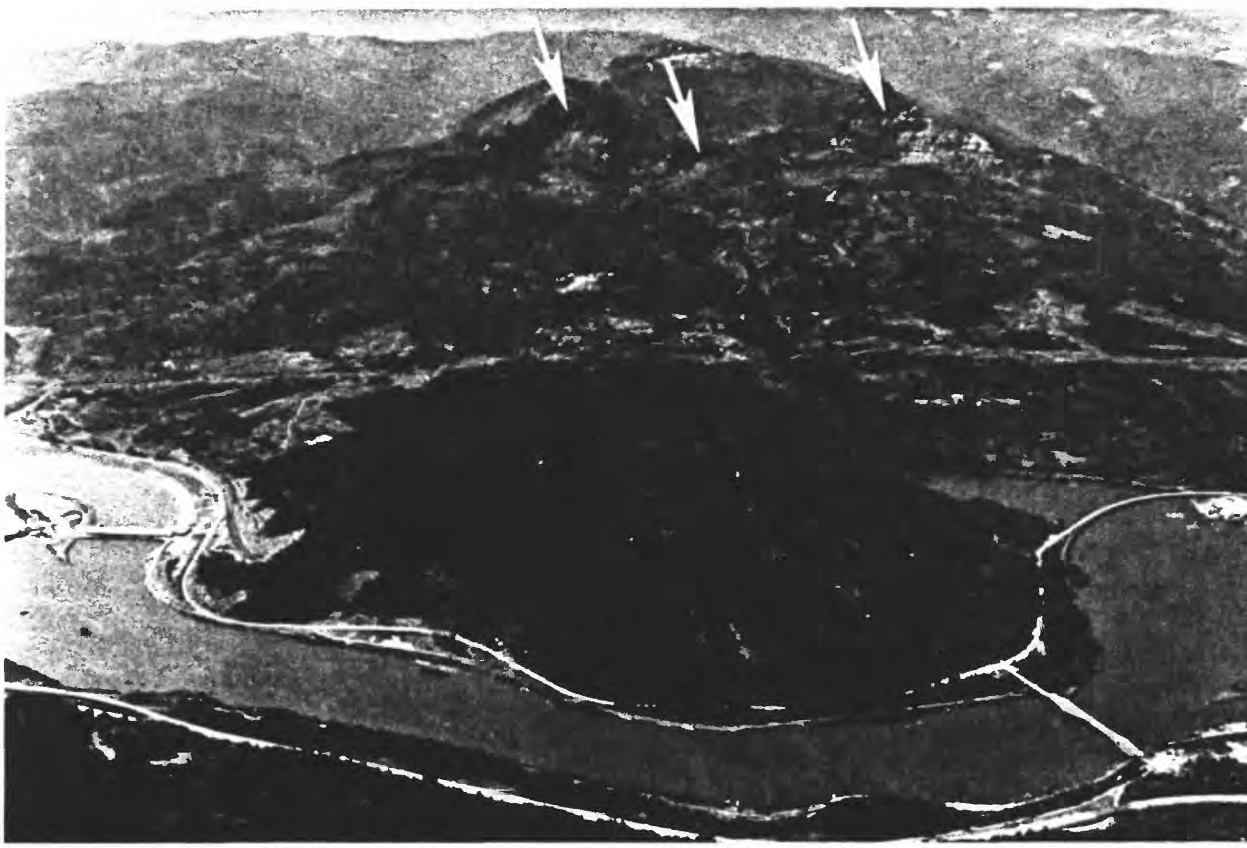

Figure 29.--Bonneville slide area along the Columbia River west of Stevenson, Wash. (pl. 5, loc. 160). Rockfall/rock avalanche activity, triggered by the April 13, 1949 earthquake, occurred along the steep headscarp (arrows), creating a dust cloud visible for miles along the Columbia River Gorge. (Photograph by Derek Cornforth, Landslide Technology, Portland, Oreg.)

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 quake, possibly related to liquefaction of Columbia River sediments, include the following: a slide involving artificial fill overlying alluvium that damaged 300 ft (100 m) of the Longview dike road (loc. 165); damage to a building at Mayger, Oregon (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, Washington (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) (previously discussed) 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 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. 1-5).

Ground failures triggered by the April 13, 1949, and April 29, 1965, earthquakes were scattered over areas of approximately 11,000 mi^2 (28,500 km^2) and 8,000 mi^2 (20,700 km^2), respectively (fig. 2). Ground failures in areas affected by both earthquakes were similar, taking the form of landslides, settlement, and ground cracks. Although most of the reported 1949 and 1965 ground failures were minor settlements and ground cracks that resulted in only minor damage to roads, sidewalks, buildings, utility lines, etc., many were a significant source of earthquake damage in several areas of intense ground shaking. Many damaging ground failures occurred in an environment 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 $<2 \times 10^3$ yds^3 (1.5×10^3 m^3) (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 the bluffs of Puget Sound occurred within a stratigraphic sequence of Vashon glacial sediments that included Esperance Sand, or its equivalent, underlain by impermeable fine-grained sediments (silts and clays). As previously discussed, such conditions often give rise to naturally unstable slopes, due largely to adverse ground-water conditions.

The importance of local ground-water 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, "opened pools of ground water," etc., 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.

Rockfalls, rock slides, and rock avalanches reported for the 1949 and (or) 1965 earthquake occurred almost exclusively in the mountainous terrain of the Cascade Mountains 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 (pls. 1-5) reveals that a high percentage of the reported failures occurred in and near the more populated and heavily traveled areas, suggesting that many ground failures which 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 Coast Ranges and much of the Cascade Mountains (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 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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APPENDIX
TABLES 1-5

Table 1.--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 found on plate 1.

Location Accuracy: A, available information allows accurate relocation, B, available information allows relocation to within a kilometer; C, available information allows relocation 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, Colorado. 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 (65)	Port Orchard, Wash.; Kitsap County	A	[Photo caption] "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, blacktop on fill material was damaged the most by the temblor." (Bremerton Sun, 4/30/65). Bremerton Sun newspaper photo (4/30/65) shows part of a badly broken asphalt-covered parking area adjacent to Sinclair Inlet in Port Orchard. Vertical displacements of approximately 2 ft (0.6 m) are apparent in the photo.

2	Slump; (65)	Port Orchard, Wash.; Kitsap County	A	A slide caused by the 1965 earthquake damaged Country Club Road southeast of Port Orchard (Blair Seymour, personal commun., 1988). Slump in artificial fill underlain by Vashon glacial drift damaged 50-100 ft (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. 14).
3	Settlement; (65)	Seattle, Wash. (Boeing Field); King County	B	"About a mile still farther south [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 (49)	Seattle, Wash.; King County	A	"Quake opens 6 inch [15 cm] cracks in yard * * * house sank 4 inches [10 cm]. " (Seattle Post-Intelligencer 4/14/49, p. 2).
	Settlement (65)	do.	A	"Similar damage [similar to that in the 1949 quake] 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, personal commun., 1988).

5	Slide(s) (65)	Maple Valley, Wash. (Renton); King County	B	"Slides were reported in the * * * Devil's Elbow Road near Maple Valley." (Seattle Times, 4/29/65). The location of the "Devils Elbow Road" referred to in the above quotation is believed to be a 0.5 mi (0.8 km) long section of paved road that joins SE 95th Way and NE 27th Street just north of Renton (8 mi (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 1 ft (0.3 m) vertically along sections 100 ft (30 m) in length on both sides of the ravine. The exact location of the earthquake-induced landsliding is undetermined.
6	Slump (65)	Mercer Island, Wash.; King County	C	[Photo caption] "The shoulders of the road cracked along East Mercer Way." (Mercer Island Reporter, 5/6/65, p. 4). City of Mercer Island photo (Mercer Island Reporter, 5/6/65) shows arcuate crack, approximately 20 ft (6 m) long and 1-3 inches (2.5-7.6 cm) wide, along shoulder of road and steep embankment. Vertical and horizontal displacements appear slight.

7	Ejection of ground water (65) Ejection of ground water (49)	Seattle, Wash. (West Seattle: Alki); King County	A	"Basement floor [damage] and fresh water came in [at the time of the April 29, 1965 quake] * * * 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 the bay." (Mrs. J. W. Woodhouse, written commun., 1965).
	Settlement (65)	do.	A	"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, 4/30/65).
	Misc. effects (65)	do.	B	"At Alki Point, * * * waterline breaks were more numerous than anywhere else in the city." (Mullineaux and others, 1967).
8	Slide (65)	Seattle, Wash. (West (Seattle): King County	A	"Cracks in swimming pool * * * shifting and sliding of dirt under pool." (John E. Smith, written commun., 1965).
9	Slide (65)	Seattle, Wash. (West Seattle); King County	B	"There was some sliding on steep bluffs at the south end of Schmidt Park." (Harold Borden, personal commun., 1988).

10	Slump (49)	Seattle, Wash. (West Seattle); King County	A	"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, 4/14/49, p. 10). [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). [Photo caption] "LONG WAY DOWN--* * * deep crevasse * * * another graphic example of damage wrought by quake showed up at 5135 Admiral Way." (Seattle Post-Intelligencer, 4/14/49, p. 1). See photo (figure 6).
11	Slump (65)	Seattle, Wash. (West Seattle); King County	A	"Fill soil settled and cracked, 5 x 40 foot [1.5 x 12.3 m] concrete bulkhead twisted and dropped on north end. Fill area slid down hill." (E. J. Carlson, written commun., 1965).
12	Slump (65)	Seattle, Wash. (West Seattle); King County	B	"Cracked cement steps. * * * Some breaking off of cliff." (A. R. Munson, written commun., 1965). "Slumping was observed along a steep slope adjacent to 36th Avenue S.W., near Admiral Way." (von Hake and Cloud, 1967).

13	Slump (65)	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 April 1965 earthquake. Original, incipient sliding may have been triggered previously by the April 13, 1949, quake. The site is located at or near the head of a large landslide mapped by Waldron and others (1962).
14	Ground crack (49)	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, 4/15/49, p. 6).

15	Lateral spread or slump(49)	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 to 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." Army Corps of Engineers, 1949).
16	Slump (49)	Seattle Wash. (Spokane Street); King County	A	[Photo caption] "Quake Cracked Street" (Seattle Post-Intelligencer, 4/14/49, p. 4). Crack and slight slump on Spokane Street approach to West Seattle (see photo, fig. 9). Failure occurred in embankment of artificial fill several tens of feet high.
	Settlements (49)	do.	B	[Spokane St. between 23rd Ave. S.W. and Harbor Ave. S.W.] "Settlements of 1" to 4" [2.5 to 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 (49)	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 during or since the quake. The joint filler in a north-south wall was squeezed out a maximum of 3 inches [7.6] at the bottom of one joint. The 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 Engineers, 1949).
18	Lateral spread or slump (65)	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 to 0.61 m] for a width of 25 to 40 feet [7.6 to 12.2 m]. The bulkhead was reported to be 6 to 8 inches [15.2 to 20.3 cm] out of line." (von 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 southerly end of the pier.
	Settlement (65)	do.	A	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 to 30 cm] at the land face of the pier." (Seattle Fire Department, 1965).

19	Settlement (49)	Seattle, Wash. (Duwamish Waterway); King County King County	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).
	Sand Boils (49)			
20	Settlement (49)	Seattle, Wash. (Harbor Island); 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).
	Misc. effects (65)			"The Fisher Flouring Mills had extensive damage * * *. Underground piping around the plant also broke * * *." (von Hake and Cloud, 1967).
21	Sand boils (49)	Seattle, Wash. (Harbor Island); King County	B	[Photo Caption] " Water flowed and spurted from sand during the earthquake consolidation of ground on Harbor Island, Seattle." (H. Edwards, 1950).
22	Lateral spread or slump (65)	Seattle, Wash. (Harbor Island); King County	A	"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." (von Hake and Cloud, 1967).
	Misc. effects (65)	do.	B	"Todd Shipyard Corporation: 3 breaks in underground mains * * *." (Seattle Fire Department, 1965).

23	Misc. effects (49)	Seattle Wash. (Duwamish Waterway), King County	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 to 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).
	Misc. effects (65)	do.	B	"* * * Both of the Southwest Spokane Street bridges were jammed shut when the shock threw them out of line." (von Hake and Cloud, 1967).
24	Settlement (65); Ejection of ground-water (65)	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 severly 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 (49)	do.	B	[Road damage to 1st Ave. S. between Lander and Holgate Sts.] "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 [on file in the offices of the City of Seattle Engineering Department]).

25	Sand boils (49); Settlement (49)	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 to 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 (65); Sand boils (65)	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 silting which now covers most of the underneath area. * * *". (Seattle Fire Department, 1965). ""We thought a sewer broke when water started coming in our basement but when the wooden floor down there splintered and a big hump 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. Fireman were called when "gases and water continued to bubble from it" (the hump of earth), she said." (Seattle Post-Intelligencer, 4/30/65, p. D-2).

26	Slump (49)	Seattle, Wash. (19th and Holgate); 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, personal commun., 1988).
27	Settlement (65); Ground cracks (49)	Seattle, Wash. (Mount Baker District); King County	A	"* * * 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 (49)	Seattle, Wash. (4th Ave. S. at Dearborn St.); King County	A	"Lateral movement to west of west half of pavement." (City of Seattle earthquake damage report, 1949, unpublished [on file in the offices of the City of Seattle Engineering Department]).
29	Slide (65)	Seattle, Wash. (Queen Anne); King County	A	"Hillside backyard sank 2 ft [0.6 m]--seems to have settled on one side more" (Mrs. Jack A. Hanover, written commun., 1965).
30	Misc. effects (65)	Seattle, Wash. (Lake Washington Ship Canal); King County	C	"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 freed. * * *." (U. S. Army Corps of Engineers, 1949).

31	Ground crack (49)	Seattle, Wash. (Union Bay, University of Washington); King County	A	[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, 4/14/49, p. 4).
	Sand boil (65); Ground crack (65)	do.	A	" * * * a fissure opened in the practice field at the University. Underground pressure from the shock sent sand spurting in a 100-foot-long [30-meter-long] zig-zag stretch on the lower football field. Behind the men's pool, areas of the ground dropped as much as a foot. Dirt floor sections in the Hec Edmondson Pavilion also sank slightly." (von Hake and Cloud, 1967).
	Settlement (65)	do.	A	
32	Settlement (65) Sand boils (65)	Seattle, Wash. (Union Bay); King County	B	"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	Slump (49); Slide (49)	Seattle, Wash. (Green Lake); King County	A	"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 to 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 to 15 cm] into the lake." (Seattle Post-Intelligencer, 4/14/49, p. 8). [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, 4/13/49). Ground failures described above are shown in newspaper photographs (figs. 10 and 11).
	Settlement (65); Slide (65); Ground cracks (65); Misc. effects (65)	do.	A	"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 ulility lines." (Mullineaux and others, 1967). "The earthquake [of April 29, 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 spurted 10 to 15 feet feet [3 to 5 m) high around the lighting standards. * * * A four-inch [10 cm] water main serving Evans Pool at Green Lake was ruptured * * *." (Seattle Times, 4/30/65).

34	Slide (65) Settlement (65)	Seattle, Wash. (Phinney Ridge); King County	A	"Bulkhead [slid] down. [Settling of] Front yard by walk at stairs to front porch. [Other damage] 35 feet [11 m] of west bulkhead fell. Doors jammed and would not close. Front door will not open--rubs 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 (49)	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	Earthslide/ mud flow (65)	Seattle, Wash. (Carkeek Park); King County	B	"An earthslide opened a pool of ground water that roared down the creek in historic Carkeek Park. Debris flooded the road, blocking it until at least next week. * * *." (Seattle Times, 4/30/65). The earthslide-mudflow (fig. 12) 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 (65)	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 (65)	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 (65)	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." (von Hake and Cloud, 1967). "A nouse 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, personal commun., 1988). The slope failure is located within a 3/4 mi (1.2 km) coastal bluff area identified as "unstable" in the Coastal Zone Atlas of Washington (Washington Department of Ecology, 1979c). Seepage occurs near mid-slope on the 50-ft (15.2 m)-high bluff. A 3- to 4-ft (1 to 1.5 m)-high stone bulkhead, emplaced to prevent further erosion, extends several hundred feet along the shoreline at the base of the slope.

40	Earthslide-earthflow (65)	Edmonds, Wash.; Snohomish County	A	[Photo caption] "A CHURNING MASS of mud, rocks and other debris in Edmonds is investigated by 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, 4/30/65, p. 2). "A huge crack appeared in the earth. Then trees still standing up began to slide slowly down * * * . The slide uncovered a stream which is mixing the dirt into a muck the consistency of wet cement." (eyewitness account, Seattle Times, 4/30/65). See photograph of ground failure (fig. 13).
41	Slump (65)	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, 4/29/65, p. 1).
42	Ground cracks (65)	Port Ludlow, Wash.; Jefferson County	C	"Beach at Port Ludlow cracked--then filled in by next day. Area 100 x 500 ft [30 x 150 m] on east side of bay (all sand)." (Mrs. John G. Jackowski, written commun., 1965).
43	Misc. effects (65)	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 preliminary report by the Washington Surveying and and Rating Bureau, von Hake and Cloud, 1967).

Table 2.--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 found on plate 2.

Location Accuracy: A, available information allows accurate relocation, B, available information allows relocation to within a kilo[illegible]; C, available information allows relocation 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, Colorado. 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 (49)	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, 4/14/49, p. 1). Failure involved steep lake bank and roadway on west side of Black Lake. Lake bank is approximately 25 ft [8 m] high. Cracks in pavement indicate continued instability at this location.

45	Slump (65)	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 photo (fig. 22).
46	Settlement (49)	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 (49)	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) (65); Sand boils (65)	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, 4/30/65, p. A-6). See photo (fig. 20). [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 Geologic Newsletter, April, 1984). See photo (fig. 21).

49	Misc. effects (49)	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 (49)	Olympia, Wash. (Port area); Thurston County	A	"The entire port area, a man-made fill, settled 5 inches [13 m]. * * * 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 (49)	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, 4/15/49, p. 1). " * * * 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 and 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, 4/13/49, p. 11). See photo (fig. 23).

52	Slides (65)	Hartstene Island, Wash.; Mason County	B	"We visited the hole in the wall settlement (Harstene 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, 5/6/65, p. 11).
53	Settlement (49)	Lacey, Wash. (McAllister Springs); Thurston County	A	"The McAllister Springs project withstood the earthquake well. The only damage was done when the temblor caused an earth fill dam at the springs to drop." (Daily Olympian, 4/14/49, p. 1).
54	Slump (65)	Orting, Wash.; Pierce County	A	A crack, 400 to 500 feet [120 to 150 m] long and 6 inches [15 cm] wide opened up along the brow of the hill and across the road. (Emmett Chase, personal commun., 1988).
55	Sand boils (49) Ground crack (49)			Sand boils occurred on a farm about 2 mi [3 km] south of Orting. Blue-gray, fine sediment was ejected from a zigzag crack in the ground. It happened in a field on the west side of the highway [Orting-Electron highway] near a small creek. The sand was somewhat "oily" and the children got very dirty playing in it (Charlotte Rogich, personal commun., 1990).[1]
56	Sand boils (49)	Sumner, Wash.; Pierce County	A	Two sand boils, about 3 ft [0.9 m] in diameter and 5 or 6 in. [13-15 cm] high, occurred at 8502 Riverside Road East in Sumner. Water from the sand boils had a salty taste (Francis Watson, personal commun., 1989).[1]
57	Sand boils (49)	Sumner, Wash.; Pierce County	A	Blows of water and sand occurred on my property about 1 mile [1.6 km] east of Sumner (Herman Nix, personal commun., 1989).

58	Sand boils (49)	Sumner, Wash.; Pierce County	A	Many sand boils, about 6 in [15 cm] in diameter and 1 or 2 in. [2.5-5.0 cm] high, were produced by the 1949 earthquake near the corner of Main and Van Tassle on the east side of Sumner. The sand was clean and black (Fred Weber, personal commun., 1989).[1]
59	Settlement (65) Misc. effects (65) Misc. effects (49)	Sumner, Wash.; Pierce County	A	"Broken water mains * * * cement porch fell toward street * * * school gymnasium walk sunk in and cracked. [In the 1949 quake] springs disappeared, water lowered." (Mrs. L.R. Bariekman, written commun., 1965).
60	Misc. effects (49)	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, 4/14/49, p. 6).
61	Sand boils (49)	Puyallup, Wash.; Pierce County	A	Approximately 20 sand boils erupted [as a result of the 1949 earthquake] at 1100 7th Avenue SE. The spurts of water were about 6 in. [15 cm] high. The mounds of sediment were composed of clean, bluish sand and were less than 1 ft [0.3 m] in diameter. An artesian well is nearby (William McAlister, personal commun., 1989).[1]
62	Sand boils (49)	Puyallup, Wash.; Pierce County	A	There were six sand blows at 1224 5th Street SW. The sand was bluish-gray and more water came from the holes after the quake (Bill Morris, personal commun., 1989).[1]
63	Sand boils (49)	Puyallup, Wash.; Pierce County	A	Five or six geysers spurted about 5 ft [1.5 m] high on West Main under where the Puyallup High School Gym stands today. They came after the quake and lasted a few minutes. The mounds were less than 1 ft [0.3 m] wide and less than 1 ft [0.3m] high (Mrs. Hoganson, personal commun., 1989).[1]

64	Sand boils (49)	Puyallup, Wash.; Pierce County	A	There were sand blows at 811 2nd Avenue NW in Puyallup. They came a little after the quake, were about 2 ft [0.6 m] high, and ejected black sand (Erlyne Eklund, personal commun., 1989).[1]
65	Sand boils (49)	Puyallup, Wash.; Pierce County	A	There were many sand blows in the backyard at 113 16th Street SW and also across the alley from that location (Mrs. Carstens, personal commun., 1989).[1]
66	Ground crack (49) Misc. effects (49)	Puyallup, Wash.; Pierce County	A	[716 7th Avenue 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 (49)	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, 1949, p. 1).
	Settlement (49)	do.	A	At the time of the 1949 quake, a crack occurred across 9th street and a car would drop when driven over it; the basement floor of the house at at 407 N. 9th St. was pushed up to the ceiling, that is, to the floor joists (Warren Picha, personal commun., 1989).

	Sand boils (49) Misc. effect (49)	do.	A	Sand boils developed in the alley west of 7th Street NW and north of 5th Avenue NW and the basement floor buckled up at 714 7th Street 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 Street NW (Merle McMullen, personal commun., 1989).[1]
	Sand boils (49)	do.	A	Sand boils occurred at 702 5th Avenue NW, 616 5th Avenue NW, 609 7th Avenue NW, 802 5th Avenue NW, and at a brick house on the corner at 9th Street NW and 5th Avenue NW (Irwin Connell, personal commun., 1989).[1]
	Sand boils (49)	do.	A	Also, there were sand boils in the 800 block of 8th Street NW. There were maybe six black sand gushers. They came a little after the quake and were about 2 ft (0.6 m) high (Erlyne Eklund, personal, commun., 1989).[1] There were sand boils at 5th Avenue NW and 6th Street NW, and the basement at 406 6th Street was pushed up. (Earle Shoupe, personal commun., 1989).[1]
	Sand boils (49)	do.	A	There were 8 to 10 "gushers" at 405 8th Street NW. The mounds were 2 to 3 in. [5 to 8 cm] high and about 2 in. [5 cm] wide. The sand was black. None appeared in 1965 (Helen Clingenpeel, personal commun., 1989).[1]
67	Ground Cracks (49); Settlement (49)	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, 4/14/49, p. 1).

68	Sand boils (49) Ground Cracks (49)	Puyallup, Wash.; Pierce County	A	[1215 3rd Avenue 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 (49)	do.	A	There were possibly twenty sand boils at 1301 4th Avenue NW. These were rather cone shaped, 5 to 7 in. [13 to 18 cm] in diameter and 5 to 8 in. [13 to 20 cm] high. The sand was light-colored and holes in the cones were maybe as much as 1/2 in [1.2 cm] in diameter. This was the site of much water and sand all over the front lawn and driveway (Richard Six, personal commun., 1989).[1] Photos (taken by Mr. Richard Six) showing sand boils associated ground cracks, and flooding at this location are presented in figures 15-17.
	Sand boils (49)	do.	A	There were sand boils at 1515 4th Avenue NW (Mrs. Carstens, personal commun., 1989).[1]
	Sand boils (49)	do.	A	A blue-gray sand came up in gushers between the daffodil rows between 12th Street NW and 13th Street NW and between 2nd Avenue NW and 3rd Avenue NW (Unidentified respondent, personal commun., 1989).[1]
	Sand boils (49)	do.	A	Sand piles, 2 to 3 ft (0.6 to 0.9 m) in diameter, appeared on the north side of Stewart Avenue between 11th Street NW and 13th Street NW (Fred Richen, personal commun., 1989).[1]
	Sand boils (65)	do.	A	There was sand boil activity [related to the April 29, 1965, earthquake] on the Aylen Junior High School playfield. There was a considerable amount of water and the long jump pit had to be moved (Lloyd Freuderstein, personal commun., 1989.; George Willfong, personal commun., 1989).[1]

69	Settlement (49)	Puyallup, Wash.; Pierce County	A	Basement was pushed up on one end so house teetered [18th Street at 4th Ave.] (Warren Picha, personal commun., 1989).
	Sand boils (49)	do.	A	The house on the NE corner of 4th Avenue NW and 18th Street NW had about 4 ft [1.2 m] of liquefied sand in the basement (Earle Shoupe, personal commun., 1989).[1] There were sand boils at 4th Avenue NW and 18th Street NW (Dorothy McCleary, personal commun., 1989).[1]
	Sand boils (49)	do.	A	There were sand boils "all over" cultivated farm property at 2001 4th Avenue NW. The geysers were about 12 in. [0.3 m] high (Mr. and Mrs. Elmer Johnston, personal commun., 1989).[1]
70	Sand boils (49)	Puyallup, Wash.; Pierce County	A	There were sand boils at 2612 Tacoma Road [at the time of the April 13, 1949, earthquake] (Marie Biehn, personal commun., 1989).[1]
71	Slump or lateral spread (49)	Puyallup, Wash.; Pierce County	A	"Cracks and destruction at the Pat Fox Farm." (Anonymous, written commun., 1949). Crack along the west bank of Clarks Creek was 200-300 feet [60-90 m] long and about 3 feet [0.9 m] high. Photo in 1949 issue of Life magazine shows the ground crack. House across creek was tilted and concrete foundation destroyed (Warren Picha, personal commun., 1949). See photo (fig. 18).
	Settlement (49)	do.		
	Misc. effects (49)	do.	A	At 5720 66th Avenue East the basement floor came up and the well became cloudy, but cleared up (Fred Richen, personal commun., 1989).[1]
	Ground crack (49)	do.	A	There was an east-west crack down Stewart Avenue that extended past the Clark's Creek bridge (Richard Six, personal commun., 1989).[1]

72	Sand boils (49)	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 15 ft [4.6 m] in diameter. The spurts of water and sand were 5 to 6 ft [1.5 to 1.8 m] high (Mrs. Eggiman, personal commun., 1989).[1]
73	Sand boils (49)	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, personal commun., 1989).[1]
74	Sand boils (49)	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, personal commun., 1989).[1]
75	Sand boils (49)	Puyallup, Wash.; Pierce County	A	Sand boils at 5820 44th Street East ejected blackish-clean sand. The sand deposits were 12 to 18 in. [0.3 to 0.5 m] in diameter and 30 to 40 ft [9 to 12 m] apart. They looked like mole hills; the wider hills were flatter (George Richen, personal commun., 1989).[1]
76	Sand boils (49)	Puyallup, Wash.; Pierce County	A	Sand boils appeared along the North Levee Road about 150 ft [45 m] from the river. The gushers were 8 to 10 ft [2.4 to 3.0 m] high. (Marie Bingasser, personal commun., 1989).[1]

77	Settlement (49) Ground crack (49)	Tacoma, Wash. (tidal flat area); 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 (65)	do.		"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, personal commun., 1988).
78	Settlement (49) Sand boils (49)	Tacoma, 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).
	Misc. effects (49)	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 (65)	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.* * *." (The Tacoma News Tribune, 4/30/65, p. A-8)

79	Sand boils (49) Ground cracks (49)	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 long [18.3 to 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, 4/15/49, p. B-4).
80	Slide (49)	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 (65)	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, personal commun., 1988).

81	Debris Avalanche (49) Ground Cracks (49)	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 x 10^6 m^3], although this is thought to be excessive. One million cubic yards [7.6 x 10^5 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 a 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).
	Sand boil (49)	do.	A?	"The crack in the cliff could send more tons of 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." (Tacoma News Tribune, 4/18/49, p. 1,2). See photo (fig. 19).

82	Slump (49,65)	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). 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 200 yards [183 m] and slump dropped about 2 feet [0.6 m]. In 1965, movement along scarp was probably somewhat shorter (maybe 150 yards [137 m]), and slump dropped about 1-1/2 feet [0.5 m] 1980 due to heavy rain. (Sydney Selden, Sr., personal commun., 1988).
83	Slides (65)	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, 4/30/65, p. A-8). "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." (The Tacoma News Tribune, 4/29/65, p. A-2).

84	Slide (49)	Fox Island (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, 4/14/49, p. 16). "I visited the site a couple of months after the earthquake. The owner had excavated a small shelf 50 to 100 feet [15 to 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, personal commun., 1988).
85	Slump/debris flow (65)	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, 5/6/65, p. 1). "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, personal commun., 1988). Failure occurred in a 30-ft [9.1 m]-high road embankment where the road crosses a small arm of McLane Cove.

86	Slump (49,65)	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, personal commun., 1988). The failure, which involved artificial fill, occurred along the highway adjacent to Case Inlet. The failed embankment is approximately 20 ft [6 m] high. Slumping caused a vertical displacement of approximately 6 in. [15 cm] along 100 ft [30 m] of highway. Continued instability is evident.
87	Slump (49)	Port Orchard, Wash. (south on old Gig Harbor highway); Kitsap County	A	"The road bed that went out [at the time of the April 12, 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. Wermer, 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, Noson 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 earthquake motion."

88	Slump (65)	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, 4/30/65, p. A-8). The highway crosses a flat swampy area at this location. Highway was less than 1 ft [0.3 m] above the Lake originally and underlying soil was probably saturated.
89	Slump (65)	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, 4/30/65, p. A-8). Slump occurred in road embankment (artificial fill) founded on tidal flat muds. Road embankment is approximately 6 ft [2 m] high.
90	Slide (65) Misc. effects (65)	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 to 2 cm] wide and about 50 ft [15 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 (65)	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 (65)	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 (65)	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 (65)	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 200 ft [60 m] long. Downhill side dropped a few inches. There were also slides on side hill behind 2nd and 3rd houses from south end. Those slides moved a couple of feet but did no damage. (Jan Weir, personal commun., 1988).
95	Slide (65)	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).
96	Settlement (65)	Vashon Island, Wash. Shawnee Beach); King 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." * * * 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 to 12 m] long." (Mrs. F.M. Urschel, written commun., 1965).
	Slide (65)	do.	A	

97	Slide (65)	Vashon Island, Wash. (Magnolia Beach); King County	A	Concrete bulkhead on beach settled. Bulkhead was built on fill which was placed on hard clay. There was approximately a 6 in. (15 cm) drop and bulkhead cracked (Robert Gorden, personal commun., 1988).
98	Ground crack (65)	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 (65)	Tacoma, Wash. (Palisades); 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 (49) Sand boils (49) Misc. effects (49)	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).
	Sand boils (65)	do.	A	"Among the strange things that came along with the earthquake Thursday was one out on 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." (Sumner News-Index, 5/6/65, p. 1). The sand boils occurred just SW of the intersection of 2nd Street East and Valentine Road. (Mrs. Palmer Johnson, personal commun., 1988)

101	Sand boils (49)	Auburn, Wash.; King County	A	Co-workers 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 quake]. (Larry Lunderg, personal commun., 1988).
102	Slide (49,65)	Auburn, Wash. (east of Auburn on the Lake Holm); King County	A	"Slides were reported in the Lake Holm Road east of Auburn * * *." (Seattle Times, 4/29/65, p. 6). In the 1949 quake, a crack about 3 inches [7.6 m] wide and several feet deep opened between the house and the garage. I think it went down to the creek [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, personal commun., 1988).
103	Ejection of ground water (65)	Auburn, Wash. (north side); King County	B	[Photo caption] "GROUND SEEPAGE--Jerry Keesee, city sewage plant superintendent, * * * checks seriousness of seepage around manhole on line leading into plant in North Auburn. Keesee 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, 5/5/65, p. 2-1).
104	Slump (65)	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, 5/5/65, p. 2-2).

105	Slump (49) Sand boils (49) Misc. effects (49)	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 givings 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 powerlines that cross the the upper part of the hillside. The reservoir was very small, not more than a few tens of feet across. (John Haverinen Jr., personal commun., 1988).
106	Sand boil (65) Ground crack (65)	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 (65)	Kent, Wash. (212 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, 5/5/65, p. 2-3). "Two sand boils appeared in the fields; one on each side of 212th Street." (Albert Dreisow, personal commun., 1988).
108	Slide (65)	Kent, Wash. (42nd 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, 5/5/65, p. 2).
109	Slide (65)	Seattle, Wash. (Burien, Three Tree Point area, 172nd Street S.W.); King County	A	"Home located above sound water 300' [90 m] on hillside. Sandy soil, facing south. * * * cracks of 2" to 3" [5 to 8 cm] were discovered across bank running east and 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. [Sketch map shows a continuous crack 3 to 4 inches (8 to 10 cm) wide on hillside overlooking Puget Sound. The crack (in the drawing) extends across the hillside parallel to 172nd Street S.W. the length of 3 or 4 residential properties.]." (Mrs. John Maass, written commun., 1965).
	Slide (65)	do.	A	"Broken [concrete walkway]. The hill pushed down on the retaining walls and pushed them out about three inches [8 cm)." (Mrs. Henry Roche, written commun., 1965).

110	Slide (65)	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 (65)	Renton, Wash. (Burnett and Seventh Streets); 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, 5/5/65, p. 1,2).
	Settlement (65)	Renton, Wash. (Shattuck 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).
112	Slide (65)	Renton, Wash. (Highlands); King County	C	"Cement block retaining wall holding back sand bank collapsed completely--wall was free standing, 5′ X 34′ [1.5 x 10.4 m]. Wall runs north and south." (Edith Look, written commun., 1965).

113	Slides (65)	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, 4/29/65).
	Ground crack (65)	do.	A	A narrow crack less than an inch [2.5 cm] wide and 150 ft [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, personal commun., 1988).
114	Slides (49) Ground cracks (65)	Mapel Valley, Wash. (Lake Youngs; King County	C	"It has been determined * * * that [due to the 1949 earthquake] 575 yards of material were required to repair slumping in one of the retaining dikes at Lake Youngs. Also, one gate chamber casting was broken due to soil displacement. * * * Dike around Lake Youngs - cracks in three places [as a result of the 1965 earthquake]." Kennedy-Jenks-Chilton Consultants, 1990.

[1]Information originally gathered by Dr. John A. Shulene of Puyallup, Washington. 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 3.--Descriptions of selected ground failures in the Cascade Mountains of Washington region

Location numbers correspond to ground failure location numbers found on plate 3.

Location Accuracy: A, available information allows accurate relocation, B, available information allows relocation to within a kilometer; C, available information allows relocation 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, Colorado. 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	Misc. effects (49)	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, 4/21/49, p. 1). "* * * 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 (49)	Randle, Wash. (just north of Cispus River bridge on old road); Lewis County	A	Slump of road on sidehill slope. Road slumped about 2 feet [0.6 m] vertically for a length of about 60 feet [18 m]. (Lawrence E. Panco, personal commun., 1988).
117	Slump (49)	Randle, Wash.; Lewis County	A	Road embankment failed about 1 mile (1.6 km) southwest of Randle during the 1949 quake (Hubert Derossett, personal commun., 1988). Slump occurred on 3-4 ft (0.9-1.2 m) high road embankment in artificial fill underlain by loose liquefiable sand. The failure extensively damaged several tens of feet of roadway (see photo, fig. 24). Numerous sand boils simultaneously erupted in nearby field (plate 3, loc. 118).
118	Sand boils (49)	Randle, Wash.; Lewis County	A	Sandboils dumped wheelbarrow loads of sand in our pasture in the 1949 quake. (Lawrence Peters, personal commun., 1988).
119	Slumps (49)	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, personal commun., 1988).
120	Rockfall (49)	Randle, Wash.; Lewis County	A	Several blocks of rock, 4-6 ft (1.2-1.8) across, came down [during the 1949 earthquake] and blocked Cline Road about 1 mile (1.6 km) southeast of Randle (Hubert Derosett, personal commun., 1988).
121	Rockfall (49)	Randle, Wash.; Lewis County	A	A large block, approximately 20 ft (6 m) on a side dropped from a steep cliff onto Cline Road at a point approximately 2 1/2 miles (4 km) southeast of Randle. This happened as a result of the 1949 earthquake (Hubert Derosett, personal commun., 1988).

122	Rockfall (49)	Randle, Wash.; Lewis County	A	A rockfall occurred along the old Randle-Packwood Highway, approximately 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, personal commun., 1988).
123	Rockfall (49)	Longmire, Wash. (Mount Ranier National Park); Lewis County	C	"* * * rocks were observed falling from the cliffs of * * * Eagle Peak." (National Park Service, 1949).
124	Rockfall (49)	Longmire, Wash. (Mount Rainier National Park); Pierce County	B	"* * * rocks were observed falling from the cliffs of Rampart Ridge * * *." (National Park Service, 1949).
125	Slide (49)	Longmire, Wash. (Mount Rainier National Park); Pierce 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 eschelon 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	Rockslide (49)	Longmire, Wash. (Mt. Rainier National Park); Pierce 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 (65)	Longmire, Wash. (Mt. Rainier National Park); Pierce	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 (49);	Buckley, Wash. (Mud Mountain Dam); King and Pierce Counties	A	"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.
	Slide (49)	do.	B	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).
	Ground cracks (65) Slides (65)	do.	A	"Small cracks from 1/2 to 1-1/2 inches (1.3 to 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).

128	Ground cracks (65)	Palmer, Wash. (Howard Hanson Dam); King County	A	"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 to 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 measureable settlement of the dam. * * *." (Steinborn, 1965).
129	Slide (65)	Ronald, Wash.; Kittitas County	C	"Large rock dump started to slide and cave." (von Hake and Cloud, 1967).
130	Rockslides (49)	North Bend, Wash. (Mount Si); King County	B	"Rockslides on Mt. Si [triggered by the April 13, 1949, earthquake]. (Murphy and Ulrich, 1951).
	Rockslides (65)	do.	A	"Press reported an extensive slide occurred on the southwest slope of Mount Si near North Bend [at the time of the April 29, 1965, earthquake]." (von Hake and Cloud, 1967). Dust cloud rose from near the bottom of the rock face on the west side of Mt. Si during the 1965 earthquake [near the 2200 ft elevation level]." (Jack Ferrell, U.S. Forest Service (retired), personal commun., 1988). 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 cliffs of Mount Si." See photo (fig. 25).

131	Rockfall (65)	Index, Wash. (Mount Persis); Snohomish County	C	"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, 4/29/65, p. 5-A). "* * * Boulders came rolling down onto the Stevens Pass Highway from Mt. Persis east of Everett, causing some damage." (Wenatchee Daily World, 4/29/65, p. 10).
132	Snow and rock avalanches (49)	Darrington, Wash.; Snohomish County	D	"Snow and rock avalanches in the mountains [in the vicinity of Darrington]." (Murphy and Ulrich, 1951).

Table 4.--Descriptions of selected ground failures in the Central Southwest Washington region

Location numbers correspond to ground failure location numbers found on plate 4.

Location Accuracy: A, available information allows accurate relocation, B, available information allows relocation to within a kilometer; C, available information allows relocation 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, Colorado. 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 (49)	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 slight slump near the base of the slope adjacent to the Winston Creek floodplain.
134	Slump (49)	Kosmos, Wash.; Lewis County	A	Road slumped into the Cowlitz River damming it for a short time. Failure occurred along approximately 100 yards (90 m) of river bank on the north side of the river. The failed slope was 50 to 70 ft [15 to 21 m] high and very steep (near vertical) in its upper part. The material involved was sand and gravel, but mostly medium sand (Hubert Derossett, personal commun., 1988).

135	Rockfall (49)	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 25 ft (8 m) high fell from the face of a near-vertical cliff frightening homeowners below (Ivy Beck and Lena Hall, personal commun., 1988).
136	Slides (49)	LaGrande, 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).
	Slides (65)			"Earth cracks along canyon of the Nisqually River; slides into rivers and onto roads." (von Hake and Cloud, 1967).
137	Slump (49)	Eatonville, Wash.; Pierce County	A	"The quake opened a crack about 100 feet [30 m] in length on the Alder * * * cutoff, about 6 inches [15 cm] wide." (Eatonville Dispatch, 4/14/49). Approximately 1 mile (1.6 km) south of Eatonville, a 100 ft (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 2 feet (0.6 m) (Percy Williams, personal commun., 1987).

138	Slump (49)	Eatonville, Wash. (Ohop Lake); Pierce County	A	"On the Lake road the crack is three to four inches [8 to 10 cm] wide and extends about 700 feet [210 m] from Point Ohop on towards Kapowsin." (Eatonville Dispatch, 4/14/49). "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 occuring 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 * * *." (The Tacoma Sunday Ledger-News Tribune. 5/15/49, p. A-2). Surface of road along the west side of Ohop lake originally developed a 700-800-ft (215 to 250 m)-long crack due to incipient slumping triggered by the April 13, 1949, earthquake. One month later, on May 13, complete failure occurred as the unstable mass slid and (or) flowed as far as 100 ft (30.5 m) out into the lake, leaving a 5 ft (1.5 m) scarp along the roadway (see photo, fig. 28). The slide involved artificial fill overlying well-consolidated alluvial sediments.

139	Soil fall (65); Ground crack (65)	Kapowsin, Wash. (road to Electron powerhouse); Pierce County	A B	Sand and gravel fell from a 50-ft [15 m]-high vertical face onto the road to the powerhouse. Approximately 50 yards [38 m^3] of material blocked the road (Emmett Chase, personal commun., 1988). "Ground cracked [near Electron]." (von Hake and Cloud, 1967).
140	Slump (49)	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 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 x 10^4 m^3] mtl * * *." (U. S. Army Corps of Engineers, 1949).

141	Sand boils (49)	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 to 1.2 m] The 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 10 feet (3 m) wide. The fissure was oriented north-south and lay east of Deep Lake (Mr. and Mrs. Conrad Newman, personal commun., 1988). Plowing, disking, etc., mixed sand with other soil, and features were obliterated in a relatively short time. Initially, and for a year or so afterward, the sand boils were visible indirectly because areas were drier and less fertile. Area is underlain by glacial drift; gravel exposed in gravel pit at south end of property is poorly-sorted sand. The key control in the formation of the sand boils was probably a high water table and a lense of well-sorted sandy stratified drift in the glacial deposits at this locality.
142	Ground cracks (49) Misc. effects (49)	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 (49)	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 inches) at edge of old gravel pit. Failure probably occurred in Vashon glacial outwash deposits (sand and gravel) present at the site.
144	Slump (49)	Centralia, Wash. (north shore of Plummer Lake); Lewis County	A	Cracks 25 to 50 ft (8 to 15 m) long and several inches wide developed on the north shore of Plummer Lake during the April 13, 1949, earthquake (Don Swanson, personal commun., 1988)
145	Settlement (49) Misc. effects (49)	Centralia, Wash.; Lewis County	A	" * * * 1 church comdemned, 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. A vault door started sticking 3 days after the quake. Horizontal and diagonal lines drawn across plaster cracks show minute displacement after a week. * * * Dust and scratches on two adjoinging masonry buildings, Warren Brothers Garage and the Pantorium Cleaners on West Main, Centralia, indicate differential vertical movement between the buildings." (U. S. Army Corps of Engineers, 1949).

146	Sand boils (49) Ground cracks (49)	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, 4/17/49, p. A-16). "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), 4/26/49, p. 1). "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 to 8 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 10-12 ft (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, personal commun., 1988). See photographs of sand boils taken by property owner (Mr. Ted Dorn) shortly after the April 13, 1949, earthquake (figs. 26 and 27).
147	Sand boil (49) Misc. effect (49)	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 Miller, written commun., 1949).

148	Ground crack (49) Ejection of ground water (49)	Adna, Wash.; Lewis County	A	"* * * the carrier on Route 1 [Chehalis] observed that following the quake a fissure appeared in the 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, written commun., 1949). Apparently this was a crack that developed at contact between artificial fill and original slope. The road was cut from a steep slope, north of the railroad, approximately 20 ft [6 m] above the Chehalis River flat.
149	Sand boil (49) Ground crack (49)	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 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 (49)	Rochester, Wash.; Thurston County	A	A crack and slight slump occurred approximately 3 miles (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, personal commun., 1988). Examination of a photograph of this 1949 ground failure (Hopper, 1981, p. 93), indicates that the shoulder of the road failed along a few tens of feet of roadway. Vertical and horizontal displacements appear to be less than 1 or 2 feet (0.3 or 0.6 m). The slide occurred in artificial fill on a very poor alluvial foundation.

151	Slump (49)	Oakville, Wash.; Grays Harbor County	A	The 1949 quake caused a crack and slump on a county road along the Chehalis River, approximately 1 mile (0.8 km) southwest of Oakville. The crack was about 200 feet (61 m) long and there was about 1 foot (0.3 m) of vertical displacement (Alan Schwiesow, personal commun., 1988). Failure probably occurred at contact between the artificial fill and original ground surface. New cracks are apparent that indicate continued instablity.
152	Misc. effects (49) Ground cracks (49)	Hoquiam, Wash.; Grays Harbor County	C	"At least a dozen water mains and pipes broken. Several sidewalks cracked." (Murphy and Ulrich, 1951).
153	Misc. effects (49)	Aberdeen, Wash.; Grays Harbor County	B	" * * * 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, 4/13/49).
154	Settlement (49)	McCleary, Wash.; Grays Harbor County	B	"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).
155	Slides (65)	Shelton, Wash. (west side of Oakland Bay) Mason County	C	"Some slides noticed along Oakland Bay closer to town." (Business Manager, Washington Corrections Center, written commun., 1965)

156	Slump (65)	Shelton, Wash.; Mason County	B	"One lane of U. S. Highway 101, four miles [1.2 km] north of Shelton, sank about a foot [0.3 m] for a distance of about 150 feet [45 m]." (Washington Highways, May 1965, p. 14). 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.

Table 5.--Descriptions of selected ground failures in the Western Columbia River, Washington and Oregon region

Location numbers correspond to ground-failure location numbers found on plate 5.

Location Accuracy: A, available information allows accurate relocation, B, available information allows relocation to within a kilometer; C, available information allows relocation 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, Colorado. 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 (49)	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, 4/28/49, p. 2). 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 approximately 4 ft (1.2 m) high, and is composed of artificial fill founded on unconsolidated granular sediments.

158	Rockfall (49)	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 x 6.1 x 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, 4/15/49, p. 2). The rockfall described in the above quotation 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, 30- to 50-ft (9 to 15 m)-high cliff.
159	Misc. effect (49)	Government Camp, Oreg. (Mount Hood); Clackamas County	C	"This mountain village exprienced 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 temblor 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, 4/13/49, p. 1).

160	Rockfall-rock avalanche (49)	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, 4/14/49). "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 focussed 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." (The Skamania County Pioneer, 4/15/49, p. 1). The rockfall-rock avalanche ground failure(s) described in the above quotations originated along part of the approximately 3 mile (4.8 km) long steep head scarp of the Cascades (Bonneville) landslide. The headscarp of the Cascades landslide exposes 1,200 ft (370 m) of the Eagle Creek Formation (conglomerates, sandstones, and minor tuff) overlain by basalt (Korosec, 1987). Airphoto studies indicate that rockfalls and other slides are common along the scarp. Debris from slide activity, possibly related to the 1949 event, extends several hundred feet downslope from the scarp on the south side of Table Mountain. See photo (fig. 29).

161	Slump (49)	Castle Rock, Wash.; Cowlitz County	B	"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 to 9 m] long." (Cowlitz County Advocate, 4/14/49). The "crack" apparently occurred on the floodplain 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.
162	Ground cracks (49) Slides (49)	Castle Rock, Wash.; Cowlitz County	D	"Many cracks up to 6 inches [15 cm] wide in fields and on river dikes. Landslides." (Murphy and Ulrich, 1951).
163	Sand boils (49) Ground cracks (49)	Longview, Wash.; Cowlitz County	A	"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, 4/14/49). "My brother said he saw 2 to 3 foot [0.6 to 0.9 m] high spurts of water and sand in the backyard (Allen Windus, personal commun., 1988). The above quotations represent two separate ground-failure locations, approximately 200 yards (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 floodplain of the Columbia River underlain by Quaternary alluvium (Walsh and others, 1987). Artificial fill may be present locally.

164	Sand boils (49) Ground crack (49)	Longview, Wash.; Cowlitz County	A	"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, 4/14/49). The ground-failure site described above was (in 1949) part of a swampy, sandy floodplain. 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.
165	Slump (49)	Longview, Wash.; Cowlitz County	A	"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, 4/15/49). [Photo caption] "Earthquake cracks as deep as can be seen * * * range up to nine inches [22.9 cm] wide." (Longview Daily News, 4/15/49, p. 2). Crack and slump in dike road in flat swampy area adjacent to the Columbia River. The cracks developed in embankment of artificial fill underlain by alluvial sediments of the Columbia River. The road surface, at the site of the ground failure, is 10 to 12 feet [3.0 to 3.7 m] above the river and approximately 6 ft [1.8 m] above swampy flat on the opposite side.

166	Rockfall (49)	Mayger, Oreg.; Columbia County	B	"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, 4/14/49, p. 1). A steep face of volcanic rock (Wanapum Basalt and (or) Grays River volcanic rocks, Walsh and others, 1987), approximately 1 mile (1.6 km) east of Mayger, is the likely origin of the "rock slide" reported in the above newspaper quote. Approximately 200 ft (60 m) of highly jointed volcanics are exposed in the steep face.
167	Misc. effects (49)	Mayger, Oreg.; Columbia County	A	"Heaviest damage reported was at Mayger where the Point Adams Fish Co. station reports a loss of approximately $4,000 when several piling were taken out by the quake and the building itself was moved about five feet toward the Washington side of the river." (Clatskanie Chief, 4/15/49, p. 1).

168	Rockfall (49)	Stella, Wash.; Cowlitz County	B	"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 dropped across the highway, spilling over into the Columbia River." (Longview Daily News, 4/15/49). 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, personal commun., 1988). The rockfall described above orginated on a 50- to 80-foot (15 to 25 m)-high face of highly jointed basalt (Wanapum Basalt, Walsh and others, 1987). The rock face is near vertical and extends from 1/4 to 3/4 mi (0.4 to 1.2 km) west of Stella on the north side of the Ocean Beach Highway.
169	Slide (49)	Clatskanie, Oreg.; Columbia County	A	"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 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, 4/15/49, p. 1).
	Misc. effects (49)	do.	B	"Three or four water mains were broken in Clats-Clatskanie * * *." (Clatskanie Chief, 4/15/49, p. 1).

170	Misc. effects (49)	Cathlamet, Wash. (Puget Island, Columbia River); Wahkiakum County	B	"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).
171	Ground crack (49) Misc. effects (49)	Skamokawa, Wash.; Wahkiakum County	B	"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 [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). Ground failure, probably caused by liquefaction of sandy alluvial sediments, occurred in flatlying swamp area on point between Brooks Slough and Steamboat Slough. Failures were foundation failures of wooden buildings founded on sand (and possibly on surface layer of sawdust from sawmills that existed on the point at that time).
172	Misc. effects (49)	Astoria, Oreg.; Clatsop County	C	"Several water mains broke and flooded basements." (Murphy and Ulrich, 1949).