ROCK AGGREGATE RESOURCE INVENTORY MAP OF LEWIS COUNTY, WASHINGTON

by Daniel W. Eungard

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Contents

FIGURES

TABLES

MAP SHEET

Rock Aggregate Resource Inventory Map of Lewis County, Washington

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INTRODUCTION

Background

Lewis County is located in western Washington and covers a 26- by 90-mile area between Pe Ell and the crest of the southern Cascade Range (Fig. 1). As of the 2010 census (U.S. Census Bureau), the population of the county was approximately 75,455 and was concentrated near the cities of Centralia and Chehalis. Lewis County ranks as the 16th most populated county in the state.

Washington State ranks as the 10th largest producer of sand and gravel aggregate by tonnage nationwide, annually providing 28.1 million tons of material valued at approximately 214 million dollars as of 2012 (Bolen, 2012). Lewis County produces a moderate amount of this aggregate, which is used predominantly for road construction and maintenance of Interstate 5 (I-5) and the cities of Centralia and Chehalis.

In July of 1990, the state legislature enacted the Growth Management Act (RCW 36.70A) to protect the environment, promote sustainable economic development, and ensure the health, safety, and high quality of life enjoyed by residents of this state. Lewis County is an area where aggregate resources could be threatened by uncoordinated and unplanned growth. This publication was written to aid county planners and other local officials with planning urban development and the reservation of identified resources—actions that will ensure a stable supply of aggregate for development and economic growth during the next 25- to 50-year planning cycle.

Intended Readership

The primary use of this inventory is to help county planners and local officials refine comprehensive plans and other zoning determinations. It will also aid legislators and other policy makers in assessing the importance of sand, gravel, and quarried bedrock resources, most of which are nonrenewable. The study will benefit engineers, transportation departments, and industry by identifying geologically feasible sites for mine development.

Primary Products

This inventory consists of the following products:

- A report that provides an overview, geologic context, and summary of aggregate resources (this pamphlet).
- A map sheet that shows the probable extent of bedrock and gravel resources and the locations of active mines, borrow pits, depleted mines, and large proposed mines (Map Sheet).
- A glossary of terms used in this report (Appendix A).
- A complete discussion of the methods used in this study (Appendix B).
- Brief descriptions of geologic units known to contain aggregate resources in Lewis County (Appendix C).
- Tabular data that contains the location, thickness, and quality of sand, gravel, and bedrock resources on the basis of well logs, mine permit files, and aggregate source testing (companion Microsoft Excel file).

Accuracy of Estimates

This report estimates the amount of construction aggregate within Lewis County that is available using existing technology under current market conditions. Over- or under-estimation of aggregate resources can result from

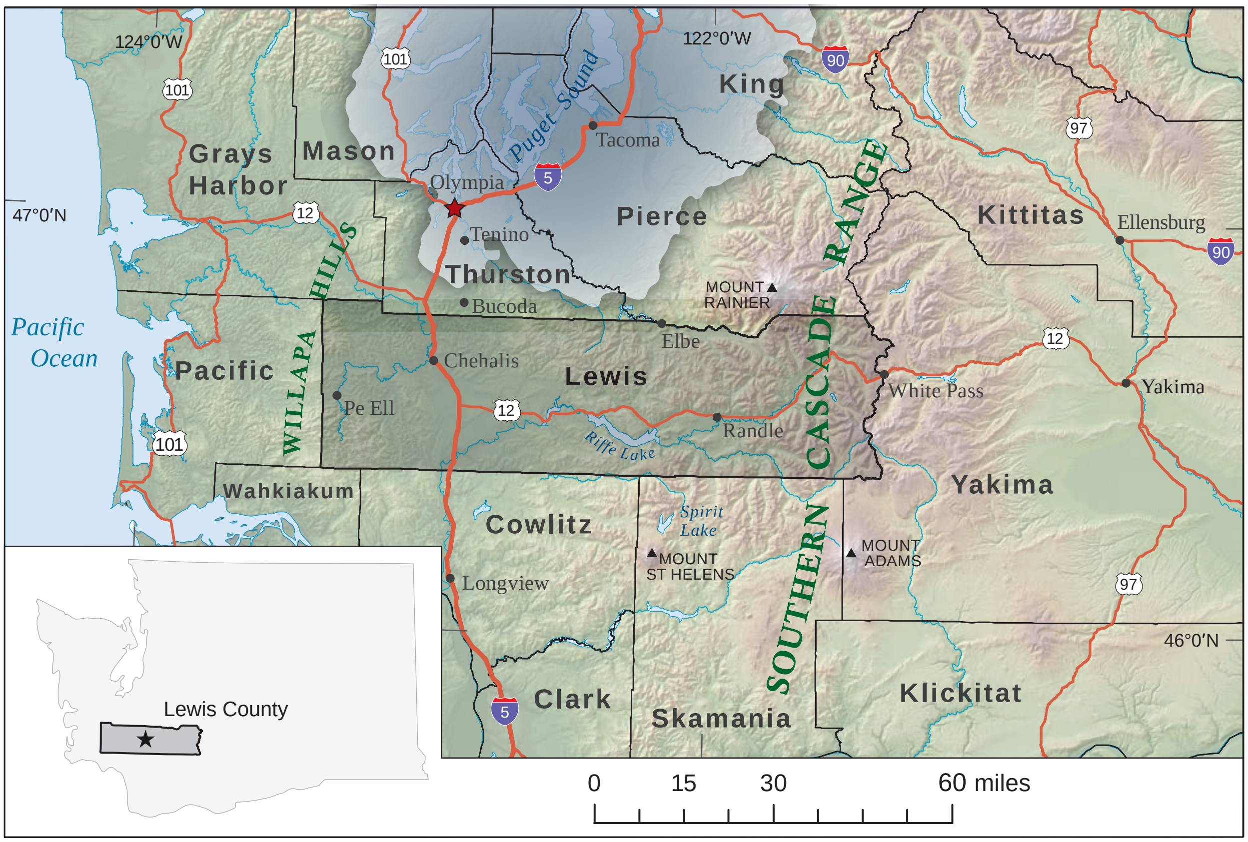

Figure 1. Lewis County covers an area from the Willapa Hills to the crest of the southern Cascade Range. Glacial ice advanced as far south as Tenino during the late Pleistocene; its maximum extent is shown in light blue.

factors such as changing land-use restrictions, unanticipated shallow bedrock beneath surficial gravel, diminishing rock quality with depth, areas of unmapped thick overburden, and lateral geologic variation. Similar studies have shown that in most cases it is more likely to overestimate the amount of recoverable aggregate (AES, 1999).

Threshold of Significant Resources

Because this study is an aid to land-use planning, we inventoried only those resources deemed significant to the long-term economic health of the region. Therefore, we restricted our investigation to those resources that exceed the following threshold criteria (see detailed description in *Appendix B*):

- The thickness of the sand and gravel or bedrock deposit must exceed 25 feet.
- The area of the deposit exposed at the surface must exceed 160 acres and have a minimum map distance of 1,500 feet, or the reserves must exceed 13.9 million tons. Exceptions may include unusually thick deposits or resources of special local importance that have consistently yielded high-quality aggregate.
- The ‘stripping ratio’ (ratio of overburden to resource) must be less than one to three (1:3).
- The strength and durability of the rock must meet the Washington State Department of Transportation (WSDOT) minimum specifications for hot-mix asphalt-wearing course, a rock product used to construct asphalt roads (Table 1).

In some markets, a lack of high-quality gravel and bedrock may force producers to mine lower quality deposits. Homes and infrastructure constructed with weak gravel or bedrock are likely to have shorter life cycles than those constructed with higher-quality aggregate. Although we have not inventoried these lower quality deposits, the tabular data for this publication will serve as a guide to the locations of some poor or uncertain quality resources and those buried below thick overburden layers. These resources may become more attractive under future market conditions.

Table 1. Aggregate specifications established by WSDOT (2014) for laboratory test results of hot-mix asphalt-wearing course. This investigation establishes threshold aggregate quality criteria using these values.

Laboratory test	Hot-mix asphalt-wearing course	Portland cement concrete
LA abrasion	<30%	<35%
Degradation factor	>30%	>30%

Scope of Deposits Inventoried

We have inventoried all deposits in the county that meet the threshold criteria without consideration of environmental impacts or land-use conflicts that may be involved in permitting or extracting these resources. Therefore, maps of environmentally sensitive areas and land-use status are necessary to obtain a complete picture of available aggregate within the county. Those deposits that lie within Mount Rainier National Park, Mount St. Helens National Volcanic Monument, Goat Rocks Wilderness, Tatoosh Wilderness, and William O. Douglass Wilderness were not included in the inventory because they have federal protection that restricts commercial development.

Previous Aggregate Reserve Studies

Lewis County has few aggregate studies. Most studies initially focused on the extent of coal reserves (for example, Snavely and others, 1958). McKay and others (2001) and Lingley and Manson (1992) both provided a statewide inventory of aggregate mines based on Washington Division of Geology and Earth Resources (WADGER) permit files. Norman and others (2001) mapped a small portion of south-central Lewis County for aggregate resources of the Mount St. Helens 1:100,000-scale quadrangle. A recent study by Shannon and Wilson (2014) provided the locations, testing data, and overall quality of aggregate within 40 miles of Pe Ell for a proposed dam site. This study incorporates the testing data from Shannon and Wilson (2014) and modifies some of the designated resources from Norman and others (2001) on the basis of additional data. Pacific Lutheran University School of Business (PLUSB, 2003) provided a market analysis for the Washington aggregate industry. We used their methods with updated census data for the present study.

GEOLOGY OF AGGREGATE RESOURCES IN LEWIS COUNTY

Numerous igneous intrusions, volcanic lava flows, and glacial processes created remarkably large volumes of sand, gravel, and bedrock in Lewis County that have moderate to excellent characteristics for use in construction aggregate. Large gravel mines in the county were developed to supply aggregate for use in portland cement concrete or asphaltic cement concrete during the construction and continued maintenance of I-5 and for the cities of Centralia and Chehalis. Small mines in the foothills and mountains of the Cascade Range and Willapa Hills were developed to serve the needs of the forest-products industry. These small mines typically produce aggregate from volcanic andesite or basalt. The widespread distribution of these igneous rocks constitutes an enormous volume of resources. However, because the cost of transport doubles for every 25 miles traveled (PLUSB, 2003), and these resources are generally in sparsely populated regions, they will likely remain uneconomic for some time.

Sand and Gravel Geology

Deposits from ice-age continental and alpine glaciers provide the source for more than half of the large sand and gravel resources in the county. Between 15,000 to 13,500 years ago, during the Vashon Stade of the Fraser Glaciation, a large sheet of ice called the Puget lobe advanced from the north and covered the entire Puget Lowland. The glacier advanced as far south as Tenino (Fig. 1), just north of Lewis County (Walsh and others, 2003). The Puget lobe deposited abundant sand and gravel near Centralia as glacial outwash. Additional glacial material was deposited along the Cowlitz River valley from alpine glaciers that flowed from Mount Rainier. Modern river deposits, known as alluvium, also constitute a significant sand and gravel resource in the county.

Sedimentary processes related to the Vashon ice sheet resulted in deposition of two layers of potential construction aggregate separated by a non-commercial clay-rich layer. The lowest layer is called 'advance outwash' (unit Qga) and is commonly suitable for finer-grained aggregate. Advance outwash was deposited by glacial streams many miles from the front of the glacier as it advanced south.

As the Puget Lobe advanced to its southernmost extent, silt and clay were shed from the glacial front and flowed over the advance outwash, covering it with glacial till (Weigle and Foxworthy, 1962). Till, also known as ‘hardpan’, is a mixture of unsorted clasts of many rock types supported in a compact matrix of clay, silt, and sand that is unsuitable for construction aggregate.

The most important sand- and gravel-producing unit in Washington is called ‘recessional outwash’ (unit Qgo) and formed when the Puget lobe receded northward near the end of the Vashon Stade of the Fraser Glaciation (about 14,000 years ago). Streams from the retreating ice flowed down the Chehalis and Skookumchuck River valleys, depositing a layer of sand, gravel, and boulders. In Lewis County, recessional outwash is mostly composed of gravel and contains volcanic clasts from the Cascade Range (Weigle and Foxworthy, 1962) with fewer granitic clasts from British Columbia (Armstrong and others, 1965). This generally clean and durable gravel is used in a variety of high-quality rock products. The overburden above these deposits may be wind-blown silt (loess), modern alluvium, and (or) peat.

Numerous alpine glaciers from Mount Rainier flowed down the Cowlitz River valley to the south-central part of the county, near the town of Vader. The alpine glaciers deposited material along the sides of their confining valleys and on the valley floors during their retreat. These glaciers have deposited till and outwash along the Cowlitz River during at least four major episodes between ~350,000 to 14,000 years ago. These deposits form distinctive terraces (Weigle and Foxworthy, 1962; Crandell and Miller, 1974). Alpine glacial deposits are a major portion of the sediment in the Cowlitz and Chehalis river valleys. Weathering in these sediments ranges from relatively minor to severe and impacts their aggregate quality.

Streams and rivers have eroded and redeposited older glacial sediment and bedrock since the end of the last ice age about 13,500 years ago. As a result, alluvial deposits (unit Qa) are similar to outwash deposits and consist chiefly of sand, gravel, and cobbles, with some clay, silt, and boulders. The quantity and quality of alluvial aggregate varies mainly as a function of drainage basin geology and geometry. More specifically, higher quality aggregate results from longer transport distance and stronger parent material. In Lewis County, the quality of aggregate from alluvial deposits varies greatly because volcanic clasts reworked from alpine glacial deposits have a wide range of weathering characteristics. Additionally, mining of alluvium from river flood plains has an adverse impact to aquatic and riparian habitat (Norman and others, 1998); thus, permitting and development will be difficult in these deposits.

Bedrock Geology

The bedrock geology of Lewis County changes substantially from east to west. Over the last 50 million years in eastern Lewis County, lava flows from eruptions in the central Cascade Range spread over large areas and quickly cooled into finely crystalline and durable volcanic rocks (for example, units Eva and ΦEv$_{ba}$). Each flow formed a distinct layer that was generally less than 150 feet thick, except where the lava ponded in topographic lows. The strongest and most durable flows commonly exhibit columnar jointing and have characteristic hexagonal cross sections. Hard and durable volcanic flows commonly form flat-topped cliffs.

Intrusive igneous rock is potentially the highest quality source of bedrock aggregate in eastern Lewis County. This rock type is typically coarsely crystalline and formed when magma cooled slowly at great depth. It is considered the plutonic root of the Cascades. Since formation, it has been brought to the surface through uplift and erosion. These intrusive igneous rocks have more uniform quality and are much thicker than volcanic units. Most of these rocks are hundreds to thousands of feet thick, so the primary limitation on the depth of aggregate mining is excavation technology and slope stability at the working face.

The bedrock geology of western Lewis County is mostly Crescent Formation (unit Ev$_c$), an Eocene extrusive basalt, and its intrusive equivalent (unit Eib). The Crescent Formation contains pillow basalts and flows extruded in a marine environment. Formation in an underwater environment caused highly variable weathering and durability in these rocks. In addition to pervasive primary fracturing from cooling joints, the unit has abundant secondary fracturing and structural deformation that increases the likelihood of extensive weathering caused by increased fluid flow.

Another important bedrock unit in the western part of Lewis County is a Columbia River Basalt (CRB) flow (unit Mv$_{gN2}$). Though limited in area compared to Crescent Formation basalt or recent lava flows in the eastern part of the county, the CRB flow is an extremely durable unit with a predictable thickness that has proven to be an excellent source of bedrock.

Other bedrock units in Lewis County—which are not suitable for aggregate—include volcaniclastic deposits and marine sedimentary rocks. Fragmented volcanic rock or ash-rich strata (conglomerate, breccia, and tuff, collectively known as volcaniclastic rock) often separate lava flows. The lower-quality volcaniclastic rocks provide aggregate for logging road surfaces, even though they rarely meet specifications for strength and durability (Koloski and others, 1989). Marine sedimentary rocks consist of sandstone, shale, and coal and rarely pass durability standards. These rocks may chemically react with cement, a characteristic that also makes them unsuitable for use in portland cement.

AMOUNT AND LIFESPAN OF AGGREGATE RESOURCES

The maximum possible amount of sand and gravel for indicated areas in Lewis County is 2.35 billion tons. This maximum estimate is calculated using aggregate test data and interpolated thickness estimates from mines and wells (Figs. 2A and 2B). The estimate does not subtract any amount that is unavailable because of current land use or reserved and protected lands, except for Mount Rainier National Park, Mount St. Helens National Volcanic Monument, and federally designated wilderness.

Of the 2.35 billion ton total, only 60.6 million tons are currently permitted. The estimate of permitted resource is made using permitted mine thickness from publicly available permit documentation and the unmined acreage within a permit area. The unmined acreage was retrieved from recent aerial photos by WADGER surface mine inspector Rian Skov (WADGER, written commun., 2014). The 60.6 million ton estimate is an absolute maximum that does not account for material loss due to slope or mine setback requirements, overburden, or volume of material removed since latest site visit or aerial photograph.

Several calculations can be made to determine the lifespan of aggregate resources in Lewis County. If only currently permitted sand and gravel resources are consumed, they will expire before 2024. This calculation is made by using a rate of 13.5 tons of aggregate per capita (PLUSB, 2003), projected population growth between 2010 (75,455 people) and 2040 (88,967 people) using projections from the Office of Financial Management (2012), and by assuming that no bedrock resources are consumed during this time. Similarly, if only bedrock resources are consumed, they will likely last until 2049. Taken together, the total amount of permitted resources (sand, gravel, and bedrock) for the county should last until 2060. The total resource life, however, could be shorter for at least four reasons: (1) per capita usage is highly sensitive to large infrastructure projects such as the continued maintenance of I-5 and may also increase if the economy improves , (2) the amount of sand gravel aggregate needed for the proposed Pe Ell dam would nearly deplete all of the currently permitted sand and gravel resources, (3) a significant portion of the total resource may be unrecoverable for various permitting or environmental reasons (slopes, setbacks, wetland protection), and (4) some deposits in remote localities are currently uneconomic because of transport costs.

SIGNIFICANT DEPOSITS OF AGGREGATE

The geologic units with the largest calculated tonnage of indicated sand and gravel aggregate resources are recessional outwash (unit Qgo, 1,444 million tons), alluvium (unit Qa, 625 million tons), and Evans Creek Stade outwash (unit Qao_e, 281 million tons). Tonnages for indicated bedrock resources were not calculated because of uncertainty in the mineable depth of the deposits.

As of March 2015, there are 21 active[1] (975 acres total) and 55 terminated or inactive mines (772 acres total) in Lewis County. Additionally, 405 disturbed areas (870 acres total) are mining locations that existed prior to the 1970 Surface Mine Act (Chapter 78.44 RCW), where small quantities of sand, gravel, and rock have been removed for local use. Table 2 is a list of the number of mines, total mine area, and estimated remaining aggregate by region and geologic unit.

Deposits from Continental Glaciers

Outwash from the Vashon Stade continental ice sheet (unit Qgo) has contributed a significant portion of the mined and currently permitted sand and gravel in Lewis County. Located in the Chehalis and Skookumchuck River valleys in the Centralia area, these outwash gravels may be 10 to 100 feet thick, are generally clean and durable, and are excavated by dredges. The depth to which dredge mining is economical depends on two main factors in Lewis County: (1) the technical limitations of dragline-dredge mining equipment—mining below 100 feet generally requires more expensive equipment, and (2) the presence, depth to, and thickness of a resistant till layer.

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[1] Two mines are not included because they are used for construction fill and other industrial purposes only.

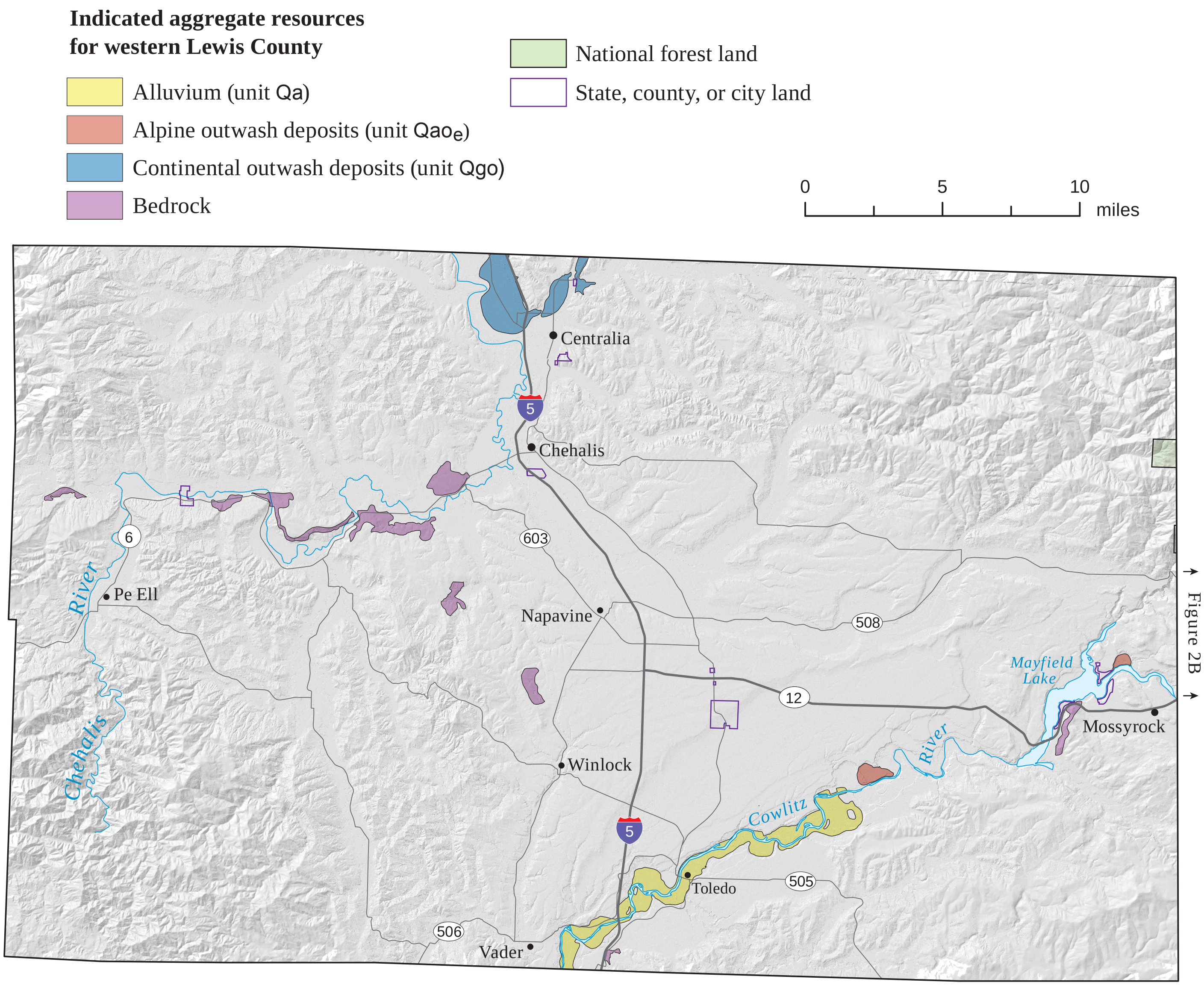

Figure 2A. Aggregate resources for the western half of Lewis County.

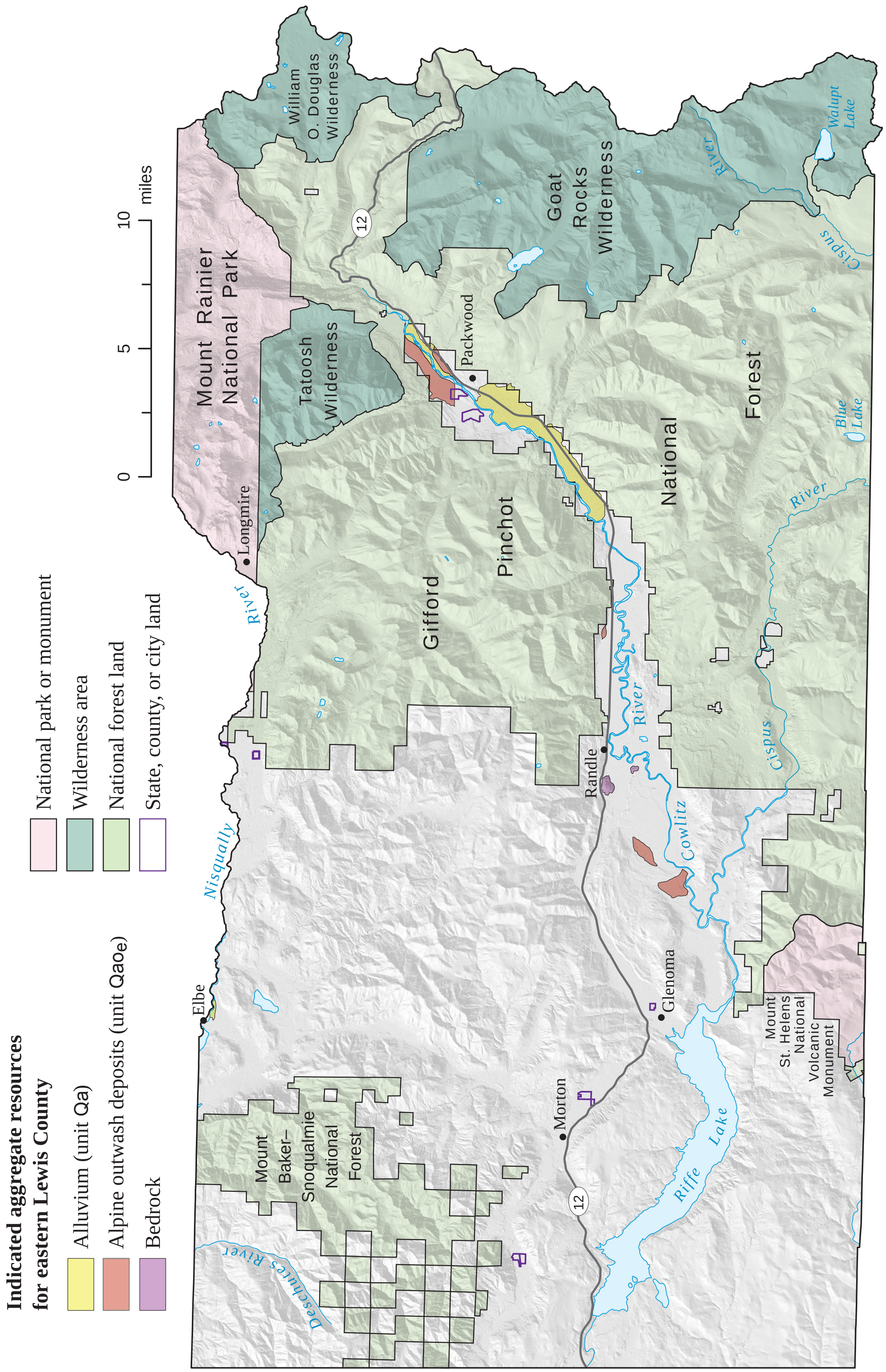

Figure 2B. Aggregate resources for the eastern half of Lewis County.

This till layer is non-commercial, difficult to penetrate with existing equipment, and occurs in several mines and valley well logs. Thick commercial-grade sand and gravel deposits may lie beneath the till. Current practice is that the till controls mine depth, but increased market favorability could change this practice. The deposits of unit Qgo currently have two active mines, although one has only 1.1 million tons of reserve. Historically, four other mines and one pit have produced aggregate from unit Qgo.

Deposits from Alpine Glaciers

Over the last 350,000 years, several episodes of alpine glaciation have scoured and filled the Cowlitz River valley with sand and gravel from the volcanic Cascade Range. From oldest to youngest these glacial deposits are the Logan Hill Formation (unit Qap_{lh}), Wingate Hill Stade outwash (unit $Qapo_{wh}$), Hayden Creek Stade outwash (unit $Qapo_{h}$), and Evans Creek Stade outwash (unit Qao_{e}). Of these, only the Evans Creek Stade and Hayden Creek Stade outwashes have yielded aggregate that meets WSDOT specifications. The older Logan Hill Formation and Wingate Hill Stade outwash are commonly heavily weathered and contain considerable clay. The Hayden Creek Stade outwash has highly variable weathering and is only considered an aggregate resource locally. The Evans Creek Stade outwash is the youngest and generally produces the least-weathered alpine glacial deposits. Deposit quality (quantity of fine-grained material and amount of weathering) generally improves with proximity to the glacial source. This suggests that the best sand and gravel deposits may be found near Packwood. Five mines in Lewis County actively work unit Qao_{e}. An additional 9 mines and 15 pits worked unit Qao_{e} in the past.

Deposits from Modern Rivers and Streams

Alluvium has historically been a significant source of aggregate for the county. Sand and gravel eroded from the Cascade Range, and reworked older glacial deposits, are deposited along modern rivers and streams. The transport of these materials commonly removes any weathering rind (if present) from gravel through abrasion. While being transported, the sand and gravel are locally concentrated, depending on channel morphology, while finer grained materials, such as clay and silt, are deposited further downstream or outside river channels during flood events. Historic mining of alluvium occurred in every major river channel within the county and is most evident in the Cowlitz River channel between Toledo and Vader. Although large volumes of aggregate still exist along many river channels, future mining will likely have difficulty obtaining permits because alluvial mining can damage aquatic and riparian habitat (Norman and others, 1998). There are 4 active mines in alluvium and 15 mines and 19 pits with historical activity.

Table 2. Number of mines, total mine area, and estimated amount of remaining permitted aggregate in Lewis County. Tonnage is calculated by multiplying the volume of material in cubic yards (yd^3) by the average density of sand and gravel (1.39 tons/yd^3) or rock (2.44 tons/yd^3).

	Location	No. of sites (permitted)	Acreage	Maximum volume (millions of yd^3)	Maximum mass (millions of tons)
	I-5 corridor (5-mile buffer)	5	511	9.2	12.7
	west of I-5 corridor	5	133	5.4	13.3
	east of I-5 corridor	11	348	14.8	34.6
	Major Geologic Unit				
Sand and Gravel	recessional outwash (unit Qgo)	2	151	1.8	2.5
Sand and Gravel	alluvium (unit Qa)	4	448	7.7	10.6
Sand and Gravel	Evans Creek Stade outwash (unit Qao_{e})	3	64	1.1	1.5
Sand and Gravel	Hayden Creek Stade outwash (unit $Qapo_{h}$)	1	26	0.1	0.1
Bedrock	Columbia River Basalt (unit Mv_{gN2})	5	133	5.4	13.3
Bedrock	other bedrock (units Φva, $ΦEv_{ba}$, Eva, $ΦEv_{c}$)	6	152	13.4	32.6

Bedrock Deposits

Large-scale mining of bedrock is common in Lewis County and will likely become the dominant source of aggregate in the future as sand and gravel deposits are depleted. Of the many bedrock units in the county (see *Appendix C* for complete listing), flows of the Columbia River Basalt Group (unit Mv$_{gN2}$) in western Lewis County are the most likely aggregate resource. These basalt flows have a generally predictable thickness and have proven to be a high-quality source of crushed rock. There are 2 active mines and 3 mines and 37 pits with historical activity. Also present on the western side of the county are rocks of the Crescent Formation (units Ev$_c$ and Eib). Although these units are common, they are highly weathered, only locally meet testing criteria, and are not a reliable source of aggregate.

Common bedrock units in central Lewis County include the Northcraft Formation (unit Eva), Goble Volcanics (unit ΦEva$_g$), and undivided Eocene to Oligocene volcanic rocks (unit ΦEv$_{ba}$). In eastern Lewis County, the most common bedrock units are younger volcanic rocks (units Φva and RΦian) from the Cascade Range. Combined, these rocks are the largest potential source of aggregate in eastern Lewis County. However, these rocks may be highly weathered locally, and they are farther away from population centers, reducing their marketability. Many bedrock resources have reactivity issues with cement mix and are more difficult to work than a sand and gravel resource. While suitable for crushed road surfacing, these rocks are less suited for structural concrete. There are 5 active mines, 8 historically worked mines, and 262 pits within the bedrock units of eastern Lewis County.

CONCLUSIONS

Aggregate from Lewis County is used for maintenance of several critical transportation routes, including I-5 and State Route 12 (SR-12), in addition to local building and road maintenance for the cities of Chehalis and Centralia. Outwash deposits near Centralia are capable of providing the county with abundant sand and gravel resources. However, these deposits may become inaccessible because of urban encroachment. Alluvial deposits, primarily near Toledo, have played a major role in the aggregate supply in the region. With increasing environmental regulation and fishery habitat concerns, the permitting of new mines in these deposits would be difficult.

Bedrock is the largest untapped aggregate reserve for the county. There are abundant high-quality basalt flows of the Columbia River Basalt Group in the western part of the county and lava flows from the Cascade Range in the eastern part of the county. The amount of bedrock resource is difficult to estimate because detailed geologic mapping does not exist in the areas where these rocks are found. Because of this, many sources may have been overlooked in our analysis. Despite these limitations, available data suggest that bedrock resources could be plentiful and that the primary limitations to their development are mining technology, land-use practices, and market conditions. The development of these resources is expected to increase in the coming decades with increased market favorability due to depletion of currently permitted sand and gravel resources within the Chehalis and Cowlitz River valleys.

At the current yearly per capita usage of 13.5 tons and total permitted aggregate supply of 60.6 million tons, Lewis County has a maximum of 45 years (until 2060) of accessible aggregate. Factors that may shorten or lengthen the timeline for resource depletion include: changes in population growth, market flux and other economic drivers, large infrastructure projects, and (or) additional permitting of aggregate resources for mining.

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Appendix A. Glossary of Mining Related Terms

The terms defined below are modified from Jackson (1997), American Geological Institute (1997), and Washington State Department of Transportation (2014).

Active permit – Permitted mine in which aggregate material is actively being removed (see also *inactive* and *terminated*).

Aggregate, construction aggregate – A mixture of sand and gravel, or sand and crushed rock, used in portland cement concrete, asphaltic concrete, mortar, plaster, or graded fill. Gravel and crushed stone that are in grain-to-grain contact in the aggregate are strong enough to support the weight of roads, buildings, or other infrastructure. The sand keeps the coarse aggregate in grain-to-grain contact by limiting the ability of the larger particles to shift laterally.

Alluvium – Unconsolidated boulders, cobbles, pebbles, sand, silt, and (or) clay deposited from a stream or river and sorted by current velocity.

Andesite – Gray volcanic rock composed of a finely crystalline groundmass that commonly surrounds a few visible crystals (phenocrysts) of feldspar and one or more black minerals such as biotite, amphibole, or pyroxene. Andesite forms much of the Cascade Range and forms most of the edifices of Mount Rainier, Mount Baker, Mount St. Helens, and Mount Adams. Most andesitic lava results from the plate tectonic process of subduction. If andesitic magma cools deep underground, the resulting rock type is granodiorite, a coarsely crystalline igneous rock.

Asphalt – Heavy oil (tar) produced from oil wells that is used to make asphalt roads.

Asphaltic concrete – Concrete made of asphalt and crushed aggregate.

Hot-mix asphalt – A specific construction aggregate used to prepare the base of an asphaltic concrete road.

Basalt – A black volcanic rock that is finely crystalline. Basalt is the most common rock in the Earth's crust and forms the floor of almost all of the oceans. In Washington, basalt underlies the entire Columbia Basin and much of the Cascade Range and high Olympic Mountains. Basalt that erupted on land (for example, the Columbia River Basalt Group) is hard and makes excellent crushed aggregate, whereas basalt that erupted on the sea floor is commonly weak (for example, much of the Crescent Formation basalt along the western edge of the Olympic Mountains).

Boulder – A rock fragment larger than 10 inches in diameter that has been somewhat rounded by abrasion during transport.

Breccia – A consolidated rock consisting of angular fragments >0.125 inches within a finer-grained matrix.

Canceled permit – A permitted mine that was worked and has either changed to a 'grading' permit allowing only minor material removal or has been abandoned by the owner/operator.

Cement – (1) Baked limestone dust and water that glues aggregate particles together to form concrete; (2) minerals, usually precipitated from groundwater, that naturally glue the grains of an unconsolidated sediment together and create a consolidated sediment or rock.

Clast – A rock fragment of any size, initially broken from bedrock by the force of water freezing in cracks or by impact from another rock. Clasts become smaller as they roll down a hillside and (or) are transported by water.

Clay – Sediment composed of particles that behave plastically while wet, are consolidated when dry, and are smaller than 0.000079 inches in diameter. Clay will not support weight (it behaves as a paste) because it is composed primarily of platy clay minerals. Clay is unsuitable for use in construction aggregates, and even small amounts must be washed from coarser aggregate.

Cobble – A rock fragment larger than a pebble, but smaller than a boulder, having a diameter in the range of 2.5 to 10 inches that has been somewhat rounded by abrasion during transport.

Conglomerate – A deposit of rounded or angular clasts larger than sand within a finer-grained matrix.

Crushed stone – Bedrock, cobbles, or boulders that have been crushed with a mechanical crusher to gravel-size rock fragments with at least three freshly broken faces. Crushed stone makes an excellent base course for road construction because the rock fragments tend to form an interlocking matrix. It is the only material suitable for asphaltic concrete because asphalt only sticks to freshly broken rock surfaces.

Degradation test – A laboratory test designed to assess the durability of rock under wet conditions. The degradation number indicates the percentage of rock remaining intact after tumbling with steel balls in a wet chamber. Large numbers indicate favorable rock.

Disturbed area – Area where a disturbance that indicates current or past mine activities is visible on aerial photos or lidar elevation models. These areas are typically, but not limited to, borrows and pits of aggregate for local use.

Dredging – Mining method involving excavation of material from a body of water. The material is brought to shore through a pipeline or conveyor into a bucket for removal. In some cases the waste material is released into the same waterbody after aggregate removal. Types of dredges may include a 'hydraulic dredge' that uses a centrifugal pump, dippers, clamshells, bucket chains, and scrapers.

Gabbro – Coarse-grained (typically 0.125 inches), dark-colored, basic intrusive igneous rock consisting of plagioclase and pyroxene with occasional olivine. Gabbro is the plutonic equivalent of basalt.

Granite – A light gray or pink, coarsely crystalline (typically 0.125 inches) intrusive igneous rock composed of the hard minerals quartz and feldspar, with minor amounts of black mica and black iron- and magnesium-rich minerals. Granite and closely related rocks can make excellent construction aggregate.

Granodiorite – A rock type that is similar to granite with a slightly higher proportion of black mica and iron- and magnesium-rich minerals.

Gravel – An unconsolidated deposit of rock fragments, typically rounded, that resulted from erosion and transport by water. Gravel consists of particles larger than sand, such as boulders, cobbles, and pebbles, in any combination.

Igneous rock – Rock that was formed through the cooling and solidification of magma (underground and termed 'intrusive') or lava (aboveground and termed 'extrusive'). Crystallization may or may not occur in extrusive igneous rocks.

Inactive permit – A permitted mine that is depleted and the permit is retained for purposes other than mining such as for stockpiles or concrete mixing.

Intrusive rock – Igneous rock that was emplaced below the Earth's surface as magma that cooled slowly to form a coarsely crystalline rock.

Loess – Silt and fine sand that is produced by the erosion of glacial outwash and transported by wind.

Los Angeles (LA) abrasion test – A laboratory test to assess the strength of aggregate under dry conditions. A 100-pound sample is placed in a tumbler resembling a washing machine with a tungsten carbide ball weighing about five pounds. The tumbler is revolved 500 times and then the sample is passed through a U.S. Standard no. 4 sieve. The larger the percent of the sample that passes through the sieve, the weaker the sample. The Los Angeles Abrasion number indicates the percent of the sample that has passed through the sieve.

Metamorphic, metamorphism – The mineralogical, chemical, and structural adjustment of solid rock to physical and chemical conditions at great depth (usually greater than several miles). Metamorphism occurs at higher temperature and pressure than near-surface weathering and cementation.

Outwash – Sand, gravel, and coarser clasts deposited by streams and rivers that flow from glaciers. Proximal outwash was deposited relatively close to the edge of a glacier, is poorly sorted, and has a large fraction of cobbles and boulders. Distal outwash was deposited miles from the edge of the glacier and is relatively well sorted and composed mostly of sand.

Overburden – The material that lies on top of an aggregate or mineral resource and must be removed before mining.

Peat – A water-saturated deposit of decayed plants found in bog or swamp environments. Peat is the first stage in the creation of coal. Peat is easily compressed and performs poorly as foundation material, in addition to being combustible when dried.

Pebble – A stone, usually rounded by water transport, with a diameter of 0.167 to 2.5 inches—the size of a small pea to that of a tennis ball.

Pit – Sand and gravel mines, regardless of size. A borrow pit is a small (<3 acre) mine that periodically produces unprocessed gravel and other sediment, generally for use as fill.

Pit run – Unprocessed material taken directly from the undisturbed geologic formation.

Pluton – A relatively large body of intrusive igneous rock that usually cooled at depths greater than several miles.

Portland cement – Cement made by heating limestone to about 2,700°F (calcining) to form lime. This lime is mixed with small amounts of water and is dried to a hard adhesive that can glue aggregate together to form portland cement concrete. Portland cement by itself does not have great compressive strength, and it is costly because of the heat used in its manufacture. For these reasons, aggregate is added to form concrete. The gravel in portland cement concrete has great compressive strength and adds inexpensive filler to the mix.

Quarry – A mine that produces aggregate by blasting bedrock.

Sand equivalent test – A laboratory test that measures the cleanness of a sample in terms of the relative proportion of fine-grained dust or clay. High numbers indicate less dust and (or) clay, whereas low numbers indicate more fine-grained material and greater plasticity. Favorable samples have values greater than 30.

Sandstone – A sedimentary rock composed of rounded to angular fragments of sand-sized (0.05 to 0.75 inch) rocks and minerals. May or may not contain a fine-grained (silt or clay) matrix; commonly cemented by silica, iron-oxides, or calcium carbonate. Sandstone has grains intermediate between a conglomerate and siltstone. Sandstone may be deposited by wind or water and often shows primary structures of transport and deposition.

Shale – A sedimentary rock composed of >67% clay-sized minerals. Shale is commonly laminated and may easily break into thin sheets or plates.

Silt – Sediment that is composed of particles that will pass through a U.S. Standard no. 200 sieve (0.0025 inches) but are larger than clay (0.000079 inches). Silt has little or no cohesive strength because it contains a small proportion of clay minerals. Abundant silt can render a gravel deposit unsuitable for use in construction aggregates.

Specific gravity – The specific gravity of a sample is the weight of the substance relative to the weight of an equal volume of water and is also known as density. Some common specific gravities are water (1.0 g/cm^3), weak aggregate (1.95 g/cm^3), granite (2.65 g/cm^3), limestone (2.72 g/cm^3), and basalt (3.2 g/cm^3).

Terminated permit – A permitted mine that has met the requirements for reclamation and is closed. This typically occurs when no economic volume of material remains. Market factors and land ownership may contribute to the closing of a mine prior to resource exhaustion.

Till – Very poorly sorted clay, silt, sand, gravel, cobbles, and boulders that were deposited directly from glacial ice in the form of a moraine or a compact layer of sediment under the ice. Till is generally unsuitable for construction aggregate.

Tuff – A rock or deposit consisting of consolidated volcanic ash that accumulated during a volcanic eruption. It is generally clay rich and not suitable as an aggregate source.

Volcaniclastic – Rock that is composed solely or primarily of volcanic materials and has been transported and reworked thorough mechanical action of wind and water. Clasts within these rocks can range from clay to boulders. These deposits are generally not considered a source of aggregate because of their poor sorting and the common occurrence of chemical reactivity with cement.

Appendix B. Methods

INVENTORY METHODS

Two end-member philosophies for the inventory of aggregate resources could be used: (1) strictly factual reporting that shows only those sand, gravel, and bedrock resources proven to exist because they are part of active mines, or (2) a speculative approach that reports all of the potential aggregate deposits that might exist, as determined from surficial geologic or soils mapping. Both approaches have shortcomings. The first philosophy results in underestimation of available aggregate in an area by ignoring high-quality deposits that have no mining history. The second philosophy results in overestimation of the resource because this method cannot adequately account for the heterogeneous nature of aggregate-bearing geologic units. In this study, we attempt to achieve a balance between these two philosophies using a method that includes the geologic and engineering criteria described below.

The most commonly used categories in current aggregate studies are defined by the USGS (2014) and consist of indicated reserves and undiscovered resources. In order to demonstrate that an indicated (commercially viable) reserve exists, the geology of the deposit must be very well known and (or) the deposit must have been defined by closely spaced exploratory drilling. Such costly work is beyond the scope of this study. Conversely, studies that rely solely on surficial information to delineate speculative undiscovered resources have greater uncertainty, are of reduced value to industry, and may inadequately inform land-use decisions.

In this study, we follow the USGS (2014) definitions with slight modifications (as defined in Table B1) to map indicated (known) resources and hypothetical or speculative undiscovered resources throughout the county. These results are shown on the map sheet. The most widely available source of subsurface geological data for mapping hypothetical reserves is water-well logs. However, the accuracy of information on these logs is generally poor and can even be misleading, depending on the knowledge, skill, and care taken by the driller. To reduce the inherent uncertainty in the quality and thickness of sand and gravel reported in these logs, we depict hypothetical reserves only where the average of data from several water wells together with other information, such as landform analysis (geomorphology), geotechnical bores, outcrop descriptions, hydrologic data, mine data, and WSDOT Aggregate Source Approval (ASA) tests, allow reasonable extrapolation of surficial data into the subsurface. Samples were collected for testing to provide additional LA abrasion and degradation information on aggregate and rock quality where such data had not previously been collected for a geologic unit, or in locations where there is conflict with other data sources. Elsewhere, speculative undiscovered resources are mapped, but only where several data sets strongly suggest the presence of a deposit that meets the threshold criteria.

THRESHOLD CRITERIA USED IN PREPARING THIS INVENTORY

Several factors can negatively affect the quality of an aggregate resource. Geologic factors, such as unfavorable alteration, weathering, and (or) the low strength of some rock types—such as claystone or layered sedimentary or metamorphic rocks—make some deposits unsuitable for construction aggregate. Furthermore, extraction or

Table B1. Listing of resource classification types and criteria.

Discovered resource	Definition
Indicated	Indicated resources are gravel or bedrock aggregate for which specific geologic evidence, limited sampling, and laboratory analysis provide confident estimation of distribution, grade, and quality. Indicated resources may include economic, marginally economic, and sub-economic components that reflect various degrees of geologic certainty. We map an indicated resource where available data appear to satisfy all of the elements of our threshold criteria (listed below).
Undiscovered resource	**Definition**
Hypothetical	Hypothetical resources are aggregate resources postulated to exist on the basis of general geologic information, aggregate test data, and production history. We map hypothetical resources where available data appear to satisfy most of the elements of our threshold criteria (listed below).
Speculative	Speculative resources are aggregate resources for which there is sparse geologic and production information and where indeterminate or no aggregate testing exists. Nevertheless, existing geologic mapping and data suggest that these rock units may have the potential for meeting the threshold criteria established for this study and possibly contain aggregate resources.

development costs may exceed expected return under current market conditions. In order to reduce the probability of including weak or insignificant resources, we have developed the following threshold criteria to determine which resources should be included in our inventory.

Thickness

This study considers only those deposits that are known or likely to exceed 25 feet in their thickest portions. Thin gravel deposits rarely contain significant resources. For example, a 20-foot-thick deposit covering 20 acres would yield only about 650,000 cubic yards of sand and gravel. The value of this gravel might not exceed proceeds from selling the land in its undisturbed state for real estate development. Moreover, current mining technology cannot efficiently excavate thin veneers of sediment or bedrock. Thin deposits must be spread over a large area in order to contain a significant volume of gravel, but relatively inexpensive excavating equipment (that is, front-end wheel loaders) cannot carry material long distances within the mine. Finally, thinner deposits require greater surface disturbance per unit of aggregate produced, and damage to the plant/soil ecosystem increases in proportion to the surface area of mining. Therefore, permitting costs are likely to increase as a function of decreasing thickness or with increasing acreage.

Surface Area and Dimensions of the Deposit

Few gravel deposits are more than 100 feet thick. In order to contain a significant volume of aggregate and be included in this inventory, the deposit must cover an area at least 0.25 square mile (160 acres). The volume of a 50-foot-thick gravel unit of this area would be about 10 million cubic yards. Additionally, we map only those deposits that have a minimum map dimension of 1,500 feet, unless they are included as a portion of—or next to—a much larger resource. Deposits that are long and narrow are generally inefficient to operate.

Geologic maps provide an initial estimate of the surface area for each deposit. Reduction of these initial areas, or placement into a lower-confidence resource classification (Table 3), occurs when some portion of the deposit fails to meet the threshold criteria. Most of the geologic areas depicted on the map sheet contain mines or outcrops with engineering tests proving that at least some of the rock or sediment meets the strength and durability threshold criteria. This approach expedites the inventory process, but may have resulted in the omission of a few significant resources. For example, locally significant small deposits or deposits with highly variable quality may not be included.

Overburden

Only those deposits that have stripping ratios (ratios of overburden to gravel or rock) of less than 1 to 3 are included in this inventory. Overburden can cost from $0.75 to more than $2.00 per ton to remove (in 2014 dollars). Typically, operators try to achieve a net profit of $1.00 per ton, and landowner royalties are typically $0.50 to $1.00 per ton (Rian Skov, written commun., 2014). Therefore, the overburden volume must be much less than the volume of underlying aggregate if the mine is to be commercially viable. The stripping ratio can be larger where supply restrictions, favorable topography, or other considerations allow the profitable removal of overburden. The largest known stripping ratio for a profitable aggregate mine in Washington was 1 to 2 (Rian Skov, written commun., 2014). The practice of topsoil sales and (or) synthesis is one method of profitably disposing of thicker organic or clay-rich overburden, but as a general rule, overburden must be saved for reclamation (Norman and others, 1998; Norman and Lingley, 1992). In Lewis County, few mines have been developed on gravel deposits with more than 10 feet of overburden.

Strength and Durability

In order to perform adequately as construction aggregate, gravel or bedrock must have high compressive strength and resist degradation when wet. Without these characteristics, the aggregate cannot support the weight of roads or buildings. Much of the vertical compressive strength, or load-bearing capacity, comes from grain-to-grain contact of individual pebbles that are effectively stacked up and prevented from shifting by cement and fine aggregate. Stronger aggregate commands a higher price, but weak rock is of no use. Minimum specifications for strength and durability of various rock products are published by WSDOT in the 2014 *Standard Specifications for Road, Bridge, and Municipal Construction*, a key reference book that is updated periodically. Specifications for gravel and bedrock are determined by laboratory tests, including the Los Angeles (LA) abrasion and degradation tests. Table 1 identifies some of the specifications required for certain uses of aggregate. Note that this study does not consider other aggregate tests, such as sand equivalent, specific gravity, and percent passing a no. 200 sieve. These tests are often no longer conducted when testing an aggregate source because the proper proportion of sand and gravel is blended on site (Rian Skov, written commun., 2014).

For this study, we inventoried gravel and bedrock that meet WSDOT specifications for hot-mix asphalt-wearing course (Table 1). Hot-mix asphalt is a compacted layer of aggregate treated with asphalt for stability and weatherproofing and is placed directly on bulldozed earth or rock of a road's subgrade. If most of an aggregate resource appears to meet these specifications, then we depict the entire deposit as meeting the strength and durability threshold criteria (Map Sheet). This specification differs from previous aggregate studies—the category for asphalt-treated base was removed from the 2014 specification manual.

Sources of Data

Data for currently active and terminated mines exist in WADGER permit files (2010) and WSDOT aggregate source approved sites (WSDOT, 2013). WADGER Surface Mining Form SM-2 and other permit-related documentation, such as Environmental Impact Statements (EIS), provide the thickness of resource units in a mine location.

The surface extent of geologic units is shown on WADGER geologic maps within Lewis County (Korosec, 1987; Logan, 1987; Phillips, 1987; Schasse, 1987a,b; Walsh, 1987), U.S. Geological Survey maps (Clayton, 1980; Evarts and Ashley, 1993a,b; Swanson, 1989, 1991, 1993, 1996a,b; Swanson and others, 1997; Wells and Sawlan, 2014).

Many logs of geotechnical bores (for example, bores for foundation engineering studies) provide subsurface information used for overburden and resource thickness designations. This subsurface data is available from the Washington State Department of Ecology (2013), the Tumwater Materials Office of WSDOT (written commun., 2014), and the WADGER Subsurface Database (Jeschke and others, 2014).

Current and historical WSDOT test data is available through the Aggregate Source Approval page of the WSDOT website at http://www.wsdot.wa.gov/biz/mats/ASA/ASASearch.cfm. A Shannon and Wilson draft report for the proposed Pe Ell dam contains six new tests for several mines in western Lewis County (Shannon and Wilson, 2014). Seven crushed rock samples were collected by WADGER employees during the winter of 2014–2015 and tested at Mayes Testing Engineers Inc. at their Lynnwood office; results from this testing are reported in Appendix D.

Appendix C. Aggregate-producing Geologic Units

This appendix lists and describes geologic units that have been mined for construction aggregates and (or) that have the potential to produce gravel or rock that meets the threshold criteria. This list is based on a reconnaissance investigation. Therefore, appreciable amounts of aggregate may be locally present in units that are not included in this list because they are part of a highly variable or typically unproductive rock unit. In order to provide data for engineers and geologists, these unit descriptions incorporate geological terms too numerous to be included in the glossary. Mine, pit, and test data mentioned in the text refers to locations with identified resources within Lewis County.

The rock and sediment descriptions listed below are synthesized from the most recent geologic maps of Lewis County (Clayton, 1980; Evarts and Ashley, 1993a,b; Gard, 1968; Korosec, 1987; Logan, 1987; Phillips, 1987; Schasse, 1987a,b; Swanson, 1989, 1991, 1993, 1996a,b; Swanson and others, 1997; Walsh, 1987; Wells and Sawlan, 2014). Unit symbols are those used by the Washington Geologic Information Portal 1:100,000-scale (WADGER, 2010) and 1:24,000-scale (WADGER, 2014) map layers. These unit symbols may differ from the original map publications.

QUATERNARY UNCONSOLIDATED DEPOSITS

Qa **Alluvium**—Moderately well sorted deposits of cobble gravel, pebbly sand, and sandy silt; found along flood plains of lowland streams. Deposit thickness and aggregate rock quality is highly variable and depends on transport distance, source rock type, and local topographic controls. WSDOT testing indicates this unit will meet road-grade specification in most locations with 21 passing tests, 4 failing tests, and 43 incomplete tests. Historically, 12 mines and 15 pits have produced from this unit. Four mines are currently active, although no new mines are expected due to environmental concerns.

Qgo **Vashon Stade recessional outwash**—Loose sand and gravel; tan to gray; moderately to well sorted and rounded; consists of plutonic and metamorphic clasts of northern or mixed northern and eastern (Cascade Range) sources; deposited by Vashon-age meltwater in outwash channels or isolated basins after glacial ice retreat; ranges from a few feet to a few tens of feet thick, but may locally exceed 100 feet in deltaic environments. This unit is often subdivided into units Qgog and Qgos, with greater concentrations of gravel or sand, respectively. Unit Qgo is generally less compact than advance outwash, but the two are difficult to distinguish without an intervening layer of till. This unit has proven to meet road specifications with 8 passing tests and 3 incomplete tests. Historically, 6 mines and 6 pits have produced from this unit; there are currently 2 active mines.

Qga **Vashon Stade advance outwash**—Pebble to cobble gravel composed mostly of polycrystalline quartz, plutonic rock, and minor metamorphic rock; also contains sand and layers or lenses of silt and clay; gray to tan; typically stratified, well rounded, well sorted, and clean (<5% silt or clay in matrix), except in less-sorted and more-angular ice-proximal deposits; typically compact and resistant to erosion except in deposits that are well sorted and well rounded; very thinly to very thickly bedded; contains planar and graded beds, cut-and-fill structures, trough and ripple crossbeds, and foresets; thickness ranges from a few feet to more than 100 feet; deposited as proglacial fluvial and deltaic sediment during Vashon-age glacial advance and is typically overlain by till along a sharp, progressive unconformity. At present, no mines have directly targeted this unit. Mines located on and removing unit Qgo might opportunistically encounter and remove unit Qga in the subsurface.

Qao_e **Evans Creek Stade outwash**—Sand and gravel deposited along the Cowlitz River between 10 and 25 feet thick; often mantled with 1 to 7 feet of loess; upper 3 feet of the deposit is commonly oxidized. Two active mines, 4 historic mines, and 1 pit have produced from this unit. The unit has 7 tests that passed WSDOT criteria, 3 tests are incomplete, and 1 test failed. The Evans Creek Stade outwash is considered a significant source of sand and gravel in the Packwood area and is a secondary source of sand and gravel (after unit Qa) between Toledo and Vader.

Qapo$_{he}$ **Post-Evans Creek, pre-Hayden Creek Stade outwash**—Sand and gravel exposed discontinuously along the Cowlitz River; between 10 and 16 feet thick; often mantled with about 1.5 to 5 feet of loess; the upper 4 feet of the deposit is commonly oxidized. Mining or testing has not occurred in this unit. This geologic unit is most likely a suitable source of sand and gravel only where it can be opportunistically mined with Evans Creek Stade outwash or alluvium.

Qapo$_{h}$ **Hayden Creek Stade outwash**—Sand and gravel deposited along the Cowlitz River. This unit includes terrace deposits to the west along the Chehalis River and the South Fork of the Newaukum River. The thickness of the deposit ranges from 15 to 50 feet. The upper 7 to 10 feet of the unit has extensive oxidization. This unit has passed 4 WSDOT tests, failed 3, and has 5 incomplete tests. Although lower-quality deposits have been mined for fill, this unit is generally too weathered to be of use except in a few locations. There is 1 active mine and 1 historical mine and 5 pits in this unit.

QUATERNARY IGNEOUS ROCKS

Qvb **Basalt and basaltic andesite flows**—Vesicular plagioclase-clinopyroxene-olivine phyric basalt and basaltic andesite. In the Carlton Creek–Summit Creek area, the unit consists of intracanyon flows of basalt and basaltic andesite. Near Blue Lake, the flows are more aphyric or contain fine-grained olivine, are hackly jointed, and form a broad volcanic cone. Only 1 pit has produced from this unit, although it passed 2 WSDOT degradation tests. These tests indicate it is likely an excellent source of crushed rock.

Qvd$_{cf}$ **Clear Fork Dacite**—Microlitic quartz-hornblende orthopyroxene dacite intracanyon lava flow along the Clear Fork of the upper Cowlitz River; sourced from the east side of Coal Creek Mountain; platy to columnar jointed; 200 feet thick with well-developed downward-tapering columns; mantled by Evans Creek Drift. The flow has an abrupt steep termination and jointing that is characteristic of a lava flow blocked by glacial ice. This unit has not been mined or tested.

QUATERNARY–PLIOCENE IGNEOUS ROCKS

QꝐva **Andesite flows**—Exposed in the north part of the Goad Rocks Wilderness, this pyroxene andesite forms ridge-capping flows partially overlain by basalts of unit Qvb. This unit may be associated with the Goat Rocks volcanic center or may be an unrelated flow. This unit has not been mined or tested.

QꝐvbh$_{m}$ **Mafic rocks of Hogback Mountain**—Hogback Mountain mafic lavas were erupted from widely distributed vents in the White Pass area and include basalt and basaltic andesite with common olivine phenocrysts, minor andesite, and dacite. A single 165-foot-thick hornblende andesite to dacite flow breaks the generally monotonous sequence of basalts near Hogback Mountain. Distal lavas originating from Hogback Mountain were deposited in paleovalleys to the north and consist of several deposits that include: basaltic pillow palagonite breccia northwest of Twin Sisters Lakes, basaltic andesite and andesite forming the ridge north of Cortright Creek, and andesite and basaltic andesite vents at Cramer Mountain. This unit has not been mined or tested.

PLIOCENE–MIOCENE IGNEOUS ROCKS

ꝐMiad **Intrusive dacite (hypabyssal)**—Light gray to dark green-gray dacite in the Silver Creek Campground and Davis Creek areas west of Packwood. There are 2 pits that produce aggregate from this unit for forestry roads. This unit has not been tested.

PLIOCENE–OLIGOCENE IGNEOUS ROCKS

ꝐΦian **Intrusive andesite (hypabyssal)**—Medium gray, aphanitic to porphyritic hornblende andesite, pyroxene andesite, and pyroxene basaltic andesite; forms shallow stocks, plugs, sills, and dike swarms that are commonly altered. Three pits produce from this unit for both forestry and major road maintenance. There are 3 tests that pass all WSDOT criteria, indicating that the unit would make an excellent source of crushed rock.

ꝐΦvb **Basalt of Spring Creek**—Aphanitic to sparsely olivine-phyric, diktytaxitic olivine basalt. A small flow crops out along Blue Lake Creek, 1,600 to 2,000 feet north-northeast of Blue Lake Creek Campground.

At this location, the basalt of Spring Creek is often covered by a glacial outwash largely derived of clasts from other basaltic flows. This unit has not been mined or tested.

MIOCENE IGNEOUS ROCKS

Mian **Intrusive andesite (hypabyssal)**—Dark to medium gray, aphanitic to porphyritic pyroxene and hornblende andesite to basaltic andesite that forms numerous dikes, sills, small plugs, and stocks. This unit has not been mined or tested.

Mid **Hornblende diorite and related rocks**—Hornblende-clinopyroxene-plagioclase-phyric diorite, quartz diorite, dacite, and andesite forming sills and dikes. Grain size is largely dependent on intrusion thickness: grains are typically microcrystalline in dikes, thin sills, and the chilled margins of larger bodies, but grains range to 0.2 inches in intrusive interiors. Hornblende occurs chiefly as individual phenocrysts with scattered megacrysts and glomerocrysts more than 0.4 inches in diameter. Modal mineralogy includes hornblende (1–5%,) clinopyroxene (1–3%), and plagioclase (5–15%; rarely 20%) with sparse orthopyroxene in some samples. Typically has only minor weathering, although certain large plug-like bodies (such as Tower Rock, Tongue Mountain, and Burley Mountain) contain abundant clay and other secondary minerals with relict hornblende and clinopyroxene. Only 1 pit exists in this unit, and it is used for forestry purposes.

Migd **Granodiorite**—Numerous dikes and irregular intrusions of fine-grained porphyritic to seriate pyroxene quartz diorite emplaced within thermally altered country rock (hornfels); also consists of small, poorly studied dikes, sills, and irregular intrusive bodies with fine- to medium-grained phaneritic to porphyritic texture of granodiorite to quartz diorite. Many of the surface exposures have moderate to complete alteration of feldspar to clay. In the Spirit Lake area, this unit is an initial phase of the Spirit Lake pluton (early Miocene). This unit has not been mined or tested; however, its proximity to SR-12 would make it a potentially useful source of crushed rock, depending on the severity of alteration—samples with too much weathering will fail degradation tests.

Miq **Quartz diorite**—Dark to light gray or pale pink, medium- to coarse-grained quartz diorite, quartz monzodiorite, granodiorite, and quartz monzodiorite forming numerous small, irregular bodies, often with complex gradational contacts. The unit contains plagioclase phenocrysts as much as 0.4 inches-long with prismatic pyroxene phenocrysts and a groundmass consisting of anhedral to granophyric quartz and alkali feldspar with minor biotite and hornblende. Most samples are moderately to extensively altered. This unit has not been mined or tested, and its suitability as a source of crushed rock will depend on the severity of alteration.

Mir **Rhyolite dike (hypabyssal)**—Gray quartz and fine-grained plagioclase-phyric rhyolite dike that cuts upper Oligocene andesite flows in the Kiona Creek area. This unit has not been mined or tested; however, its proximity to SR-12 may make it a potentially useful source of crushed rock.

Mv$_{gN2}$ **Grande Ronde Basalt**—Aphanitic to fine-grained basaltic andesite flows and flow breccia. The upper flows have well-developed colonnades, while the lower flows have well-developed entablature jointing. The flows grade from low-Mg chemistry at their base to high-Mg chemistry at their tops. The flows normal magnetic polarity in the upper flows, but reversed polarity in lower flows (Korosec, 1987). With 2 active mines, 3 historic mines, and 37 pits, this unit is the largest producer of crushed rock in the county. Every complete WSDOT test conducted on this unit has passed, indicating that it is an excellent source of durable rock.

Mva **Andesite and basaltic andesite flows**—Light to dark gray orthopyroxene andesite to basaltic andesite and two-pyroxene basaltic andesite flows and flow breccia south of the Cowlitz River near Silver Creek. At Lookout Mountain, the unit includes an olivine basalt flow interbedded with andesitic flows and flow breccias. West of Skyo Mountain, the unit is a vitric, aphanitic, black to very dark gray basalt and andesite lithologically similar to the flows of Lookout Mountain. North of Randle, the unit is a plagioclase-clinopyroxene-phyric andesite flow. There are 3 pits that produce aggregate from this unit for forestry purposes; no test data is available.

Mvb **Basalt flows**—Dark gray, aphyric to porphyritic clinopyroxene basalt flows at Huffaker Mountain. The unit is similar in appearance to most of the lower Miocene basaltic andesite flows (unit Mva), but chemical analyses reveal a slightly less silicic composition (49–53% SiO_2). The basalt flows and associated flow breccia form a broad shield volcano south of Huffaker Mountain. There are 2 pits that mine this unit for forestry purposes; no test data is available.

Mvd **Dacite flows**—Light to dark gray, porphyritic hornblende dacite, hornblende-pyroxene dacite, clinopyroxene dacite, and hornblende pyroxene andesite flows and flow breccia. The unit is interbedded with volcaniclastic deposits and andesite to basaltic andesite flows of unit Mva. Northeast of Iron Creek Butte, a black, glassy 30-foot-thick dacite flow is columnar jointed, has a vesicular flow top, and forms a cap to a ridge. The dacite is porphyritic to glomeroporphyritic, with phenocrysts of plagioclase and clinopyroxene in a very fine grained groundmass of plagioclase microlites, clinopyroxene, and brown glass. This unit is similar to flows at Bluff Mountain, at the North Fork Cispus Campground, and northwest and south of Tongue Mountain. Only 1 pit has developed this unit for forestry purposes; no test data is available.

MIOCENE–OLIGOCENE IGNEOUS ROCKS

MΦiad **Intrusive andesite and dacite (hypabyssal)**—Dikes, sills, or plugs of plagioclase-quartz-hornblende-phyric andesite or dacite; minor alteration of mafic minerals to chlorite. The unit cuts rocks of Eocene through early Oligocene age and may have been feeders for Miocene volcanic rocks. This unit has not been tested or previously mined. Though lithology suggests the unit could be suitable for crushed rock, weathering and chloritization may limit its use for aggregate.

MΦian **Intrusive andesite (hypabyssal)**—Dikes, sills, or plugs of dark-colored plagioclase-pyroxene and hornblende-phyric andesite dikes that locally grade into andesite porphyry and pyroxene diorite; commonly has chlorite and argillite alteration. The unit cuts rocks of Eocene through early Oligocene age and may have been feeders for Miocene volcanic rocks. There are 7 pits that produce aggregate for forestry purposes; no test data is available. Though lithology indicates that the unit could be suitable for crushed rock, weathering and chloritization may limit its use for aggregate.

MΦib **Basalt or gabbro dikes and sills**—Dark greenish-gray, plagioclase-clinopyroxene-phyric basalt with minor olivine and amygdules of zeolites and chlorite; forms dikes and sills southeast of Meridian Hill, near Packwood, and south of Riffe Lake. The unit cuts rocks of Eocene through Oligocene age and may have been feeders for Miocene volcanic rocks. This unit has not been developed or tested; however, its proximity to Packwood and SR-508 could make it a useful source of crushed rock.

MΦid **Intrusive diorite**—Medium- to coarse-grained dikes and sills composed of plagioclase, pyroxene, and magnetite, with minor olivine, ilmenite, interstitial quartz, and orthoclase; completely unaltered to extensively altered. The unit is black to medium gray with orange weathering, cuts upper Oligocene to early Miocene volcanic rocks, and may be associated with the lower Miocene Spirit Lake pluton. Only 1 pit has developed this unit for forestry practices. One test conducted on an exposure along SR-7 failed, and one test along SR-12 near Silver Creek passed. It is possible that this unit may be a useful source of aggregate due to its proximity to SR-7 and Packwood, pending additional testing and consideration of the severity of weathering.

MΦva **Basaltic andesite and andesite lava flows**—Porphyritic pyroxene andesite and basaltic andesite flows and flow breccia; locally includes minor basalt and dacite flows, breccia, and interbedded volcaniclastic rocks. The flows typically consist of plagioclase and pyroxene phenocrysts in a pilotaxitic groundmass of plagioclase, pyroxene, magnetite, quartz, and interstitial glass (usually altered to fine-grained smectite). Crops out as hypabyssal sills or dikes. This unit would make a suitable source of crushed rock and currently has 12 pits producing for forestry purposes. The unit passed WSDOT specifications on an outcrop near Elbe and failed a test near Silver Creek.

MΦvb **Basalt lava flows**—Black to dark gray-green aphyric to sparsely porphyritic, massive to vesicular basalt and basaltic andesite lava flows and flow breccia; locally includes interbedded mafic tuff, lahars, and minor sedimentary rocks. Within the contact aureole of the Spirit Lake pluton, the unit is recrystallized to fine-grained hornblende-pyroxene hornfels. This unit has 3 pits used for forestry purposes. Unclear age relations near Glenoma create an arbitrary boundary with unit Φvb. One site tested by DNR failed WSDOT specifications by not meeting the minimum wet-degradation requirement. Basalt and basaltic andesite can have widely varied degradation values, but this does not exclude the unit as a whole as a suitable source of crushed rock.

MΦvd **Dacite flows, plugs or lava domes**—White to light greenish gray, sparsely phyric, commonly flow-banded dacite flows, flow breccia, or hypabyssal, chaotically jointed plugs or lava domes. The unit typically contains less than 10% plagioclase and 5% pyroxene phenocrysts, with minor hornblende, quartz, and biotite in a groundmass of devitrified glass consisting of fine-grained granular to spherulitic quartz and feldspar. Secondary alteration is more common in interbedded mafic volcanic rocks. Commonly contains pyrite resulting from supergene oxidation. This unit has not been mined or tested.

OLIGOCENE IGNEOUS ROCKS

Φva **Andesite flows**—Andesite and basaltic andesite flows and flow breccia. Near Randle, the unit is a gray porphyritic pyroxene basaltic andesite with minor andesite. In the Skate Creek and Butter Creek areas, the unit is characterized by cliff-forming greenish- to brownish-gray andesite. At Skyo Mountain, the unit consists chiefly of gray to brownish-green andesite flows and flow breccia, with minor lahar breccia and tuff breccia. There are 2 active mines and 12 pits in this unit. Tests show the unit to be highly variable in quality, with 2 passing, 2 incomplete, and 3 failing tests.

Φvb **Basaltic andesite flows**—Gray, porphyritic to glomeroporphyritic pyroxene basaltic andesite, minor andesite, and flow breccia associated with these flows; weathers tan and brown. The rocks have phenocrysts of plagioclase, clinopyroxene with a groundmass of plagioclase, clinopyroxene, opaque minerals, and glass. The groundmass is typically altered to chlorite, clays, and zeolites. Unclear age relations near Glenoma create an arbitrary boundary with unit MΦvb. This unit has 2 pits; 1 test passed WSDOT specifications. The proximity of this unit to SR-12 makes it a potentially useful source of crushed rock.

Φvd **Dacite flows**—Complex of plugs, flows, interstratified tuff-breccia, and hypabyssal intrusive rocks of light gray pyroxene dacite near Coyote Mountain. In other locations the unit consists of platy pyroxene dacite that weathers to form bright red soil and locally includes small zones of argillic hydrothermal alteration where country rock is altered to a white, friable mass of clay and finely disseminated pyrite. This unit has 5 pits that produce aggregate for forestry purposes; 1 test was incomplete, but showed favorable LA abrasion values.

OLIGOCENE–EOCENE IGNEOUS ROCKS

ΦEva$_g$ **Goble Volcanics, basaltic andesite lava flow**—Porphyritic pyroxene basaltic andesite lava flows and flow breccia with thin interbeds of red-brown siltstone, sandstone, conglomerate, and tuff. May contain minor olivine basalt, pyroxene andesite, and platy to irregularly jointed dacite. Lava flows are typically thin (3–15 feet) and lenticular or ovate with undulating top and bottom contacts. Non-commercial layers of thin (2–20 inches) siltstone or sandstone often separate flows. Flow centers are typically dense and blocky jointed to platy, with well-developed columnar jointing or rare entablature jointing. Locally, scoriaceous flow-breccia forms the bulk of the unit and envelopes small lenticular and dense flow centers. Vugs and fractures contain characteristic secondary mineralization of calcite and a complex suite of zeolite minerals. This unit has 48 pits, which predominantly produce aggregate for forestry purposes. Two tests conducted on this unit near SR-505 failed WSDOT specifications. A DNR sample site south of Silver Creek (DNR-105) passed degradation tests.

ΦEv$_{ba}$ **Basaltic andesite and andesite flows**—Platy to massive, vesicular to dense, porphyritic to aphanitic basaltic andesite to andesite, with rare dacite flows and flow breccia; flows commonly have oxidized and wavy bases and thin interbeds of shale, tuff, or volcanic sandstone and conglomerate; forms complexes of numerous, thin, irregularly shaped flows of limited aerial extent; most flows are plagioclase-clinopyroxene-phyric; two-pyroxene or olivine-phyric flows are also present; zeolites and calcite are common in amygdules and fractures. Unit potentially provides a source of aggregate, though the interbedded marine and volcaniclastic layers may limit the usefulness of the deposit. One active mine and 37 pits have produced from this unit, predominantly for forestry purposes, although the active mine provides crushed rock to the Silver Creek area and SR-12. Testing shows a high variability in quality for the unit with 5 passing, 3 incomplete, and 2 failing tests.

ΦEv$_{cg}$ **Goble Volcanics, volcaniclastic sedimentary rocks**—Light-colored volcanic-lithic sandstone, siltstone, conglomerate, ash fall and ash tuff, breccia, and minor coal and carbonaceous shale of various thicknesses. Sedimentary layers are thinly bedded to massive, with coarser grained strata commonly crossbedded. Tuffs are commonly normally graded and produce characteristic brilliant red, sticky, clay-rich soils when weathered. The unit locally contains interbedded lava flows similar to unit ΦEva$_{g}$. Only considered an aggregate source due to a high-quality deposit near exit 57 of I-5. Two mines, each with a test passing WSDOT road-grade specifications, historically worked that outcrop.

EOCENE IGNEOUS ROCKS

Eib **Gabbro and basaltic intrusive rocks**—Forms a fine- to very coarse-grained gabbro sill complex. The marginal facies of the sill complex are basalt and have well-developed columnar jointing. The interior of the complex is very coarse grained to pegmatitic. The gabbro and basalt are vesicular and typically flow-banded, which results in planar concentrations of vesicles and crystals. Interstitial glass is generally altered to green clay that commonly fills vesicles. Some gabbro and basalt from unit Eib that intrudes the Crescent Formation (unit Ev$_{c}$) likely correspond to Crescent Formation magmatism, while some may be younger and related to the Grays River Volcanics (unit Evb$_{gr}$). This unit has 25 pits that produce aggregate for forestry purposes. One test by DNR and 1 test by WSDOT failed WSDOT specifications by not meeting the minimum wet-degradation requirement. Basalt and gabbro commonly have widely variable degradation values; thus the unit as a whole may still be considered a suitable source of crushed rock.

Ev$_{c}$ **Crescent Formation**—Pillow flows, massive and columnar-jointed flow interiors, pillow breccia, lapilli-tuff breccia, and filled lava tubes of tholeiitic and alkali basalt; groundmass commonly alters to green and brown clay with secondary zeolite and calcite filling fractures. The unit may also contain minor amounts of non-commercial mudflow breccia, basaltic sandstone, and interbedded laminated siltstone. The unit is heavily faulted, deformed, and represents a clockwise-rotated seamount built on oceanic crust. This unit has 25 pits that produce aggregate for forestry purposes. Two DNR tests failed WSDOT specifications. The unit is included in the inventory due to its importance as a local source of crushed rock for forestry roads; however, thorough testing and careful site selection will be required to obtain reliable sources of durable rock that passes WSDOT specifications.

Eva **Northcraft Formation and undivided andesite flows**—Massive aphanitic to porphyritic pyroxene andesite or basaltic andesite with minor interbedded matrix-supported volcanic breccia; includes dark reddish-brown to dark greenish-gray andesitic and basaltic pyroclastic breccia and mudflow breccia, with minor interbeds of volcaniclastic sandstone, conglomerate, and tuff (Gard, 1968). This unit has 56 pits that produce aggregate predominantly for forestry purposes. This unit had 6 tests that provided highly varied results, with 2 passing, 2 incomplete, and 2 failed tests. The close proximity of the unit to SR-12 and several towns, such as Morton and Cinebar, would make this an important source of crushed rock if adequate testing is conducted to ensure quality.

Evb$_{gr}$ **Grays River Volcanics**—Subaerial basalt flows with columnar and platy jointing, weathered flow tops, and oxidized, red basal-flow breccias overlying and interbedded with baked and altered siltstone and sandstone. The basalts are typically aphyric to densely porphyritic and contain phenocrysts of plagioclase, clinopyroxene, and olivine. No testing or mining has been done; however, an outcrop exposed near Vader may provide a local source of crushed rock for the town and I-5 maintenance.

Appendix D. Field Notes from DNR Test Sites

The following is a table of locations that were visited to collect samples for degradation tests and improve existing geologic descriptions. Each site lists the age, geologic name, location (using the WGS84 datum), and a detailed hand sample and outcrop description. Degradation test results are also listed. A full listing of county-wide degradation test results is provided in the accompanying Microsoft Excel file.

Table D1. Field notes and degradation test results.

Site and geologic unit	Location (lat/long)	Nearest town; access road	Geologic description	Sample number	Degradation sample notes	LA abrasion test result	LA wet-degradation test result
Site 1 Evc	46.52880 -123.29097	Pe Ell; 1000 Rd off Muller Rd	Eocene basalt—aphanitic with <1 millimeter spherical voids and <5% subhedral pyrite and feldspars also 1 millimeter in size. Varies from lightly to moderately fractured, with deposition of secondary quartz. Outcrop consists of bedded basalt flows and pillows tilted to a ~45 degree angle. Weathering is minor.	DNR-101	Sampled from crushed/shot pile to left of the main working face. Fragments sand to boulder size.	59.8	2
Site 2 Eib	46.50240 -123.14435	Boistfort; 5000 Rd off Pe Ell–McDonald Rd	Eocene gabbro—aphanitic; includes 1-millimeter- to 2-centimeter-long pipe vesicles on cooling surfaces. Minerals include <5% of 1 millimeter feldspar and clinopyroxene with rare crystals demonstrating acicular texture. Outcrop is generally unweathered except for the first meter. Forms entablature columns ~0.5 meter in diameter and is heavily fractured from primary jointing and blasting.	DNR-102	Sampled from shot pile directly in front of working face. Fragments gravel to boulder size.	30.9	5
Site 3 Evc	46.70073 -123.29252	Pe Ell; W 3000 Rd off of Chandler Rd	Eocene basalt—two types of rock were present: (1) competent basalt blocks 15 centimeters to 1 meter in diameter that are aphanitic with abundant microcrysts; (2) volcaniclastic material containing basaltic cobbles (pillows?) in a friable to semi-indurated tuffaceous matrix; vuggy quartz commonly fills fractures and void spaces. Outcrop is moderately weathered and oxidized at the top, grading to minor weathering at the base; has massive to entablature colonnade; overlain and underlain by brecciated volcaniclastic material.	DNR-103	Sampled from boulder/crushed pile to right of working face. Care taken to avoid sampling the tuffaceous brecciated material, which is likely overburden.	19.6	2
Site 4 Eva	46.73595 -122.74630	Bucoda; on private timber road off of Big Hanaford Dr	Eocene andesite—porphyritic with 20–25% subhedral feldspars 1 millimeter to 1 centimeter in diameter that are altered to clay on exposed surfaces; <5% subhedral pyroxene (orthopyroxene?) <1 millimeter diameter. Outcrop is predominantly unweathered with massive to crude entablature colonnade in the center.	DNR-104	Sampled from crushed pile to right of working face. Care taken to avoid sampling the tuffaceous overburden, which was mixed in during mechanical sorting.	18.3	5
Site 5 ΦEva$_g$	46.46850 -122.53704	Silver Creek; W 2000 Rd off Salmon Creek Rd	Oligocene–Eocene basalt to basaltic andesite—porphyritic basalt to basaltic andesite with 5% euhedral 1-centimeter clinopyroxene and trace <1 millimeter iron-titanium oxides; includes cobbles of an earlier basalt to basaltic andesite within the flows. Outcrop has minor weathering throughout, with moderate to advanced weathering along one side. Massive with well-developed vertical and horizontal cooling fractures. Vertical fractures may have greater degrees of alteration and weathering of basalt to clay likely from hydrothermal action.	DNR-105	Sampled from scree in front of the working face.	12.2	58

Site and geologic unit	Location (lat/long)	Nearest town; access road	Geologic description	Sample number	Degradation sample notes	LA abrasion test result	LA wet-degradation test result
Site 6 ~~M~~Φvb	46.50171 -122.09570	Glenoma; NF-240 off Falls Rd	Miocene basalt—phaneritic with 60% pyroxene (both clino- and orthopyroxene), 20–30% feldspar, 10% olivine, and trace oxides. All crystals are euhedral to subhedral and 1 to 5 millimeters in length. Exposed surfaces show minor alteration of feldspar and olivine to clay, making modal identification difficult. Outcrop has minor to moderate weathering, with one side of the pit showing prominent development of basalt blocks into boulders; remainder of the pit is unweathered. Central part of the outcrop has well-developed 0.5-meter-diameter entablature colonnade.	DNR-106	Sampled from crushed rock pile separated from the working area.	22.3	23
Site 7 ~~M~~Φva	46.75161 -122.20924	Elbe; DNR forest road off Pleasant Valley Rd	Miocene basaltic andesite—Rust red to brown to white; predominately aphanitic with <5% iron-titanium oxides and 1- to 2-millimeter euhedral pyroxene (orthopyroxene?). Samples had abundant microfractures and veins; veins are stained much darker then the rock. Rock and vein coloration likely represents moderate to intense leaching of Fe, Mg, and Mn oxides. Outcrop is moderately to heavily weathered; heavily fractured and jointed with occasional, wide near-vertical fractures (faults?) with intense alteration of basalt to clay and realgar/cinnabar.	DNR-107	Sampled from shot pile on the left side of the pit.	16.1	57