USGS
science for a changing world

Landslides Triggered by the Winter 1996-97 Storms in the Puget Lowland, Washington

(paper edition)

Rex L. Baum[1] , Alan F. Chleborad[1], and Robert L. Schuster[1]

U.S. Geological Survey Open-File Report 98-239

[1]Denver, CO

1998

U.S. Department of the Interior
U.S. Geological Survey

Landslides Triggered by the Winter 1996-1997 Storms in the Puget Lowland, Washington

by Rex L. Baum, Alan F. Chleborad, and Robert L. Schuster

ABSTRACT

Snowmelt and rainfall events triggered many landslides and debris flows in the Seattle, Washington, area during late December 1996 and January and March 1997. Landslides caused the deaths of at least four people, millions of dollars in damage to public and private property, lost revenues, traffic diversions, and other direct and indirect losses. Although shallow slides and debris flows were the most common slope failures, many deep-seated slides also occurred. Comparing maps that show distribution of historic landslides with reports of landslides compiled by city and county governments for the winter of 1996-97 and our field reconnaissance of recent landslide deposits and scars indicates that many bluffs and steep hillsides are sites of recurring failures. Investigation of the 1996-97 landslides indicates that houses and other structures built downslope from steep bluffs are in particular danger of impact by debris flows, while those on the benches, slopes, or rim of bluffs are subject to severe damage by deep slides.

INTRODUCTION

Heavy precipitation near the end of December 1996 resulted in widespread flooding and localized landsliding in the western states of California, Oregon, Washington, Nevada, and Idaho. Many of the landslides occurred in the Puget Lowland of western Washington (fig. 1). Total precipitation for December 1996 was 287 mm, or 191 percent of normal at the National Weather Service station in Seattle. Total precipitation from Dec. 20, 1996 to January 3, 1997, was 177 mm at Everett and 223 mm at Sea-Tac Airport (Lott and others, 1997). Much of the late-December precipitation was in the form of snow (Gerstel and others, 1997; Craig Weaver, USGS, written commun., 1997). North of Tacoma, 300-350 mm of snow fell on December 26 and 27; another 280-300 mm fell on December 28 and 29, 1996. Total accumulation over the northern Puget Lowland was 450-600 mm. On the morning of December 29, the snow changed to rain and at least 25 mm per day of rain fell for the next 3 days at Sea-Tac Airport. As the rain continued, the snow quickly melted causing much urban flooding (streets and waterways) and landsliding. The Woodway landslide (at the mouth of Deer Creek in Woodway, #27, pl. 1), which derailed five cars of a freight train, occurred on January 15, 1997 about two weeks after the major snow and rain storms. Additional rain fell in mid-January and more landslides occurred, including the highly publicized debris flow at Rolling Bay Walk, on Bainbridge Island, that killed a family of four on January 19, 1997 (#20, pl. 1 and fig. 2). Rainfall triggered slides and flows on March 18 and 19, 1997, including about three dozen in Seattle, several more at Rolling Bay Walk, and several near Mukilteo (Wallace, 1997). Many of the slides caused by the March 1997 rainfall were in the same areas as those in January.

This report describes a representative sampling of the types, sizes, geologic materials, damage, and hydrologic settings of landslides triggered by the December 1996 and January 1997 storms (table 1). Local newspapers reported locations of some of the more damaging landslides, but most reports of landslide locations came from telephone, electronic-mail, or personal contacts with state and local agencies in the Puget Sound area. We also obtained landslide locations from postings of flood- and landslide-related road closures on World Wide Web sites of King and Pierce Counties. We conducted a reconnaissance on January 8-10, 1997, in the Seattle area and on January 22-25 in King, Snohomish, Kitsap, and Pierce Counties. We observed many slides and debris flows to estimate the dimensions, identify the dominant materials and processes, and photograph the damage, scars, and deposits of the landslides.

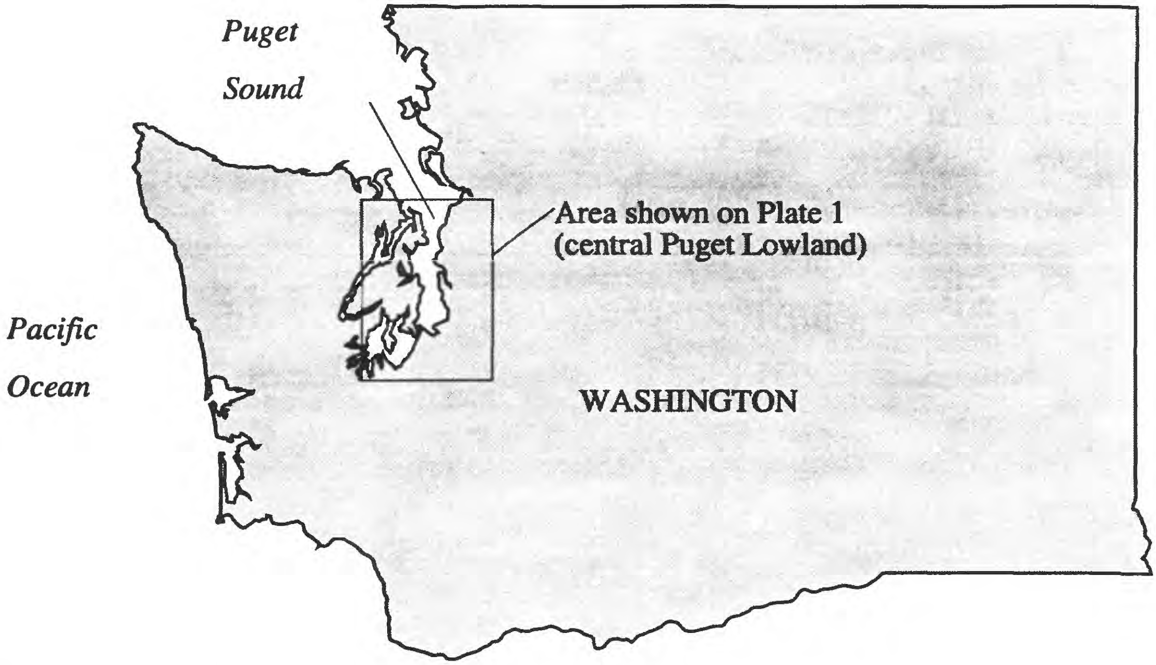


Figure 1. Map of Washington State showing the Puget lowland and the approximate area of reconnaissance.

GEOLOGIC SETTING AND LANDSLIDES

The surficial geology of the Puget Lowland consists mainly of Pleistocene glacial, alluvial, and marine sediments; little bedrock is exposed. Major Quaternary stratigraphic units exposed in coastal bluffs overlooking Puget Sound include nonglacial sand, silt, and clay which are overlain by a sequence of glacial deposits, primarily the Vashon Drift (Mullineaux and others, 1965). The basal member of the Vashon Drift is a widespread deposit of dense glacial clay and silt, called the Lawton Clay Member (Tubbs, 1974a). A deposit of sand, known as the Esperance Sand Member, overlies the Lawton Clay Member. For convenience we will refer to these units as the Lawton Clay and the Esperance Sand. The basal contact of the sand is transitional over a few tens of meters, where layers of sand and clay interfinger; within this transition zone, individual strata are laterally discontinuous. The Esperance Sand becomes pebbly near the top and grades into the Vashon Drift advance outwash. The Vashon Till, which is generally compact and hard, overlies the advance outwash or the Esperance Sand. The majority of landslides that we observed occurred in glacial sediments, including outwash, till, Esperance Sand, and Lawton Clay. A number of landslides also occurred in postglacial colluvial deposits derived from the glacial sediments.

Landslides have been a significant problem in the Puget Lowland for many years, and several landslides occur every year during the rainy season (generally from November through April, Thorsen, 1989). Storms have triggered significant numbers of landslides in 1972, 1986, 1990, 1996, and 1997 (Tubbs, 1974a, b; Laprade, 1986; Miller, 1991; Gerstel, 1996; Harp and others, 1976). Tubbs reported on 1972 storm-induced landslides in Seattle and noted that many of the landslides occurred in or near the transitional zone between the Esperance Sand and the underlying Lawton Clay. Comparison of the locations of recent landslides with those mapped by Tubbs (1974a, b) reveals that many of the 1997 landslides are in the same general areas as the 1972 landslides. Thorsen (1989) attributed most landslides in the Puget Lowland to excess ground water, while Gerstel (1996) concluded that both seepage of perched ground water and infiltration of

Figure 2. Oblique aerial view of the landslide at Rolling Bay Walk on Bainbridge Island (#20, pl. 1) (photograph by T. Tamura, The Seattle Times, © 1997, used by permission). The slide scar is shallow and planar, and the slide transformed into a flow. This thin slide is three lots north of a slide that pushed an adjacent house off its foundation during the spring of 1996.

Figure 3. Shallow debris slide blocking California Way SW in West Seattle (#9, pl. 1).

surface water contributes to instability of thin colluvium and fill overlying glacial materials.

Efforts to reduce landslide-related losses have been ongoing for at least 20 years. Relative-slope-stability maps at several scales were developed in the 1970s for many of the urbanized areas surrounding Puget Sound (Miller, 1973; Artim, 1976; Smith, 1976; Laprade, 1989). Most cities and many counties in the area regulate development of steep hillsides (Laprade, 1989). Despite these efforts, losses continue to mount because (1) economic growth continues to exert pressure to develop in or near landslide-prone areas, (2) increased erosion and consequent downcutting caused by urban runoff has locally reduced slope stability (Booth, 1989), and (3) new or previously unidentified landslides damage structures that were built in unstable areas before regulations existed.

DISTRIBUTION AND TYPES OF LANDSLIDES

Although our investigation was limited to landslides in King, Kitsap, Pierce, and Snohomish Counties (pl. 1, table 1), landslides undoubtedly occurred in neighboring counties as well. News reports suggested that landslides occurred mainly in and north of Seattle. Landslides were most abundant along the bluffs of Puget Sound, Lake Washington, Lake Union, and Portage Bay. West Seattle and Magnolia Bluff had many damaging landslides, while few landslides occurred along the I-5 corridor. Many small landslides were scattered west and south of Seattle in Kitsap and Pierce counties.

SEATTLE

Shallow slides, many of which mobilized into debris flows were by far the most common type in Seattle. A number of debris flows partially blocked roads or impacted structures (#9 and 14, pl. 1; figs. 3 and 4). Structural damage from debris flows ranged from slight to severe. At least two homes in the Magnolia Bluffs area were damaged by debris flows (#15, pl. 1; fig. 5). Debris-flow sites we studied January 8-10 at Magnolia Bluff and near Lake Union (#16, pl. 1) showed no signs of renewed activity when we returned on January 22.

Slumps and deep-seated slides, though less common than debris flows, caused severe damage to land and structures. A deep slide at Magnolia Bluff undermined and destroyed a covered porch at the back of one house and endangered several other houses (#12, pl. 1; fig. 6A and 6B). Part of this slide mobilized

Figure 4. Shallow debris-flow scar about 1 km east of Lake Union, upslope from Interlaken Boulevard (#14, pl. 1). Trees in scar were in danger of falling onto road. Mud line on tree near right edge of photograph indicates approximate depth of flow (1 m).

Figure 5. House in the Magnolia Bluffs area overlooking Puget Sound that was struck by a debris flow (#15, pl. 1). The flow deposited material in the garage (upper level) and collapsed the front wall of the living quarters (lower level).

A

B

Figure 6. Slide at Magnolia Bridge, Seattle (#12, pl. 1). *A*. Head of slide, porch at back of light-colored house was undermined and collapsed. Head of slide covered with plastic sheets to prevent additional rain water from entering the slide. *B*. Slide deposits on uphill side of bridge.

A

B

Figure 7. Large, deep-seated slide in Magnolia Bluffs area of Seattle (#13, pl. 1). *A*. Graben at head of slide, looking north. House at left edge of photograph was beginning to tilt downslope by January 22, 1997. The house appeared to be plumb two weeks earlier when we surveyed the same site. *B*. Scarp at right flank of slide is about 1 m high.

Figure 8. Slide on wall of small drainage in northwest Seattle (#21, pl. 1). Foundation of house on right edge of photograph and decks of neighboring houses had been undermined.

into debris flows that damaged supports for the Magnolia Bridge. Another deep slide on a bench at Magnolia Bluff destroyed part of a residential street and severely damaged several homes founded on the slide (#13, pl. 1; fig. 7*A* and 7*B*). This slide was active previously in March 1996 and renewed or continuing movement between January 8 and January 22, 1997, caused additional damage to the homes. Evidently, the slide remained active throughout 1997 and into 1998, because it had enlarged and still appeared to be active when we observed it again in February 1998. A deep slide in the extreme northwestern part of Seattle seriously damaged several homes early in January 1997 but showed no signs of additional movement between January 9 and 22, 1997 (#24, pl. 1). Debris flows from the front of this slide deposited debris on the railroad tracks downslope from the toe of the slide; the tracks had been cleared by the time of our survey on January 9, 1998. Another deep slide in northwest Seattle undermined the foundations of houses built on its margin (#21, pl. 1; fig. 8).

KING COUNTY, EAST OF SEATTLE

Landslides in areas of King County, east of Seattle seemed to be less abundant away from the lake and coastal bluffs. Most of the landslides in these areas affected roadways, were classified as rotational slides, and appeared to have occurred in glacial outwash of gravely sand (#23, pl. 1; fig. 9). One landslide, which had a volume of about 1500 m3, had broken apart and may have turned into a flow or avalanche according to the description given by a county employee we met at the site. Unfortunately, King County road crews had nearly finished repairing the road and landslide scar by the time we were able to study it (#5, pl. 1).

SNOHOMISH COUNTY

Many slides and debris flows were reported along bluffs at Edmonds, Mukilteo, and Woodway in Snohomish County. Of these landslides, we had time to observe only the destructive Woodway landslide, directly south of Deer Creek, in Woodway (#27 pl. 1; fig. 10A and 10B).

Initial estimates (H. G. Landau, oral commun., 1997) placed the volume of the slide at 150,000-200,000 m3; however, later estimates, based on additional data, ranged from 75,000 to 150,000 m3. The head of the slide is downslope from (west of) the Rosary

Figure 9. Slump in outwash deposits on bluff east of Lake Washington (#23, pl. 1). On January 25, 1997, water was flowing from seeps on the uphill side of the road (left side of photograph).

Heights Convent. The bluff here is about 70 m high, and the head scarp appears to be about 100 m wide. The slide deposit extended from the base of the scarp across railroad tracks and into Puget Sound. Except for a large, partially intact slide block resting at the base of the scarp, the deposit consisted mostly of remolded sand and silt, containing logs and boulder-sized, joint-bounded blocks of intact Lawton Clay (fig. 10B). The remolding indicates that much of the slide broke apart and mobilized into a debris flow.

The slide occurred about 10:30 p.m. Wednesday, January 15, 1997. An Amtrak train carrying 650 passengers passed over the track two hours before the slide (The Edmonds Paper, January 22, 1997, p. 3). The first pulse of the slide deposited about a meter of landslide debris on the tracks. The locomotives of a Burlington Northern freight train approached the slide and pushed through its toe. As the train crossed the slide area, a large pulse of debris swept five freight cars into Puget Sound. This pulse deposited 6-8 m of debris on the tracks. About 5:30 a.m. Thursday morning, January 16, another pulse of debris fell from the south part of the scarp (H.G. Landau, oral. commun., 1997). The scarp exposes advance outwash, transition beds, and the Lawton Clay. Water was still trickling down the face of the clay on the afternoon of January 24, 1997. Months later, on May 29, seepage near the top of the clay was still evident at the left flank of the slide. The scarp was irregularly arcuate in plan view, and in section nearly vertical and locally overhanging, but little cracking or other evidence of deformation was visible in the ground surface a few meters upslope from the scarp. Near the south end of the slide, a few small scarps at the edge of the bluff indicated where additional blocks might eventually detach and some of them did detach during a storm in March 1997. On the bluff north of the convent, H.G. Landau (oral commun., 1997) noted 10 or 11 new slides that had resulted from the storms of December 1996 and January 1997. Although freight traffic was running again at reduced speed by January 24, 1997, there was an indirect economic loss to Amtrak, which was not able to use the tracks until safety issues related to the slide were resolved.

KITSAP COUNTY

Kitsap County had many small landslides and a few large ones. One notable slide occurred north of Poulsbo, in a cut slope

Figure 10. (Facing Page) Oblique aerial views of the Deer Creek landslide (#27, pl. 1) in Woodway (both photographs by M. Siegel, The Seattle Times, © 1997, used by permission). *A*. Looking north, the slide debris appears to have flowed over the railroad tracks without deforming the underlying fill. *B*. Looking east, Esperance Sand is exposed in the head scarp. The landslide appears to consist of two blocks, the toes of which have broken apart and flowed over the tracks and into Puget Sound. The southern block appears to have failed last.

above Big Valley Road (#26, pl. 1). This slide mobilized into a debris flow, which crossed the road and was deposited in a downslope from it. This slide originated in sandy deposits resembling glacial outwash; the scar was about 15 m wide, 15-20 m high, and 1-2 m deep. The head of the scar was downslope from a private gravel road, and at the time of our observation, water trickled from a drain pipe at the top of the scar. A deep-seated slide near Brownsville Marina closed Illahee Road (#17, pl. 1) and downed power poles on January 20, 1997, causing closure of the road and a nearby public school (The Sun, of Bremerton, January 22, 1997). The slide was about 20 m wide, 20-30 m high and appeared to be several meters deep. We observed a deep-seated slide near Warrenville being excavated (#19, pl. 1). A county employee at the site stated that a side-hill fill had previously been constructed on the head of the slide and evidently contributed to its movement. The basal failure surface was in blue clay. The slide had been moving for "some time" and Kitsap County officials had planned to repair it. The storms accelerated movement of the slide. At Prospect Point, in Olalla, a debris flow (#3, pl. 1) did minor damage to a house that suffered major damage in 1996 (Harp and others, 1996). This house was a few lots south of a site where a house had been pushed into the Puget Sound in 1996. Clear cutting of timber and leveling of a lot upslope from these houses may have contributed extra run off to the flows.

The Bainbridge Island landslide at Rolling Bay Walk is about three houses north of one that was pushed off its foundation on April 23, 1996 (#20, pl. 1; fig. 2). The landslide scar, deposits, and overturned house were still intact at the time of our observations, except for the disturbance caused by recovery operations. The scar of the slide was about 15 m wide, 15-20 m high, and averages 1 m deep. News reports indicated that the owner had built a retaining wall of unknown quality and design (Maier, 1997; Crist, 1997). Newspapers and a local resident indicated that the landslide happened shortly before 8:00 a.m., Sunday, January 19, 1997 (Maier 1997). A neighbor stated that the landslide lasted only a few seconds (Bjorhus and Tu, 1997). The row of houses appear to be constructed in a cut at the base of a steep bluff that rises from a narrow beach area. We observed scars of many old landslides on the bluff to the north of the houses. About five recent slides from 1996 and 1997 storms were visible along undeveloped bluffs not far north of the houses. More slides occurred at Rolling Bay Walk on March 18 and 19, 1997; these slides damaged two houses and pushed another house onto the beach (Wallace, 1997).

PIERCE COUNTY

About 20-30 landslides were reported in Pierce County (Steve Hansen, Pierce County, oral commun., 1997), these included several minor ones near Tacoma. Scars of small, shallow slides 10-15 m wide and 10-20 m high, were visible upslope from Schuster Parkway in Tacoma (#2, pl. 1). Newspaper reports indicated that two minor slides occurred at Salmon Beach; one of these occurred December 27, 1996 and cut off telephone service to Salmon Beach residents (Tacoma News Tribune, January 26, 1997). We observed several recent shallow slides on bluffs overlooking Tacoma Narrows, many of which may have occurred in 1996. Unfortunately we were not able to visit Salmon Beach or observe the slides from vantage points on the opposite side of Tacoma Narrows. According to newspaper accounts, the only major slide in the Tacoma area in January 1997 was one just north of the Tacoma Narrows Bridge (#1, pl. 1); its scar is readily visible from the bridge. This slide exposed the deck footings of a home at the rim of the bluff.

DISCUSSION AND CONCLUSIONS

Our surveys of landslides that were triggered by the December 1996 and January 1997 storms resulted in several observations that are relevant to improving public safety and reducing property damage related to landslides in the Puget Lowland.

Although slow-moving slides were less common than debris flows, they caused significant property damage. Slow, deep-seated slides severely damaged several homes, roads, and utilities on the rim, bench, or sloping face of bluffs. Many of the deep slides appeared to result from reactivation of preexisting landslide deposits. Detailed engineering-geologic mapping to identify existing landslides before development and establishing minimum setback distances for structures at the rim of bluffs could help reduce damage caused by deep slides.

The distribution and likelihood of debris flows and shallow landslides occurring in any given area are crudely predictable. In general, such landslides occurred in the same areas and relative abundance as they have previously. Analyzing the spatial and temporal distributions of historic landslides and debris flows could aid in delineating areas of significant landslide hazard for parts of the Puget Lowland.

Though debris-flows were abundant and widespread on lake and coastal bluffs, debris flows were particularly hazardous in certain settings and any attempt to delineate debris-flow hazard zones should include the potential paths (run-out zones) as well as the source zones. Several homes on beaches or benches that were directly downslope from steep bluffs were struck and destroyed or damaged by debris flows. One such debris flow killed a family of four people sleeping in the lower level of their home, which was built directly downslope from a steep bluff. A freight train was also struck and derailed by a debris flow that started as a large slide. Bluff height is a poor indicator of potential hazard because debris flows accelerate rapidly on steep bluffs; significant damage resulted to homes in the path of debris flows even where the vertical distance traveled by the debris flow was less than 10 m.

ACKNOWLEDGMENTS

Employees of state and local agencies provided information about locations of reported landslides. These included W. Gerstel, Washington Division of Geology and Earth Resources; H. Allwine, Seattle City Engineers office, J. Petersen, City of Seattle Department of Construction and Land Use; J. Pillsborough, Snohomish County Engineer; G. Eckstead, County Department of Public Works; and S. Hansen, Pierce County Roads Department. Maintenance crews and other city or county employees we met in the field provided useful information about the landslides and debris flows. H.G. Landau, Landau Associates, Inc., and G. Beckett, Mayor Pro Tem of Woodway, led us on an inspection of the site of the Woodway landslide, and the Rosary Heights Convent kindly granted access to the site. P.S. Powers compiled the map in plate 1.

REFERENCES CITED

Artim, E.R., 1976, Slope stability map of Thurston County, Washington, Washington Department of Natural Resources, Division of Geology and Earth Resources, Geologic Map GM-15.

Bjorhus, Jennifer, and Tu, J.I., 2 witnessed fatal slide, Seattle Times, January 24, p. A1, A23.

Booth, D.B., 1989, Runoff and stream channel changes following urbanization in King County, *in*, Engineering Geology in Washington, Richard W. Galster, ed.: Washington Division of Geology and Earth Resources Bulletin 78, v. II, p. 639-649.

Crandell, D.R., Mullineaux, D.R., and Waldron, H.H., 1965, Age and Origin of the Puget Sound trough in western Washington: U.S. Geological Survey Professional Paper 525-B, p. B132-B136.

Crist, Douglas, 1997, Slide claims island family: Bainbridge Island Review, January 22, p. A1-A2.

Gerstel, W.J., 1996, The upside of the landslides of February 1996--Validating a stability analysis of the Capitol Campus Bluffs, Olympia Washington: Washington Geology, v. 24, no. 3, p. 3-16.

Gerstel, W.J., Brunengo, M.J., Lingley, W.S., Jr., Logan, R.L., Shipman, Hugh, and

Walsh, T.J., 1997, Puget Sound Bluffs: the where, why, and when of landslides following the 1996/97 storms: Washington Geology, v. 25, no. 1, p. 17-31.
Harp, E.L., Chleborad, A.F., Schuster, R.L., Cannon, S.H., Reid, M.E., and Wilson, R.C., 1996, Landslides and landslide hazards in Washington State due to February 5-9, 1996 storm. U.S. Geological Survey Administrative Report to the Federal Emergency Management Agency, 29 p.
Laprade, W.T., 1986, Unusual landslide processes, January 17 and 18, 1986 storm, Seattle, Washington, *in* Better living through Engineering Geology: Association of Engineering Geologists, 29th Annual Meeting, San Francisco, p. 55.
Laprade, W.T., 1989, Building codes for construction on steep slopes in western Washington, *in* Engineering Geology in Washington, Richard W. Galster, ed.: Washington Division of Geology and Earth Resources Bulletin 78, v. I, p. 151-155.
Lott, N., Ross, D., and Sittel, M., 1997, The winter of '96-'97 west coast flooding: National Climate Data Center Technical Report 97-01, 11 p.
Maier, Scott, 1997, Family of 4 killed in mudslide: Seattle Post-Intelligencer, January 20, p. A1, A6.
Miller, D.J., 1991, Damage in King County from the Storm of January 9, 1990: Washington Geology, v. 19, no. 11, p. 28-37.
Miller, R.D., 1973, Map showing relative slope stability in part of west-central King County, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map, I-852-A, 1:48,000.
Mullineaux, D.R., 1967, Gross composition of Pleistocene clays in Seattle, Washington: U.S. Geological Survey Professional Paper 575-B, p. B69-B76.
Mullineaux, D.R., Waldron, H.H., and Rubin, Meyer, 1965, Stratigraphy and chronology of late interglacial and early Vashon glacial time in the Seattle area, Washington: U.S. Geological Survey Bulletin 1194-O, 10 p.
Mullineaux, D.R., Nichols, T.C., and Speirer, R.A., 1964, A zone of montmorillonitic weathered clay in Pleistocene deposits at Seattle Washington: U.S. Geological Survey Professional Paper 501-D, p. D99-D103.
Smith, Mackey, 1976, Relative slope stability of Gig Harbor Peninsula, Pierce County, Washington, Washington Department of Natural Resources, Division of Geology and Earth Resources, Geologic Map GM-18.
Thorsen, G.W., 1989, Landslide provinces in Washington, *in* Engineering Geology in Washington, Richard W. Galster, ed.: Washington Division of Geology and Earth Resources Bulletin 78, v. I, p. 71-89.
Tubbs, D.W., 1974a, Landslides in Seattle, Washington Division of Mines and Geology Information Circular 52, 15 p., scale 1:31,680.
Tubbs, D.W., 1974b, Landslides and associated damage during early 1972 in part of west central King County, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map, I-852-B, 1:48,000.
Wallace, James, 1997, Awash in mud, flood: Seattle Post-Intelligencer, March 20, p. A1, A6.

Table 1. Landslides in the Puget Sound area, January 1997
[locations keyed to Plate 1]

Location number	Landslide type	Estimated volume (m^3)	Source material	Damage	Comments
1	Debris slide or flow	?	Sand	House deck footings exposed; yard partially removed	Occurred January 2, 1997. Pictured in Tacoma News Tribune, January 26, 1997
2	Debris flows	<100 each	Sand & silt	Southbound lane of Schuster Parkway temporarily blocked	Small, shallow failures; some <30 cm thick
3	Debris flows	<100	Outwash sand and gravel	Street blocked; house slightly damaged	Same house damaged 1996 by flow that pushed nearby house into Puget Sound
4	Earth slide	150	?	House deck undermined	
5	Rapid debris slide or flow	1500	Sandy gravel (outwash?)	Part of north-bound lane of highway removed	Slide debris excavated and replaced with rock fill
6	Earth slide	?	?	Slide broke pavement	Vegetation obscured most of slide. Slide still active in April 1997
7	Debris flows	100 to 200	Sand and silt	Building pushed from foundation	
8	Debris slides and flows	<100	Sand and silt	Buildings struck; house yards filled with debris	
9	Debris slide and flow	500 (?)	Sand and silt	Street intersection blocked	Street blocked near same place 1996

Table 1. (cont.)

Location number	Landslide type	Estimated volume (m^3)	Source material	Damage	Comments
10	Rapid earth slide and flow	>2000	Sand and silt	House foundation 3/4 undermined	Slide may be source of debris that impacted buildings at north end of Alki Avenue
11	Earth slide	1000	Clay or silt and fill	Retaining wall broken and overturned; enclosed porch of house crushed	Occurred 6:00 a.m., January 1, 1997
12	Earth slide and flow	9000	Sand and silt, fill(?)	Secondary supports of bridge broken; house partially undermined; parts of house yards destroyed	Occurred January 2, 1997
13	Debris slide	100,000	Glacial till, silt(?)	Street and utilities destroyed; houses deformed and tilted	Deep, slow-moving slide; large graben at head
14	Debris flows	<100	Sand	Road blocked; mud in yards	City crews removed trees that might have fallen onto road
15	Debris flows	<100	Glacial till	House partially filled with debris; street temporarily blocked	Occurred about January 1, 1997
16	Debris slides and flows	<100	Sand and silt	Lane temporarily blocked; old building damaged	
17	Earth slide and flow	1500-2500	?	Road blocked; power lines down	Occurred early evening, January 20, 1997
18	Earth slide	3000-6000	Outwash sand and gravel	Road impassable	Deep slide, head scarp 1 to 2 m high. Remedial work already in progress late January 1997

Table 1. (cont.)

Location number	Landslide type	Estimated volume (m^3)	Source material	Damage	Comments
19	Earth slide	1000-2000	Artificial fill, silt and clay	Road impassable	Chronic slide aggravated by 1996-1997 storms. Slide excavated and road rebuilt
20	Debris flow	500-1000	Outwash sand & gravel	Four people killed; house collapsed; top story pushed into Puget Sound	Occurred between 7:30 and 8:00 a.m., January 19, 1997
21	Earth slide	3000	?	House undermined; yards destroyed; culvert blocked	
22	Debris slides and flows	200 (largest)	Colluvium derived from glacial sand and silt	Trail temporarily blocked by debris	Small, shallow slides
23	Rotational earth slump	200	Outwash sand and gravel	About 6 m of westbound lane destroyed	1-m-high scarp
24	Earth slide	100,000	Sand and silt	Several homes deformed; roads impassable	Shallow debris flows from north flank of slide area covered railroad tracks
25	Earth slide	?	?	Collapsed garage	2- to 3-m-high scarp
26	Debris flows	200-400	Sand and silt	Road temporarily blocked; field covered with debris	Several smaller debris flows on nearby slopes
27	Earth slide	75,000-150,000	Esperance Sand, Lawton Clay	Train derailed; tracks blocked; part of convent yard destroyed	Main slide Janaury 15 1997, about 10:30 p.m. Second slide January 16, 5:30 a.m. Remaining unstable blocks could move and block railroad tracks

Note for "New Publications of the U.S. Geological Survey"

Open File Report 98-239

Landslides Triggered by the Winter 1996-97 Storms in the Puget Lowland, Washington, by R.L. Baum, A.F. Chleborad, and R.L. Schuster, 1998, p. $.

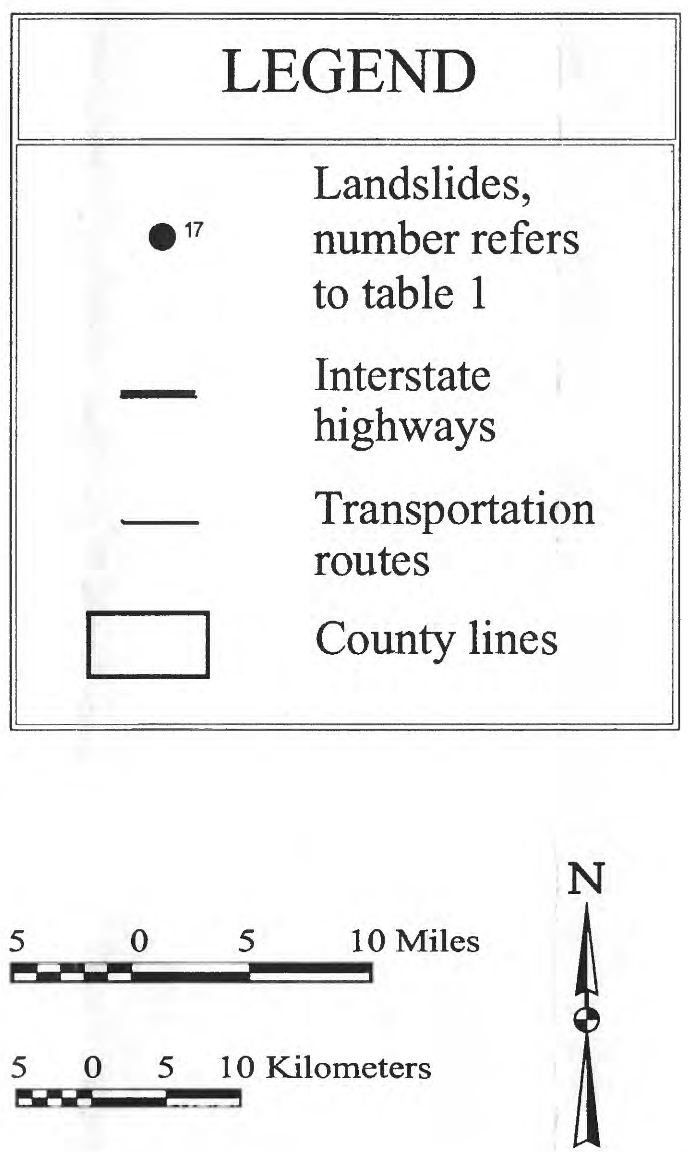
On-line edition at http://geohazards.cr.usgs.gov/pubs/ofr/ofr98-239/ofr98-239.html

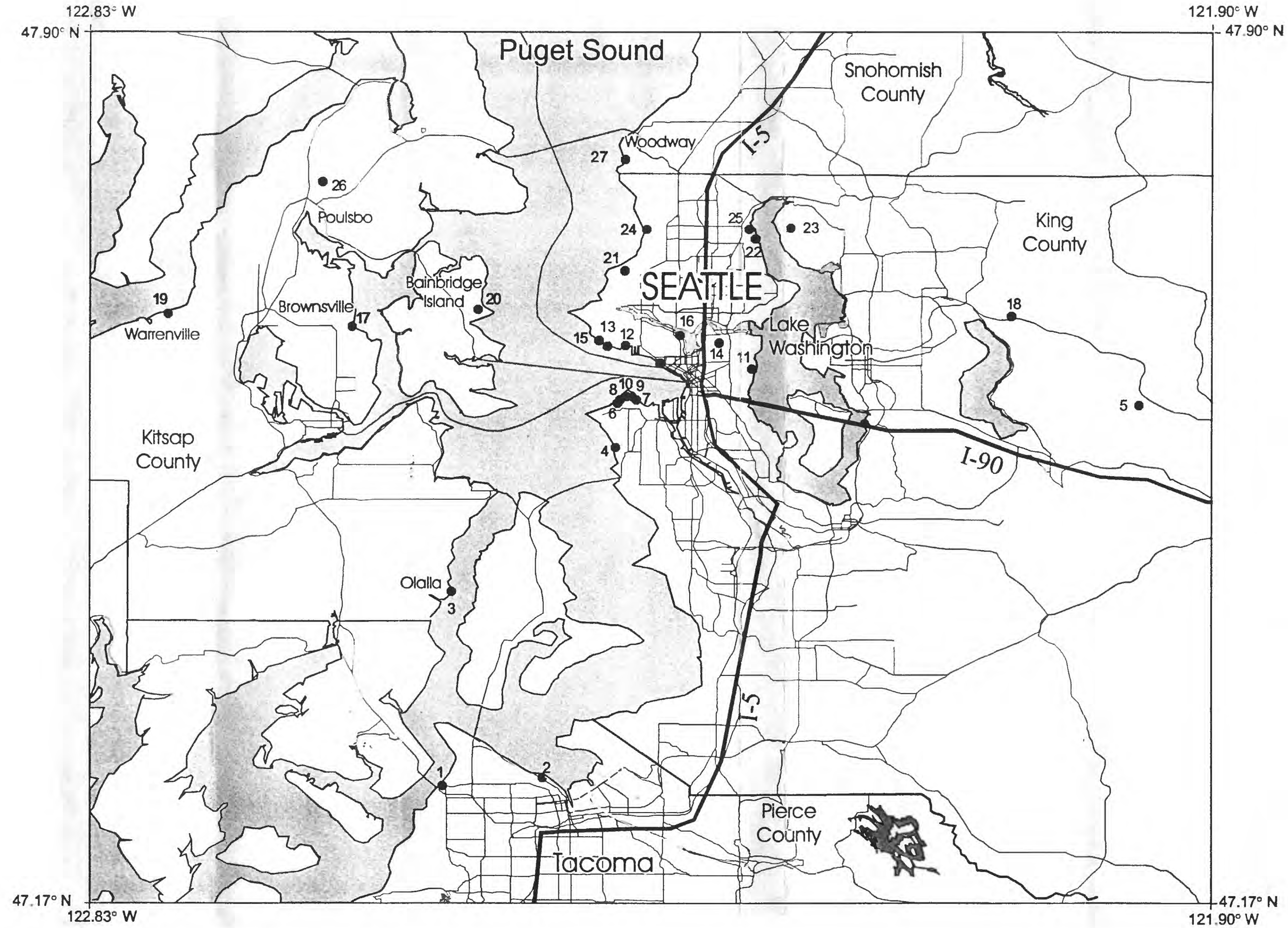
Examples of landslides resulting from storms in December 1996 and January 1997 are described from King, Snohomish, Pierce, and Kitsap Counties, Washington. Data on the classification, size, materials, and damage are tabulated for typical slides. Settings where structures are subject to significant threat from debris flows and deep seated slides are identified.

U. S. Department of the Interior
U. S. Geological Survey

Open File Report 98-239
Plate 1

Selected Landslides Triggered by Winter Storms 1996-97, Puget Sound Area, Washington





by

R. L. Baum, A. F. Chleborad, and R. L. Schuster

1998