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Landslides mapped using LIDAR imagery, Seattle, Washington

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Photograph from the Seattle Municipal Archives of residential distress in the Magnolia area of Seattle during 1954.

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U.S. Geological Survey Open-File Report 2004-1396

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

ABSTRACT

Landslides pose a significant hazard in Seattle, Washington, where historical records of destructive landslide events date back to the late 1800s. Seattle landslides generally occur on hillslopes along Puget Sound and Lake Washington coastlines, hillslopes along drainages, and on steep, glacially formed ridges. Shallow flows, slides, falls, and topples, and deep-seated slides of earth and debris are common types of Seattle landslides. Inventories compiled of historical Seattle landslides highlight areas prone to landslide activity, but many of the inventories include only landslides that were reported to various government agencies, so they exclude unreported and prehistoric landslides. Geologic, coastal, and landslide-specific maps of the Seattle area also have been created. These maps primarily were constructed using aerial photographs and ground-based study, which is problematic in an area such as Seattle where dense vegetation substantially obscures hillslope morphology. Airborne LIDAR (light detection and ranging) surveys have recently been completed of the Seattle area and provide a clearer representation of the ground surface than is possible with aerial photographs because LIDAR penetrates vegetation. A LIDAR-derived DEM (digital elevation model) was used in the present study to map landslides in Seattle. Shaded relief, slope, and topographic contour maps were generated from the DEM and used to identify morphologic features indicative of landslides. Topographic profiles also were constructed from the DEM to aid visualization of hillslope morphology. Landslide deposits and scarps were mapped and classified based on the degree of certainty with which they were identified, which depended on the continuity and strength of morphologic features as expressed in the LIDAR imagery. Ground reconnaissance was performed to confirm and refine the results of the LIDAR mapping. The resulting map shows 173 landslides, which is nearly 4 times the number identified during previous mapping efforts. Ground reconnaissance and review of previous landslide maps and inventories indicate that most of the LIDAR-mapped landslides are complexes consisting of multiple landslides. Nearly all (93 percent) of the LIDAR-mapped landslides occur on hillslopes above drainages and coastlines. Historical landslide locations appear to be concentrated within the LIDAR-mapped boundaries of landslides and along landslide scarps. Traditional landslide mapping methods involving interpretation of aerial photography and ground-based study were more effective than LIDAR in identifying boundaries of some recently active landslides, but those methods were less effective in identifying large landslide complexes that have experienced significant historical activity. The LIDAR landslide map presents a valuable tool in hazard reduction efforts because it identifies previously unrecognized landslide areas in which significant historical landslides have occurred, and also areas that are likely prone to future landslide activity.

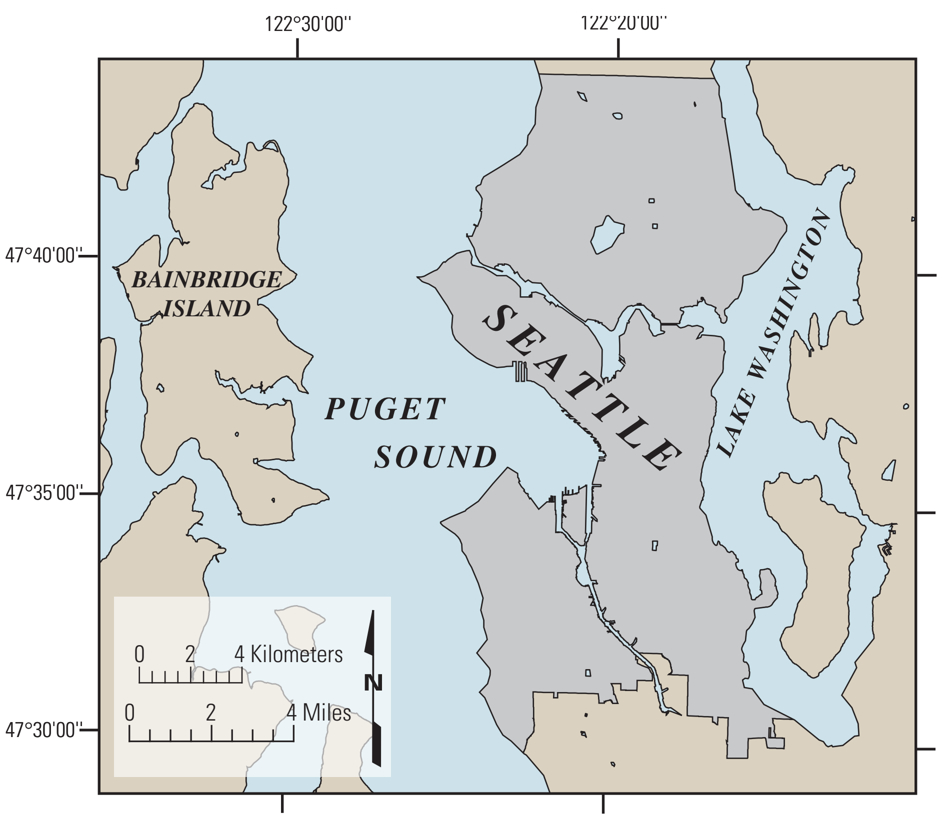

Figure 1. Map showing location of Seattle, Washington, (gray area) in relation to Puget Sound, Lake Washington, and Bainbridge Island.

Introduction

Landslides occur on many hillslopes in Seattle, Wash. (fig. 1), and often result in significant property damage and human casualties. For example, heavy precipitation during early 1972 triggered hundreds of landslides that were responsible for hundreds of thousands of dollars in public and private property loss (Tubbs, 1974). Storms during the early part of 1990 resulted in landsliding throughout the Puget Lowland (Miller, 1991). Rainfall during the winter of 1996–97 triggered at least 114 landslides in Seattle (Gerstel and others, 1997) that resulted in a loss of over $34 million in city property (Paegeler, 1998), 4 deaths on nearby Bainbridge Island, and the derailment of a freight train north of Seattle (Baum and others, 1998). Landslides are not just a recent phenomenon in Seattle. The long-standing recognition of the significant hazards they pose is illustrated by the extensive landslide records compiled by the city of Seattle since the late 1800s. Analysis of these records by Laprade and others (2000) indicate that over 1,300 landslides were reported in the city during a 109-year period.

Most Seattle landslides are triggered by heavy winter precipitation and occur on hillslopes above Puget Sound and Lake Washington coastlines, above drainages, and along steep flanks of glacially formed ridges (Galster and Laprade, 1991; Gerstel and others, 1997; Laprade and others, 2000; Montgomery and Greenburg, 2001). Seattle landslides include rapid, shallow slides, flows, falls, and topples, as well as generally slower moving, deep-seated translational, rotational, and complex slides of earth and debris (terminology from Cruden and Varnes, 1996) (Tubbs, 1974; Thorsen, 1989; Galster and Laprade, 1991; Harp and others, 1996; Gerstel and others, 1997; Baum and others, 1998; Baum and others, 2000; Laprade and others, 2000). Historical landslide inventories have been compiled for the Seattle area (Tubbs, 1974; Harp and others, 1996; Gerstel and others, 1997; Baum and others, 1998; Baum and others, 2000) and include a comprehensive inventory generated from municipal records that date to 1890 (Laprade and others, 2000). The inventories that cover all of Seattle are based on reports of landslide damage made to various government agencies so are biased toward developed areas because landslides typically are unreported in undeveloped areas, and it follows that these inventories exclude prehistoric landslides. Coastal, geologic, and landslide-specific maps also have been created of the Seattle area (Waldron and others, 1962; Waldron, 1967; Youngmann, 1979; Yount and others, 1993; Wait, 2001). These maps generally include only larger landslides and landslide complexes due to map scale limitations, but they may include prehistoric landslides and do not have the reporting bias of some historical landslide inventories. However, these maps were largely created using aerial photographs and ground-based study to identify features indicative of landslides, many of which are obscured by the dense vegetation typical of Seattle hillslopes.

The dense vegetation and short historical landslide record have made it difficult to construct a map that appears to document most Seattle landslides. LIDAR (light detection and ranging) technology substantially addresses the difficulty of observing hillslope morphology in conditions present in Seattle because it virtually sees through vegetation, potentially revealing both historic and prehistoric landslides. The benefits of using imagery derived from LIDAR DEMs (digital elevation models) for identifying geomorphic landforms have only recently been realized, but have already been demonstrated in the Puget Sound region. For example, LIDAR-derived DEMs of this region have been used to identify previously unmapped landslides (Haugerud, 2001; Gold and others, 2003; Haugerud, 2003; Haugerud and others, 2003), previously unknown tectonic fault scarps (Harding and others, 2002; Haugerud and others, 2003; Johnson and others, 2003; Sherrod and others, 2004), and other geomorphic landforms (Haugerud, 2001; Haugerud, 2003). As part of the U.S. Geological Survey (USGS) landslide hazard reduction efforts, the present study involved mapping landslides in Seattle using high-resolution LIDAR topographic data. The landslide map (pl. 1) does not provide definitive information regarding current or future landslide activity. However, historical landslides appear to have been concentrated within the boundaries of the landslides mapped using LIDAR. In addition, landslides characteristically occur in areas subject to certain geologic, topographic, and hydrologic conditions; thus, areas where landslides occur may be most susceptible to future landsliding (Thorsen, 1989; Baum and others, 1998; Laprade and others, 2000).

Setting

The topography and geology of Seattle primarily are the result of a series of glacial and interglacial cycles that occurred during the Late Pleistocene, and secondarily the result of Holocene fluvial and coastal processes and human modifications. Seattle occupies an isthmus between Puget Sound and Lake Washington (fig. 1), and its topography is characterized by rounded, elongate, north-south trending, glacially sculpted hills and steeper slopes above coastlines and drainages (pl. 1). Bluffs up to 125 m high occur along much of the Puget Sound and Lake Washington coastlines, as well as former coastlines along the perimeter of the filled Interbay area and the northwestern part of Beacon Hill. The bluffs result from coastal erosion that has accompanied sea-level rise since retreat of the last continental glacier from the region about 13,600 years ago (Downing, 1983; Booth, 1987; Terich, 1987). In the past 5,000 years, the relative level of Puget Sound in the Seattle area has risen about 6 to 10 m (Booth, 1987, fig. 7; Sherrod and others, 2000), which provides an average rate of 12–20 cm/century, and it continues to rise but at an apparently increasing rate of approximately 20–30 cm/century (Downing, 1983; Terich, 1987). The rising level has resulted in an estimated 150 to 900 m of bluff retreat along the Puget Sound shoreline of Seattle, which primarily is accomplished by landsliding (Galster and Laprade, 1991). On the eastern border of Seattle, the level of Lake Washington generally increased along with that of Puget Sound and resulted in formation of retreating coastal bluffs there, as well (Thorson, 1998). Since 1917, the level of Lake Washington has been controlled by manmade structures at about 3 m below the previous average level (Thorson, 1998), which should reduce erosion of the Lake Washington coastline and retreat of adjacent bluffs.

Seattle is situated in a geologically complex, tectonically active region that was repeatedly glaciated in the recent geologic past. Consequently, glacial sediments overlie and conceal bedrock throughout most of the city (Waldron and others, 1962; Mullineaux and others, 1965; Galster and Laprade, 1991; Booth and others, 2000; Kathy G. Troost, written commun., 2003). Geologic maps of the Seattle area vary because of the complexity of the geologic record and the evolving understanding of Seattle's geologic history (Mullineaux and others, 1957; Waldron and others, 1962; Liesch and others, 1963; Crandell and others, 1965; Mullineaux and others, 1965; Easterbrook and others, 1967; Waldron, 1967; Luzier, 1969; Galster and Laprade, 1991; Yount and others, 1993). The Seattle Geologic Mapping Project (SGMP, a cooperative effort of the city of Seattle, the University of Washington, and the USGS) is creating new, more detailed geologic maps of Seattle than previously created by utilizing results of previous geologic mapping efforts, records of subsurface geologic investigations, findings of recent geophysical investigations, and original geologic mapping and dating activities (Troost and Booth, 1999; Booth and others, 2002; Shimel and others, 2003; Kathy G. Troost, written commun., 2003, http://depts.washington.edu/sgmp/index.shtml). The geologic conditions described below are largely from the SGMP maps, most of which are currently in review.

Tertiary volcanic and sedimentary rock underlies Seattle, but is overlain and concealed throughout most of the city by Quaternary sediments. Sedimentary rock is exposed near Alki Point and in the southern part of Beacon Hill, and volcanic rock is exposed along the west-facing slope above the Duwamish River valley in the extreme southeastern part of the city (geographic locations are labeled on pl. 1). The Quaternary sediments rest on an unconformable bedrock surface that is highly irregular due to pro- and interglacial erosion, glacial scour, and tectonic folding and faulting (Yount and others, 1985). The majority of these Quaternary sediments are the result of cyclic episodes of continental glaciation that occurred during the last 2 million years. Most of these sediments result from the youngest glaciation, the Vashon stade of the Fraser glaciation (about 14,500 to 13,600 ka; Booth, 1987). The Vashon deposits overlie deposits of both glacial and nonglacial origin, including volcanic ash, lahar deposits, peat, lacustrine deposits, alluvium, and glacial outwash and till.

The oldest Vashon unit is the Lawton Clay, which comprises the lower parts of many of the coastal bluffs and drainage slopes in Seattle, and is composed of massive to laminated silt, clayey silt, and silty clay. Vashon advance outwash overlies Lawton Clay and older deposits beneath most of Seattle, and comprises the upper parts of many of the coastal bluffs and drainage slopes. The unit consists of well-sorted sand and gravel, and it is the primary aquifer of the region (Liesch and others, 1963; Vaccaro and others, 1998). The advance outwash is capped by Vashon Till throughout most of Seattle. The till is very dense, poorly sorted, and composed of silt, sand, and gravel. The youngest of the Vashon deposits is recessional outwash, which occurs only sporadically throughout Seattle and consists of stratified sand and gravel with occasional silt.

Geologic deposits that postdate the Vashon glaciation are of very limited extent in Seattle. They include alluvium, fan deposits, beach deposits, landslide deposits, colluvium, soil, and human-placed fill. Alluvium is extensive primarily in the Duwamish River valley. Fan deposits have extremely limited extent; they are located at the mouths of some steep drainages. Extensive beach deposits are located along perhaps one-fourth of the Puget Sound coastline and in very limited areas along Lake Washington. Landslide deposits, colluvium, and soil mantle most of the steep slopes above drainages and coastlines. Lastly, human-placed fill is very extensive in parts of Seattle. Major grading activities occurred in the latter part of the 19th and early part of the 20th centuries and included filling of tidal flats and marshes at the mouth of the Duwamish River, in the Interbay area, along the Duwamish River, on the north side of Union Bay, and at Sand Point. The most extensive fill placement occurred at the mouth of the Duwamish River, where fill extends from the bluffs between Pigeon Point and Duwamish Head to the east beneath downtown Seattle and to the south along Beacon Hill. Much of the fill was derived from hydraulic sluicing of Beacon Hill between 1901 and 1904 (Bortleson and others, 1980). Major grading also was performed to reduce topographic relief between Lake Union and Elliott Bay.

Landslides in Seattle are concentrated along coastal bluffs, but also occur on hillslopes along drainages and on steep glacial landforms (Waldron and others, 1962; Waldron, 1967; Tubbs, 1974; Youngmann, 1979; Yount and others, 1993; Harp and others, 1996; Gerstel and others, 1997; Baum and others, 1998; Baum and others, 2000; Laprade and others, 2000; Wait, 2001). About 80 percent of reported historical landslides appear to have been at least partly caused by human activity (Laprade and others, 2000). Tubbs (1974) concluded that the contact between the Vashon advance outwash and underlying units defines the location most susceptible to landsliding in Seattle. His conclusions were based on his finding that 40 percent of the largest landslides that occurred during the winter of 1971–72 were located at least partly within a zone 61-m (200 ft) wide centered on this contact. He attributed the occurrence of landslides at least partly within this zone to the presence of perched ground water in the lower part of the advance outwash. Tubbs' conclusions have since been advanced by many scientists and engineers (Tubbs, 1975; Galster and Laprade, 1991; Laprade and others, 2000; Savage, and others, 2000; Wait, 2001; Coe and others, 2000; Coe and others, 2004).

Description of Seattle LIDAR data

Regional airborne LIDAR surveys were first utilized in the Puget Sound region on Bainbridge Island (fig. 1) under the direction of the Kitsap Public Utility District in 1996. This survey resulted in identification of previously unrecognized tectonic features (Haugerud, 2001), which illustrated the value of using LIDAR in the heavily vegetated Puget Sound region. LIDAR surveys of other parts of the region followed under contract to the Puget Sound LIDAR Consortium (PSLC). Most of the information provided here regarding the Seattle LIDAR data, as well as the LIDAR data, are available at the PSLC website (http://pugetsoundlidar.org).

The Seattle airborne LIDAR surveys utilized a monostatic, pulsed, 0.9-m diameter laser rangefinder (Haugerud and Harding, 2001). Laser pulses generally were uniformly spaced within 600-m-wide swaths with an average pulse density of 1/m^2. Laser return data were collected thousands of times per second by a pyramidal scan rotating mirror. Up to four laser returns were collected for each pulse and resulted in a vertical profile of ground features for each pulse location (Harding and Berghoff, 2000). Each pulse generated multiple returns due to reflections from features such as power lines, buildings, vehicles, trees, undergrowth, and the ground surface. The last return from each pulse was assumed to be from the ground surface, although this was not always the case. In fact, ground-surface returns were obtained from only about one-third of all pulses in heavily forested areas. Simultaneous acquisition of aircraft position and laser direction was performed using a differential kinematic Global Positioning System (GPS) and an Inertial Navigation System (INS). Geolocated laser returns were calculated with absolute vertical and horizontal accuracy of 15 cm and less than 1 m, respectively, by combining GPS coordinates and the INS roll, pitch, and yaw of the aircraft (Hill and others, 2000; Haugerud, 2001). Extensive areas were mapped by surveying multiple parallel swaths with narrow corridors of data overlap. The swaths were latticed together into one seamless DEM during processing.

All ground features that produced returns were represented in the laser survey, including buildings, trees, boulders, vehicles, and bridges. Creation of the bald-earth DEM from the LIDAR data required the use of algorithms during processing to remove undesired ground features. The algorithm nicknamed “virtual deforestation” (Haugerud, 2001) was utilized to create the bald-earth DEM of Seattle. This algorithm identifies laser return signals as either ground or not-ground depending on the surface geometry obtained at nearby locations. According to Haugerud and Harding (2001), limitations of the algorithm include rounding of corners between low-slope surfaces and vertical faces, such as at escarpments. Processing of “negative blunders” (incorrect distance measurements with resulting elevations that were significantly lower than surrounding ground elevations) yielded “bomb craters” where surrounding valid ground points were removed from the data. False ground-surface roughness was created during processing and increased as a function of increased land cover, thereby reducing vertical accuracy of the DEM. Interpolation between returns in surveyed areas with low-return density locally produced a faceted texture in the DEM. These faceted areas are especially common along escarpments. The final DEM has vertical accuracy that is typically on the order of 30 cm, but is considerably worse in some areas. Horizontal accuracy is such that PSLC recommends use of the data at a horizontal scale of 1:12,000 or smaller. Final data are in Washington State Plane projection with English units and have a grid cell size of 1.8 m (6 ft).

Mapping landslides using LIDAR

The landslide map (pl. 1) was created in a GIS (geographic information system) using derivatives of the LIDAR DEM, including shaded relief maps (hillshades), a slope map, a topographic contour map, and ground-surface profiles. Hillshades were calculated from the DEM with varying sun azimuths (45°, 135°, and 315°), constant sun angle (45° above the horizon), and no vertical exaggeration. The variation in sun azimuth was used to provide suitable lighting conditions for different slope areas as different combinations of sun azimuth and slope orientation provided drastically different representations of the ground surface (fig. 2). The slope map was used because it lacked the limitations of hillshades imposed by adversely oriented sun angles (fig. 2); however, it was occasionally difficult to determine the vertical orientation of some slopes on this map. The topographic contour map assisted in locating slope breaks and other morphologic features. This map was calculated with a 2-m contour interval and overlaid on the hillshades and slope map. Over 300 topographic profiles were constructed to assist evaluation of landforms. In addition to the imagery derived from the LIDAR data, an unpublished, orthorectified aerial photograph compilation (black and white, nonstereo) was occasionally used to differentiate between some manmade and natural landforms.

Landslides were identified in the LIDAR imagery based solely on ground-surface morphology, as that is all that can be represented by a DEM and its derivatives. Morphologic characteristics that were used to map landslides included headscarps, hummocky topography, convex and concave slope areas, mid-slope terraces, offset drainages, and drainages whose courses have been controlled by landslide features. Thus, mapping landslides using LIDAR imagery is very similar to mapping using topographic maps and stereoscopic aerial photographs (Keaton and DeGraff, 1996; Soeters and Van Westen, 1996). Hillshades and the slope map were visually evaluated for the presence of landslides by systematically panning through the imagery at scales ranging from 1:30,000 to 1:2,000. Landslide boundaries and headscarps generally were drawn at a scale of 1:5,000; however, the final map is intended to be viewed at a scale of 1:20,000 or smaller.

Ground reconnaissance was performed within suspected landslide areas after mapping using the LIDAR imagery was completed. Suspected landslide areas were evaluated for the presence of the morphologic characteristics listed above, as well as for ground deformation, springs, seeps, ponds, phreatophytes, and distressed vegetation and manmade structures (Keaton and DeGraff, 1996). Observations made during ground reconnaissance were used to revise the LIDAR landslide map, as appropriate.

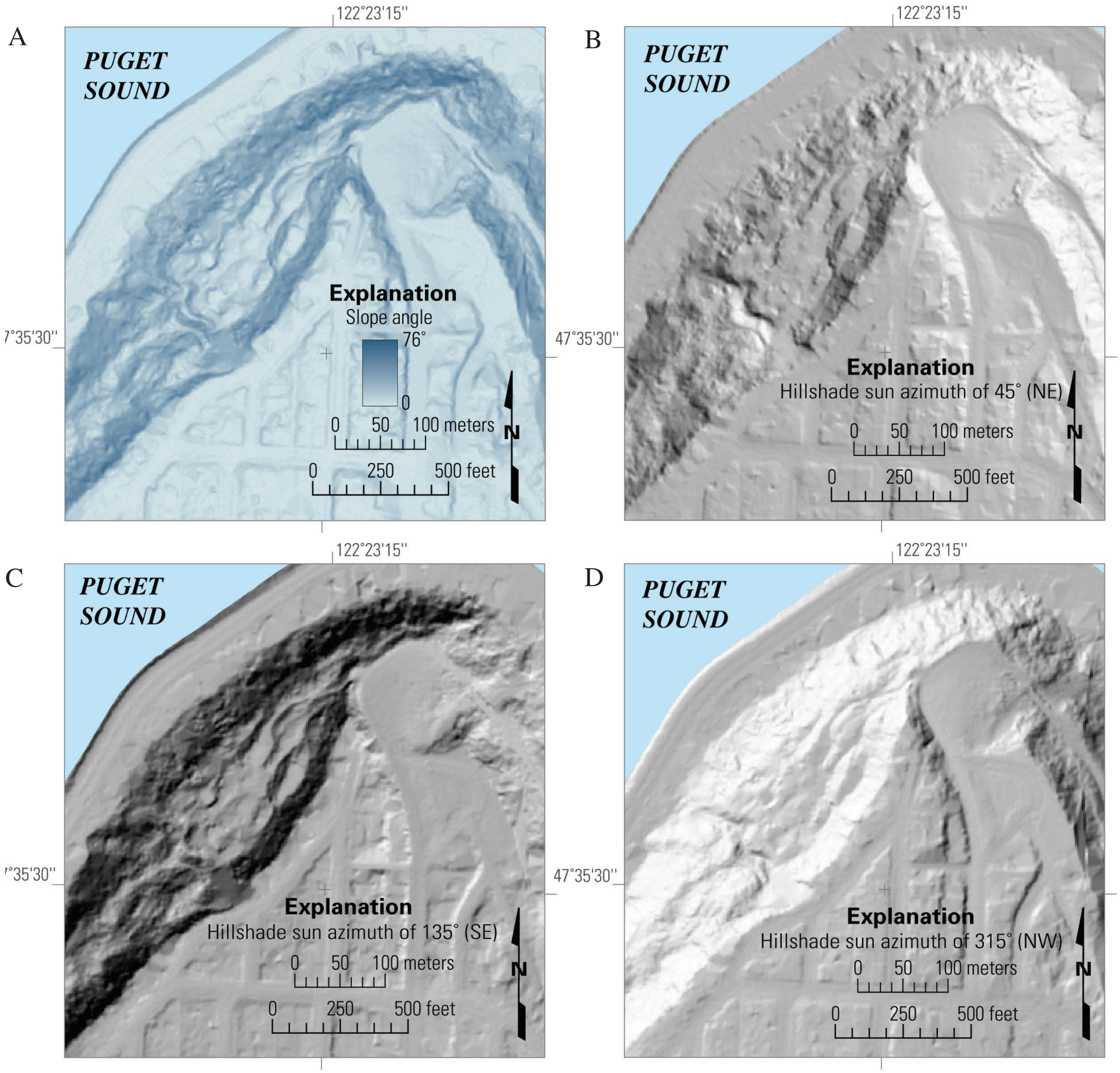

Figure 2. Comparison of the LIDAR-derived slope map (*A*) and hillshades with sun azimuths of 45° (*B*), 135° (*C*), and 315° (*D*). All hillshades have a sun angle 45° above the horizon and no vertical exaggeration. The location of the imagery is Duwamish Head.

Results

The LIDAR-based map of Seattle landslides is provided on plate 1. The base map is a LIDAR-derived hillshade with sun azimuth of 315°, sun angle of 45° above the horizon, and no vertical exaggeration. Landslides are indicated by colored, semi-transparent polygons. Landslide scarps are indicated by lines with hachures pointed downslope. Many of the landslides on plate 1 have internal scarps that, in most cases, appear to indicate that these are landslide complexes consisting of multiple landslides. Ground reconnaissance also indicated that most of the mapped landslides are landslide complexes. Individual landslides within landslide complexes were mapped where differentiable in the LIDAR-imagery, but this generally was not possible.

Morphologic characteristics of all features mapped as landslides and landslide scarps on plate 1 were sufficiently well developed and present in combinations such that a landslide origin for these features is definite to very probable. The mapped landslide features were categorized by the relative degree of certainty of landslide origin, with red features indicating certainty of origin and orange features indicating that some uncertainty of origin exists. The degree of certainty was primarily due to the strength and continuity of morphologic features as expressed in the LIDAR imagery.

Most of the LIDAR-mapped landslides were evaluated during ground reconnaissance. Observations made during reconnaissance necessitated very few revisions to the LIDAR landslide map. Many of the landslides mapped using LIDAR showed field evidence of partial, episodic movement, indicating that many of the landslide boundaries on the LIDAR map delineate landslide complexes. Except for some of the smaller landslides, entire landslides usually were not identifiable during ground reconnaissance due to visibility limitations imposed by vegetation and manmade structures. However, individual features indicative of landsliding commonly could be identified. Landslide features were more difficult to discern in heavily developed areas as grading and construction activities have obscured morphologic features and construction of drainage measures has controlled subsurface and surface drainage. In addition, distress to the built environment that could be attributed to landsliding generally was not observed, possibly due to repair of structures damaged by recently active landslides.

Some features on plate 1 suggest the presence of landslides where none were mapped. For example, the area along the Lake Washington coast in central Seattle between two large uncertain landslides (pl. 1) appears to contain landslides; however, topographic profiles constructed through this area and observations made during ground reconnaissance indicate that extensive landslide deposits are absent. Many coastal bluffs and hillslopes above drainages display similar evidence of possible past landslide activity in the LIDAR imagery but lack identifiable landslide deposits; thus, no landslides were mapped on these hillslopes.

The smallest landslide identified using the LIDAR data was just over 20 m across; however, a few larger landslides were observed during ground reconnaissance that were not initially identified using the LIDAR data (these were subsequently added to pl. 1). Landslides were consistently identified using the LIDAR imagery if they had well-developed morphologic features that were at least 30-m long and a few meters high.

The accuracy with which parts of landslides were located on plate 1 varied systematically. In general, the locations of headscarps and heads of landslides were mapped with relative certainty, lateral margins with less certainty, and toes with a significant degree of uncertainty. This variability probably does not represent a shortcoming of the LIDAR imagery but rather reflects inherent characteristics of landslides such as the reduced amount of abrupt, pronounced ground deformation that generally occurs beyond the head of most landslides in unconsolidated and semi-consolidated sediments, which are typical of Seattle. In many cases, only morphology indicative of a landslide head and headscarp was clearly identified so margins were approximately located downslope of the head and the landslide toe was approximately located at the slope toe. It has been noted that many landslides in Seattle have toes in midslope areas (Thorsen, 1989; Harp and others, 1996). Perhaps one-half of the LIDAR-mapped landslide toes were not identified during this study; toes of these landslides were generally mapped at slope toes. The LIDAR landslide map was created with the intention of identifying landslides within a large region with sufficient accuracy to permit recognition of general areas in which landslides presently exist. The map is not intended to replace site-specific engineering geologic and geotechnical investigations.

A total of 173 landslides and landslide complexes were mapped using LIDAR imagery. Ninety-six of the landslides are categorized as uncertain and 77 as certain. At least 93 percent of the mapped landslides are located along coastal bluffs and drainages. Some of the landslides that appear to occupy inland areas actually occupy former coastal bluffs above areas that were filled during grading activities such as Beacon Hill, above Sand Point, the slope between Duwamish Head and Pigeon Point, and near Meadow Point. Primary drainages along which landslides were identified include the Duwamish River, Longfellow Creek, the unnamed drainage below the east flank of Beacon Hill, Ravenna Creek, the south fork of Thornton Creek, and the tributaries of Pipers Creek.

Discussion and Conclusions

The LIDAR landslide map (pl. 1) includes all landslides shown on published geologic, regional landslide, and coastal maps of Seattle (Waldron and others, 1962; Waldron, 1967; Youngmann, 1979; Yount and others, 1993; Wait, 2001), and shows many more that apparently have not previously been identified. For example, Wait (2001) produced the only published map with boundaries of landslides throughout Seattle, and her map shows 45 landslides, or about one-fourth the number shown on plate 1. Wait constructed her map using aerial photographs, historical landslide records, and ground reconnaissance. Yount and others (1993) show only 15 landslides in Seattle on their geologic map of the Seattle 30' by 60' quadrangle. LIDAR clearly permitted identification of a greater number of landslides than traditional techniques involving evaluation of aerial photographs and ground-based study.

The LIDAR map and previous maps each have relative strengths and weaknesses. To illustrate, a part of the LIDAR landslide map with a large LIDAR-mapped landslide complex in the Magnolia Bluff area is depicted in figure 3. Also shown on the figure are landslides mapped previously (Youngmann, 1979; Yount and others, 1993; Wait, 2001). The earlier maps show a landslide within the northern part of the LIDAR-mapped landslide. Wait (2001) mapped two landslides that fall within the northern part of the LIDAR-mapped landslide complex and three landslides within the southern part. The four smaller landslides mapped by Wait probably were active during the winter of 1996–97 as she identified them on aerial photographs taken in 1997, but not on those taken in 1995 or earlier. The northern part of the LIDAR-mapped landslide complex displayed many characteristics indicative of active or recently active landslide activity during ground reconnaissance performed during August 2003. However, no smaller, recently active landslides were differentiable in the LIDAR imagery from adjacent landslide debris in this landslide complex. This possibly is due to displacement of recently active landslides being below the resolution of the LIDAR data. The recently active landslides mapped by Wait (2001) were probably identified on aerial photographs because of distress to vegetation and manmade features. Therefore, aerial photographs appear to be more effective than LIDAR in the Seattle area for discerning boundaries of recently active landslides with small (< 1–2 m) displacements. However, the landslide complex of which the recently active landslides are part was not identified during the previous mapping efforts that used aerial photographs and ground-based study; thus, older landslides are more readily identifiable using LIDAR.

Figure 3 also provides locations of reported historical landslides (Laprade and others, 2000). Note that the northern end of the LIDAR-mapped landslide complex in this figure lacks reported historical landslides because it is a city park; it is largely uninhabited and uncrossed by utilities so landslides are not reported, which illustrates the reporting bias of many Seattle landslide inventories. Reported historical landslide locations are clearly concentrated within the boundaries of the large LIDAR-mapped landslide complex and scarp, thus, the LIDAR-mapped features delineate the area that was most prone to historical landslide activity. These historical landslides did not entirely produce the LIDAR-mapped features; in fact, review of the descriptions of the historical landslides indicates that they only account for a very small part of the area within the LIDAR-mapped landslide complex. Furthermore, evaluation of the historical records of reported landslides throughout Seattle indicates that only eight of the LIDAR-mapped landslides were historically active in their entirety, and some were not reported to be historically active at all. Thus, based on the Magnolia Bluff example, LIDAR-mapped landslides and complexes delineate areas that have experienced significant historical landslide activity, yet only a small fraction of the total delineated areas have been historically active. It follows that the historically inactive parts of the LIDAR-mapped landslide complexes are prone to future landslide activity.

There were 124 landslides reported within the LIDAR-mapped landslide complex shown in figure 3 during a 70-year period (1928–1998). At least 12 homes were destroyed and 25 damaged by these 124 landslides, and they also commonly damaged or destroyed roadways and utilities. Some of the landslides extended to Puget Sound and drove homes into it, and some involved headward retreat of the bluff top. Use of LIDAR was effective for identifying the entire landslide complex of which these historically significant landslides are part, while aerial photographs and ground-based study were not. In addition, although aerial photographs have demonstrated advantages in identifying recently active Seattle landslides, they were only effective in identifying a very small number of significant historically active landslides. Since most of the example landslide complex on Magnolia Bluff was not historically active, it follows that LIDAR also allowed identification of prehistoric landslide areas that are potentially active in the future. The LIDAR landslide map clearly provides advantages in identifying areas prone to future landslides in Seattle and reducing the hazards they pose.

Acknowledgments

This study was initiated upon the recommendation of Jeff Coe and benefited from discussions with Jeff Coe, Dave Lidke, John McKenna, and Rex Baum. John McKenna provided valuable information regarding acquisition of the LIDAR data. Sophie Langard and Agnès Bourgine assisted with ground reconnaissance. Ed Harp and Dave Lidke provided valuable suggestions for improving the manuscript.

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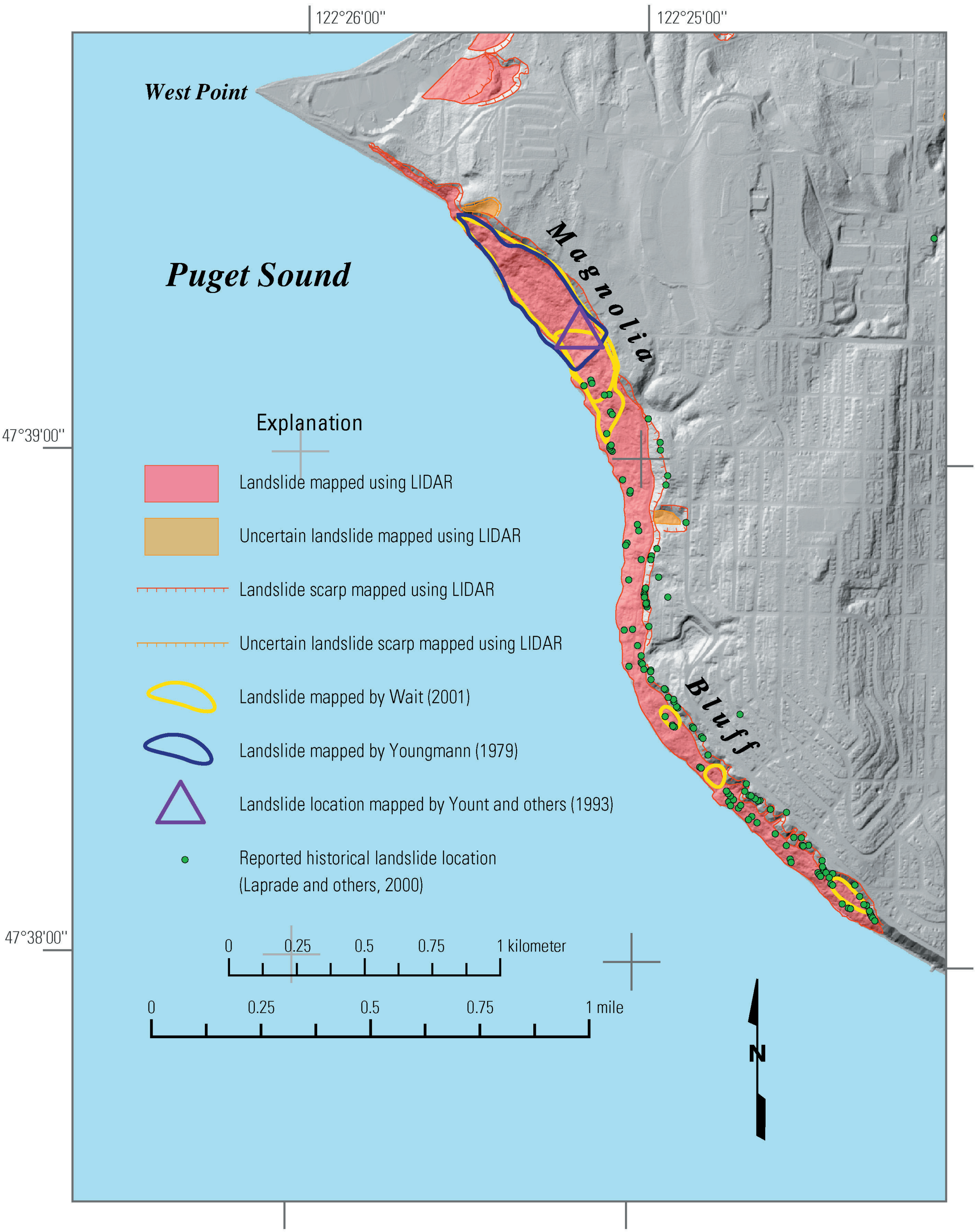

Figure 3. Landslides along part of Magnolia Bluff in western Seattle that were mapped by Wait (2001), Youngmann (1979), Yount and others (1993), Laprade and others, (2000), and during the present study using LIDAR.

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