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Oregon Department of Geology and Mineral Industries
Ruarri J. Day-Stirrat, State Geologist

OPEN-FILE REPORT O-24-10

LANDSLIDE INVENTORY AND RISK REDUCTION IN GRANT COUNTY, OREGON

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DISCLAIMER

WHAT'S IN THIS REPORT?

Landslides are one of the most widespread and damaging natural hazards in Oregon. To continue reducing damage and losses from landslides, areas of landslide hazard must first be accurately located. We mapped 1,507 landslide deposits within three Grant County study Regions: 398 deep-seated landslides, 718 debris flows, 259 rock falls, and the rest shallow landslides or unclassified. Risk reduction discussions identified actions that can be taken in the areas of public awareness, planning and regulation, and emergency response. State, local government, and public participants in these discussions identified preferred pathways for risk reduction strategies most appropriate for Grant County.

Cover photograph: View north toward the city of John Day and the John Day River Valley from the Grant County Regional Airport (44.412284°, -118.964866°). Photo credit: Jason McClaughry, 2023.

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https://storymaps.arcgis.com/stories/0ba26f975c8342a7839cbb4b83339a3c

GEOGRAPHIC INFORMATION SYSTEM (GIS) DATA

See the digital publication folder for files.
Geodatabase is Esri® v10.7.1 format. Metadata is embedded in the geodatabase and provided as xml.

Grant_LSInventory.gdb
- ***feature classes:***
  - **Deposits (polygons)**
  - **Scarp_Flanks (polygons)**
  - **Scarps (polylines)**
  - **Study Area (polygon)**

1.0 EXECUTIVE SUMMARY

Landslides are common in Oregon, representing a serious natural hazard that can disturb lives, property, infrastructure, and the environment. A first step to reduce landslide-related damage and losses is by knowing where previous landslide activity has occurred, followed by targeted risk reduction actions. In June 2020, the Oregon Department of Geology and Mineral Industries (DOGAMI) received a grant from the Federal Emergency Management Agency (FEMA) through the Risk MAP (Mapping and Planning) program as a Cooperating Technical Partner (CTP) (Cooperative Agreement EMS-2020-CA-00010) to perform modern regional landslide inventory mapping for parts of Grant County. The purpose of this project was to provide detailed information about the landslide hazards in this area and provide aid to ongoing local landslide risk reduction efforts. The main tasks included creating a lidar-based landslide inventory and identifying priority landslide risk reduction actions for Grant County communities.

Three areas covering 285 square miles (738 square kilometers) within Grant County and holding the centers of population and infrastructure, were selected for detailed landslide inventory mapping. We identify these study areas as Region 1 including the cities of Mount Vernon, John Day, Canyon City, and Prairie City, Region 2 between the city of Dayville and Sheep Rock, and Region 3 including the city of Monument (see Plates 1, 2, 3, 4). Prior to this study, the Statewide Landslide Information Database for Oregon (SLIDO) contained 81 mapped landslide deposits within the three study Regions: 72 deposits in Region 1, six in Region 2, and three deposits in Region 3. New landslide inventory mapping presented here delineates 1,507 landslides, including 1,068 in Region 1, 303 in Region 2, and 136 in Region 3. Of these mapped landslides, 398 are deep-seated, 718 are debris flow fans, 259 are rockfalls, and 132 are shallow-seated or unclassified. The number of mapped landslides is significantly more than was captured in previous studies, with a much greater level of detail and certainty. Improvements in the landslide inventory primarily resulted from mapping with the intent to identify landslide deposits and features, while using 1-meter lidar DEMs and derivatives as basemaps.

Many prehistoric (>150 years), deep-seated, rotational landslides are mapped in the John Day River Valley between Mount Vernon and John Day (Plate 1). Debris flow fan deposits are found throughout the study area, predominantly at the outlets of basins with high gradient channels and steep slopes (Plates 1, 2, 3, 4). Rock falls are located mostly along the steep basalt gorge area of Picture Gorge and in the upper plateau and cliffs high above Monument (Plates 3, 4). The activation, reactivation, and distribution of landslides in Grant County is related to geologic conditions such as rock strength, structure, and contacts, but also to steep slopes, accumulations of colluvium, deep valley incision, precipitation, infrequent but very intense or long duration rain or rain-on-snow events, earthquake shaking, certain human activities, or some combination of these factors.

Landslide risk reduction discussions with Grant and Wasco County representatives, identified specific actions to encourage public awareness, land use planning and regulation, and emergency response. Awareness of landslide hazard and risk is increased in Grant County through release of this publication and Esri ArcGIS™ StoryMap, and inclusion of the new data in scheduled updates of SLIDO. This information allows the public and community leaders to implement awareness education campaigns about landslide hazards and to prioritize future risk reduction actions. Land use planning and regulation is an effective method to work on risk reduction and can be initiated in a variety of ways using the maps and digital spatial data produced in this project. Targeted planning can result in avoidance or alteration of development in high hazard areas. Results of our study and greater experience statewide also underline the benefits of developing emergency response plans and public engagement before a landslide disaster, and the critical need of early notification during times of increased landslide potential.

2.0 INTRODUCTION

Landslides are common in Oregon, representing a serious natural hazard that can disturb lives, property, infrastructure, and the environment. The term landslide refers to a range of mass movements (also referred to as slope failures) including rock falls, debris flows, earth slides, and other mass movements (Varnes, 1978). Different landslide types have varying frequencies of occurrence, triggering conditions, and very different resulting hazards. All landslides can be classified into six types of movement: 1) falls, 2) topples, 3) slides, 4) spreads, 5) flows, and 6) complex (a combination of movements). Most slope failures are complex combinations of these distinct types (Burns and Madin, 2009). Landslides can develop with little warning, or may take place over a period of days, weeks, or longer; landslides may remain inactive for centuries only to reactivate as conditions change.

A first step to reduce landslide-related damage and losses is by accurately locating where previous landslide activity has occurred, followed by practicing specific risk-reduction actions. In June 2020, the Oregon Department of Geology and Mineral Industries (DOGAMI) received a grant from the Federal Emergency Management Agency (FEMA) through the Risk MAP program as a Cooperating Technical Partner (CTP) (Cooperative Agreement EMS-2020-CA-00010) to perform modern regional landslide inventory mapping for three regions of Grant County in northeastern Oregon (**Figure 2-1**). The maps provide both insight into regional and local landslide hazard assessments and form the basis for recommendations for landslide risk reduction activities developed in cooperation with Grant County.

This report describes the methods and results of landslide inventory mapping completed for Grant County. Landslide inventory maps were developed following a methodology outlined in DOGAMI Special Paper 42, Protocol for Inventory Mapping of Landslide Deposits from Light Detection and Ranging (Lidar) Imagery (called SP-42 for the remainder of this paper; Burns and Madin, 2009). Landslide inventory mapping in Grant County has been performed in the past by geologic mappers, student researchers, consultants, and DOGAMI (Thayer, 1956; White, 1964; Wilcox, 1966; Brown and Thayer, 1966a, b; Schlicker and Brooks, 1976; Walker, 2002; Busskohl, 2006). However, none of these past studies had high-resolution airborne light detection and ranging (lidar) topographic data available to them. Burns (2007) concluded that lidar data should be used for all future landslide studies in Oregon, as this data provides a high-resolution view of the bare ground surface. The use of 1-meter lidar-derived bare-earth digital elevation models (DEMs) was fundamental to the landslide inventory mapping performed in this study.

Recently, the Oregon Lidar Consortium collected high-resolution, high accuracy lidar data to produce detailed 1-meter DEMs for much of Grant County. The lidar data provide a detailed image of the surface geomorphology, allowing for the identification of landform features associated with landslides. These features include concave slope depressions, vertical or steep scarps, shear zones located along the flanks of landslides, and shortening features of landslides such as toes, transverse ridges, and snouts (Burns and Madin, 2009). Distinctive landslide features recognized in lidar-derived datasets can be used to identify individual landslides with a high level of certainty and to map the boundaries of landslide deposits accurately.

Throughout this report we use the engineering geology terms *hazard*, *susceptibility,* and *risk*. The term hazard is defined as a possible source of danger and in this report, we consider landslides as a hazard. The term susceptibility is defined here as capable of a specified action or process, and in this report the process is landsliding. The term risk is defined here is the possibility of property loss or injury to life, when exposed to landslide hazards.

2.1 Project Area

Grant County covers 4,527 square miles (mi^2) (11,725 square kilometers [km^2]) in northeast Oregon (**Figure 2-1**). Three areas covering 285 mi^2 (738 km^2) within the county, which include population centers and associated infrastructure, were selected for detailed landslide inventory mapping. In this report, we identify these study areas as Region 1 including the cities of Mount Vernon, John Day, Canyon City, and Prairie City, Region 2 between the city of Dayville and Sheep Rock, and Region 3 including the city of Monument (**Figure 2-1**, **Figure 2-2**, **Figure 2-3**).

Grant County is located within the Blue Mountains physiographic province and includes a varied landscape of alpine to timbered mountains, deep canyons, and areas of rolling hills, grassland steppe, and rangeland. Major mountain ranges include the Aldrich-Strawberry Mountains in the southern part of the county and Greenhorn Mountains to the east and northeast (**Figure 2-1, Figure 2-2**, **Figure 2-3**). Grant County hosts the headwaters of the west-to-north-flowing John Day River and is traversed by all three forks (North, Middle, South) (**Figure 2-1**). Elevation in the county ranges from 1,820 feet (ft)(555 meters [m]) on the John Day River at Kimberly on the northwest to 9,038 ft (2755 m) at the summit of Strawberry Mountain, south of Prairie City (**Figure 2-1**, **Figure 2-2**, **Figure 2-3**). The total population in Grant County is 7,233 people, most of whom reside in the towns of John Day, Prairie City, Dayville, and Monument (**Figure 2-1**; U.S. Census Bureau, 2020). The primary transportation routes are state highways 26 (east-west) and 395 (north-south). The town of Monument is accessed via state highway 402 (**Figure 2-1**).

Much of the upland areas of Grant County are managed by the United States Forest Service (USFS), including the Umatilla National Forest northwest of Monument (Region 3) and the Malheur National Forest on the south, east and north of the two more southerly study areas (Regions 1 and 2) (**Figure 2-1**). The westernmost boundary of the Region 2 study area includes part of the Sheep Rock Unit of John Day Fossil Beds National Monument (**Figure 2-1**, **Figure 2-3**), an area, protected for its unique geology and wealth of Cenozoic mammalian fossils (National Park Service, 2023).

Grant County includes high desert grasslands, sage and juniper, pine fir and other tree species in the forested areas. The uplands are more forested, and the valleys consist of rangeland, shrublands and agricultural land (Nelson and others, 2016). There are extensive livestock ranges, which occupy the lowlands and highlands throughout the year. The mean annual precipitation is between 10 to 15 inches (in)(25 to 38 centimeters [cm]) annually at the valley floor, where the cities of John Day and Dayville are located, with up to 20 to 40 in (51 to 102 cm) in the uplands of the Strawberry Mountains on the south and toward the Blue Mountains to the north (PRISM Climate Group, 2022). The summers can be warm and dry, and much of the annual precipitation falls as winter snow.

Figure 2-1. Map of Grant and neighboring counties in northeastern Oregon showing individual study areas identified as Region 1, Region 2, and Region 3 (outlined in red).

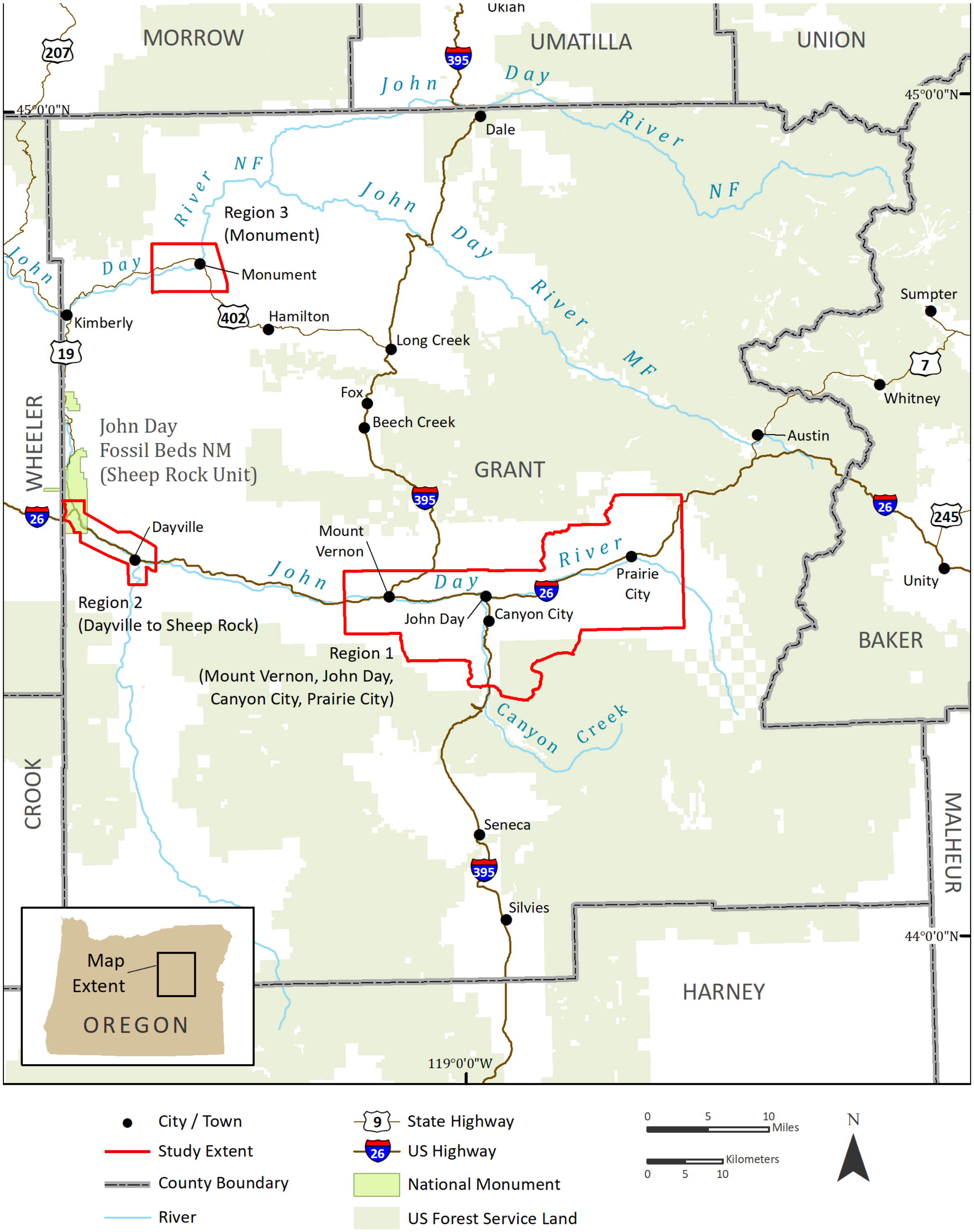


Figure 2-2. Map of the Region 1 project area in Grant County (outlined in red).

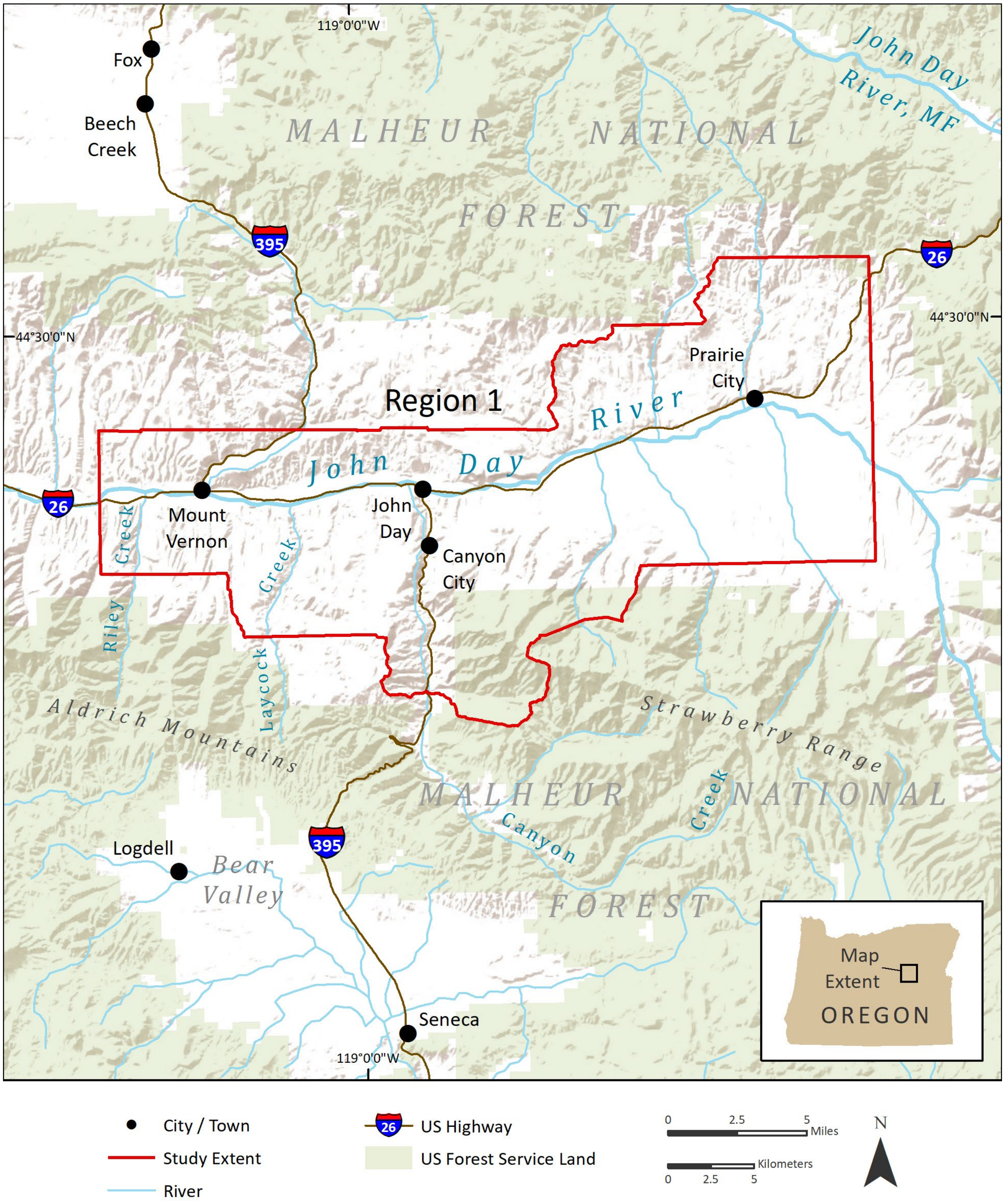
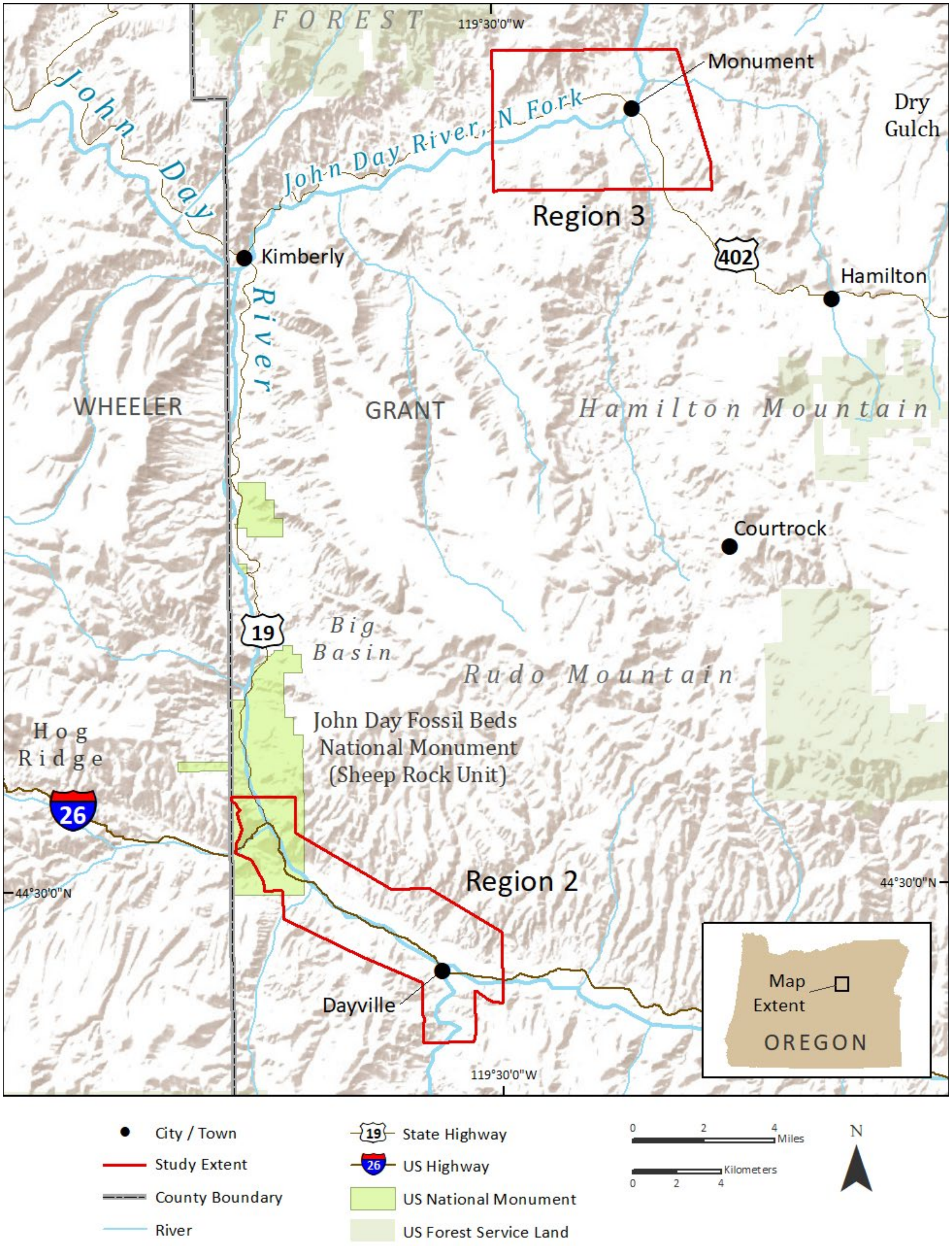


Figure 2-3. Map of the Region 2 and 3 project areas in Grant County (outlined in red).



3.0 GEOLOGY OF THE STUDY REGIONS

3.1 Overview

The following list summarizes the geologic units mapped in three regions of Grant County (Region 1, Region 2, Region 3) and compiled in the Oregon Geologic Data Compilation, OGDC-7 (Franczyk and others, 2020). Geologic map units are shown at the Thematic Terrane Group-Thematic Formation scale of OGDC-7. Ages are shown as Ma, millions of years before present.

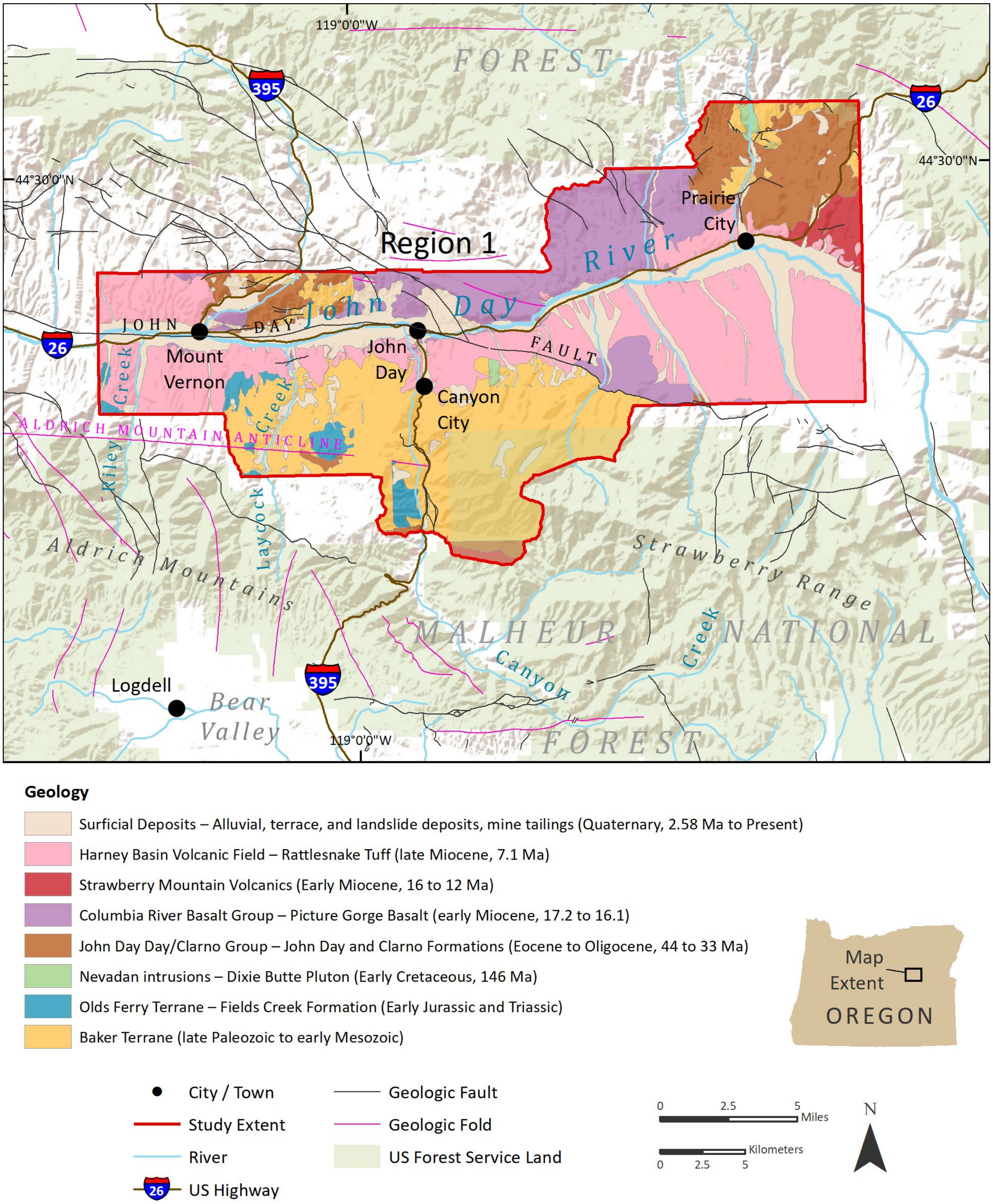
- Surficial Deposits – Alluvial, terrace, and landslide deposits (superseded by mapping in this publication, DOGAMI OFR O-24-10), mine tailings (Quaternary, 2.58 Ma to Present)
- Harney Basin Volcanic Field – Rattlesnake Tuff (late Miocene, 7.1 Ma)
- Strawberry Mountain Volcanics (middle Miocene, 16 to 12 Ma)
- Neogene Sedimentary Rocks – Mascall Formation (middle Miocene, ~16 Ma)
- Columbia River Basalt Group – Picture Gorge Basalt (early Miocene, 17.2 to 16.1 Ma)
- John Day/Clarno Group – John Day and Clarno Formations (Eocene to Oligocene, 44 to 33 Ma)
- Nevadan intrusions – Dixie Butte Pluton (Early Cretaceous, 146 Ma)
- Olds Ferry Terrane – Fields Creek Formation (Early Jurassic and Triassic)
- Baker Terrane (late Paleozoic to early Mesozoic)

The following sections provide a broad overview of the geologic and structural relationships in each of the three mapped regions in Grant County. While geologic mapping was not the focus of this study, the type of geology (e.g., bedrock, surficial) underlying each region directly influences the causes and location of landslides. In the Results **Section 4.1**, we discuss observations about the relationship of bedrock geology to landslide features mapped during this study.

3.1.1 Region 1 – Mount Vernon, John Day, Canyon City, and Prairie City

The oldest rocks in study area of Region 1 – Mount Vernon, John Day, Canyon City, and Prairie City, are part of the late Paleozoic to early Mesozoic Baker Terrane, an accretionary complex composed of highly variable rock types and ages forming the core of the Blue Mountains uplift in northeast Oregon (**Figure 3-1**; Silberling and others, 1992). These rocks crop out in three principle areas in Grant County: 1) forming the western flanks of the Strawberry Mountains southeast of Canyon City, where the Baker Terrane consists primarily of rocks of the Permian Canyon Mountain Complex which includes an ophiolite sequence of ultramafic rocks, layered ultramafic-mafic rocks, gabbro, sheeted sills, and volcanic rocks (Thayer, 1956, 1963; Brown and Thayer, 1966b; Mullen, 1983; Leeman and others, 1995); 2) forming the northern flanks of the Aldrich Mountains southwest of Canyon City and north of the John Day River between the city of John Day and Mount Vernon, where Baker Terrane rocks assigned to the Miller Mountain Melange include Paleozoic metasedimentary and metavolcanic rocks, shale, argillite, and chert, and amphibolite, sheared in with Triassic serpentinite (Thayer, 1956; Brown and Thayer, 1966a, b); and 3) northeast of Prairie City between Dixie Creek and Jeff Davis Creek, where units include Paleozoic cherty shale and metavolcanic rocks, pre-Upper Jurassic to post-middle Permian Dixie Butte meta-andesite, Triassic and Permian argillite and chert in the Badger Creek metasedimentary unit, and serpentinite and serpentinite matrix mélange (**Figure 3-1**; Thayer and others, 1967; Brooks and others, 1984; Ferns and Brooks, 1995; LaMaskin and others, 2009). Along Dixie Creek, rocks of the Baker Terrane are intruded by Early Cretaceous and Late Jurassic quartz diorite and granodiorite of the 146 Ma Dixie Butte Pluton (**Figure 3-1**; Brooks and others, 1984; Ferns and Brooks, 1995; LaMaskin and others, 2009).

Figure 3-1. Generalized geology of Region 1.



Mudstone, shale, graded graywacke, and tuff interbedded with lava flows, chert, breccia, and basaltic pillow lava of the Fields Creek Formation of the Olds Ferry Terrane unconformably overlie the Baker Terrane south, southwest, and west of Canyon City (Brown and Thayer, 1966 a, b; Silberling and others, 1992). Variably altered andesitic to basaltic lava flows, breccias, and conglomerate of the Eocene-Oligocene Clarno Formation overlie older rocks of the Baker Terrane north of the John Day River between the city of John Day and Mount Vernon (**Figure 3-1;** Brown and Thayer, 1966 a, b). Erosional remnants of this unit also unconformably overlie the Olds Ferry and Baker terranes in the study area along Fall Creek, south of Canyon City (**Figure 3-1**). Areas mapped as Columbia River Basalt along the John Day Valley between Picture Gorge and Prairie City include basaltic lava flows now correlated to the lower Miocene Picture Gorge Basalt and a compositionally diverse basalt-to-rhyolite volcanic suite assigned to the middle Miocene Strawberry Volcanics (**Figure 3-1**; Steiner and Streck, 2013; Cahoon and others, 2021). From west to east in the John Day Valley, between Picture Gorge and Prairie City, lava flows display a progressively changing geochemical signal from Picture Gorge Basalt compositions on the west to Strawberry Volcanics compositions on the east. This section is now recognized to also host the ~15.5 Ma cooling unit 2 of the Dinner Creek Tuff (Streck and others, 2015; Cahoon and others, 2021). Gravel, sand, and clay in the upper Miocene Rattlesnake Formation and the 7.1 Ma reddish-orange, ridge-capping Rattlesnake Tuff mantle the Picture Gorge Basalt, Strawberry Volcanics, and older rocks in broad aprons along the south side of the John Day River between Prairie City and Mount Vernon (**Figure 3-1**; Brown and Thayer, 1966 a, b; Thayer and others, 1967). The unit is also mapped north of the John Day River at Prairie City and again at Mount Vernon west to Picture Gorge (Brown and Thayer, 1966 a, b).

Both the John Day River and Canyon Creek are deeply entrenched, creating valleys with ~1000 ft (305 m) of vertical relief (**Figure 3-2**). Valley bottoms are filled by modern alluvium composed of gravel, sand, and silt (**Figure 3-1**). Smaller tributaries contain alluvial fans. Along the John Day River, Thayer (1956) and Brown and Thayer (1966 a, b) mapped a limited number of alluvial terrace deposits consisting of unconsolidated gravel, sand, silt, and clay, especially near the city of John Day. Terrace deposits represent eroded, incised, and now abandoned older flood plains of the John Day River. Most areas of alluvium in the John Day Valley, near the city of John Day, were placer mined for gold in the late 1800s (**Figure 3-1**). Much of this disturbed alluvial ground has been reclaimed for urban and commercial use.

Figure 3-2. View north toward John Day and the John Day River Valley from the Grant County Regional Airport (44.412284°, -118.964866°). Geology underfoot includes Picture Gorge Basalt over the older Baker Terrane, tightly folded into an east-west trending syncline. These rocks are capped above an angular unconformity by the Rattlesnake Tuff. North of the valley, Picture Gorge Basalt and Dinner Creek Tuff overly the Clarno Formation and the Baker Terrane, forming the south-dipping limb of the Davis Creek anticline. The John Day fault is concealed beneath the John Day Valley. Photograph by Jason McClaughry, 2023.

3.1.2 Region 2 – Dayville to Sheep Rock

Between Dayville and Sheep Rock (study Region 2), the main stem of the John Day River has incised down through a southwest-dipping section of Oligocene to upper Miocene rocks including from oldest to youngest, the John Day Formation, Picture Gorge Basalt, Mascall Formation, and Rattlesnake Formation (**Figure 3-3**, **Figure 3-4**; White, 1964; Brown and Thayer, 1966 b; Thayer and Brown, 1966; Thayer, 1977; Ferns and others, 2017). Bluish-green to white and variably zeolitized tuffaceous sedimentary rocks and interbedded tuffs forming spectacular pinnacled cliffs and badlands along the John Day River, north of Picture Gorge, are part of the Turtle Cove Member of the John Day Formation (**Figure 3-3**; Bestland, 1995). These rocks dip ~20° SW, and are the oldest exposed geologic units mapped in the Dayville to Sheep Rock study area (White, 1964). John Day Formation strata are unconformably overlain, across an angular unconformity, by a flow-on-flow succession of basaltic lavas flows of the Picture Gorge Basalt. Two Picture Gorge subunits are mapped, including the Dayville and Monument Mountain basalts (Cahoon and others, 2023). Picture Gorge Basalt in the study area typically occurs as individual, columnar- to hackly-jointed dense lava flows, ranging between 60 and 130 ft (18 and 40 m) thick. Interflow breccias are widespread. Locally, tuffs, red volcanic siltstones, and very fine-grained sandstones are present as interbeds between lava flows (White, 1964). The Picture Gorge Basalt is in turn overlain, across a very slight angular unconformity, by the Mascall Formation (**Figure 3-3**, **Figure 3-4**). The Mascall Formation, forming both the north and south valley walls of the John Day River Valley between Picture Gorge and Dayville, is composed of ~500 to 2100 ft (150 to 640 m) of buff to white bedded tuffaceous siltstones and fine-grained sandstones (White, 1964). In the formation at Picture Gorge, the Mascall includes rhyolitic ash-flow tuff units of the regionally widespread Dinner Creek Tuff (Streck and others, 2015; Ferns and others, 2017). The Rattlesnake Formation is the youngest geologic unit mapped in the study area and includes poorly sorted, poorly indurated gravels and the prominent 7.1 Ma cliff-forming, welded Rattlesnake Tuff. The Rattlesnake Tuff dips ~5° SW, above a significant angular unconformity on the Mascall Formation at Picture Gorge (**Figure 3-3**, **Figure 3-4**).

The John Day River has deeply incised through the southerly-dipping section of the Rattlesnake and Mascall Formations and Picture Gorge Basalt, creating a strike valley with ~1000 ft (305 m) of vertical relief, as seen below in **Figure 3-4**. The valley bottom is filled with alluvium composed of gravel, sand, and silt. Smaller tributaries are associated with alluvial fans.

Figure 3-3. Generalized geology of Region 2.

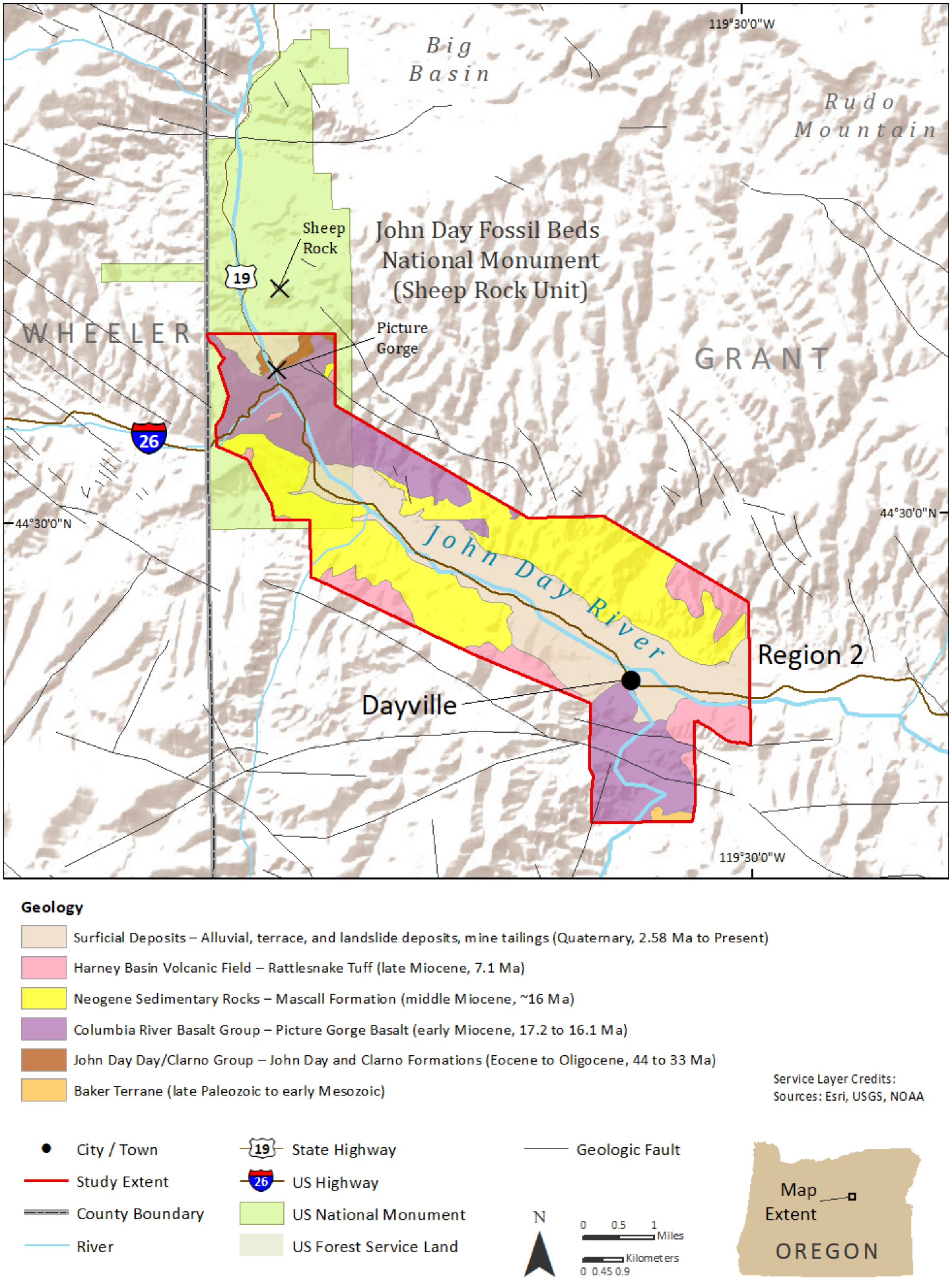
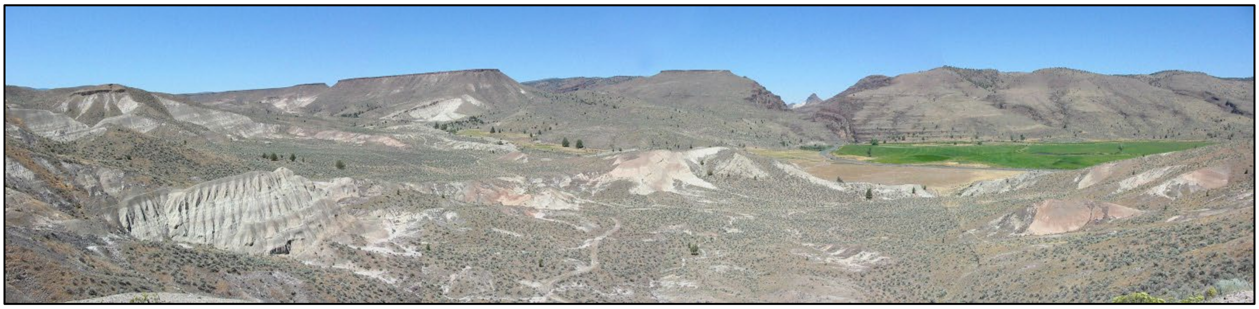


Figure 3-4. View north toward Picture Gorge and the John Day River Valley from the Mascall Overlook (44.500812°, -119.622184°). Visible in order of their deposition and geologic age from oldest to youngest, southwest-dipping (~20°SW) Picture Gorge Basalt and bedded tuffaceous sedimentary rocks of the Mascall Formation. The reddish-orange, cliff-forming Rattlesnake Tuff caps the ridgeline. This unit dips ~5° SW, lying above a significant angular unconformity formed on the older rocks. Photograph by Jason McClaughry, 2004.



3.1.3 Region 3 – Monument

Bedded, variably zeolitized, gray, green, yellow, and red fine-grained tuffaceous sedimentary rocks and tuffs of the John Day Formation are the oldest rocks cropping out along the North Fork John Day River in the Region 3 - Monument area (**Figure 3-5**, **Figure 3-6**; Wilcox and Fisher, 1966). The John Day Formation is overlain by >1000 ft (305 m) of Picture Gorge Basalt, capping the high ridges (**Figure 3-5**, **Figure 3-6**; Waters, 1961; Wilcox and Fisher, 1966; Fruchter and Baldwin, 1975; Cahoon and others, 2020, 2023). Cahoon and others (2023) subdivided the Picture Gorge Basalt in the Monument region into three subunits, including from oldest to youngest: Dayville, Monument Mountain, and Twickenham Basalt. Picture Gorge Basalt in the Monument region typically occurs as individual, columnar- to hackly-jointed dense lava flows, ranging between 20 and 50 ft (5 and 15 m) thick; where lava flows are in direct contact with the older John Day Formation, horizons of brecciated basalt, pillow basalt, or basaltic sandstone are common (Wilcox and Fisher, 1966). Lava flows are now eroded to form near-vertical cliffs and deeply incised canyons. Numerous and conspicuous NNW-striking basalt dikes also are mapped to crosscut the John Day Formation. These dikes are part of the Monument dike swarm, representing remnant eruptive sites for some of the Picture Gorge Basalt (Fruchter and Baldwin, 1975; Cahoon and others, 2023).

The North Fork John Day River and Cottonwood Creek have both deeply incised through the thick section of John Day Formation and Picture Gorge Basalt lava flows and dikes, creating valleys with 1000 to 1500 ft (305 to 460 m) of vertical relief, seen in **Figure 3-6**. Valley bottoms are filled with alluvium consisting of gravel, sand, and silt. Smaller tributaries are associated with alluvial fans.

Figure 3-5. Generalized geology of Region 3.

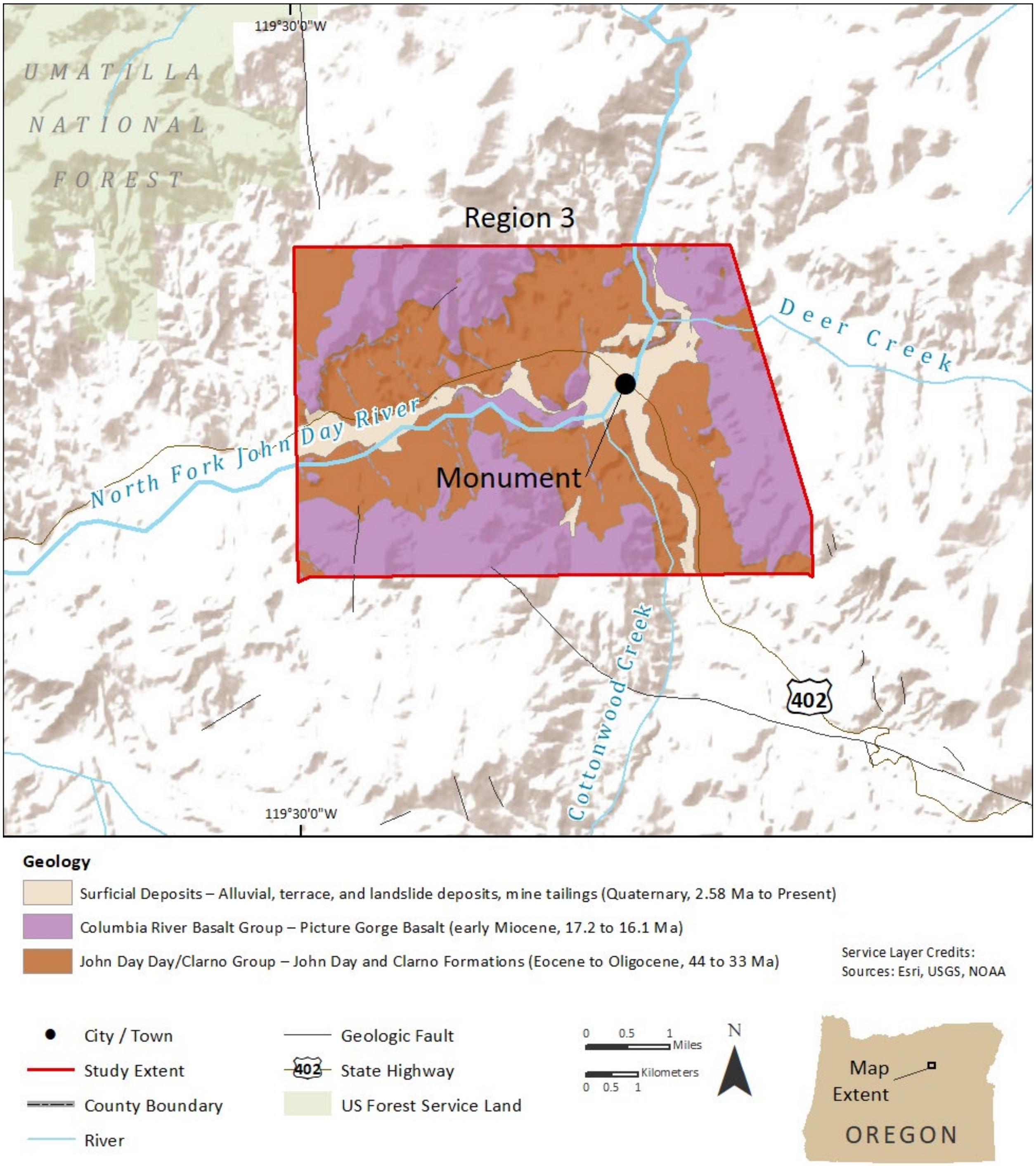


Figure 3-6. View south-southeast toward the city of Monument and the North Fork John Day River Valley from Top Road (44.843727°, -119.439173°). Geology in this area is characterized by generally undeformed lava flows of the Picture Gorge Basalt overlying tuffaceous sedimentary rocks and tuff in the John Day Formation. Photograph by Jason McClaughry, 2004.

3.2 Structural Geology

3.2.1 Regions 1 and 2 – John Day River – Prairie City to Sheep Rock

The deeply incised John Day Valley in study Regions 1 and 2, between Prairie City and Sheep Rock, began to take form in the Pliocene after deposition of the Rattlesnake Tuff. Geologic structure is mapped as folds in the Picture Gorge Basalt and older rocks about WNW-trending to NW-trending fold axes and a series of WNW-striking faults (**Figure 3-1**, **Figure 3-3**; Brown and Thayer, 1966b). Prominent among fault structures is the John Day fault, a WNW-striking, steeply dipping reverse fault that approximately follows the trough of the John Day syncline and is paralleled by the course of the modern John Day River for 45 mi (70 km) between Prairie City and Picture Gorge (**Figure 2-2**, **Figure 2-3**; Thayer and Brown, 1966). The Picture Gorge Basalt, Mascall Formation, and Rattlesnake Tuff and older units are displaced and variably tilted along the John Day fault in an up-on-the-north sense. The total amount of dislocation of the base of the Rattlesnake Formation by folding plus faulting is at least 1,000 ft (305 m) between Mount Vernon and Picture Gorge (**Figure 3-3**, Brown and Thayer, 1966b).

Dunning (2023) identified youthful scarps in lidar imagery and used cosmogenic and radiocarbon age dating in offset glacial moraines on the north face of the Strawberry Mountains, ~5 mi (8 km) south of Prairie City, to estimate the slip rate on the fault and associated recurrence rate of recent earthquakes. Results of this study indicate activity younger than 11,000 years with at least one estimated Mw 6.7 to 6.8 earthquake occurring ~1,200 to 1,400 years ago (Dunning, 2023).

3.2.2 Region 3 – Monument

Wilcox and Fisher (1966) do not show faulting on the rocks that underly the Monument study Region 3. Cross sections by Wilcox and Fisher (1966) illustrated a relatively flat-lying succession of Eocene through lower Miocene rocks. South and north of the city of Monument, several NNW-striking faults are drawn cutting Picture Gorge Basalt and paralleling NNW-striking dikes in the Monument dike swarm (**Figure 3-5**).

4.0 LANDSLIDE INVENTORY

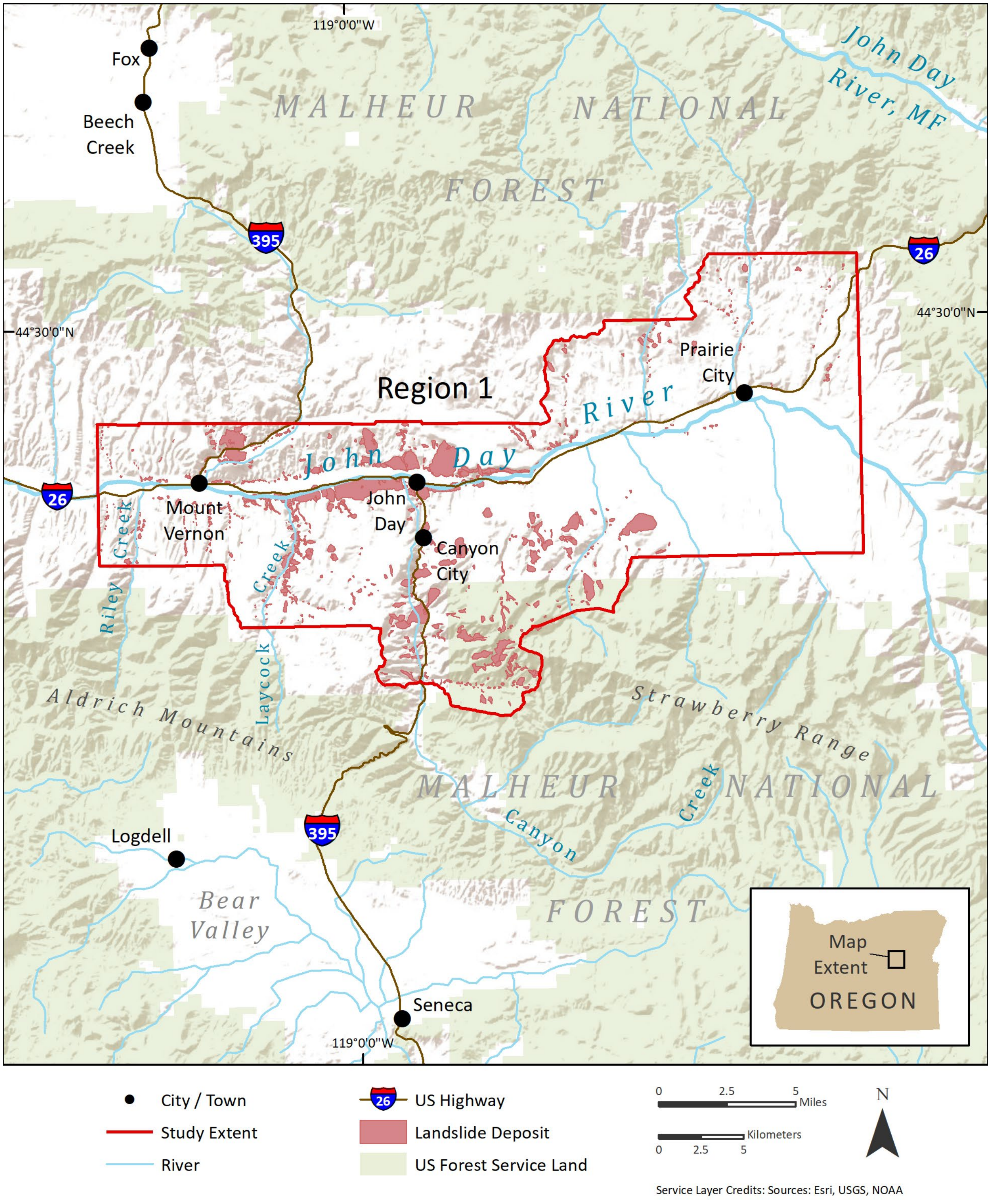
Prior to beginning lidar-based mapping of landslides, we reviewed details on all published landslides in the Statewide Landslide Information Database of Oregon (SLIDO-4.5), a statewide database of all mapped landslides compiled from published geologic and landslide hazard-specific maps (Franczyk and others, 2024; https://www.oregon.gov/dogami/slido/pages/index.aspx). We also consulted direct sources of geologic mapping compiled in the Oregon Geologic Data Compilation, OGDC-7 (Franczyk and others, 2020). Landslide inventory mapping in Grant County, before this effort, included work by geologic mappers, student researchers, consultants, and the Oregon Department of Geology and Mineral Industries (DOGAMI) (Thayer, 1956; White, 1964; Wilcox, 1966; Brown and Thayer, 1966a, b; Schlicker and Brooks, 1976; Walker, 2002; Busskohl, 2006).

The Grant County landslide inventory was created following the SP-42 lidar-based landslide inventory mapping and attributing procedures detailed in Burns and Madin (2009) (Plates 1, 2, 3, 4). Landslide features and deposits mapped by this study were compared against features mapped in previous non-lidar based efforts (Thayer, 1956; White, 1964; Wilcox, 1966; Brown and Thayer, 1966a, b; Schlicker and Brooks, 1976; Walker, 2002; Busskohl, 2006). Limited field checking was done in Regions 1 and 2 to verify desktop mapping interpretations (**Figure 2-1**). The lidar data used was collected in 2017, with areas near Monument and on the margins of the study area collected in 2020 (https://www.oregon.gov/dogami/lidar/Pages/index.aspx). We make a distinction between the apparent ages of landslide events mapped; those known or inferred to be less than 150 years old are attributed as historic, while those likely older than 150 years are attributed as prehistoric. The fully attributed landslide inventory data is compiled in an Esri™ geodatabase, which accompanies this report.

4.1 Results

High-resolution 1-meter lidar topographic data provides an unparalleled view of the bare ground surface of the Earth, revealing distinctive landform features associated with landslides. The use of 1-meter lidar bare earth DEMs along with a variety of lidar derivatives as basemaps allows for a significant increase in the number landslides recognized and provides a significantly greater level of confidence and detail, both in terms of spatial extent and landslide characteristics. Prior to this study, SLIDO contained 81 non-lidar mapped landslide deposits within the three study Regions of Grant County: 72 deposits in Region 1, 6 in Region 2, and 3 deposits in Region 3 (**Figure 2-1**, Franczyk and others, 2024). New lidar-based inventory mapping delineated significantly more landslides, with 1,507 now mapped across the three regions of Grant County, including 1068 in Region 1, 303 in Region 2, and 136 in Region 3. Of these features, 398 are deep-seated landslides, 718 are debris flow fans, 259 are rock falls, and 132 are shallow-seated landslides or unclassified (**Figure 2-1**, Plates 1, 2, 3, 4). Landslide inventory results are discussed in **Sections 4.1.1**, **4.1.2**, and **4.1.3** and are graphically displayed on four accompanying map plates (Plates 1, 2, 3, 4). Smaller landslide overview maps are provided within the text report as **Figure 4-1**, **Figure 4-2**, and **Figure 4-3.**

Figure 4-1. Landslide inventory overview map for Region 1. See plates 1 and 2 for detailed map data.



Service Layer Credits: Sources: Esri, USGS, NOAA

Figure 4-2. Landslide inventory overview map for Region 2. See plate 3 for detailed map data.

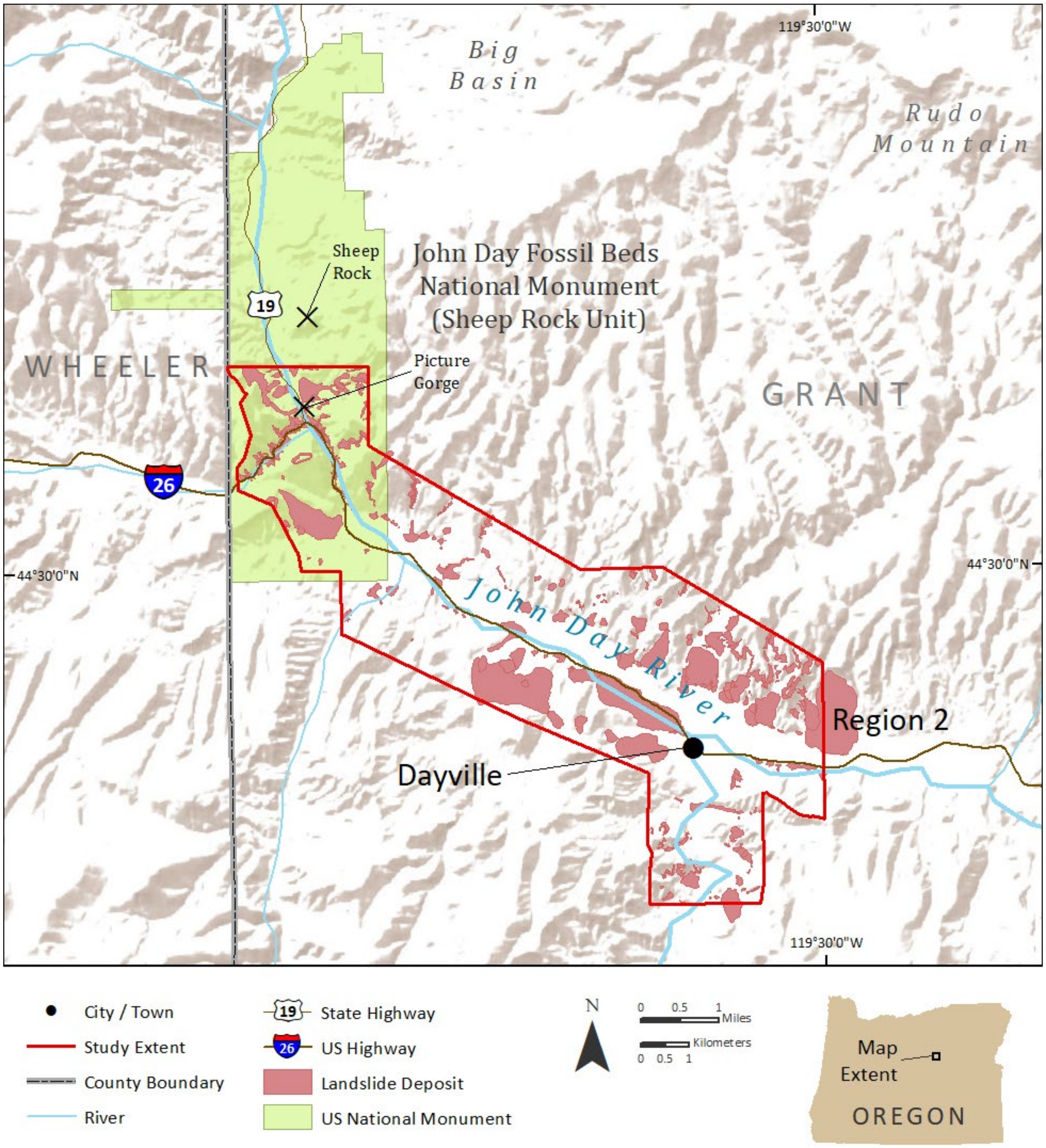
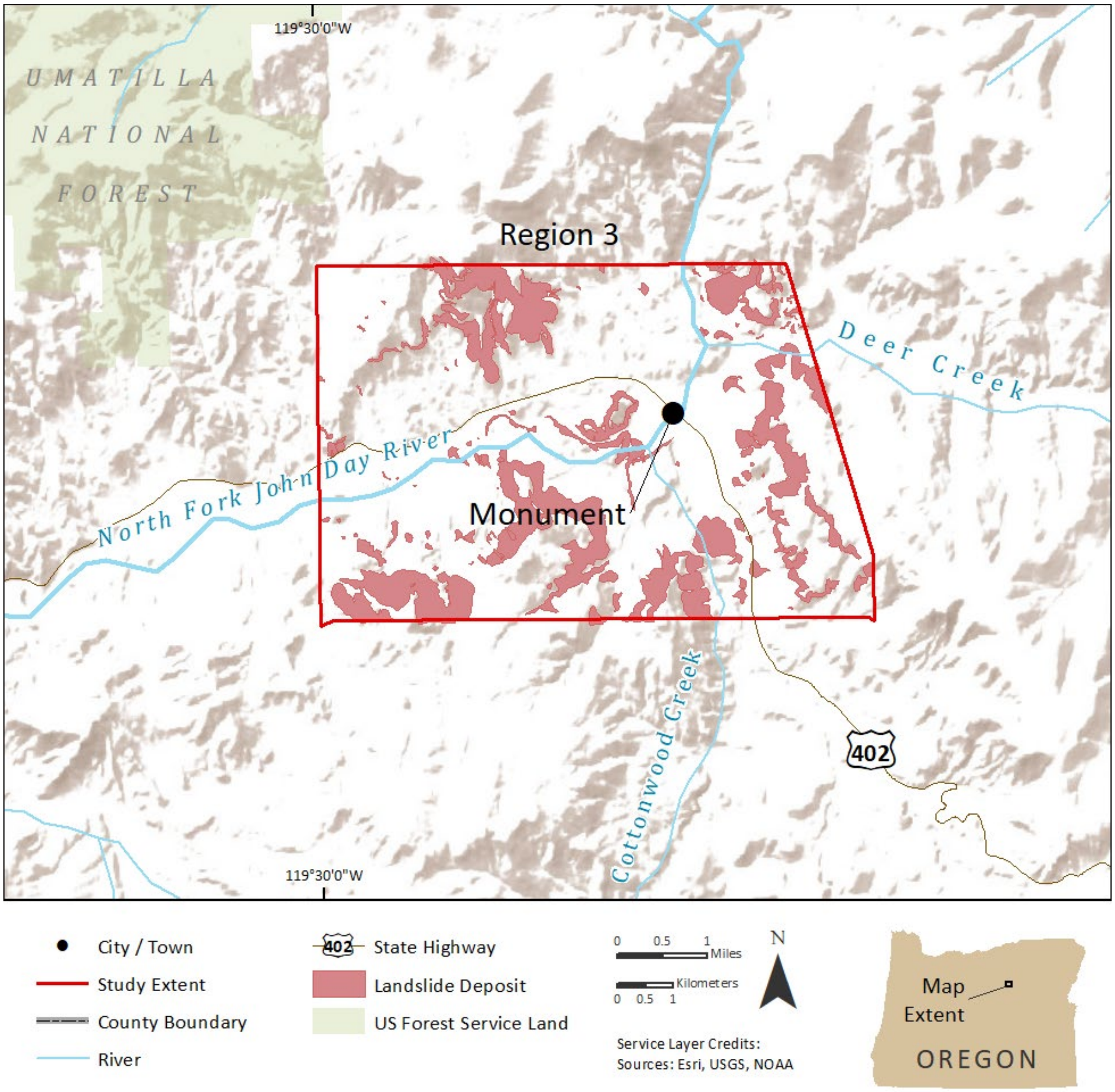


Figure 4-3. Landslide inventory overview map for Region 3. See plate 4 for detailed map data.



4.1.1 Region 1 – Mount Vernon, John Day, Canyon City, Prairie City

Geologic mapping by Thayer (1956), Brown and Thayer (1966a,b), and Walker (2002) and engineering geology by Schlicker and Brooks (1976) in the John Day area delineated extensive landslide deposits along the John Day River between John Day and Mount Vernon (**Figure 2-1**, **Figure 4-1**; Plates 1, 2; Franczyk and others, 2024). Other significant deposits were mapped along Canyon Creek (Schlicker and Brooks, 1976) and Laycock Creek (Brown and Thayer, 1966a) south and southwest of John Day respectively. Mapping during this study inventoried 1,068 landslide deposits in Region 1 (**Figure 4-2,** Plates 1, 2), including a mixture of deep-seated landslides, rockfall, and debris flow deposits.

Similar to Schlicker and Brooks (1976) and Brown and Thayer (1966a), we mapped an extensive belt of deep-seated landslides for ~8 mi (13 km) along the south wall of the John Day River Valley between Little Pine Creek and Mount Vernon (**Figure 4-1**; Plate 1). Landslides on the south wall of the valley are readily identified in 1-meter lidar DEMs and are characterized by hummocky and rolling ground, littered with large, disoriented blocks of Rattlesnake Tuff. These landslides form flat benches between 40 and 470 ft across (12 and 143 m, mean = 181 ft [55 m]), which are blocks within the body of the slide that have rotated from the original hillside slope angle to an angle closer to level. Due to their flat nature, many buildings have been developed atop these benches.

The deposits originated from distinct north-facing rimrock headscarps, which form steep (~30 to 40°) slopes, sometimes resulting in rockfall talus slopes below. The distribution of this deep-seated landslide complex along the south wall of the John Day Valley corresponds with an area where layered sections of Picture Gorge Basalt, Rattlesnake Formation, and Rattlesnake Tuff overlie older Baker Terrane across a major erosional and structural unconformity. The unconformity itself is inclined toward the river valley, forming the north-dipping (22° to 40° N) limb of the E-W-trending Aldrich Mountain anticline (Brown and Thayer, 1966a). The south wall of the John Day River Valley also corresponds with the up-on-the-north hanging wall of the WNW-striking, steeply dipping John Day reverse fault (**Figure 3-1**, **Figure 3-2**).

The prevalence of deep-seated landslides in around the city of John Day is likely caused by a combination of structural dip of the unconformity north toward the river and differences in rock type across the unconformity (**Figure 3-1**, **Figure 4-1**; Plate 1). Landslides are especially common where Picture Gorge Basalt rests on weathered tuffaceous rocks or where the Rattlesnake Tuff has been undermined by deep erosion of poorly consolidated gravels of the underlying Rattlesnake Formation (**Figure 3-1**; Schlicker and Brooks, 1976). Lateral migration of the John Day River across the valley floor over hundreds to thousands of years has also led to river erosion, triggering, and reactivation of the large landslide complexes. Most of these landslides are inferred to be prehistoric (>150 years old) rotational rockslides as they appear eroded and have a subdued or smoothed geomorphology (Plate 1). However, the slide areas are notably steep, and some parts may still be active (Schlicker and Brooks, 1976). A few small, historic landslides that caused damage were described by Schlicker and Brooks (1976) near the mouth of Canyon Creek with the John Day River (**Figure 4-1**; Plate 1). Schlicker and Brooks (1976) reported one instance of property damage due to localized movement within a larger landslide block in the Crisp Heights subdivision, between the Grant County Regional Airport and the mouth of Canyon Creek (Plate 1). Another small landslide was noted on the east wall of Canyon Creek, just south of the city of John Day water tank. Within the city of John Day, along West Main Street (U.S. Hwy 26) ~ 1 mi (1.6 km) west of the mouth of Canyon Creek, there are several historic rockfalls (Plate 1). These historic rockfalls are located within older large deep-seated landslide deposits and may be related to oversteepening and reactivation of the landslide toe due to road construction or erosion by the John Day River.

A comparable set of deep-seated landslides was recognized by Schlicker and Brooks (1976) on the north side of the John Day River Valley from the western city limit of John Day to the intake of Trowbridge Ditch on the east (**Figure 4-1**; Plate 1). Our mapping confirms their prior work and expands their mapped deposits to cover a greater area. Landslides on the north wall of the valley are characterized by hummocky and rolling ground, littered with jumbled blocks of basalt and tuffaceous sedimentary rocks. Depressions on the surface are disconnected and no discernible drainage system developed on the landslides. Large south-facing landslide deposits lie north of the John Day fault and parallel the dip slope of the south-dipping Picture Gorge Basalt (12°S), Dinner Creek Tuff, and interbedded sedimentary rocks that unconformably overly the older Eocene Clarno Formation and Baker Terrane in this area (**Figure 3-1**, **Figure 3-2**, **Figure 4-1**; Plate 1).

Landslide deposits are also mapped along Laycock Creek southwest of the city of John Day from the mouth at the John Day River, south to the confluence with Fall Creek and along Canyon Creek between Canyon City and Berry Creek (**Figure 4-1**; Plate 1). In these deeply incised drainages, steep valley walls are associated with large, bench-forming deep-seated landslide deposits, rockfall talus, and small- to medium-sized debris flow fans. Slopes in these drainages are as much as 45° and expose mixed-lithology and structurally complex bedrock of the Baker Terrane or are variably covered by thin accumulations of colluvial material (volcanic ash, clay, cobble gravel) (Schlicker and Brooks, 1976). A series of rockfall talus deposits and small- to medium-sized debris flow fans were also mapped in the higher ridges of the Strawberry Mountains (**Figure 4-1**; Plate 1). This portion of the map area is characterized by steep slopes and is underlain by the Baker Terrane. Landslides in these drainages and in the Strawberry Mountains likely result from the combination of complex geologic and structural relationships, deep incision by stream drainages, critical steepness of canyon slopes, and input of moisture into the landscape. Most landslide deposits in the Laycock and Canyon City drainages are inferred to be prehistoric (>150 years old), based on surface morphology. A few of the rockfall and earthflow deposits are inferred to have occurred in historic time (<150 years old).

There are numerous parallel incised creeks between Mount Vernon and John Day, including McClellan, Harper, Riley, Ingle, Hadson, Laycock, Luce, and East Fork Luce creeks, and several smaller drainages, where we mapped many debris flow fans (**Figure 4-1**; Plate 1). Their geomorphic expression in 1-meter lidar DEMs is muted, leading us to interpret prehistoric ages of activity. Debris flows are the likely dominant style of erosion in this part of study Region 1, however they may be infrequent and occur only under very intense or long-duration rain or rain-on-snow events. Damon and Clark Creek along the north wall of the John Day River Valley, in the northwest corner of Region 1, have a similar concentration of debris flow fans, with very few other landslide types (**Figure 4-1**; Plate 1).

East of the city of John Day, the John Day River Valley narrows, with bedrock cliffs and terraces flanking the north and south sides (**Figure 4-1**; Plates 1 and 2). There are rockfall and debris flow deposits along the steepest and highest portion of these slopes, with landslide density lessening toward Prairie City (Plate 2). The lack of landslides along the valley walls in this area is due to the strong Picture Gorge Basalt and Dinner Creek Tuff, which hold near-vertical cliff faces. We do see intermittent rockfall talus and small debris flow fans below gullies (**Figure 4-1**; Plate 2).

As noted in **Section 3.2.1,** a set of scarps identified along the north face of the Strawberry Mountains, may indicate an active fault, with the latest stages of fault movement estimated to have occurred ~1,200 to 1,400 years ago (Dunning, 2023). Local crustal earthquake shaking associated with such a fault rupture could trigger new landslides in the area, including rockfall and shallow slides, as well as reactivating existing deep-seated landslides. We suggest that further research on the local seismic hazard and associated coseismic landslide hazard is warranted.

4.1.2 Region 2 – Dayville to Sheep Rock

Brown and Thayer (1966b) and Thayer and Brown (1966) mapped several large landslide deposits originating from the Mascall Formation, west of Dayville (**Figure 2-1**, **Figure 3-3**). White (1964) did not map any landslide deposits within Region 2 but did delineate many large landslide deposits originating from the John Day Formation or initiating at the contact between the John Day Formation and overlying Picture Gorge Basalt, north of Picture Gorge (**Figure 3-3**). Mapping during this study inventoried 303 landslide deposits in Region 2 (**Figure 4-2,** Plate 3).

Near Dayville, large, southwest-directed, deep-seated rotational landslides are mapped where the Rattlesnake Tuff overlies the southwest-dipping Mascall Formation on the north side of the John Day Valley (**Figure 3-3**, **Figure 4-2**; Plate 3). Similar large deep-seated landslides are also mapped antithetic to the southwest dip slope where the Rattlesnake Tuff overlies the Mascall Formation on the south side of the valley (**Figure 3-3**, **Figure 4-2**; Plate 3). These landslides originate near the top of the ridges both to the north and south of John Day River and extend all the way to the toe of the slope along the John Day River. Northwest of Dayville, moving toward Picture Gorge, deep-seated landslides become scarce; instead, very small alluvial fans predominate within gullies and small gorges (**Figure 3-3**, **Figure 4-2**; Plate 3). Picture Gorge is a steep, narrow gorge with rockfall talus slopes blanketing the walls and debris flow fans at the toes of the slopes. Both rockfall and debris flows are fast-moving and can be life-safety concerns, especially when near infrastructure like roadways or buildings. Large rockfall talus slopes are associated with steep cliffs within the Picture Gorge Basalt (**Figure 4-2**; Plate 3).

4.1.3 Region 3 – Monument

Wilcox and Fisher (1966) mapped only three small landslide deposits near Monument: one along the North Fork John Day River, one adjacent to Cottonwood Creek, and one located high on a slope east of Cottonwood Creek (**Figure 2-1**, **Figure 3-5**). These landslide deposits generally coincided with the contact between the John Day Formation and the Picture Gorge Basalt (**Figure 3-5**). Using our updated techniques, we identified 136 landslide deposits in the Monument area, mostly within talus- and colluvium-mantled slopes high on the landscape to the north, south, and east of the town (**Figure 4-3;** Plate 4). Talus from historic and active rockfall blankets the steep slopes coming off the high plateaus above Cottonwood Creek and the North Fork John Day River (**Figure 4-3;** Plate 4). These broad talus sheets are prevalent within flow-on-flow successions of Picture Gorge Basalt, where differential weathering between erosion-resistant and bench-forming solid flow cores alternates with more easily eroded lava flow contacts. We also identified numerous debris flow fans within drainages sourced from steep slopes around Monument (**Figure 4-3;** Plate 4). Larger rotational, deep-seated landslides are observed along the contact between the John Day Formation and Picture Gorge Basalt to the northeast and southwest of Monument (**Figure 4-3;** Plate 4).

4.2 Recent Wildfires and Debris Flow Potential

This study did not focus specifically on mapping post-fire debris flows. However, the debris flow fans mapped in this study can be used as an indicator of where debris flows have occurred in the past and where fire-related debris flows may occur in the future. In 2015, the Canyon Creek Fire burned areas south of John Day, along Canyon Creek Gorge and encroached on the towns of Canyon City and John Day (**Figure 2-1**, **Figure 4-1**; Plate 1). Researchers with the U.S. Forest Service (USFS) Burned Area Emergency Response (BAER) and a subsequent U.S. Geological Survey (USGS) Post Wildfire Debris Flow Hazard assessment analyzed the post-wildfire debris flow potential for the Canyon Creek area (U.S. Geological Survey Post-Fire Debris-Flow Emergency Assessment, 2015; Plate 1). The USGS modeled the probability for debris flows in the first five years following the fire as 0 to 20% for most watersheds/stream segments, with a few watersheds/stream segments having a 20 to 40% likelihood (U.S. Geological Survey Post-fire Debris Flow Emergency Assessment, 2015). No significant debris flows following the Canyon Creek Fire have been confirmed.

Three other nearby areas affected by wildfires have been assessed by the USGS Post-fire Debris Flow Hazard Team: the 2016 Rail Fire, 2019 Cow Fire, and 2021 Black Butte Fire. These fires occurred in the mountain ranges immediately to the south of the John Day River and over the divide into the prairies and gulches near the South Fork of the Malheur River. In the majority of the USGS post-fire assessments, researchers modeled a low likelihood for debris flows, with the Black Butte Fire having a few high probability areas in watersheds and stream segments.

5.0 DISCUSSION

5.1 Landslide Density in Grant County

Burns and others (2016) concluded the following relative landslide density classes in Oregon: Low < 7%, Moderate 7% to 17%, and High > 17%. Burns and others (2016) also examined all cities across Oregon using the landslide mapping as of 2015 and found a range from 0% to ~75% with a mean of 3% and a standard deviation of 10%. In this study, the combined three mapped regions in Grant County have an overall landslide density of 8%, which is a low to moderate in the relative hazard classification of Burns and others (2016) (Plates 1, 2, 3, 4). Grant County landslide coverage can be compared to previous DOGAMI landslide studies in Oregon (**Table 5-1**). However, landslide density can vary significantly depending on the location and size of the area examined. The cities within the study area have the following coverage of landslides: 35% of John Day, 16% of Dayville, 11% of Canyon City, 1% of Monument, 2% of Mount Vernon, and 0% of Prairie City. These numbers indicate a relatively higher hazard within the city of John Day than in other cities/urban areas of Grant County.

In Oregon, landslides have caused damage to houses, infrastructure, and sometimes entire neighborhoods (Burns and Mickelson, 2013). Limited landslide insurance is available, and it is common for damage and losses to be borne by the property owner or result in litigation between neighbors. Thus, pre-disaster mitigation and risk reduction are preferred paths.

Table 5-1. Landslide density reported from past studies in Oregon.

Study	Percent Landslide Coverage	Relative Overall Hazard Classification
Grant County (this study)	8% (cities range from 0% to 35%)	Low to Moderate
North Fork Siuslaw Watershed (Burns and others, 2012)	37%	High
Astoria (Burns and Mickelson, 2013)	27%	High
Coastal Curry County (Burns and others, 2014)	25%	High
Clatskanie (Mickelson and Burns, 2012)	25%	High
Bull Run Watershed (Burns and others, 2015)	15%	Moderate to High
Tillamook (Calhoun and others, 2020)	13%	Moderate to High
Eugene-Springfield (Calhoun and others, 2018)	6%	Low to Moderate

5.2 Landslide Risk Reduction Priorities and Pathways

The primary purpose of this publication is to help communities become more resilient to landslide hazards by providing new, detailed landslide inventory maps and establishing community-driven action items to reduce the risk of loss from future landslides. Landslide risk reduction strategies vary depending on the type and size of landslide hazard. Mitigation of landslide hazards may require cooperating efforts from both private and public entities (e.g., city, county, federal) as landslides can cover multiple properties or may even cross entire neighborhoods. This is often the case for deep-seated rotation slides like those seen in the city of John Day (Plate 1).

Landslide risk reduction strategies described in this report are based upon published recommendations and community priorities established in three meetings held in July 2021, February 2022, and March 2022, between DOGAMI, the Oregon Department of Land Conservation and Development (DLCD), and stakeholders from Mosier, The Dalles, John Day, and Grant and Wasco counties (Sears and others, 2019; Calhoun and others, 2020; Burns and others, 2023; Washington Geological Survey and Oregon Department of Geology and Mineral Industries - A Homeowner's Guide to Landslides). Broad consensus among participating stakeholders identified publicly accessible and usable lidar-based landslide inventory mapping as the first priority for landslide risk reduction and mitigation efforts. This report (DOGAMI OFR O-24-10) and Burns and others (2023) fulfill the landslide inventory mapping request and summarize risk reduction options. Although stakeholder meeting participants had a variety of priorities, action items around awareness, land use planning and regulation, and emergency response were of chief importance among all stakeholders. Awareness, planning and regulation, and emergency response are discussed further in **Sections 5.2.2**, **5.2.3**, and **5.2.4** The following three topics were also at the top of stakeholders' prioritized lists:

- Geotechnical analysis – the process of investigating the physical and chemical properties of soils and rock;
- Public information – information that is disclosed, disseminated, or made available to the public by a public sector institution; and
- Land use codes – a planning implementation tool of a community's comprehensive plan that may include zoning, regulations, fees, and public hearing processes.

The full list of prioritized landslide risk reduction and mitigation strategies, categorized by *first*, *high*, and *long-term* priorities, is captured in the following **Section 5.2.1.** This list is a beginning point, and if actions from it are implemented at the local level, this will result in landslide risk reduction.

5.2.1 Prioritized List of Landslide Risk Reduction and Mitigation Strategies

First Priority

- Landslide inventory mapping: DOGAMI is to create and make modern lidar-based landslide inventory maps, and supporting digital data, available for public use and decision-making in Wasco County and three regions of Grant County (Plates 1, 2, 3, 4). Publication of this report (DOGAMI OFR O-24-10) and Burns and others (2023) completes this task.

High Priority for New Construction

- Geotechnical analysis: For new construction, it is recommended that the Grant County Planning Review process use DOGAMI landslide inventory mapping products to determine building requirements; county codes should include site-specific geotechnical analysis or evaluation; landslide inventory maps should be used to determine whether further geologic studies are needed for a development proposal; landslide inventory maps should be used to determine when to require geotechnical evaluations for new construction using a clear and objective method.

- Land use codes: Define how and when geotechnical analysis requirements apply to new construction. Scale the requirements for geotechnical review for new construction based on the level of risk from landslide hazards. Develop a risk assessment matrix for new development, like that used by the City of Salem, Oregon. Salem scores risk using environmental factors and activity levels to rank landslide susceptibility. The scores determine the level of geotechnical review required. For example, the construction of an outbuilding may require a less detailed site assessment than would a residence or an essential building like a hospital. Landslide risk scores in the Salem code also incorporate mapped earthquake-induced and water-induced landslide susceptibilities (Harvey and Peterson, 1998, 2000; Hofmeister and Wang, 2000; Hofmeister and others, 2000, 2002). https://library.municode.com/or/salem/codes/code_of_ordinances?nodeId=TITXUNDECO_UDC_CH810LAHA
- Land Use Codes: Use questions about construction methods, in particular cut and fill earth work, to determine what level of study is required.
- Land Use Codes: Update codes (land use, stormwater, building, grading, and erosion control) to include grading and tree removal restrictions in existing landslide areas and on already developed lots. Require revegetation as part of conditions of approval for new construction on landslide hazard areas.
- Land Use Code: Grading – For existing structures built on landslides, consider grading and fill restrictions to avoid reactivation. Useful examples could include thresholds for the amount of grading (e.g., >4 ft (1.3 m) cut and fill requires geotechnical analysis) or use of preexisting thresholds in engineering guidelines. Also, developers might consider population density and parcel size (e.g., agricultural land use) when determining thresholds or grading code language.
- Land Use Code: Surface water – For new and existing structures on landslides, municipalities should develop guidelines for water management to slow water movement on the surface and allow slow infiltration of stormwater into the soil, avoiding concentration of flows or accumulation of infiltrated water in landslide areas. Examples and illustrations may be helpful to illustrate code language as well as for recommendations.
- Land Use Permitting: For new construction, use site-specific engineering reports to develop conditions of approval and specific mitigation strategies for the site.
- Awareness: For existing structures on landslides, provide information to property owners about how landslides can be reactivated and how to reduce the risk.
- Awareness: Communicate with private property owners about the multiple layers of planning and building rules.
- Awareness: Communicate information to the public about landslide hazards and how to address risks.
- Resources to Property Owners: Provide information on resources and funding sources to property owners to allow them to become educated about the risk and make decisions for themselves.
- Advice to Property Owners: Provide advice to property owners with existing structures located on landslides to help them reduce risk. For example, share maps so they can see the location of the hazard compared to their structure; advise property owners to contract for a

geotechnical report, so they know what to do to mitigate the risk. For example, a geotechnical expert can evaluate if they need to control water or if they need to build a retaining wall.

- City and County Staff Capacity: Provide guidelines for geotechnical reports to ensure completion and publication. Support staff capacity to review geotechnical reports through in-house training and/or using other resources such as another department's skillset, or another county's knowledge.
- City and County Staff Capacity: Increase the capacity of local staff to provide technical information to citizens; develop relationships between local planners and DOGAMI staff. Citizens need to be able to easily call on the experts to answer questions about landslide inventory mapping and technical aspects of risk reduction.
- City and County Staff Capacity: Increase capacity of local staff to address administrative aspects of risk reduction activities, such as the drafting of ordinances or ordinance updates.
- Self-Certification: Develop a method of self-certification of landslide risk reduction efforts, like wildfire defensible space self-certification.

Long Term

- Insurance: Establish definitions to help insurance companies protect structures, by establishing a set of parameters for rating risk at the structure level.
- State Level: State building codes could include precautions for landslide areas.

5.2.2 Awareness

One outcome of this publication is to help public officials communicate and make the public aware of the roles they can play in readiness for hazardous landslide events and risk reduction. Without a clear understanding of the potential hazard, there is little incentive for the public to work on risk reduction. To increase public awareness resulting from landslide inventory mapping in Grant County, this publication is accompanied by a streamable Esri ArcGIS™ StoryMap (https://storymaps.arcgis.com/stories/0ba26f975c8342a7839cbb4b83339a3c). A StoryMap is a web-based application used to create and share a memorable multimedia digital experience, where stakeholders can engage map content through a combination of text, images, animation, and video.

Additional visibility will be given to this work by adding the mapping data to future scheduled updates of SLIDO and into DOGAMI's interactive SLIDO web map (Franczyk and others, 2024). Informational fact sheets are also available on the DOGAMI website, with the purpose to educate the public about activities and actions that can be taken to reduce landslide risk. These include the DOGAMI fact sheet *Landslide Hazards in Oregon* (https://pubs.oregon.gov/dogami/fs/landslide-factsheet.pdf) and the *Homeowners Guide to Landslides* (Washington Geological Survey and Oregon Department of Geology and Mineral Industries).

City, county, neighborhood, and other local community leaders can implement awareness campaigns to educate neighborhoods, businesses, and individual homeowners about the locations of hazards and how to reduce risk. For example, homeowners can unintentionally increase their own risk through discharge of stormwater onto slopes that are susceptible to landslides. Landslides resulting from this type of discharge were observed after major landslide events in Oregon in 1996 (Burns and others, 1998). Knowing which slopes are susceptible to landsliding can provide the impetus to switch from unknowingly increasing risk to actively reducing risk through cost-effective methods (e.g., extending stormwater discharge pipes beyond the high hazard zone).

When development already exists on land now identified as a large deep landslide, neighborhood-scale educational efforts may be warranted. A public awareness campaign could be undertaken to educate homeowners and landowners about the landslide hazard and risk in their areas and to prioritize future risk reduction actions. Residents on mapped landslide areas could participate in a neighborhood risk reduction program where all affected entities work together to help reduce the overall risk.

5.2.3 Planning and Regulation

Land use planning and regulation is an effective method to work on risk reduction and can be initiated in a variety of ways using the maps and data produced in this project. Two types of planning that engage leaders, residents, and landowners include: 1) focus on future development; and 2) focus on existing infrastructure. A joint publication from DLCD and DOGAMI entitled *Preparing for Landslides: A Land Use Guide for Oregon Communities* (Sears and others, 2019) identified various land use tools and strategies to help communities reduce potential losses from landslides. Landslide inventories like the one produced here for Grant County are essential in long-term planning, such as urban growth boundary expansions and comprehensive plans, which most cities and counties use to identify community goals. Planning can result in the avoidance of proposed development in high hazard areas and even public buyouts in very high or life-threatening hazard areas. Additional planning efforts can focus on maintenance of road-related grading, repeated asphalt overlays, or expanding roadways. Keeping specific records of maintenance practices is a good way to track risk reduction effects.

Stormwater runoff routing must be done carefully so that water is not directed onto or into landslide hazard areas. Planning of the public stormwater system, for example, should include location of culvert outlets to evaluate potential impacts of any discharge onto landslide hazard areas. Planning staff could implement private landowner education to promote awareness and potentially gain landowner partnerships in the control of stormwater.

Connecting landslide inventory maps and data to regulations such as development codes and ordinances can be very effective at limiting future loss of property and life due to landslides. Such regulations require consulting landslide hazard maps when identifying areas for proposed development and limiting or preventing grading or other activities that may increase landslide risk in high hazard areas. Examples of code are provided by Sears and others (2019). These regulations also typically include requirements to perform site-specific geotechnical analysis and mitigation design. Regulations can also target grading-related landslides. For instance, relatively shallow grading activities can unintentionally cause slope failures, especially in conditions where existing landslides may be only marginally stable. Placing debris or soil in the wrong location, for example near the heads of existing landslides, can also unknowingly cause slope failure simply by adding more weight to the slope.

Developing appropriate regulations or conditions of approval for land use permits in landslide hazard areas involves clear guidelines about when more stringent conditions apply based on the use proposed, who can conduct a geotechnical analysis, and how a local planner can determine that such an analysis contains all the needed information.

In summary, site development measures that can reduce the risk of landslide include:

- Limit grading, excavation, or filling;
- Minimize or eliminate irrigation;
- Intercept and collect surface water on and above the area to reduce natural water infiltration;
- Collect surface water runoff from impervious surfaces (i.e., roof downspouts, streets, and driveways) and discharge into a suitable receptacle;

- Minimize onsite storm water retention and infiltration within the area; and
- Require detailed site-specific evaluation prior to development or grading.

Care should be taken when developing land use codes to ensure that they provide clear and objective standards for housing in compliance with SB 1051 (amended Oregon Revised Statute (ORS) 197.307(4)). https://library.municode.com/or/salem/codes/code_of_ordinances?nodeId=TITXUNDECO_UDC_CH810LAHA

5.2.4 Emergency Response

We recommend that neighborhoods and communities create landslide emergency response plans before a landslide disaster. One component of the plan could include identifying local engineering geologists and geotechnical engineers and establishing working relationships with them so they can be asked to evaluate areas of interest during and/or directly after a landslide disaster. Their evaluations would help determine what actions to take immediately following the event, such as if a neighborhood should be evacuated or if the area is stable enough to perform an emergency response.

It is also important for the public to be notified during times of increased landslide potential. Oregon currently has a landslide warning system operated in partnership by the National Oceanic and Atmospheric Administration National Weather Service (NWS), DOGAMI, ODOT, and the Oregon Department of Emergency Management (Burns and Franczyk, 2021). NWS initiates the system by sending out landslide watches, and the state agencies help citizens become aware of the heightened potential for landslides. In the future, this information could be streamlined to the local municipalities (counties and cities) via RSS feeds and live web pages. During these periods of increased landslide potential, the public could then access hazard maps to find locations where this potential is most likely.

6.0 CONCLUSIONS

The primary purpose of this publication is to help communities become more resilient to landslide hazards by providing new, detailed landslide inventory maps and establishing community-driven action items to reduce the risk of loss from future landslides. Although we cannot predict when or where the next landslide will occur in Grant County, knowing where they have occurred in the past provides valuable insight into which areas may be prone to failure in the future. This study provides the most comprehensive evaluation to date of past landslide activity for three regions within Grant County, holding the centers of population and infrastructure.

There are a wide variety of landslide types within Grant County, including a mixture of deep- and shallow-seated landslide deposits, debris flow fan deposits, and rockfalls (Plates 1, 2, 3, 4). Prior to this study, SLIDO contained 81 mapped landslide deposits within the three study Regions: 72 deposits in Region 1, six in Region 2, and three deposits in Region 3. New landslide inventory mapping presented here delineates 1,507 landslides, including 1,068 in Region 1,303 in Region 2, and 136 in Region 3. Of these mapped landslides, 398 are deep-seated, 718 are debris flow fans, 259 are rockfalls, and 132 are shallow-seated or unclassified (Plates 1,2,3,4). The number of mapped landslides is significantly more than was captured in previous studies, with a much greater level of detail and certainty. Improvements in the landslide inventory primarily resulted from mapping with the intent to identify landslide deposits and features, while using 1-meter lidar DEMs and derivatives as basemaps.

Many prehistoric (>150 years), deep-seated, rotational landslides line the John Day River Valley between Mount Vernon and John Day. Debris flow fan deposits are found throughout the study area, predominantly at the base of steep channels and valley walls. Rock falls are located mostly along the steep basalt gorge area of Picture Gorge and in the upper plateau and cliffs high above Monument. The activation, reactivation, and distribution of landslides in Wasco and Grant counties is related to geologic conditions such as rock strength, structure, and contacts, but also to steep slopes, accumulations of colluvium, deep valley incision, precipitation, infrequent but very intense or long duration rain or rain-on-snow events, earthquake shaking, certain human activities, or some combination of these factors.

Landslide risk reduction discussions with the public in Grant County identified specific actions to encourage public awareness, land use planning and regulation, and emergency response. Awareness of landslide hazard and risk is increased in Grant County through release of this publication and Esri ArcGIS™ StoryMap, and inclusion of the new data in scheduled updates of SLIDO. This information allows the public and community leaders to implement awareness education campaigns about landslide hazards and to prioritize future risk reduction actions. Land use planning and regulation is an effective method to work on risk reduction and can be initiated in a variety of ways using the maps and digital spatial data produced in this project. Targeted planning can result in avoidance or alteration of development in high hazard areas. Connecting landslide inventory maps and data to regulations such as development codes and ordinances can be very effective at limiting future loss of property and life due to landslides. Results of our study and greater experience statewide also underline the benefits of developing emergency response plans and public engagement before a landslide disaster, and the critical need of early notification during times of increased landslide potential.

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