Lidar-Based Surficial Geologic Map of the Greater Portland Area

Clackamas, Columbia, Marion, Multnomah, Washington, and Yamhill Counties, Oregon and Clark County, Washington

2012

STATE OF OREGON
DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES
www.OregonGeology.org
Larry Givens, Governing Board Chair
Vicki S. McConnell, Director and State Geologist
Don W.T. Lewis, Assistant Director and Chief Operating Officer
Rachel R. Lyles Smith, Projects Operations Manager and GIS Program Lead
Ian P. Madin, Chief Scientist

OPEN-FILE REPORT O-12-02

Lidar-Based Surficial Geologic Map and Database of the Greater Portland Area, Clackamas, Columbia, Marion, Multnomah, Washington, and Yamhill Counties, Oregon, and Clark County, Washington

By Lina Ma, Ian P. Madin, Serin Duplantis, and Kendra J. Williams
Oregon Department of Geology and Mineral Industries

Prepared in collaboration with and supported in part by the U.S. Geological Survey's National Earthquake Hazards Reduction Program under assistance awards G09HQAG0013, G09HQAG0140, and G11AC20312.

EXPLANATION OF MAP SYMBOLS

- Boring Volcanic Vent
- Lidar-Derived Elevation
- USGS 7.5' Quadrangle Boundary
- Perspective View Image Locator and Angle Direction
- Interstate Highway
- Federal or State Highway
- State Boundary
- County Boundary
- Water

Fault — Long-dashed where approximately located, short-dashed where inferred, dotted where concealed, queried where uncertain.

Normal fault — ball and bar on downthrown side; solid line where accurately located, long-dashed where approximate, short-dashed where inferred, dotted where concealed; queried where uncertain.

Strike-slip fault, right-lateral offset — location concealed. Arrows show relative motion.

Strike-slip fault, left-lateral offset — location approximate. Arrows show relative motion.

Thrust fault — long dash where approximately located, dotted where concealed. Sawteeth on upper (tectonically higher) plate.

Introduction

The Oregon Department of Geology and Mineral Industries (DOGAMI) and the U.S. Geological Survey are collaborating to prepare a detailed digital geologic map and database for the greater Portland, urban area. This new geologic information will be used to improve earthquake and landslide hazard mapping and to support groundwater, engineering, and environmental applications. As one part of this multi-year project, DOGAMI has prepared a detailed surficial geology database that uses high-resolution light detection and ranging (lidar) topographic imagery. The database is in the form of Geographic Information Systems (GIS) data on CD-ROM and requires specialized software to view and interpret. This map is a thematic view of the data in the database and highlights some of the dramatic geologic events and processes that have shaped the greater Portland area.

Surficial Geology and Bedrock Geology

This map focuses on surficial geology. Surficial deposits are rock and sediment that were deposited or are being deposited in the current landscape. For example, the sand and gravel alluvium in a river bed is surficial because it is actively being deposited by the river. An adjacent alluvial terrace is no longer being deposited, but it is still near the river that deposited it and in the same landscape in which it was deposited. Bedrock geologic units are rocks, or compacted and cemented sediments, that were deposited in a landscape that no longer exists. For example, marine sedimentary rocks in the Portland area are bedrock, because Portland is no longer in a marine environment. Bedrock units have typically been buried and/or eroded substantially since they were formed.

Portland: A Landscape Shaped by Disturbance

The greater Portland area has been shaped by and continues to be shaped by geologic events (Trexler, 1942; Trimble, 1963; Madin, 2004; Evarts and others, 2009c). The geologic history of the Portland area is one of catastrophes and dramatic transformations rather than slow steady evolution: some events took place over days or weeks, while other events lasted centuries or millennia. Many geologic processes that built our landscape are active today, and the connection between the shape of the land and geology can be clearly seen in many places.

Volcanoes and volcanic eruptions have been a major agent of change in the Portland area. Most of the bedrock in the region is the result of enormous volcanic eruptions that produced the Columbia River Basalt. The Portland area is dotted with dozens of young volcanoes, many of which preserve their conical shape and central crater. The Sandy River canyon, at the east end of the map area, has been repeatedly filled and flushed by volcanic debris from recent eruptions of Mount Hood.

Glaciers and the most recent ice age have had a huge impact. Changes in the glaciers of the Cascades resulted in terraces on the Clackamas River, windblown sediment in the Tualatin Mountains and, above all, the great Missoula floods that reshaped large parts of Oregon and Washington.

In more recent geologic time, a few thousand years ago to the present, the *stormy winter climate and mountain snowpack moleculers* of the Pacific Northwest have caused rivers to flood frequently; the flooding modifies floodplains and reshapes river channels. **Landslides and debris flows** triggered by heavy rainfall are found throughout the area and cause millions of dollars worth of damage in very wet winters.

Humans have also had a role in disrupting and reshaping the landscape by covering thousands of acres with artificial fill, buildings, pavement, landscaping, and agriculture.

Over 80% of this map of the greater Portland area is covered by young surficial deposits, most of which were deposited during relatively short-lived geologic events. Although we can never know for certain when the next flood, landslide, or volcanic eruption will happen, the geologic history of Portland tells us to expect more dramatic changes to the landscape in the future.

Location Map

Geologic Unit Descriptions

See accompanying text report for detailed unit descriptions

Artificial Fill

Artificial Fill (Af) is sand, gravel, and rock placed for building foundations, dams, highway embankments, culverts, and other engineered features. Large areas of the floodplains of the Willamette and Columbia Rivers have been extensively filled to support development. Although modern engineered fill is generally safe and stable, older uncontrolled fill may liquefy, spread or slump during strong earthquake shaking.

Af = geodatabase unit Auf.

Landslides

A **landslide (Ls)** is a mixed mass of rock, soil, sediment, and colluvium that has slid down slopes during one or more past landslide events. More than 3,400 landslides have been mapped in the area. About 1,700 of these are small, covering a half acre or less, while almost 280 are larger than 20 acres. Geologists consider any landslide to be at risk for resumed activity when disturbed by construction, excavation, earthquake shaking, or heavy rainfall. Many of these landslides are hundreds or thousands of years old, and some may be tens of thousands of years old. Detailed landslide inventory maps (Burns, 2009a,b; Burns and Madin, 2009a,b; Burns and Duplantis, 2010a,b; Burns and Mickelson, 2010; Burns and others, 2011a,b) are available for many parts of this map area, with more complete coverage planned in the next few years.

Two ancient **mega-landslides (Mls)** occupy the northeast slopes of the Tualatin Mountains at the north edge of the map. The Wildwood landslide covers about 1,730 acres, and the Dutch Canyon landslide covers about 6,175 acres. Together, they cover an area larger than the city of Tigard. Both have been moving periodically for tens or hundreds of thousands of years and are so old that streams have cut deep canyons through the landslide bodies.

Most of the Dutch Canyon landslide appears to have been inactive for over 10,000 years, but many parts of the Wildwood landslide are currently active.

Ls = geodatabase units Als and Qls. Mls = geodatabase units Qlwsc and Qld.

Debris Flow Fans

Debris flows or flash floods that occur during periods of heavy rain deposit flattened, cone-shaped fans of mud, rock, and woody debris where small, steep streams and canyons reach flatter ground. Most **debris flow fans (Df)** are built up by repeated events over hundreds or thousands of years, and geologists expect that these areas will be buried again in future storms. **Older debris fans (Of)** and thick deposits of colluvium (a layer of loose soil, rock, and other sediment that covers steep bedrock slopes) cover many slopes in the Clackamas River drainage. These deposits probably formed at the same time as some of the terraces on the Clackamas River, perhaps during glacial or interglacial periods. In contrast to debris flow fans, where streams are actively building deposits, older debris fans are being eroded by streams.

Df = geodatabase unit Qf. Of = geodatabase unit Qof.

Alluvium

Alluvium is sediment deposited by a river or stream. During low and normal flows, most rivers are confined to a channel, but during floods they spread out across the surrounding floodplain and most of the alluvium is moved and deposited during high flows or floods. The type of alluvium a river deposits depends on how steep the channel is, how fast the water flows, and the kind of rock that makes up the drainage basin.

The **alluvium of the Columbia River (Alc)** is a thick deposit of fine sediment. The channel of the Columbia River was 250 to 300 feet lower than today when the Missoula floods ended 12,000 years ago. Since then, that deep channel has been steadily filled with sand, silt, and clay deposited during frequent floods (Gates, 1994; Baker, 2002). Although mostly obscured by development, the Columbia River floodplain still contains landforms like sloughs, lakes, natural levees, and bars that show that the area flooded frequently before modern flood control was developed. The loose, water-saturated sediment is vulnerable to liquefaction during strong earthquake shaking.

Coarse alluvium (Alg) made mostly of gravel and sand fills the channels and floodplains of the Clackamas and Molalla Rivers. These rivers flow down steep canyons out of the Cascade Range, and their rugged rocky headwaters add plenty of volcanic rock to the alluvium. All of these deposits have formed since the end of the Missoula floods and are therefore younger than 12,000 years.

Fine alluvium (Alf) made of sand, silt, clay, and a small amount of gravel fills the channels and floodplains of the Tualatin and Willamette Rivers. Both rivers have very gentle slopes, so most of the sediment they move is fine material. The Willamette River is home to Ross Island, a large deposit of gravel that is over 130 feet thick and that may be left over from the Missoula floods. All these deposits have formed since the end of the Missoula floods and are therefore younger than 12,000 years. These deposits of loose, water-saturated sediment are very susceptible to liquefaction during strong earthquake shaking

Ale = geodatabase unit Hace. Alg = geodatabase units Hael and Ham. Alf = geodatabase units Hte, Hat, and Hsw. Alck = geodatabase units Hta, Hal, Qel, Qly, and Qcr.

Volcanic Sediment of the Sandy River

The Sandy River has its headwaters on the slopes of Mount Hood, an active volcano in the Cascade Range. Volcanic eruptions over the last 30,000 years have sent huge masses of volcanic rock, mud, and debris, called lahars, into the river (Scott and others, 1997). Many of these lahars filled the canyon of the Sandy tens of feet deep, raising the entire valley floor almost instantly. Over time, the river cut its way back down through these terrace deposits of **volcanic sediment (Vs)**, only to have the cycle repeated. There are many levels of terraces in the Sandy canyon, each related to different volcanic events (Pierson and others, 2009, 2011). The majority of the alluvium in the Sandy canyon is also derived from these eruptions. Where the Sandy River enters the Columbia River, the Sandy has built a large delta of volcanic debris (Rapp, 2005) from eruptions about 1,500 years ago and 200 years ago.

Vs = geodatabase units Hsa, Hael, and Qtes.

Terraces of the Clackamas River

Climate, river flow, and the amount of sediment available in the Clackamas River drainage have all changed dramatically over the past tens of thousands of years as the last ice age came to an end (Wampler, 2004). These changes caused the Clackamas River to build a series of broad, flat terraces that flank the current channel and floodplain. Some were built up as the river choked on too much gravel and filled the valley; other terraces have been carved out of the soft bedrock as the river migrated back and forth across the valley. At 60 to 80 ft above the river, the **lowest Clackamas terrace (Tcl)** is the youngest, and best preserved, terrace. It is about 10,000 years old (Wampler, 2004). The **middle Clackamas terrace (Tcm)** is about 50 to 60 feet above the river, is the least well preserved terrace. Only a few large areas are left on the south side of the river and only small remnants remain on the north side. The age of this terrace is unknown.

Tcl = geodatabase units Hte and Htex. Tcm = geodatabase units Qtcm and Qtcmx. Tcu = geodatabase unit Qtcu.

Missoula Flood Deposits

From about 21,000 to 12,000 years ago, dozens of gigantic floods swept down the Columbia River and through the Portland area as huge lake in Montana broke through the glacier that dammed it (Bretz and others, 1956; Bretz, 1969; Allen and others, 2009). The floodwaters reached an elevation of about 400 feet (Allen and others, 2009) above sea level in Portland and scoured many areas down to bedrock, which is a familiar sight along I-84 through the Columbia River Gorge. Geologists recognize sight to ten different Columbia River Basalt flow types in the Portland area. There may be as many as two dozen individual flows, but the physical properties of the flows are so similar that the flows can be difficult to tell apart.

Older bedrock that underlies the Columbia River Basalt can be found in parts of the area where erosion has removed the basalt. These older rocks cover very small areas and are grouped on the map with Columbia River Basalt flows. In the northern area of the map, sandstone of the Scappoose Formation contains fossil shells that show that the sand was deposited in the ocean (Madin and Niewendorp, 2008). Along the Willamette River through Lake Oswego and Oregon City, the Basalt of Waverly Heights can be found on islands and shores of the Willamette River (Beeson and others, 1989b). These lava flows were erupted on the ocean floor about 40 million years ago and look a lot like Columbia River Basalt. In the far southeastern part of the map, the Rhododendron Formation can be found in the bottoms of canyons. These rocks were formed by a series of volcanic mudflows, or lahars, that started on ancient Cascade Range volcanoes and flowed down valleys of the ancestral Cascade rivers (Trimble, 1963). The rocks are typically jumbled masses of mud, sand, clay, and sub-rounding blocks of lava of all sizes.

Columbia River Basalt is mined for crushed rock. The Columbia River Basalt also hosts an aquifer system widely used as a source of groundwater. However, the basalt holds a relatively small amount of water and it is very easy to extract. This leads to declining water levels, and drilling and pumping restrictions in some areas. Although the lavas themselves are very strong and stable, they are often separated by clay-rich soil or sediment layers that are the cause of landslides. Most the large landslides in the Tualatin Mountains formed this way. Many landslides also occur where the Columbia River Basalt sits on top of old marine sandstone and siltstone. Weak layers in these sandstones and siltstones are also the cause of the two mega-landslides (Ml).

Although the Tualatin Mountains are made almost entirely of Columbia River Basalt, there are very few places where the basalt is actually seen. Rock quarries and road cuts provide most of the areas of visible basalt, because the slopes are covered with a thick layer of loess (Wo) and colluvium. On the steep slopes of the Tualatin Mountains, heavy rainfall, small landslides, and gravity cause the material at the surface to creep downhill. This mass of colluvium, a mix of loess and sand, clay, and rock fragments from the breakdown of the basalt, can be tens of feet thick. The map shows areas where the bedrock is largely covered by this material as a separate unit, **bedrock and loess (Br-Ls)**, 1981). Related sand dunes occur at several places near Gresham (Powell Butte, Walters Hill), above the level of the Missoula floods. On Sauvie Island, much younger sand dunes cover part of the Columbia River floodplain. Because the alluvium of the Columbia River is a few hundred to a few thousand years old on the floodplain, these dunes must be very young, perhaps only hundreds of years.

Ws = geodatabase units Hfd, Ql, Qe, and Qdtn.

Windblown Sediment

Several different types of **windblown sediment (Ws)** have been deposited in the Portland area. The bedrock of the Tualatin Mountains is covered with a layer of windblown silt, called loess, that is 30 to 100 feet thick. Over time, the loess layer is stable, but as slopes steepen and descend into the nearby canyons, the loess moves slowly downhill under the influence of gravity, water, and numerous small landslides. The blanket of moving and mixing colluvium includes fragments of the underlying bedrock and is shown on the map as bedrock and loess (Br-Ls). Where roads and rock cuts or excavations, the loess is featureless and tan. When saturated by heavy rainfall or runoff, the loess is very susceptible to landslides and can liquefy and flow down slopes. The loess may be as old as 700,000 years in places, but most of it dates from the most recent glacial period, perhaps 30,000 to 40,000 years ago (Lentz, 1981). Related sand dunes occur at several places near Gresham (Powell Butte, Walters Hill), above the level of the Missoula floods. On Sauvie Island, much younger sand dunes cover part of the Columbia River floodplain. Because the alluvium of the Columbia River is a few hundred to a few thousand years old on the floodplain, these dunes must be very young, perhaps only hundreds of years.

Ws = geodatabase units Hfd, Ql, Qe, and Qdtn.

Boring Volcanoes

Dozens of young extinct volcanoes, scattered across the Portland area, are collectively known as the Boring volcanic field (Trexler, 1942; Madin, 1994; Fleck and others, 2002; Evarts and others, 2009a, b). The volcanic field is named after the town of Boring, Oregon. The volcanoes consist of cinder cones and lava flows of various sizes. Most of these volcanoes erupted for only a brief period. Typically, each volcano built up a cinder cone, which may have then filled with a lava lake that eventually broke out of the crater and flowed across the surrounding landscape. The lavas are either basalt or basaltic andesite and almost always have small visible crystals of reddish brown olivine (Madin, 1994). The Boring cinders and lavas weather very rapidly in the wet Portland climate. Cinder cones become masses of red and yellow clay, and lava flows decompose into large rounded core-stones surrounded by sticky red clay. In some places, like Elk Point, Scooter Mountain, and the summit of Mount Scott, the original shapes of the cinder cones are visible, in some cases even the craters remain. A cross-section of a tiny cinder cone on the north end of Mount Tabor was exposed when the area, now a city park, was quarried for road metal. The Mount Tabor cone has a volume of about 800,000 cubic yards (80,000 dump-truck loads). In contrast, Mount Sylvania has a volume of about 1.3 billion cubic yards, almost 1,600 times as large.

Radiometric dating of the volcanoes (Conrey and others, 1990; Fleck and others, 2002; Evarts, 2009a,b) allows geologists to divide the volcanoes into groups according to age, with the age generally increasing, or getting older, to the southeast. The **youngest Boring volcanoes (B1)** range in age from about 120,000 years to 203,000 years. The **Boring Hills volcanoes (B2)** range in age from 427,000 years to 932,000 years. The **older Boring volcanoes (B3)** range from about 1 million years to about 1.5 million years. The **oldest Boring volcanoes (B4)** are about 2.4 million years old.

Boring volcanoes are generally stable and rarely experience landslides. However, where Boring lava flows lie on top of older mudstone and sandstone bedrock, landslides are common. In the Oregon City area, where canyons are cutting into a plateau of Boring lava sitting on top of mudstone, virtually all of the canyons are ringed with large landslides (Madin, 2009).

B1 = geodatabase units Qbab, Qbeb, Qbar-l, Qbwt, and Qbhb. B2 = geodatabase units Qbso, Qbcr, Qbr-l, Qcrr, Qbhe, Qbw, Qbs, Qbj-l, Qbjs, Qbo, QTbz, and QTbt. B3 = geodatabase units Qbh-l, Qbd, Qbsy, Qbsy-l, Qbc, Qcc, Qbh, Qbbc, Qbm, QTbh-l, and QTb. B4 = geodatabase units Tbr, Tvr, Tbc, Tvc, Tbf, Tvf, Tbh, and Tbb.

Ancient River Rocks

The youngest bedrock in the Portland area is made of cemented and compacted sediments deposited by the ancestral Tualatin, Willamette, Clackamas, Sandy, and Columbia Rivers. These **ancient river rocks (Rr)** include layers of sandstone, mudstone, siltstone, and conglomerate or cemented gravel (Trimble, 1963; Madin, 1994, 1998, 2009; Evarts and O'Connor, 2009). The Tualatin Valley and the broad basin occupied by Portland have existed for at least 15 million years. During much of that time, ancestors of the modern rivers flowed into and through the basin. The rivers left behind a complex accumulation of sedimentary rocks. In the Tualatin Valley there are almost 1,000 feet of siltstone, mudstone, and sandstone mostly derived from older sedimentary rocks of the Coast Range. In the Portland basin, the Columbia River deposited and eroded from distant granite landscapes in Idaho, Washington, and Canada along with conglomerate composed of black basalt from the Columbia Plateau and lava and volcanic glass fragments from the Cascade Range. These sedimentary rocks are about 1,500 feet thick near the Portland airport. In Oregon City the ancient river sediments are up to 1,100 feet thick, and clean white sandstone from the Columbia River mixes with brown and gray mudstone rich in volcanic ash and glass, brought in by the ancient Clackamas or Willamette Rivers. In east Portland, distinctive golden colored sandstone resulted when hot lava flows from the Cascades met the Columbia River, shattering and sending tons of fine volcanic glass particles downstream to accumulate in thick layers.

The ancient river rocks may have been laid down starting as long ago as 15 million years, when the lava flows of the Columbia River Basalt ceased, up until about 2.5 million years ago, when the Boring volcanoes began erupting. It is very difficult to establish the age of this kind of sedimentary rock, but volcanic ash samples from the mudstone near the mouth of Eagle Creek were dated at about 3.25 and 4 million years old.

The conglomerate layers can be good sources of groundwater, and are mined for sand and gravel. The mudstone and siltstone are a poor source of groundwater, and are very prone to landslides. The extensive landslides around the Eagle Creek area are all due to weak layers of mudstone.

Br = geodatabase units QTb, QTb-l, QTc, QTc-l, Tm, Ts, Tg, and Tg-l.

Bedrock

The **bedrock (Br)** that underlies the map area is almost all lava flows of the Columbia River Basalt. These dramatic flows were erupted during incredible volcanic eruptions that occurred about 15 to 16 million years ago and that were among the largest anywhere on earth (Tolan and others, 2009; Beeson and others, 1989a,b, 1991; Madin, 1998, 2009; Madin and others, 2008; Madin and Niewendorp, 2008; Burt and others, 2009). The lava erupted from fissures that stretched for miles across far eastern Oregon and Washington. Floods of hot, fluid lava flowed across much of the eastern half of both Oregon and Washington and eventually reached the Pacific Ocean. Dozens of these great eruptions built up as much as 10,000 feet of lava in eastern Washington and 850 feet in Portland. The distinctive dark grey and black basalt lava, often with well-developed columns, is a familiar sight along I-84 through the Columbia River Gorge. Geologists recognize sight to ten different Columbia River Basalt flow types in the Portland area. There may be as many as two dozen individual flows, but the physical properties of the flows are so similar that the flows can be difficult to tell apart.

Older bedrock that underlies the Columbia River Basalt can be found in parts of the area where erosion has removed the basalt. These older rocks cover very small areas and are grouped on the map with Columbia River Basalt flows. In the northern area of the map, sandstone of the Scappoose Formation contains fossil shells that show that the sand was deposited in the ocean (Madin and Niewendorp, 2008). Along the Willamette River through Lake Oswego and Oregon City, the Basalt of Waverly Heights can be found on islands and shores of the Willamette River (Beeson and others, 1989b). These lava flows were erupted on the ocean floor about 40 million years ago and look a lot like Columbia River Basalt. In the far southeastern part of the map, the Rhododendron Formation can be found in the bottoms of canyons. These rocks were formed by a series of volcanic mudflows, or lahars, that started on ancient Cascade Range volcanoes and flowed down valleys of the ancestral Cascade rivers (Trimble, 1963). The rocks are typically jumbled masses of mud, sand, clay, and sub-rounding blocks of lava of all sizes.

Columbia River Basalt is mined for crushed rock. The Columbia River Basalt also hosts an aquifer system widely used as a source of groundwater. However, the basalt holds a relatively small amount of water and it is very easy to extract. This leads to declining water levels, and drilling and pumping restrictions in some areas. Although the lavas themselves are very strong and stable, they are often separated by clay-rich soil or sediment layers that are the cause of landslides. Most the large landslides in the Tualatin Mountains formed this way. Many landslides also occur where the Columbia River Basalt sits on top of old marine sandstone and siltstone. Weak layers in these sandstones and siltstones are also the cause of the two mega-landslides (Ml).

Although the Tualatin Mountains are made almost entirely of Columbia River Basalt, there are very few places where the basalt is actually seen. Rock quarries and road cuts provide most of the areas of visible basalt, because the slopes are covered with a thick layer of loess (Wo) and colluvium. On the steep slopes of the Tualatin Mountains, heavy rainfall, small landslides, and gravity cause the material at the surface to creep downhill. This mass of colluvium, a mix of loess and sand, clay, and rock fragments from the breakdown of the basalt, can be tens of feet thick. The map shows areas where the bedrock is largely covered by this material as a separate unit, **bedrock and loess (Br-Ls)**.

Br = geodatabase units Tbeb, Tr, Trr, Tvfug, Tufsh, Tvfg, Tpsh, Tgsw, Tgu, Tgs, Tgr, Ts, and Tsh. Br-l = geodatabase units Tvr-l, Tufsh-l, Tvfg-l, Tgsh-l, Tgsw-l, Tgs-l, Tgwr-l, and Tsh-l.

References

Allen, J.E., Burns, M., and Burns, S.F., 2009, Cataclysms on the Columbia: Portland, Ooligan Press, 284 p.

Baker, D.L., 2002, Holocene (0-14 ka) sedimentation in the Columbia River floodplain, Portland, Oreg.: Portland State University, M.S. thesis, 207 p.

Beeson, M.H., Tolan, T.L., and Anderson, J.L., 1989a, The Columbia River Basalt Group—From gigantic floods to the Grande Ronde lava flow field controlled flow emplacement patterns, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America, Special Paper 239, p. 223-241.

Beeson, M.H., Tolan, T.L., and Madin, I.P., 1989b, Geologic map of the Lake Oswego quadrangle, Clackamas, Multnomah, and Washington Counties, Oregon: Oregon Department of Geology and Mineral Industries Geologic Map GMS-59, scale 1:24,000.

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: Washington Division of Geology and Earth Resources Geologic Map GM-36, 2 sheets, scale 1:24,000.

Benito, G., and O'Connor, J.E., 2003, Number and size of last-glacial Missoula floods in the Columbia River valley between Pasco, Washington, and Portland, Oregon: GSA Bulletin, v. 115, no. 5, p. 624-638.

Bretz, J H., 1969, The Lake Missoula floods and the Channeled Scabland: Journal of Geology, v. 77, p. 505-543.

Bretz, J H., Smith, H.T.U., and Neff, G.E., 1956, Channeled Scabland of Washington—New data and interpretations: Geological Society of America Bulletin, v. 67, no. 8, p. 957-1049.

Burns, W.J., 2009a, Landslide inventory map of the southwest quarter of the Oregon City quadrangle, Clackamas County, Oregon: Department of Geology and Mineral Industries Interpretive Map IMD-27, scale 1:8,000.

Burns, W.J., 2009b, Landslide inventory maps of the Cooks quadrangle, Clackamas, Marion, and Washington Counties, Oregon: Department of Geology and Mineral Industries Interpretive Map IMD-28, scale 1:8,000.

Burns, W.J., and Madin, I.P., 2009a, Protocol for inventory mapping of landslide deposits from light detection and ranging (lidar) imagery: Oregon Department of Geology and Mineral Industries Special Paper 41, 30 p.

Burns, W.J., and Madin, I.P., 2009b, Landslide inventory map of the northwest quarter of the Oregon City quadrangle, Multnomah and Clackamas Counties, Oregon: Department of Geology and Mineral Industries Interpretive Map IMD-29, scale 1:8,000.

Burns, W.J., and Duplantis, S., 2010a, Landslide inventory maps of the Lake Oswego quadrangle, Clackamas, Multnomah, and Washington Counties, Oregon: Department of Geology and Mineral Industries Interpretive Map IMD-32, scale 1:8,000.

Burns, W.J., and Duplantis, S., 2010b, Landslide inventory maps of the southwest quarter of the Lake Oswego quadrangle, Clackamas County, Oregon: Department of Geology and Mineral Industries Interpretive Map IMD-33, scale 1:8,000.

Burns, W.J., and Mickelson, K.A., 2010, Landslide inventory maps of the Oregon City quadrangle, Clackamas County, Oregon: Department of Geology and Mineral Industries Interpretive Map IMD-30, scale 1:8,000.

Burns, W.J., Madin, I.P., and Mickelson, K.A., 2011a, Landslide inventory maps of the Damascus quadrangle, Clackamas County, Oregon: Department of Geology and Mineral Industries Interpretive Map IMD-34, scale 1:8,000.

Burns, W.J., Madin, I.P., Mickelson, K.A., and Deszcz, M.C., 2011b, Landslide inventory maps of the Lusted quadrangle, Multnomah and Clackamas Counties, Oregon: Department of Geology and Mineral Industries Interpretive Map IMD-35, scale 1:8,000.

Burt, W., Conlon, T., Tolan, T.L., Wells, R.E., and Mitchell, J., 2009, Hydrogeology of the Columbia River Basalt Group in the Portland, Oregon, area, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to vineyards: geologic field trips through the dynamic landscape of the Pacific Northwest: Geological Society of America Field Guide 15, p. 567-716.

Conrey, R.M., Uto, K., Uchiumi, S., Beeson, M.H., Madin, I.P., Tolan, T.L., and Swanson, D.A., 1996, Potassium-argon ages of Boring Lavas, northwest Oregon and southwest Washington: Isochron West, no. 63, p. 3-5.

Evarts, R.C., and O'Connor, J.E., 2009, Geologic map of the Camas quadrangle, Clark County, Washington, and Multnomah County, Oregon: U.S. Geological Survey Scientific Investigations Map 3077.

Evarts, R.C., Conrey, R.M., Fleck, R.J., and Hagstrum, J.T., 2009a, Fusion volcanism in Cascadia: the Boring Volcanic Field: Geological Society of America Field Guide 15, p. 567-716.

Evarts, R.C., Conrey, R.M., Fleck, R.J., and Hagstrum, J.T., 2009b, The Boring Volcanic Field of the Portland/Vancouver area, Oregon and Washington: tectonically anomalous flower volcanoes in an arc forearc: Geological Society of America Field Guide 15, p. 717-736.

Fleck, R.J., Evarts, R.C., Conrey, R.M., and Hagstrum, J.T., 2002, Volcanoes to vineyards: geologic field trips through the dynamic landscape of the Pacific Northwest: Geological Society of America Field Guide 15, p. 251-270.

Frazier, R.C., O'Connor, J.E., Wells, R.E., and Madin, I.P., 2009a, The Missoula floods: a flood river tour through it: GSA Today, v. 19, no. 5, p. 4-10.

Gates, E.D., 1994, The Holocene sedimentary framework of the lower Columbia River floodplain, Portland, Oregon: Portland State University, M.S. thesis, 207 p.

Lentz, R.F., 1981, The petrology and stratigraphy of the Portland area Tertiary rocks, Oregon-Washington: Corvallis, Oreg., 61 no. 1, p.

Madin, I.P., 1994, Geologic map of the Damascus quadrangle, Clackamas and Multnomah Counties, Oregon: Oregon Department of Geology and Mineral Industries Geological Map GMS-80, scale 1:24,000.

Madin, I.P., 1998, Earthquake hazard geologic maps of the Portland, Vancouver, and surrounding areas, *in* Burns, S.F., Madin, I.P., Wang, W.Z., and Yeats, R.S., eds., Assessing and reducing risk in the Pacific Northwest, vol. 2: U.S. Geological Survey Professional Paper 1560, p. 267-286.

Madin, I.P., 2009, Geologic map of the Oregon City 7.5' quadrangle, Clackamas County, Oregon: Oregon Department of Geology and Mineral Industries Geologic Map OMG-119, 49 p., plus appendices, scale 1:24,000.

Madin, I.P., and Niewendorp, C.A., 2008, Preliminary geologic map of the Dixie Mountain 7.5' quadrangle, Multnomah and Washington Counties, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-08-07, 49 p., scale 1:24,000.

Madin, I.P., Ma, L., and Niewendorp, C.A., 2008, Preliminary geologic map of the Lusted 7.5' quadrangle, Multnomah and Washington Counties, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-08-08, 33 p., scale 1:24,000.

Pierson, T.C., Scott, W.E., Vallance, J.W., and Pringle, P.T., 2009, Eruption-related lahars and sedimentation response downstream of Mount Hood, Oregon, to 95 years of climate change, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to vineyards: geologic field trips through the dynamic landscape of the Pacific Northwest: Geological Society of America Field Guide 15, p. 221-238.

Pierson, T.C., Pringle, P.T., and Cameron, K.A., 2011, Magnitude and timing of downstream channel aggradation and degradation in response to a dam-building eruption at Mount Hood, Oregon: Geological Society of America Bulletin, v. 123, no. 1-2, p. 3-20.

Rapp, R.E., 2005, The Holocene stratigraphy of the Sandy River floodplain, Portland, Oregon: Portland State University, M.S. thesis, 97 p.

Scott, W.E., Pierson, T.C., Schilling, S.P., Costa, J.E., Gardner, C.A., Vallance, J.W., and Major, J.J., 1997, Volcanic hazards in the Mount Hood region, Oregon: U.S. Geological Survey Open-File Report 97-89, 14 p.

Tolan, T. L., Martin, B. S., Reidel, S. P., Anderson, J. L., Lindsey, K.A., and Burt, W., 2009, An introduction to the stratigraphy, hydrology, and structure of the Columbia River Basalt Group in the basalt province: A primer for the GSA 2009 field trips, *in* O'Connor, J. E, Dorsey, R. J., and Madin, I. P., eds., Volcanoes to vineyards: Geologic field trips through the dynamic landscape of the Pacific Northwest: Geological Society of America Field Guide 15, p. 395-431, doi: 10.1130/2009.fld015(20).

Trimble, D.E., 1963, Geology of Portland, Oregon, and adjacent areas: U.S. Geological Survey Bulletin 1119, 119 p.

Trimble, D.E., 1963, Geology of Portland, Oregon, and adjacent areas: U.S. Geological Survey Bulletin 1119, 119 p.

Wampler, P., 2004, Contrasting geomorphic responses to climate, anthropogenic, and fluvial change across students to millennial time scales, Clackamas River, Oregon: Portland State University, Ph.D. thesis, 177 p., accessed March 11, 2009 [http://ir.library.oregonstate.edu/dspace/handle/1957/10072].

Watts, R.B., 1985, Cost for periodic, colossal pluvial/loess from Pleistocene glacial Lake Missoula: Geological Society of America Bulletin, v. 96, p. 1271-1286.

Watts, R.B., Bentinger, H.P., and O'Connor, J.E., 2009, Many mysterious Missoula floods down Channeled Scabland and Columbia River Gorge, *in* O'Connor, J. E, Dorsey, R. J., and Madin, I. P., eds., Volcanoes to vineyards: geologic field trips through the dynamic landscape of the Pacific Northwest: Geological Society of America Field Guide 15, p. 75-84.

Projection: North American Datum 1983, Lambert Conformal Conic.

Source data: Lidar data from DOGAMI Lidar Data Quadrangles: LDQ-2009-45 (2273-Estacada), LDQ-2009-45 (2287-Redland), LDQ-2009-45 (2288-Oregon City), LDQ-2009-45 (2302-Lake Oswego), LDQ-2009-45 (2317-Sherwood), LDQ-2009-45 (2332-Sandy), LDQ-2009-45 (2333-Damascus), LDQ-2009-45 (2347-Dixie Mountain), LDQ-2009-45 (2348-Oswego), LDQ-2009-45 (2362-Lusted), LDQ-2009-45 (2363-Dunthorpe), LDQ-2009-45 (2377-Camas), LDQ-2009-45 (2378-Washougal), LDQ-2009-45 (2379-Portland), LDQ-2009-45 (2407-Lacamas), LDQ-2009-45 (2422-Hillsboro), LDQ-2009-45 (2423-Forest Island), LDQ-2009-45 (2438-Cornelius), LDQ-2009-45 (2439-Forest Grove), LDQ-2009-45 (2453-Scholls), and Lidar data from United States Army Corps of Engineers (2010), and Clark County, Washington (2004). Elevation data derived from lidar data. Hydrography, transportation, boundaries, and other base layers, and geologic data from Oregon Department of Geology and Mineral Industries (2011). Infrastructure and political boundaries base layers from Oregon Department of Transportation (2007, 2008).

The lidar data used to create this map were collected from a helicopter flying 1,000 feet above the ground. The laser sent a scanner some over 150,000 measurements each second to build up a three-dimensional "point cloud" model of the ground surface