# Landslides in the Portland, Oregon Metropolitan Area Resulting from the Storm of February 1996: Inventory Map, Database and Evaluation

Comment [SFB1]:

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We would also like to thank all of the reviewers of this report which has been through many revisions. We have tried to produce a report and GIS database that can be used in the future by decision makers in the Portland region. First, we thank the members of Metro's Natural Hazard Technical Advisory Committee for their many comments. Members of the committee are: Mike Cheston (Port of Portland), David Douthwaite (Associated General Contractors), William Elliott (City of Portland Water Bureau), John Godsey (Home Builders Association), Warren Harris (Northwest Natural), Marianne Macina-Hoffman (Western Insurance Information Services), Bert Kile (American Red Cross), David Stokey (Hospitals Delegate), Margaret Mahoney (City of Portland Bureau of Buildings), Scott Porter (Washington County Office of Consolidated Emergency Management), David Rankin (Golder Associates), Mike Maloney (Beaverton School District), and Edward Trompke (Tarlow Jordan and Schrader). Second, many important comments came from the reviews of the Metro personel who were in charge of this report, especially Dr. Gerald Uba (Natural Hazards Mitigation Coordinator), Benjamin Rice (GIS Specialist), Jennifer Budhabhatti (Parks and Greenspaces), Elaine Wilkerson (Growth Management Services), Rosemary Furfey (Growth Management Services), Laura Mundt (Growth Management Services), and Michael McGuire (Senior Emergency Management Analyst). Third, some excellent suggestions came from the Department of Geology and Mineral Industries, especially Dr. John Beaulieu, Associate Director. This report is the result of the input of many excellent suggestions from outside reviewers.

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(Cover Photo: Landslide 695 on S.W. Benchview Place on Bull Mountain. This is an area that is not highly susceptible to landslide activity, but this house was built on the toe, or end, of an ancient landslide that reactivated during the climatic event in February 1996. The house was destroyed and has since been torn down.)

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**ABSTRACT: KEY FINDINGS**

Abundant landslide activity resulting in region-wide disruptions was associated with the flooding of the storm of February 6-9, 1996. Landslides were so abundant that the distribution of the landslides has been equated to a 100-year return interval event. Of the total of 705 landslides studied in this project, 297 have been repaired by May 1998 by re-establishing slope stability.

Based on the dominant landslide process and distribution density, four landslide provinces have been delineated in the Portland area that are prone to landslides. The four regions with the number of failures that occurred in each are: the West Hills Silt Soil Province (374), the Debris Flows in Valley Bottoms Province (45), the Steep Bluffs Along Rivers Province (40), and the Fine-grained Troutdale Formation Province (72). The other 174 landslides were dispersed across the Portland region.

The majority of the failures were earthflows and slump earthflows in the wind-blown silt (i.e. loess) deposits of the West Hills of Portland. Debris flows were abundant in the steep drainage bedrock streams along the Columbia and Willamette Rivers. Humans were involved in helping increase the risk of landsliding in 76% of the cases, mainly through formation of cutslopes (52% of cases) and fill failures (15% of cases). It is estimated that 9% of the landslides could have had reduced damage by using better storm water control measures or better siting of the home on the property. Based on observations made from visiting the 705 landslides, this report summarizes some strategies for reducing landslide damage in the future.

Comment [SFB2]:

## INTRODUCTION

The four days of February 6-9, 1996 will not be forgotten by the people of northwest Oregon and southwest Washington. A rain on snow climatic event caused extensive flooding of the rivers with estimated peaks ranging from 25 to 100 year recurrence interval events. A 100-year recurrence interval has a 1-in-100 chance of occurring every year. Most of the population was prepared for the flooding because of accurate weather forecasting by the National Weather Service. But, the population was not ready for the many landslides that occurred over that time period. Comparing landslide distributions and damage to past climatic events, this series of landslides appears to have been a 100 year event.

The effects of the landslides can still be felt in the region today. A great loss of property resulted from this event, and a few lawsuits have followed. Local governments have current hazard maps for floods and earthquakes, but few for landslides, and these few have not been updated in the past 15 years. As the population grows and occupies land at a faster rate on hillslopes, more landslide activity can be expected in the future. Planners in the Portland region have asked for tools to help them reduce future vulnerability to landslides.

Metro asked the geology department at Portland State University (PSU) to help them develop landslide susceptibility maps for the Portland metropolitan area. PSU has been involved in landslide research for many years and has the expertise to carry out such a mission. This report, database, GIS disk and accompanying maps are the result of a contract between Metro and Portland State University to produce the first step in the development of landslide susceptibility maps through the production of a landslide inventory from the storm event.

The project was conducted from August 1997 to May 1998. The first part of the project was to collect data on all of the landslides that occurred in the Metro area from February 1996 until May 1998 from surface investigations and interviews. Data collected from each landslide included location, size, slope angle, geology, soils, hydrologic conditions, slide history, and probable cause factors. The data were then summarized into a database which is found in the appendix of this report and is also available on the GIS disk from Metro. The data were processed into an ArcView geographic information system (GIS), and a map of the landslide distribution was produced. After analysis of the data, four areas of landslide susceptibility were denoted, and a second landslide potential map was produced.

Of the 705 landslides studied in the Portland metropolitan area, approximately 25 homes were "red tagged" and 90 homes were "yellow tagged" (Burns, 1998). A house receives a red tag when it is determined that the house is not liveable until a problem has been fixed. A yellow tag is received when a house has problems, but the house is liveable without endangering its occupants. Most red and yellow tags were received from landslides either hitting the house or moving the ground underneath the house.

## CLIMATIC EVENT LEADING TO THE STORM

The climatic event that caused the many landslides and flooding in February of 1996 in Portland was a classic example of a “rain on snow event” (Taylor, 1997). The last similar major event in the Portland region occurred in December of 1964 and also caused extensive flooding. Two important precursors happened before February in the region. First, there was abundant precipitation in the fall of 1995, and the ground became saturated. Second, large snowfalls during the last two weeks of January led to mountain snowpacks 120% of normal by February 6th. Then, on February 6th, the “Pineapple Express” air mass and storm system arrived in the Pacific Northwest (Taylor, 1997). This moisture-rich air mass came from Hawaii and raised the temperature over 30 degrees F in a day. The National Weather Service reported that 7.00 inches of rain fell on Portland from February 6 - 9th (Taylor, 1997). (Some of the surrounding areas unofficially received between eight and ten inches of rain.) In the mountains, the rain melted the snow rapidly, and all of this water went into the streams. On Saddle Mountain in the Coast Range, a total of 34 inches of water drained into the rivers from the 19 inches of rainfall that fell and the melting of snow that was equivalent to 15 inches of precipitation (Taylor, 1997). Such large precipitation equivalents expressed by those numbers led to extensive flooding in the Tualatin River drainage basin.

George Taylor, Oregon State Climatologist, believes that we are now into a 20 year wet cycle after just having come out of a 20 year dry cycle (Taylor, 1997); the fact that 1996 was the wettest year on record this century supports his ideas. Many sites in the Portland area have “two strikes” against them already (geology that is susceptible to landslides and steep slopes), and that “third strike” comes when abundant storm water is not controlled on the site. Taylor (1997) believes that in the Portland area that the two most important climatic factors that delivered the “third strike” causing the landslides were the precursor soil moisture and the intense rainfall over the four day period of time.

## GEOLOGY OF THE PORTLAND METROPOLITAN AREA

The geology of Portland region is very simple and can be modeled as a large bowl or basin. The “bowl” is made of basalt called the Columbia River Basalt Group. It formed from flows that came down the ancestral Columbia River 14 million to 16 million years ago and solidified in the area (Beeson et al., 1991). Since that time the center of the bowl has sunk in the middle, and the edges have uplifted to form the Tualatin Mountains (Portland’s West Hills) to the west and the Cascade Mountains to the east. It has filled up with sediments (gravels, sands, silts, clays) that have come down the Columbia River and streams from the Cascade Mountains. In fact, the sediments are over 1500 feet thick in the deepest part of this basin near the Portland airport. This layer of sediments is called the Troutdale Formation (Beeson et al., 1991). Deposition of the Troutdale Formation occurred over a twelve million year period, ending about two million years ago (Beeson et al., 1991). In the eastern part of the Metro area the Troutdale Formation is mainly gravels, but in the southern portion of the basin, near Oregon City and the Clackamas River, it consists of mainly the “fine-grained facies” of sands, silts and clays. Where impermeable clay layers are exposed in this fine-grained formation on the slope, the slope is prone to landslides. Many devastating slides occurred in the fine-grained Troutdale Formation region during the last two years. From about two million years ago to about 260,000 years ago, many small volcanic vents occurred around the Portland area forming Mt. Tabor, Mt. Scott, Rocky Butte, and Mt. Sylvania to name a few. The basalts forming these hills are called the Boring lavas (Beeson et al., 1991).

On top of the Troutdale Formation is a layer consisting mainly of silts and sands deposited 12,700 to 15,300 years ago from more than 90 gigantic floods that came down the Columbia River after a series of glacial dam breaks in Montana (Waitt, 1985; Atwater, 1984). These catastrophic floods are called the “Missoula Floods” and filled the basin with water to an elevation over 400 feet. The fine sediment settled out of the water as the flood waters receded, forming deposits that are more than 100 feet thick in some places. During previous glacial periods and after each of the floods, the sediment that was exposed in the floodplains was eroded by wind. These silts were blown onto the hillslopes surrounding Portland, especially the West Hills of Portland. This wind-deposited silt is called loess and has been named the Portland Hills Silt Formation (Beeson et al., 1991).

Landslides have always been an active process in the Portland area. The two most famous slides are located close to one another in the West Hills of Portland. One is where Washington Park in now located. This ancient slide was reactivated in 1894 when the city cut off its toe to build two reservoirs for the city water bureau (Clark, 1904). The problem was mitigated by installing dewatering tunnels throughout the slide in the late 1800’s. Today, the slide moves as fast as a person’s fingernail grows. The Portland Zoo, the World Forestry Center and the former OMSI buildings are all built on Portland’s other famous slide (Hammond and Vessely, 1997). This slide was also reactivated by humans cutting off the toe in the 1950’s to widen Canyon Road. It too has been slowed by installing dewatering tunnels, horizontal drains, and a buttress at the edge of Canyon Road. Every winter small landslides are found along road cuts in the West Hills and along steep slopes in east Multnomah and Clackamas Counties, but they are not usually in the number and density characterized by this 100-year event.

## PROJECT METHODOLOGY

The process of this study entailed two steps. First information on landslides needed to be gathered in the field. Second, the information needed to be organized into a database that could be presented graphically. These GIS maps, the GIS disk and the database could then be used by the public, consultants, and governmental agencies in making decisions related to land use.

### A) Field Methods:

Locations of landslides were found through many methods. The PSU team used pre-existing databases from counties, cities, the Oregon Department of Transportation, and fire departments. The team also drove many of the streets in the landslide prone areas and found additional slides. Additionally, landowners with landslides had contacted Portland State over the past two years providing another data source. Graduate students visited all of these landslides and characterized them. All landslides were field checked by the complete team to make sure that all team members agreed upon the data.

A standard landslide inventory form was used for the study (Appendix 1). Many items were recorded on the sheet, but some items such as date investigated, landslide name, investigators, and photo number were not entered into the database (Appendix 2). The following items for each slide are found in the database:

1) Landslide Number: Each slide was assigned a number that starts with an abbreviation of the U.S. Geological Survey topographic quadrangle map it is found on followed by consecutive and unique numbers. We have also given each landslide a number from 1 to 705 so the slide can be found more easily in the database.

2) Location: Each slide is listed by an address or approximate location.

3) County: The county is listed for each slide.

4) Topographic Quadrangle: The title of the U.S.G.S. 7.5 minute quadrangle map is given.

5) City: The city is listed. If it is outside of the city limits, the county name is given.

6) Process: The type of landslide is listed. The name is based on the classification discussed below.

The term landslide is a general term used to describe most mass wastage processes. Commonly, the term "mudslide" is used by the news media to describe landslides. We do not use that term. The most common landslides found in the Portland area are what we call earthflows, earth slumps or just "slumps," debris slides, rockfalls, and debris flows. Don Easterbrook (1993), a well-known Pacific Northwest geomorphologist, defines these different landslides as follows. An **earthflow** is a downslope flow of unconsolidated, water-saturated material. It is generally slow moving and produces a well-defined scarp and a tongue-shaped debris deposit. This process is common in the loess of the West Hills of Portland (Figure 1). A **slump** is the downward slipping of a mass of rock or unconsolidated material along a concave-upward plane of failure, usually with backward rotation. See the cover photo for an excellent example of a slump. Many times slumps have earthflows developing at the bottom of the slump, and we call them a **slump-earthflow**. Slumps were most common in the fine-grained Troutdale Formation. A **debris slide** is a detachment and rapid downward movement of predominantly unconsolidated and incoherent debris. Generally, this slide occurs on a failure plane of weak rock, like clay or shale. We also mapped many of these thin slides on the steep bluffs above the rivers, and in their cases there was no failure plane (Figure 2). A **rockfall** is a free falling of newly detached rock from a cliff. Many times a pile of rocks, called talus, is found at the bottom of the cliff. A **debris flow** is a flowing mass of water saturated debris. Most of the time debris flows occur in stream drainages. Debris flows have sediment contents up to 70% and water contents around 30% so they are very much like a slurry of wet concrete. In the valley bottoms these landslides scour the valleys (Figure 3), but when the debris flow leaves the constriction, the load is deposited on a fan.

Figure 1: An earthflow on S.W. 16th Street in the West Hills of Portland that moved on a paleosol in the loess (Slide # 599).

7) Geology: The underlying geological formation is important. The units given by Beeson et al (1991) include: Portland Hills Silt (PHS), Columbia River Basalt Group (CRBG), Troutdale Formation, Boring Lava, Fill, stream alluvium (Qal), terrace deposits (Qt), Missoula Flood deposits (Qff/Qfc), marine sediments, Eagle Creek Formation (older volcanics in the Cascade Mountains), and Qes (undifferentiated eolian silt).

8) <u>Soils:</u> Using the county soil surveys of the Portland area (Green, 1982; Green, 1983; Gerig, 1985), we have provided the soil series found at the site of the landslide. We have listed the series number found in the Metro RLIS database as well as the name. There are over 50 series listed in the database.

Figure 2: A debris slide produced at the end of N.W. Raleigh Street in northwest Portland. The slope became saturated from a broken water line and then the debris moved down the slope in the absence of a failure plane. (Slide # 302).

Figure 3: A debris flow in Dodson. This is a view looking south up the Royse debris flow canyon. Note the complete scouring of the valley bottom from the debris flow. (Slide #128)

9) Contributing Factors: Our basic question when analyzing the slides was to determine the influence of human activity. Obviously, the increased precipitation was the main cause for failure, but had human activity influenced the landslide? Was the site in a cutslope where the slope angle had been oversteepened? Was the site on fill? Had human activity (or lack of activity) caused water to be concentrated on the slope by things such as a broken pipe or drainpipe, clogged gutter, patio runoff, or driveway runoff. We listed this last group as “water control.” If we could not find an association with humans, we labeled it “natural”.

10) Repair: If the landslide had been repaired, we noted that it had been “fixed.” Otherwise, we listed it as “unfixed.” See the last section of the report (Possible Future Actions) for examples.

11) Landslide Dimensions: The length and the width of the slide was recorded after measuring in the field by the pace method (Compton, 1985). The average scarp height was also approximated. The volume was estimated by multiplying the length by the width by the average scarp height. Linear dimensions were measured in feet and volumes in cubic yards. Slides with a volume under ten cubic yards ( i.e. the volume of one dump truck load) were not usually mapped.

12) Slope Angle: Using a brunton compass, the angle of the original slope was approximated in degrees by measuring the angle of the adjoining slope (Compton, 1985).

13) Dates of Movement: Most of the slides occurred in February of 1996, but a few have occurred since then so those dates were also recorded based on local residents’ reports.

14) Corrective Actions: The type of repair was noted if the slide had been fixed. The range of strategies varied widely. Some slides just had the slide material removed from the road (which we called a "scooper," a term commonly used by highway personel) whereas others had elaborate retaining walls built near the failure area.

### B) Mapping Methods:

The data were all recorded into an EXCEL 4.0 database. The points plotted on the maps in the field were converted into a GIS database using ArcView 3.0. This database and resulting computer generated maps will become part of Metro's RLIS (Regional Land Information System) database for the Portland metropolitan area.

## RESULTS:

**A) Numbers of Slides:** A total of 705 landslides were mapped during the project. It is likely that the majority of the failures that occurred near traffic routes have been mapped, but some of the landslides on private property remain unmapped.

A map of the distribution of the landslides (Figure 4) shows that most of the failures occurred in the West Hills, along the rivers, and in the southeast in the Clackamas River drainage. At the scale of the map in Figure 4, many of the dots represent landslides that are superimposed on one another. In the ArcView electronic database the landslides are easily differentiated and are located to within 20 feet of the location.

Most of the "documented" landslides are located in Multnomah County (528 or 75%). Clackamas County is the location of 131 (18%) of the landslides, and Washington Country had 40 (6%) landslides. Four landslides were also located in Hood River County, and two were located in Yamhill County along the Willamette River. The Hood River slides were included in the study because of their proximity to the nearby slides in Multnomah County that had similar processes.

### B) Geological Relationships:

**Table 1: Geology Under the Landslides**

| Geological Unit | Numbers | Percentage |
|---|---|---|
| Portland Hills Silt | 334 | 48% |
| Fill | 106 | 15% |
| Troutdale Formation | 87 | 12% |
| Missoula Flood Deposits | 58 | 8% |
| Columbia River Basalt | 43 | 6% |
| Boring Lava | 16 | 2% |

| | | |
|---|---|---|
| Eagle Creek Formation | 9 | 1% |
| Other | 52 | 7% |

Most of the landslides (48%) surveyed in this study (Table 1) occurred in the West Hills within the Portland Hills Silt or loess. This material is very strong when it is dry, but the silt soils are very weak when they are saturated. Many of the failure planes were on paleosols (old buried soil surfaces) in the loess. A significant number of landslides were recorded in the Troutdale Formation (12%). The majority of the landslides within Missoula Flood Deposits (Qff/Qfc) are along the steep slopes next to the Willamette and Clackamas Rivers. The common processes in areas of exposed basalt were rockfall and debris flows. A total of 15% of the landslides occurred in sidecast fill, and 60% of those fill sites used loess as the fill.

### C) Landslide Types and Mechanisms

Many types of landslides occurred in the Portland area (Table 2), but ones involving earthflows dominated the processes. Earthflows by themselves and in combination with slumps make up 69% of the landslides, mainly because so many of the

failures occurred in the loess of the West Hills. Slumps and earthflows dominated the slide activity in the Troutdale Formation sites. Debris slides were the common mechanism along the steep cliffs along the rivers. The most dangerous type of landslide is the debris flow, and a total of 45 of them (found by themselves or in combination with other processes) occurred mainly in the steep valleys draining into the Columbia River and west of the Willamette River in northwest Portland. Only 4% of the sites had a rockfall, and those were associated with basalt outcrops around the Portland area.

**Table 2: Landslide Types and Mechanisms**

| Process | Number | Percentage |
|---|---|---|
| 1) Earthflows (EF) | 354 | 50% |
| 2) Slump-Earthflows (SEF) | 135 | 19% |
| 3) Slumps (SL) | 67 | 9% |
| 4) Debris Slides (DS) | 78 | 11% |
| 5) Debris Flows (DF) | 45 | 7% |
| 6) Rockfall (RF) | 26 | 4% |

Table 3 summarizes the landslide types by jurisdiction in the Portland metro area. Most of the landslides (58%) were in the city limits of Portland. The county numbers at the top of Table 3 are the unincorporated sections of the counties.

**Table 3: Landslide Types by Local Governments**

| | Landslide Types (From Table 2) : | | | | | |
|---|---|---|---|---|---|---|
| **Jurisdiction** | **EF** | **SEF** | **SL** | **DS** | **DF** | **RF** |
| Clackamas Co. | 73 | 14 | 4 | 7 | 2 | 2 |
| Multnomah Co. | 43 | 19 | 11 | 9 | 21 | 14 |
| Washington Co. | 25 | 7 | 2 | 0 | 2 | 0 |
| Hood River Co. | 0 | 0 | 0 | 2 | 1 | 1 |
| Yamhill Co. | 0 | 0 | 0 | 2 | 0 | 0 |
| Beaverton | 1 | 1 | 0 | 0 | 0 | 0 |
| Estacada | 2 | 0 | 0 | 0 | 0 | 0 |
| Gresham | 1 | 0 | 2 | 0 | 2 | 0 |
| Lake Oswego | 2 | 1 | 0 | 0 | 0 | 0 |
| Oregon City | 14 | 5 | 0 | 0 | 0 | 1 |
| Portland | 191 | 88 | 47 | 57 | 17 | 7 |
| Rivergrove | 1 | 0 | 0 | 0 | 0 | 0 |
| Tigard | 0 | 0 | 1 | 0 | 0 | 0 |
| Troutdale | 1 | 0 | 0 | 1 | 0 | 0 |
| West Linn | 0 | 0 | 0 | 0 | 0 | 1 |

**D) Sizes and Volumes of Slides:**

**Table 4: Landslide Volumes:**

| Landslide Volumes | Percentage of Total Slides |
|---|---|
| < 100 cubic yards | 18% |
| 100 - 499 cubic yards | 39% |
| 500 - 999 cubic yards | 14% |
| 1000 - 4999 cubic yards | 20% |
| 5000 - 9999 cubic yards | 6% |
| 10,000 - 40,000 cubic yards | 2.8% |
| 40,000-1,000,000 cubic yards | 0.9% |
| > 1,000,000 cubic yards | 0.3% |

Compared to the sizes of landslides in the Portland metropolitan area from this storm event to other well-known local large landslides such as the Zoo/OMSI and Washington Park landslides in Portland and the Cascade or Bonneville landslide in the Columbia Gorge, we find that these recent slides are mainly small to medium in size. Approximately 96% of the landslides studied in this report were less than 10,000 cubic yards in size and about 98.9% were less than 40,000 cubic yards (Table 4). Only two landslides were considered "large" or megalandslides (> a million cubic yards in volume), and one was a debris flow (Tumult Creek debris flow, slide #130) and the other a reactivation of an old paleoslide (Dixie Mountain slide, slide #657).

This was a major climatic event that triggered a multitude of landslides, but only two large slides happened. This suggests that the large landslides found in the Portland metropolitan area have probably been triggered by other mechanisms than climatic events. Two non-climatic event trigger possibilities for the large landslides are large subduction earthquakes along the Oregon coast or saturated slopes failing as waters from the Missoula Floods left the Willamette and Columbia River valleys over 12,000 years ago.

Excluding the two megalandslides, the volumes ranged from 10 to 150,000 cubic yards, the average volume is 2794 cubic yards, and the median size is 414 cubic yards. The low median reflects the large number of small landslides (Table 4). For comparison, a dumptruck carries a load that is approximately 10 cubic yards.

The largest slides in the Portland Hills Silt were at the Riverside Cemetery (slide 20, 106,800 cubic yards) and the corner of Cornell and Thompson in the West Hills (slide 323, 38,478 cubic yards). The largest slides along the river bluffs were in Newberg (Gill slide 696, 120,000 cubic yards) and along the Clackamas River (slide 230, 33,200 cubic yards). The largest fill failure occurred along Salmon River road in Welches (slide 197, 128,480 cubic yards).

Trying to estimate the volumes of landslides in the Troutdale Formation in southeast Portland was difficult for the paleolandslides might only have moved a couple of feet vertically or laterally, but it was over three to four acres. Examples like this can lead to large volumes like at the Matthew Court slide (slide 263; 26,660 cubic yards), the Holly Lane slide (slide 272; 93,087 cubic yards), the Beaver Lake slide (slide 704), the Bruin slide (slide 679; 16,700 cubic yards), and the 99E slide south of Oregon City (slide 229; 33,200 cubic yards).

**E) Soil Relationships:**

There is an interesting relationship between the soils and the landslides. The two most common soil series developed on the Portland Hills Silt are the Goble and Cascade soil series, and they make up 48% of the soils under the landslides (Table 5). Haploxerolls and Xerochrepts are young soils developed on steep slopes of the Portland area that are not found in enough abundance to be considered soil series. Beyond those four groups, there was no real correlation between landslides and soil series.

**Table 5: Soil Relationships Related to the Landslides**

| Soil Series | Numbers | Percentage of Total |
|---|---|---|
| Goble Silt Loam | 183 | 27% |
| Cascade Silt Loam | 140 | 21% |
| Haploxerolls | 66 | 10% |
| Xerochrepts | 31 | 6% |
| Ashcroft | 21 | 3% |
| Saum Silt Loam | 14 | 2% |
| Others (Over 40 series) | | 31% |

**F) Slope Angles:**

The majority of the landslides occurred on slopes with slope angles between 30 degrees and 50 degrees (Table 6). Relatively low angle slopes (<25 degrees) accounted for 8% of the landslides, most of which were in the Troutdale Formation on the toes of paleoslides that had been reactivated. Also, some of the long angle failures were at sites with broken water lines. The failures that occurred on slopes above 66 degrees (4% of the total) were mainly rockfall.

**Table 6: Slope Angles of the Landslides***

| Approx. Degrees | Numbers | Percentage of Total Landslides |
|---|---|---|
| 10 | 2 | .3% |
| 15 (30% slopes) | 5 | .7% |
| 20 | 13 | 2% |
| 25 | 35 | 5% |
| 30 | 65 | 10 % |
| 35 | 123 | 19% |
| 40 | 96 | 15% |
| 45 (100% slopes) | 116 | 18% |
| 50 | 78 | 12% |
| 55 | 28 | 4% |
| 60 | 53 | 8% |
| 65 | 13 | 2% |
| 70 | 7 | 1% |
| 75+ | 20 | 3% |

* Note: not all landslides had slope angles recorded for them, especially the debris flows.

### G) Contributing Factors of the Landslides

The primary contributing factor to most of the landslides appears to have been the increased water in the soil system. Many of the sites were prone to failure (steep slopes and weak geological unit/soil under the site), and the addition of seven inches of precipitation in four days on top of already saturated soils led to landslides. For 24% of the landslides we could not find any human action that could have increased the chances for the landslide occurring, hence these are called "natural slides." Human influence was noted in 76% of the landslides. The most common human factor was that 52% of the landslides occurred in cutbanks where humans had cut into the slope for roads or driveways. Failures along roads in the road prism (the fill) resulted in 15% of the slides.

In 9% of the cases, we could actually point to places where humans had influenced the concentration of storm water on the slopes. Broken water pipes, broken drain pipes, clogged gutters, and runoff from driveways and patios were examples of humans inadvertently helping the landslides. If the people at these sites had controlled the storm water, the landslides could have been prevented or at least decreased in severity. An example of a clogged gutter concentrating water on the slope below a house leading to a landslide is in Figure 5.

Figure 5:  An example of a earthflow in the West Hills  that started where an overflowing gutter had been depositing water for a couple of days (Slide # 119).

**DISCUSSION: GEOLOGICAL PROVINCES OF GREATEST LANDSLIDE OCCURRENCE**

Landslides  were concentrated in certain geological provinces of the metropolitan area.   Of the 705 landslides that were documented, most were concentrated in the West Hills that are covered with loess.  We have called this province the **West Hills Silt Soil Province.**    Quite a few landslides were concentrated on the steep slopes along the Willamette, Clackamas and Sandy Rivers in a region we call the **Steep Bluffs Along the Rivers Province**.  Some large landslides also occurred in southeast Portland on  slopes of the Troutdale Formation.  This province was given the name the **Fine-grained Troutdale Province.**  The most devastating and dangerous landslides were the debris flows that developed along bedrock streams feeding into the Columbia  and lower Willamette Rivers.  This province was called the **Debris Flows in Valley Bottoms Province.**  The few exposures of basalt cliffs that could lead to rockfall were not mapped.   That could be done in a follow-up study to this one.    These four provinces are denoted in Figure 4.  A good portion of Portland is flat and those areas were practically devoid of landslides.

**A) The West Hills Silt Soil Province**

The greatest concentration of landslides in Portland was in the West Hills in the wind-blown loess of the Portland Hills Silt Formation. A total of 374 slides were mapped in this province with 84 occurring in the area where the West Hills Silt Soil Province overlaps the Debris Flows in Valley Bottoms Province. The loess varies in thickness from one foot to over 100 feet at the crest of the Tualatin Mountains. When loess is dry (as in August), it is very strong, but when it is wet, especially saturated, it loses most of its strength, and slopes fail. Most of the failures occurred on steep slopes in the loess. Most of the failures were earthflows, but there were a few slumps, and the sizes were relatively small, being mostly in the range of 25 - 500 cubic yards. Many roads became blocked (Figure 1). The greatest concentrations of slides in this province were found along the following roads: Fairview, Fairmont, West Burnside, Cornell, Skyline, Germantown, Humphrey and Thompson.

Even small landslides in this province can cause great destruction and inconvenience (Figure 6). An example is a small earthflow (833 cubic yards) at the 800 block of Broadway Drive (slide #597) that destroyed a complex of seven condominiums on February 8th. Another small earthflow destroyed the home in the 4000 block of SW Fairvale (slide #124, 778 cubic yards) in Glencullen when a 40 feet high cliff of loess collapsed into the back of the house.

A medium-sized earthflow occurred on SW Highway 26 (slide #299, 8889 cubic yards) between Sylvan and the Zoo on the south side of the road (Figure 7). It shut down this major artery for weeks because an important utility pole was in the middle of the slide, and repairs had to be designed to protect the pole. Some slopes remain active today, such as the one in Figure 8 near Sylvan.

Many of the failure planes of the earthflows and slumps in this province occurred along paleosols in the loess. A paleosol is an old weathering surface of a layer of soil, and it tends to be clay rich and holds up water that is trying to pass through it. There are anywhere from one to four paleosols in the loess between the modern soil surface and the paleosol resting on the basalt bedrock. Two examples of failures on paleosols are located on SW 16th between Elm and Laurel (Figure 1, slide #599) and in the 2700 block of SW Fairmont (slide #611). One can see these paleosols in the slope ( exposed by a landslide) in the northwest quadrant of the intersection of SW Terwilliger and Barbur Blvd (slide #66).

Figure 6: A multitude of earthflows surrounding S.W. Terwilliger Terrace in February, 1996 (slides #120 and #121).

Figure 7:  Earthflow on SW Highway 26 just east of Sylvan is being repaired by building a boulder wall at the base and backfilling with rockfill (slide #299).

Figure 8: Active earthflow slope near Sylvan in the West Hills Silt Soil Province. A modular concrete wall has been constructed at the bottom of the slope to protect cars parked there, but the wall has been overtopped at least once in the last two years (slide #573).

A video was shown on television during the storm about a fast moving landslide chasing a pickup truck down a narrow street, pushing a couple of vehicles in front of it and bouncing off houses and the hillside. This occurred on NW Monte Vista Terrace just below the Pittock Mansion. This landslide (slide #355) originated as a very small earthflow ( 417 cubic yards) that failed on an old paleosol in the hillside. It should have stopped in the middle of the street, but because the storm drains up the hill were plugged, there was an inch or so of water covering the street as it ran downhill. The small earthflow hit the thin water layer and hydroplaned down the street at velocities of over ten miles per hour. It may have set a record velocity for an earthflow.

A total of 73 slides were located in the eight square mile Forest Park of northwest Portland (40 earthflows, 14 slumps, 11 debris flows, and 8 debris slides) (Burns and Fiedorowicz, 1997). Most of the slides were along Leif Erickson Drive in the cut slopes of the loess, but some were in the side-cast road prism. Most ranged from 100-1000 cubic yards in size, and the largest slump in Forest Park is in Figure 9 (slide #504, 8875 cubic yards).

Figure 9: Forest Park slump near N.W. Leif Erickson Drive. Note the trees are pointed in many directions which is typical of a landslide (slide #504).

**B) The Fine-Grained Troutdale Formation**

A total of 72 landslides have been mapped in the fine-grained Troutdale Formation of southeast Portland. Landslides are not very common (other than rockfall) in outcrops of the coarse-grained Troutdale Formation. Rainfall percolates into the soil and moves through the alluvial (river) sediments until the water intercepts a clay layer, the finest-grained layers of the Troutdale. On slopes where this clay layer daylights, one generally finds a spring. If the clay layer is dipping out of the slope, it can become the failure plane for a slump or slump-earthflow when the pore water pressure has built up to a critical value on top of the clay layer. These landslides are most common in this type of geology, but occur on slopes of lesser values, with some being in the range of 15 - 30 degrees. The sizes of the slides range from 50 to 160,000 cubic yards. Most of the slides along the Clackamas River were in the Troutdale Formation. Landslides in the Troutdale Formation generally are slower to react to storm events than the slides in the loess. Therefore, some failures did not start their movement until February 20th.

Many paleolandslides (ancient landslides) dot the landscape in southeast Portland in the Troutdale Formation, and some of these ancient slides reactivated after the storm. Movement on some of these slides was only a foot or two. The Bruin slide (Hinkle Road, slide #679, 16,703 cubic yards) and the Jacobs slide (slide #680, 6700 cubic yards) caused little destruction, but the reactivation of the Matthew Court (slide #263, 26,660 cubic yards) and 401 Warren Street (slide #279, 8890 cubic yards) paleoslides disabled and destroyed two homes (Figures 10 and 11). A scarp of five feet high developed across five lots of the Beaver Lake subdivision (slide #704) when this ancient landslide started moving again. Reactivation of the paleoslide on Holly Lane (slide #272) destroyed four homes with a two feet drop at the headscarp in February, 1996 and then another drop of two feet the following winter (Figure 12). Identification of these paleolandslides can be made by locating ancient headscarps and the hummocky topography (rolling hills) of the slide surface (Figure 13).

Figure 10: Toe of ancient landslide in fine-grained Troutdale reactivates, moves laterally a foot, and causes distress for house on S.E. Matthew Court (slide #263).

One of the greatest concentrations of landslides in the Troutdale Formation is found in the 600 acres of Newell Canyon next to Oregon City. The canyon is bisected by Highway 213 which has had yearly landslide problems since it was built. A total of 53 older landslides were mapped in the canyon in 1993 (Burns, 1993), and 17 new earthflows and slumps were discovered after February 1996. The largest earthflow occurred in the northwest corner of the canyon just off of Alden Street. The first day of the slide, it was approximately 200 cubic yards in size (Figure 14). After two months, it was 1500 cubic yards and had developed into a debris flow that had moved over fifty yards down the valley at the base of the slope. After the rains of November and December 1996, the slide had enlarged to 44,550 cubic yards (Figure 15a and 15b).

Figure 11: Ancient landslide at edge of Newell Canyon in Oregon City at 401 Warren Street reactivates, drops two feet, and the house receives a “red tag”. (slide #279).

Figure 12: Ancient landslide in the fine-grained Troutdale moves on  S.E. Holly Lane and drops four feet slicing  through houses built on the scarp.(Slide #272).

Figure 13: Hummocky topography of the S.E. Holly Lane paleoslide. One cannot see any new movement.(Slide #272).

Figure 14: Earthflow in fine-grained Troutdale after one day near Alden Lane, Newell Canyon. It is approximately 200 cubic yards in volume (slide #705).

Figure 15a: Earthflow near Alden Lane, Newell Canyon,  ten months later after the next winter's rains.  This is the left side of the slide (slide #705).

Figure 15b:  Earthflow in fine-grained Troutdale after one year near Alden Lane has expanded from 200 cubic yards to 44,550 cubic yards.  This is the right side (slide # 705).

**C) The Steep Bluffs Along the Rivers Province**

Forty landslides were mapped along the steep bluffs on the Willamette, Clackamas and Sandy Rivers. The geology of these sites is mainly Missoula Flood sediments which are sometimes fine-grained (Qff) and sometimes coarse-grained gravels (Qfc) (Beeson and others, 1991). These sediments fail mainly as shallow earthflows and debris slides. Many slides were recorded above Mocks Bottom and along NE Greeley Avenue at the base of Overlook Park in north Portland. Another large number of landslides could be found surrounding Oaks Bottom. Most of these slopes are over 50 degrees. Most of the slides were less than 1000 cubic yards. Two exceptions to the small size are the 120,000 cubic yard Gill slide (slide #696) in Newberg and the mobile home park along the Clackmas River (slide #230, 33,200 cubic yards) which is discussed below.

Many landslides in this province were aided by humans who over the years had dumped soil and yard debris over the edge of the cliff thus increasing the driving forces by adding weight to the tops of the slopes. The worst earthflow occurred at the end of Ramona Street (slide #69, 2306 cubic yards) above Oaks Bottoms where a home received a red tag. The slide got within three feet of the house. The house had to be moved back on the lot.

Where the slope was in contact with the river, undercutting occurred and caused the slope to fall into the river. These slides were especially common in the meander bends of the rivers. Fourteen lots of a mobile home park were undermined in the meander bend of the Clackamas River just west of where Highways 212 and 224 merge (slide #230). The only death during the storm in the Portland area occurred when the Sandy River undercut the bank of the home of Harold and Jacqueline Jank on the Old Columbia Highway in east Troutdale (slide #162). The landslide carried their home into the Columbia River.

Gravel mining in the Clackamas River floodplain by the Clackamas Sand and Gravel Company upstream of Barton Park created a large gravel pit and separated it from the river by a human-made levee. During the flood the levee breached causing the river to reroute through the center of the gravel pits on the old point bar. The gravel pits had captured the stream, and the new stream undercut the banks of the pit causing a slide to occur under the offices of the operation (Figure 16). Today, the condemned office sits precariously perched on the alluvium of the old flood plain (Darienzo, 1997) (Slide #615).

**D) The Debris Flows in Valley Bottoms Province**

Debris flows are the most dangerous of the landslides because they move so rapidly, have so much force, and often come unannounced. A total of 45 debris flows were mapped in the study area, primarily along the Columbia River and the northern Willamette River. Debris flows occur in bedrock stream bottoms and on the alluvial fans at the ends of those canyons. Most of them occurred when debris slides, slumps or earthflows in the upper reaches of the streams blocked the streams by forming a dam. A lake formed in back of the landslide dam, but because of the high precipitation rates, the dam breached, and the landslide deposit was turned into a slurry that rushed down the stream valley. The debris flow would erode and scour the valley bottom to the basalt bedrock. They carried some very large boulders (Figure 17). Volumes ranged from 1000 cubic yards to millions of cubic yards.

The two most famous debris flows occurred on Thursday, February 8th at Dodson, 35 miles east of Portland in the Columbia Gorge (Powell, 1998). At the west end of Dodson, a slow moving debris flow (moving at about five miles per hour) half buried the 50 year old homestead of Carol and Hersh Royse (Figure 18) (slide #128). A fast moving debris flow came down Tumult Creek (slide #130) at a rate estimated to be 30 miles per hour. Both of these debris flows crossed I-84 and the Union Pacific Railroad tracks. The highway was closed for three weeks. Resident Mark Chandler of Dodson reported that the Tumult Creek stopped flowing for a while just before the first

Figure 16: Example of Clackamas River undercutting slope in the Steep Slopes along the Rivers Province. Site is located at the Clackamas Sand and Gravel Company, upstream from Barton Park. (Slide #685)

Figure 17:  Boulder the size of a pickup truck carried by the Royse debris flow, Dodson, Columbia Gorge. (slide #128).

Figure 18: Debris flow that buried the Royse homestead, Dodson, Columbia River Gorge. (slide #128).

debris flow came rushing down. The stoppage probably was created by debris slides upstream blocking the creek; the debris flow originated when the debris dam was breached. Estimates of the volume of the debris flow deposits range from one million to 2.5 million cubic yards (Powell, 1998). The area around Dodson received 13" of rain in the four day event.

These debris flows are not a new phenomena. The last major one was in 1918. Carol Royse remembers playing as a child on her land on a buried tractor that was lost in that event. Smaller debris flows also occurred in 1964, 1972, and 1974 (Wickwire, 1996). Dodson and the neighboring town of Warrendale are on an alluvial fan at the bottom of the basalt cliffs at the edge of the Columbia Gorge. That fan has formed in the past 12,700 years , the date of the last Missoula Flood (Waitt, 1985). The Missoula Floods scoured the gorge; the fan is a result of debris flows since that time building it back up. These are natural phenomena.

Another debris flow hit an A-frame house located at the intersection of Germantown Road and Harbor Blvd in northwest Portland (slide #536). This house was located in the bottom of the small ephemeral stream valley. It was hit by a debris flow that knocked it off of its foundation by 14 feet, and it crushed the owner's car that was sitting in front of the house. Again, a small debris slide upstream caused a landslide dam that eventually breached sending the slurry down the stream valley.

### E) Other Significant Landslides Outside of the Provinces

Outside the four provinces, 174 other landslides were mapped around the Portland region. Twenty six rockfall events were recorded at some of the outcrops of basalt in the region, but these are too dispersed to make up a province. Most of the other failures fell into three categories of slides. First, and probably foremost, was the reactivation of old landslides. Most of the landslides at the northern and western ends of Washington County were in reactivated paleolandslides such as Dixie Mountain and Scoggins Reservoir in the Yamhill Formation. The landslides at Bull Run Reservoir east of town were also in old landslide deposits. Second, fill failures resulted from improper drainage possibly caused by poor maintenance. An example of one of these failures occurred below Salmon River Road in Welches destroying one house and causing over $150,000 of damage to another (slide #197, 128,480 cubic yards). Third, where water was uncontrolled, low angle slopes could fail. For example, a slope slid at apartments at the base of Mt. Tabor when a drainage pipe broke and spread the water across the slope (slide #701).

## CONCLUSIONS

We mapped 705 landslides that resulted from the February 6-9, 1996 storm that hit the Portland metropolitan area and from more recent storms. The mapping area extended beyond the Metro boundaries to get a better feeling for the landslide activity in the region. Therefore, the study area extended from Banks in the west to Welches in the east and from the Columbia River in the north to Canby in the south. Most of the landslides were earthflows and slumps, with the majority of them occurring in the loess soils of the West Hills of Portland. The most dangerous and devastating slides were the debris flows that developed in bedrock streams along the Columbia River and lower Willamette Rivers. Based on the abundance of the landslide activity, it was estimated that this was probably a 100 year event for landslide recurrence. The slides caused significant damage to over 100 homes in Portland alone. Up to 10% of the damage could have been reduced or prevented if humans had controlled the water on the sites. Human activities were contributing factors to 76% of the landslides.

**POSSIBLE FUTURE ACTIONS:**

**A) Applications of This Report:**

Strategies must be devised by local governments and planning organizations that focus on the areas of high landslide potential with emphasis on prevention of future landslides. This report has outlined the areas where landslides are most likely to occur, i.e. the four landslide provinces. These provinces serve only as starting points for use by communities in going further to define their hazard zones based on additional characterization and field verification needed in their respective boundaries. These provinces also illuminate areas where local communities can focus policy for landslide mitigation for such topics as storm water drainage managment and other off-site factors. Five recommendations for future actions are:

- Local communities must remember that landslides will occur anywhere where water is not controlled, but they have the highest probability of occurrence in the four provinces noted in this report. Each province is important, but for different reasons. This report with its accompanying RLIS GIS database should be made available to local planners, realtors and neighborhood associations to help them understand these provinces.
- Any new development in these provinces should have a qualified geologist evaluate the property for landslide potential before building permits are issued. Certified engineering geologists are probably the most qualified to perform these tasks. There is a need to carefully examine the placement of structures with respect to old landslides and breaks in the slope.
- These reports must be forwarded to the geotechnical engineers and architects who design the structures and foundations for the properties.
- Local governments and planners must also remember the extent of these provinces when developing ordinances and codes. Any laws that put storm water onto slopes in these regions could cause landslide problems. Broken water lines in these provinces should receive high priority for immediate repair.
- Metro is encouraged to develop a handbook for homeowners and developers aimed at landslide mitigation.

**B) Corrective Actions for the Landslide Provinces:**

Because this study was performed 18 months after the majority of the landslides occurred, the team was able to observe many of the different techniques of repairing the landslides.

**1) West Hills Silt Soil Province:**

Mitigation of landslides in the loess has been generally successful. Most of the repairs were accomplished first by removing the slide debris, then building a buttress (like a gabion wall or a line of large boulders) at the base of the slope, and followed by backfilling behind the buttress up the slope with rockfill. This method is fairly cheap, is easy to install, and provides a wall that is well-drained (Figures 19 and 20). The earthflow on Highway 26 (Figure 8) was also repaired in this way. If the slide had originally moved on a paleosol, it is recommended to put in drainage tile at the contact to drain the site before the rockfill is emplaced. Other walls, such as modular concrete walls, were also built that included the rockfill in back of the wall (Figure 21). On steep slopes, tieback walls (Figure 22) and pin pilings have been used with success. In some instances for the smaller earthflows in the loess, just rockfill of the scar was performed. Where the earthflows were small and not close to structures, the deposit was removed and the scar was left unrepaired (Figure 23).

Figure 19: Gabion wall at the bottom with rockfill above and a geogrid wall at the top of the slope is a complex repair strategy for landslide repair. The gabion wall and rockfill is

one of the most common repair strategies used  in the West Hills Silt Soil Province. (slide #535)

Figure 20: Boulder buttress with rockfill mitigation strategy which is common in the West Hills Silt Soil Province. (slide #393)

Figure 21: Modular concrete wall with rockfill mitigation strategy which is less common in the West Hills Silt Soil Province because it is more expensive than gabion walls. (slide #342)

Figure 22: Tieback wall corrective action used in the West Hills Silt Soil Province on a steep slope near S.W. Montgomery Drive and Elm in the West Hills of Portland. (Slide #602, 9259 cubic yards). This repair was very expensive.

Figure 23: Unrepaired slump on S.W. Fairview Drive. If the earthflow is not close to a structure and it is not significantly large, it might be all right to leave it. (slide #397, 926 cubic yards)

**2) Fine-grained Troutdale Formation Province:**

The slides in the Troutdale Formation are very difficult to repair because they are so large that walls are cost-prohibitive. Once the landslide has started to move, it is difficult to stop the slide. One could try to dewater the slides by horizontal drains or vertical wells, but there is so much silt in the Troutdale Formation that the soils are too "tight" to give up enough water to stop movement. The use of a shear key in Oregon City above the Clackamas River to save Forsythe Road and a house will probably work, but the project cost over $900,000 (slide #698). It is recommended that the paleolandslides be mapped in the Troutdale Formation and that people not build on them, especially along the head scarps and toes. It is also recommended that there be significant setbacks from the breaks in slope between upland basalt flows and slopes in the fine-grained Troutdale Formation.

**3) Steep Slopes Along Rivers Province:**

Prevention of these slides is mainly through larger setbacks from the cliffs where springs are common in the slopes and enforced regulations of prevention of dumping debris over the sides of the bluffs. Most mitigation strategies for slopes that have failed are very expensive to build so most landowners have resorted to larger setbacks.

**4) Debris Flows in Valley Bottoms Province:**

It is difficult to mitigate debris flows. The best way to deal with them is through land use planning, by not allowing people to build or rebuild in valley bottoms and on alluvial fans that may have the potential of debris flows.

**5) Rockfall areas:**

Most rockfall areas are above roads. Oregon Department of Transportation has already begun to install cyclone fence netting on some of these rockfall source slopes. The use of Jersey barriers and ditches to catch the rocks at the bottom of the cliffs is also becoming more common.

**C) Future Work:**

As the population expands in the Portland metropolitan area, there seem to be a couple of areas that have large numbers of paleolandslides that should be mapped. This report has focused on the fine-grained Troutdale Formation province as one such area. A very helpful map for planners might be a map of all paleolandslides in the fine-grained Troutdale formation in the Portland region since the movement on ancient landslides were the sites of the greatest problems. Another potentially hazardous region is the north side of the Tualatin Valley. Abundant paleolandslides are found in this region such as the Dixie Mountain landslide. Another region is the west side of the Tualatin Valley where the Yamhill Formation is common. Accurate maps of past landslides should be constructed for these regions to help planners help citizens to stay away from potential landslide hazards. The relationship between fault zones and springs in the West Hills might also be investigated.

## REFERENCES


Atwater, B.F., 1984, Periodic floods from glacial Lake Missoula in the Sanpoil arm of glacial Lake Columbia, northeastern Washington. *Geology*, Vol. 12, pp. 464-467.

Beeson, M.H., Tolan, T.L., and Madin, I.P., 1991, *Geologic Map of the Portland Quadrangle, Multnomah and Washington Counties, Oregon, and Clark County, Washington.* Oregon Department of Geology and Mineral Industries, GMS-75.

Burns, S.F., 1998, Landslides in the Portland area resulting from the winter storm of February, 1996" in S.F. Burns, editor, *Environmental, Groundwater, and Engineering Geology: Applications from Oregon.* Star Publishing, Belmont, California. p. 353-366.

Burns, S.F., 1996, Landslides in the West Hills of Portland: a preliminary look. *Oregon Geology*, Vol. 58, No. 2, pp. 42-43.

Burns, S.F., editor, 1993, Environmental Assessment of Newell Creek Canyon, Oregon City, Oregon, Dept. of Geology, Portland State University, 180 pp

Burns, W.J. and Fiedorowicz, B.F., 1997, Landslide inventory and slope stability of Forest Park, Portland, Oregon. Proceedings of the Oregon Academy of Science, Vol. 33, p. 35.

Clarke, D.D., 1904, A phenomenal landslide, *Transactions of the American Society of Civil Engineers*, Vol. 53, pp. 322-412.

Compton, R.R., 1985, Geology in the Field, J.F. Wiley Publishers, New York, 398p.

Darienzo, M., 1997, Dramatic channel changes on the Clackamas River upstream of Barton Park during the great flood of 1996, *Proceedings of the Oregon Academy of Science*, Vol. 38, pp. 36.

Easterbrook, D.J., 1993, *Surface Processes and Landforms*. MacMillan Publishers, New York. 620 p.

Gerig, A.J., 1985, *Soil Survey of Clackamas County*, Soil Conservation Service, National Printing Office, Washington, D.C.

Green, G.L., 1983, *Soil Survey of Multnomah County,* Soil Conservation Service, National Printing Office, Washington, D.C.

Green, G.L., 1982, *Soil Survey of Washington County,* Soil Conservation Service, National Printing Office, Washington, D.C.

Hammond, C.M. and Vessely, D.A., 1997, Engineering geology of the ancient Portland Highlands landslide, in S.F. Burns, editor, *Environmental, Groundwater and Engineering Geology: Applications from Oregon*, Star Publishing, Belmont, California.

Powell, B., 1998, Dodson/Warrendale debris flows, Proceedings of the 34th Symposium on Engineering Geology and Geotechnical Engineering, Reno, Nevada, March 28-30, 1998

Taylor, George H., 1997, Causes of the great flood of 1996 and a comparison to other climatic events, in Antonius Laenen, editor, The Pacific Northwest Floods of February 6-11, 1996: Proceedings of the Pacific Northwest Water Issues Conference, Portland, Oregon, American Institute of Hydrology, p. 3-6

Waitt, R.B., 1985, Case for periodic, colossal jokulhlaups from Pleistocene glacial Lake Missoula. *Geological Society of America Bulletin*, Vol. 96, pp. 1271-1286.

Wickwire, Patti, 1996, The great flood of 1996: geology of the Dodson debris flow. *Mazama*, Vol. 78, No. 13, p 6.

Appendix 1

Field Description Sheet Used in the Study

Appendix 2

Landslide Database

**Contributing Factors**