ROCK AGGREGATE RESOURCE INVENTORY MAP OF PIERCE COUNTY, WASHINGTON

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Contents

FIGURES

TABLES

MAP SHEET

Rock Aggregate Resource Inventory Map of Pierce County, Washington

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INTRODUCTION

Background

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. After significant population growth over the last several decades, Pierce County is an area where natural resources could be threatened by uncoordinated and unplanned growth. This publication seeks 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.

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). The largest market share of this aggregate is produced within Pierce County and is used by the metropolitan areas of Seattle and Tacoma.

Pierce County is located in western Washington and covers an area that includes the southern Puget Sound up to the crest of the southern Cascade Range (Fig. 1 and map sheet). As of the 2010 federal census, the population of the county was approximately 795,225, and is concentrated near the city of Tacoma. Pierce County ranks as the second-most populated county in the state after King County.

Intended Audience

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 also benefit engineers, transportation departments, and industry by identifying sites geologically feasible for mine development.

Primary Products

This inventory consists of the following products:

- A map 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 report that provides an overview, geologic context, and a summary of the aggregate resources (this pamphlet).
- A glossary of terms used in this report (Appendix A).
- A complete discussion of the methods used in this study (Appendix B).
- Tabular data that contains the location, thickness, and quality of sand, gravel, and bedrock resources based on well logs, mine permit files, and aggregate source testing (companion Microsoft Excel file).
- Brief descriptions of geologic units known to contain aggregate resources (Appendix C).

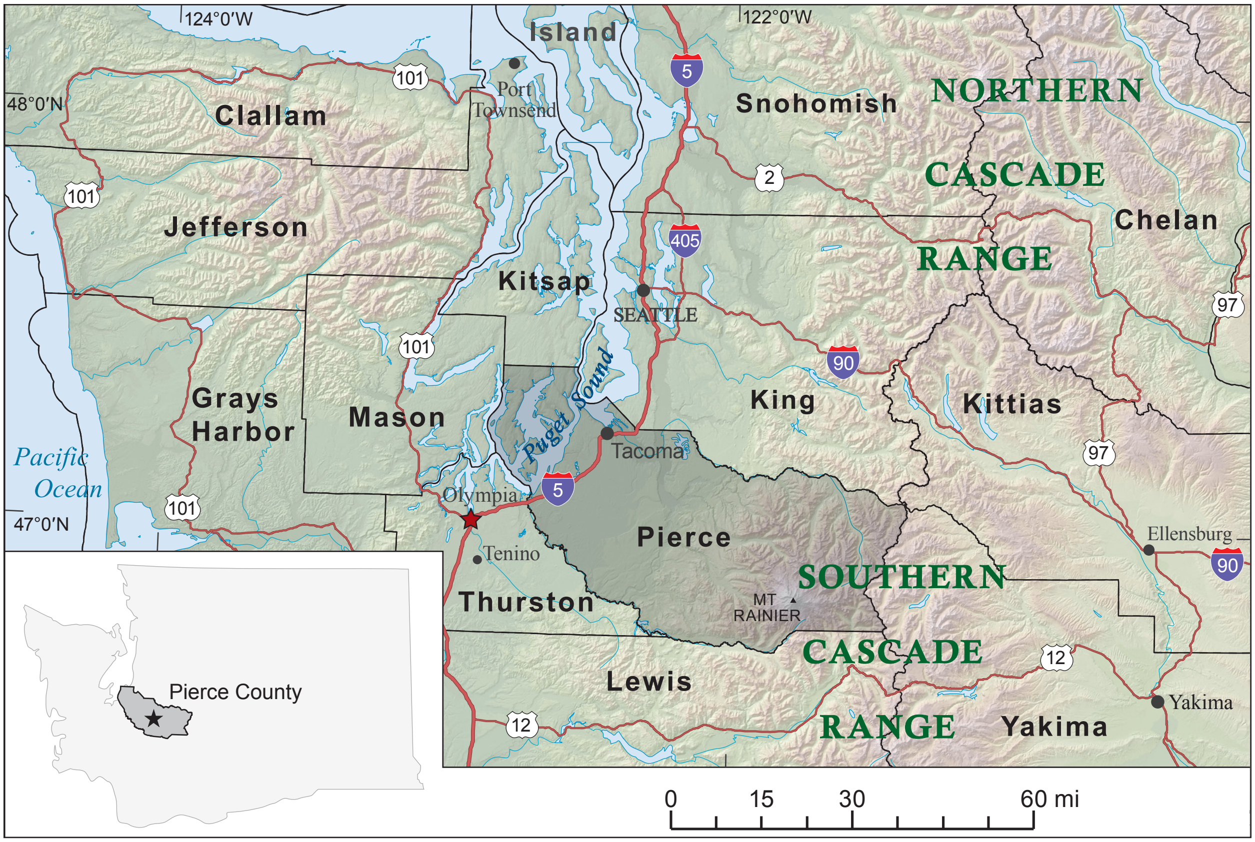

Figure 1. Pierce County includes parts of the southern Cascade Range and its foothills, Puget Lowland, and southern Puget Sound.

Accuracy of Estimates

This report is an estimate of the amount of construction aggregate within Pierce County that is available under current market conditions. Over- or under-estimation of aggregate resource can result from factors such as land-use restrictions, shallow bedrock under surficial gravel, diminishing rock quality with depth, areas of unmapped thick overburden, and lateral geologic variation. Similar studies have shown that in most cases overestimation of the amount of recoverable aggregate is more likely (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 resources 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 might force producers to mine lower quality deposits. Homes and infrastructure constructed with weak gravel or bedrock are likely to have shorter life cycles

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%

than those constructed with higher-quality aggregate. We have not inventoried these lower quality deposits because they do not meet the criteria of this study. However, the tabular data in this publication will serve as a guide to the locations of some resources of poor or uncertain quality, and those that are buried below thick overburden layers that may become more attractive under future market conditions.

Scope of Deposits Inventoried

We have inventoried all deposits in the county meeting 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 and the Clearwater, Glacier View, and Norse Peak wilderness areas were not included in the inventory because they have federal protection that restricts commercial development. In addition, river flood plain (alluvial) deposits have historically been a major gravel resource and numerous alluvial mines still operate along rivers in other regions of the state. In Pierce County, however, no mines currently operate in flood plains, and future mining operations will likely encounter difficulty obtaining permits because alluvial mining can cause adverse impacts to aquatic and riparian habitat (Norman and others, 1998).

Previous Aggregate Resource Studies

Gence (1934) mapped gravel resources exposed at the surface in parts of King and Pierce Counties, but did not assess the engineering properties or the subsurface extent of these deposits. Huntting (1982) also listed the resources of major sand and gravel producers and discussed general aspects of the sand and gravel industry in the Puget Lowland. White and others (1990) presented the results of a regional market study of the western Washington sand and gravel industry. Lingley and others (2002) mapped a small portion of the northeast corner of Pierce County for aggregate resources. Our new study modifies some of the designated resources from Lingley and others (2002) on the basis of additional data. Pacific Lutheran University School of Business (PLUSB) (2003) provided a market analysis for the Washington aggregate industry and their methods were used, with updated census data, for the present study.

GEOLOGY OF AGGREGATE RESOURCES IN PIERCE COUNTY

Numerous igneous intrusions, volcanic lava flows, and glacial processes resulted in remarkably large volumes of sand, gravel, and bedrock in Pierce County that have moderate to excellent characteristics for use in construction aggregate. Large gravel mines in the county were developed to supply aggregate to the metropolitan areas of the Puget Lowland for use in portland cement concrete or asphaltic cement concrete. Small mines in the eastern part of the county were developed to serve the needs of the forest-production industry in the foothills and mountains of the Cascade Range. These small mines typically produce aggregate from the andesitic or basaltic volcanic rocks that are common in the mountainous areas. Development of intrusive igneous rocks, such as granodiorite, has the potential to yield enormous volumes of aggregate. However, because the cost of transport doubles for every 25 miles traveled (PLUSB, 2003), and these resources are generally in remote regions, they will likely remain uneconomic for some time.

Sand and Gravel Geology

Ice-age continental glaciers provided the majority of large sand and gravel deposits in the county. These sheets of glacial ice advanced from the north and covered the entire Puget Lowland on at least four occasions during the past 1.6 million years. The latest advance was the Vashon Stade of the Fraser Glaciation. The Puget lobe of this glaciation (the part of the glacier that covered the Puget Lowland) terminated its advance south of the county near

Tenino (Fig. 1) about 14,000 years ago (Walsh and others, 2003). Older continental glaciers traveled somewhat farther south and west. Secondary deposits of aggregate include modern river deposits, known as alluvium, and constitute a minor amount of sand and gravel resource in the study area.

Sedimentary processes related to the Vashon ice sheet resulted in two layers of potential construction aggregate that are separated by a clay-rich layer that is non-commercial. The lower layer is known as ‘advance outwash’ (unit Qga) and is commonly suitable for finer grained aggregate. In Pierce County, advance outwash consists of well-bedded sand, subordinate gravel and cobbles, and a base that is commonly silty or clay-rich. These rock types were deposited by glacial streams many miles from the edge of the glacier.

A non-commercial layer called ‘till’ (unit Qgt) was deposited as the ice progressively covered more of the Puget Lowland and overrode the advance outwash. Till is deposited directly along the margins of and underneath glaciers and consists of a mixture of unsorted clasts of various rock types supported in a compact matrix of clay, silt, and sand. Locally this has resulted in hummocky topography, evident in both topographic maps and aerial photography. Till is unsuitable for construction aggregate and commonly constitutes a thick overburden on top of advance outwash gravel that may otherwise be an acceptable resource.

The recession of the Puget lobe marked the end of the Vashon Stade, and streams from the shrinking ice flowed across the surface of the till. These streams deposited the third layer, ‘recessional outwash’ (unit Qgo), which is composed of sand, gravel, and boulders and constitutes the most important sand- and gravel-producing unit in Washington. Three types of recessional outwash are present in the study area: channel, deltaic, and kame deposits; these are discussed in more detail below. In Pierce County, recessional outwash is composed mostly of gravel clasts that originated from granitic sources in British Columbia, with fewer volcanic igneous clasts sourced from the Cascades (Armstrong and others, 1965). These generally clean and durable gravels are made into a variety of high-quality rock products. The overburden on these deposits may consist of wind-blown silt (loess), modern alluvium, and (or) peat.

Channel and delta deposits were created during an extensive reorganization of the rivers in the Puget Lowland. Each time an advancing sheet of ice passed present-day Port Townsend, the ice blocked the northern end of Puget Sound and isolated the area to the south from the Pacific Ocean. This blockage forced rivers from the Cordilleran ice sheet and the Cascade Range to divert along the western edge of the Puget Lowland and flow southwestward to the Pacific Ocean at Grays Harbor (Bretz, 1913; Thorson, 1980). This huge drainage system carved numerous southwest-trending channels and deposited extensive high-quality boulder and gravel channel outwash. Proglacial lakes (lakes that formed in front of the glacial ice) also formed at this time, and several rivers formed deltas as they deposited sand and gravel into these lakes. Two of these deltas (one near Steilacoom—now depleted by mining—and another near Dupont) contain high-quality construction aggregate, which has served the metropolitan areas of Seattle and Tacoma for several decades.

A ‘kame’ is a deposit that formed in contact with glacial ice and can be a source of aggregate. The retreat and break-up of the Puget ice lobe created hummocky kame fields and eskers as meltwater flowed over and under stagnant ice, depositing fluvial sand and gravel. Additionally, kame terrace deposits formed at the margin of ice sheets where the ice was in contact with confining topography. These deposits typically consist of fine- to coarse-grained gravel and irregular or distorted beds of poorly sorted sand and gravel and are particularly abundant on the northeast side of the Puyallup River and near McKenna.

Since the end of the last ice age, modern streams and rivers have eroded glacial sediments and bedrock, transporting and re-depositing them as alluvium. As a result, alluvial deposits (unit Qa), like outwash deposits, 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 Pierce County, the quality of aggregate varies because the alluvial deposits contain a mixture of durable granitic clasts reworked from Vashon recessional outwash and more weathered, weaker, volcanic clasts from the southern Cascade Range. Because mining of alluvium from river flood plains has adverse impacts to aquatic and riparian habitat (Norman and others, 1998), these sand and gravel deposits may encounter difficulty with permitting and development.

A locally important source of sand and gravel in Pierce County is gravel deposits of pre-Vashon age (older than ~14,000 years). While these older deposits typically do not pass WSDOT specifications because of weak to moderate oxidation, there are some less-weathered locations that do pass degradation tests. These less weathered deposits are found in the northern bluffs and cliffs along the Hylebos Waterway and Puyallup River and in the western bluffs of the White River channel. While economically important in these areas, adequate test data is critical when considering these deposits at a county scale, as the degree of weathering—and thus rock quality—can change rapidly over relatively short distances.

Bedrock Geology

During the last 50 million years, lava flows from eruptions in the central Cascade Range spread over large areas and cooled quickly to form finely crystalline volcanic rocks. Unlike southwestern Washington, where most lava was extruded on the sea floor and rapidly altered to weaker materials, volcanic rocks in eastern Pierce County were extruded on land, preserving their original strength. 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 contain columnar jointing or vertical palisades that have characteristic hexagonal cross sections. Hard and durable volcanic flows commonly crop out as flat-topped cliffs. These rock types are abundant throughout Pierce County and may become an important source of aggregate in the future.

Another extensive and important type of bedrock in Pierce County is intrusive igneous rock. This rock type is mostly coarsely crystalline and formed when magma cooled slowly at great depth. Since formation, it has subsequently 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 limitations to the depth of aggregate mining are excavation technology and slope stability at the working face.

Other bedrock units found in Pierce 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, siltstone, mudstone, and coal and rarely pass durability standards. These rocks are often highly chemically reactive, which also makes them unsuitable for use in road-grade aggregate and portland cement.

AGGREGATE MINING AND SIGNIFICANT DEPOSITS

The maximum estimated volume of geologically available sand and gravel resource for Pierce County is approximately 12.6 billion tons of material for the indicated resource areas. This maximum estimate was calculated using rock quality from aggregate test data and interpolated thickness estimates from mines and wells (Fig. 2) and does not take into account current land use or reserved/protected lands. Of the total 12.6 billion tons, only 1.61 billion tons of resource are permitted and available in Pierce County. This estimate represents an absolute maximum that does not account for material loss due to slope or mine setback requirements, overburden, or volume of material removed since permitting. Assuming (1) a usage rate of 10.2 tons per capita calculated from PLUSB (2003) to account for the population density of Pierce County, and (2) projected population growth that uses the 2010 county-wide population of 795,225 and projections until 2040 from the Office of Financial Management (2012), currently permitted sand and gravel resource will last until 2125. The total resource life, however, is likely to be shorter for at least two reasons: (1) an improving economy would likely mean an increase in per capita usage, and (2) a significant portion of the total resource may be unrecoverable for various permitting reasons or could be exported to nearby markets (as indicated by current practices).

As of 2014, there are 26 active (4,170 acres total) and 58 terminated or inactive mines (2,136 acres total) in Pierce County as well as 361 disturbed areas (2,720 acres total) indicative of large abandoned aggregate mines and pits. These disturbed areas represent mining locations that existed prior to the 1970 Surface Mine Act (Chapter 78.44 RCW) or are locations where small quantities of sand, gravel, and (or) rock have been removed for local use. The geologic units that produce the largest amount of aggregate in Pierce County are recessional outwash (unit Qgo, 760 million tons), advance outwash (unit Qga, 470 million tons), and ice-contact (kame) deposits (units Qgic and Qgik, 229 million tons). Table 2 provides a breakdown of the number and size of mines by region and geologic unit.

Advance outwash deposits are most often located in cliffs and bluffs of Puget Sound and river channels (Fig. 3). While these deposits have historically contributed a significant amount of aggregate to the region, their mapped extents are limited. The largest concentration of economically significant advance outwash deposits is in the northern and western cliffs of the Puyallup and White River channels. In these locations, erosion by the

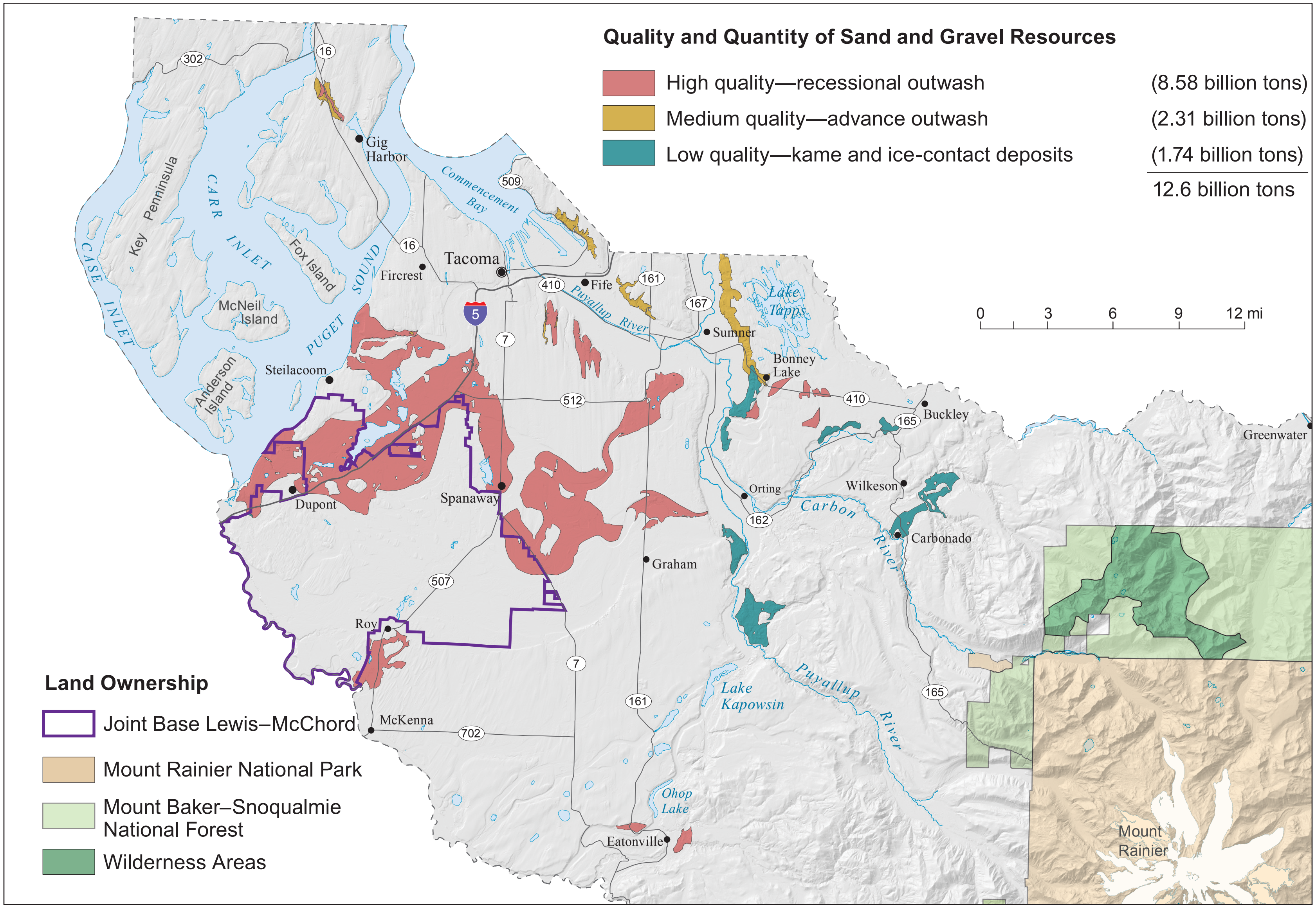

Figure 2. Maximum estimated volumes of indicated sand and gravel resources. Quality of the deposit is a relative assignment based on whether it is likely that the material would pass WSDOT testing specifications and the potential amount of clay and silt that may be present in the deposit.

Table 2. Number and size of permitted aggregate mines in Pierce County by region and major geologic unit. Tons are 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 igneous rock (2.44 tons/yd^3).

Location	No. of sites (permitted)	Acreage	Max volume (millions of yd^3)	Max weight (millions of tons)
West of Tacoma Narrows	2	78	13.2	18.3
Between Tacoma Narrows and Puyallup River	14	2,235	361.5	559.5
East of Puyallup River	9	1,806	770.8	1177.3
Major Geologic Unit				
Recessional outwash (unit Qgo)	9	2,132	547.0	760.3
Ice-contact deposits and kames (units Qgic and Qgik)	4	267	105.3	146.4
Advance outwash (unit Qga)	8	682	338.3	470.2
Intrusive andesite (unit MΦian)	2	538	60.7	148.1
Basaltic andesite to andesite flows (ΦEv$_{ba}$)	2	500	94.4	230.3

modern river has removed much of the overlying till and exposed the advance outwash deposits. Elsewhere, in the outwash plain of central Pierce County, well logs and limited surficial mapping provide evidence that advance outwash directly underlies recessional outwash where the intervening layer of till has been scoured away. In many other areas, however, advance outwash is often unrecoverable because a thick layer of non-producing till separates it from the overlying recessional outwash. Additionally, the likelihood of developing the advance and recessional outwash in central Pierce County is uncertain because of current land-use restrictions on Joint Base Lewis–McChord (JBLM) and because of urban encroachment.

Recessional outwash deltas (unit Qgo) that were created at the margins of proglacial lakes contain the largest and highest-quality sand and gravel deposits in Washington (Lingley and Jazdzewski, 1994). This type of geologic deposit is present in three locations in Pierce County: on the east shore of Puget Sound at Dupont and Steilacoom and on the eastern bluff of the Puyallup River at Fennel Creek. The Dupont and Steilacoom mines have historically produced a majority of the sand and gravel used in the Seattle–Tacoma metropolitan area as well as the entire Puget Sound area through a barge-based transport system. Channel-based gravel deposits occur east of the proglacial lake delta deposits. These channels are prevalent throughout central Pierce County and can contain tens to hundreds of

Figure 3. Advanced outwash sand and gravel mine in Pierce County.

feet of sand and gravel interspersed with till 'islands', ice-contact deposits (unit Qgic), and peat. Of the resources identified in this study, channel-based gravel deposits have the largest untapped potential. However, between the restricted land access on the JBLM military reservation and urban encroachment from the Tacoma metropolitan area, many of these significant deposits are unavailable for development.

Ice-contact (kame) deposits occur in areas where glacial ice broke off of the main ice sheet and melted in place, creating localized sand and gravel deposits. Geomorphic features such as kettles, kames, and eskers are common indicators of ice-contact deposits and can serve as aggregate resources. This deposit type is the third largest in terms of historically permitted mine acreage. These deposits are locally significant on the Key Peninsula where several permitted mines are producing from moderately sized eskers. Most of these deposits, both currently permitted and untapped potential resources, are located on the west bank of the Puyallup River and along the South Prairie Creek channel. However, due to the lack of sorting and highly variable grain size of ice-contact deposits there is a large degree of uncertainty in the quality of this resource. Localized pockets of clay and silt-rich till are common in these deposits and emphasize the need for site-specific reconnaissance and aggregate testing prior to development.

Large-scale mining of bedrock is fairly limited in Pierce County. To date, only five bedrock mines are permitted, though hundreds of small borrows and pits have removed bedrock for local forestry road-building. Of the five permitted mines, two mine intrusive andesite exposed along the Puyallup River, as well as opportunistically retrieving sand and gravel from ice-contact deposits that are local overburden. Two additional mines produce from basaltic-andesite, one in the lower Puyallup River canyon and one east of the town of Wilkeson. Both also produce sand and gravel from ice-contact deposits. The fifth permitted mine produces from a bedrock sandstone unit that crops out just east of the town of Wilkeson. Although this sandstone has historically been used as a decorative stone for many buildings, including the capitol dome in Olympia, it is unsuitable for use as aggregate. Reconnaissance geologic mapping at 1:100,000 scale indicates that large volumes of bedrock aggregate exist just outside the National Forest and Mount Rainier National Park boundaries. However, distance from population centers and low market demand has made these rocks uneconomic for mining.

CONCLUSIONS

Pierce County has historically led the state as the largest producer of sand and gravel. This is largely owing to voluminous deposits of clean deltaic gravels found near Steilacoom and Dupont, though the deposit at Steilacoom is now exhausted and fully reclaimed. In central Pierce County, 8.6 billion tons of undeveloped resources exist where glacial processes have created a large outwash plain filled with channelized gravels. These deposits have limited potential, however, as urban development and restricted land use limit their availability. Western Pierce County has limited aggregate availability (103 million tons), and most of these sand and gravel resources have already been identified and developed. Future development of ice-contact deposits on the Key Peninsula may prove feasible pending land availability and market demand. Eastern Pierce County has the potential for developing abundant sand and gravel resources (4 billion tons). While currently developed on a limited basis, increased market demand and depletion of outwash gravels in central Pierce County may make the ice-contact deposits found in the eastern parts of the county more favorable. Eastern Pierce County also has the potential to produce abundant crushed rock from bedrock quarries. The scale of these bedrock resources is difficult to estimate because detailed mapping does not exist in these areas, and many source areas may have been overlooked in our analysis. However, available data suggest that bedrock resources could be plentiful, and the primary limitation to their development is mining technology and land-use practices. The development of these resources is expected to increase in the coming decades with eastward expansion of urban centers and increased market favorability due to depletion of currently permitted sand and gravel resources.

At the current yearly per capita usage of 10.2 tons and total permitted aggregate volume of 1.61 billion tons, Pierce County has a maximum of ~110 years of accessible aggregate. Factors that may shorten or lengthen the timeline for resource exhaustion include: changes in population growth, market flux and other economic drivers, additional permitting of aggregate resources for mining, and greater reliance on bedrock resources in east Pierce County.

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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, Cancelled, and Terminated permits).

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

Asphalt, hot-mix – 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 (256 millimeters) in diameter that has been somewhat rounded by abrasion during transport.

Breccia – A consolidated rock consisting of angular fragments (>2 millimeters) within a finer-grained matrix.

Cancelled 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 to 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 (0.002 millimeters) 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 (64–256 millimeters), that has been somewhat rounded by abrasion during transport.

Conglomerate – A consolidated rock consisting of rounded individual clasts (>2 millimeters) within a finer-grained matrix.

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.

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 sticks only 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.

Esker – A long and winding ridge of stratified sand and gravel formed by glaciers, examples of which are found in glaciated and formerly glaciated regions of Europe and North America. Eskers are frequently several miles in length and, because of their peculiar uniform shape, somewhat resemble railroad embankments.

Granite – A light gray or pink, coarsely crystalline (typically 1/8-inch crystals) 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 predominantly 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, termed ‘intrusive’) or lava (aboveground, termed ‘extrusive’). Crystallization may or may not occur in extrusive igneous rocks.

Inactive permit – A permitted mine that is depleted and the permit retained for purposes other than mining, such as stockpiling 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.

Kame – A hummock, terrace, or short ridge composed of stratified sand and gravel deposited at the margin of a glacier as a delta or fan. In Washington, the term is generally applied to landforms created by deposition in the low areas between the margin of a glacial ice sheet and the confining hills. After the ice has melted away, a high-quality sand and gravel deposit frequently remains.

Kettle – A landform that results from blocks of ice calving off the front of a receding glacier and becoming partially to wholly buried by glacial outwash. When the ice melts, a topographic depression remains and may fill with water and become a lake. The quality of the sand and gravel that surrounds these depressions may vary greatly over relatively short distances.

Limestone – A rock composed of the mineral calcite. Normally, these rocks are deposited in the ocean from materials that are by-products or remnants of shells. Limestone is an important source of construction aggregate in much of the nation.

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.

Outwash – Sand, gravel, and coarser round rock 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 the underlying material.

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.

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 dries 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 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.

Silt – Sediment composed of particles that are unconsolidated or poorly consolidated when dry and 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 weight of the substance relative to the weight of an equal volume of water, also known as density. The units of specific gravity are commonly in grams/cubic centimeter (g/cm^3). Some common specific gravities are water (1.0 grams/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 blanket 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 – Rocks that are composed solely or primarily of volcanic materials and have 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.

Appendix B. Methods

Inventory Methods

Two end-member philosophies for resource inventory could be used: (1) strictly factual reporting that shows only those sand, gravel, and bedrock resources that have been 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 and show these results on the map sheet. The most widely available source of subsurface geological data for mapping hypothetical reserves is water-well logs, but the accuracy of information on these logs is generally poor and can even be misleading, depending on the knowledge, skill, and care taken by each well driller as they complete their report. 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 and (or) weathering and the low strength of some rock types (such as claystone or layered sedimentary

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.

or metamorphic rocks) make some deposits unsuitable for construction aggregate. Furthermore, extraction or 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, and the value of the 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 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 pit run 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 and increasing acreage.

SURFACE AREA AND DIMENSIONS OF THE DEPOSIT

Few gravel deposits are more than 100 feet thick, and consequently, the deposit must cover an area large enough to contain significant volumes of construction aggregate. The smallest geologic areas inventoried as significant gravel resources cover at least 0.25 square miles (160 acres). The volume of a 50-foot thick gravel unit of this size would be about 10 million cubic yards. Additionally, we map only those deposits that have a minimum map distance dimension of 1,500 feet unless it is included as a portion of—or proximal to—a much larger resource body. As suggested above, deposits with long, narrow map patterns are generally inefficient to operate. Although this study does not consider most environmental issues, long, narrow deposits are generally associated with rivers or streams where mining cannot occur owing to environmental considerations.

Geologic maps provide an initial estimate of the surface area of each deposit. Reduction of these initial areas, or placement into a lower-confidence resource classification (Table B1), occurs when some portion of the deposit fails to meet the threshold criteria. Most of the geologic areas depicted on this compilation 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 was taken to expedite the inventory process and may have resulted in the omission of a few significant resources, for example areas on the Key Peninsula and near McKenna that lack testing and thickness measurements for ice-contact deposits.

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 (DGER surface mine inspectors, 2014, oral commun.). 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 (DGER surface mine inspectors, 2014, oral commun.). 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 Pierce 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 with laboratory tests, including the Los Angeles 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 no. 200 sieve. These tests are often no longer conducted when considering an aggregate source because the proper proportion of sand and gravel is blended on site (DGER surface mine inspectors, 2014, oral commun.).

For this study, we inventoried gravel and bedrock that meet WSDOT specifications for hot-mix asphalt (HMA) wearing course (Table 1). HMA is a compacted layer of aggregate treated with asphalt for stability, weatherproofing, and placed directly on bulldozed earth or rock of the 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 differs from previous aggregate studies—the category for asphalt-treated base no longer exists in the 2014 specification manual.

Sources of Data

Data for currently active and terminated mines exist in DGER permit files (2010) and WSDOT aggregate source approved sites (WSDOT, 2013). DGER 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 depicted on DGER geologic maps within Pierce County (Logan and others 2003, 2006; Logan and Walsh, 2007; Polenz and others, 2009a,b; Walsh and others, 2003a,b), U.S. Geological Survey maps (Booth and others, 2000; Booth and Troost, 2005; Gard, 1968; Mullineaux, 1965; Savoca and others, 2010), a Washington State Department of Ecology (WADOE) map (Walters and Kimmel, 1968), and maps from Kathy Troost (University of Washington, written commun., 2014).

Hydrologic studies are particularly useful in assessing the stratigraphy of gravel deposits. Such reports are included in various types of environmental documentation, wellhead protection studies, and water-resource reports. 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 WADOE (2013), the Tumwater Materials Office of the WSDOT (2014, written commun.), and the DGER Subsurface Database (Jeschke and others, 2014).

Current and historical WSDOT test data is available through the Aggregate Source Approval page of the WSDOT website (WSDOT, 2013, http://www.wsdot.wa.gov/biz/mats/ASA/ASASearch.cfm). One aggregate and six crushed rock samples were collected by DNR employees during the summer of 2014 and tested at Mayes Testing Engineers, Inc., Lynnwood, WA, and 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 potential to produce gravel or rock meeting the threshold criteria. This list is based on a reconnaissance investigation, and therefore appreciable amounts of aggregate may be locally present in units 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.

The rock and sediment descriptions listed below are synthesized from the most recent geologic maps of Pierce County (Booth and others, 2004; Booth and Troost, 2005; Gard, 1968; Logan and others, 2003, 2006; Logan and Walsh, 2007; Mullineaux, 1965; Polenz and others, 2009a,b; Savoca and others, 2010; Schasse, 1987a,b; Tabor and others, 2000; Troost (2014, written commun.); Walsh, 1987; Walsh and others, 2003a,b; Walters and Kimmel, 1968). Unit symbols are those used by the Washington Geologic Information Portal (DGER, 2014) and may differ from the original map publication.

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. Historically, 1 mine and 13 pits have produced from this unit, though no permitted mines now exist or 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 lithic fragments 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 Qgo_g and Qgo_s, representing greater concentrations of gravel and 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 typically produces very clean and high-quality aggregate and is one of the most productive units in the county with 34 mines and 161 pits current or historically active. Locally subdivided into:

Qgo_g **Vashon Stade recessional outwash gravels**—Mostly gravel with a clean, sandy matrix; grades to or includes lenses and beds of sand and silt; gray to tan, locally iron-stained to red and yellow, but clasts and grains typically unweathered; clasts are moderately to well rounded and moderately to well sorted; unit is loose and generally less compact than, but in some exposures difficult to distinguish from, advance outwash gravel (unit Qga); typically 10 to 50 feet thick. Geomorphic relations suggest that thickness may locally exceed 100 feet.

Qgic **Vashon Stade ice-contact deposits**—Mixture of deposits from both dynamic-ice and dead-ice environments. Dynamic-ice deposits include lodgment till, drumlins, and advance outwash; dead-ice deposits include ablation till, subglacial water-flow deposits (such as eskers), and recessional outwash; typically lacks thick, continuous, or widespread deposits of lodgment till at the ground surface, though small till exposures and detrital till fragments are common; topography formed by a mix of subglacial, ice-marginal, and recessional processes. The unit provides an aggregate source locally, though the variable nature of the unit limits certainty of deposit quality. Mining of this unit often occurs in conjunction with other aggregate units, such as units Qgo and Qgo_e. Two mines are currently producing from this unit and 11 pits produced historically. Locally subdivided into:

Qgo_e **Vashon Stade recessional outwash (eskers)**—Loose sand and gravel; tan to gray; moderately to well sorted and rounded; consists of sediment rich in plutonic, volcanic, and metamorphic clasts and polycrystalline quartz; deposited by Vashon-age meltwater in areas occupied by stagnant ice; forms low, elongate, sinuous hills in recessional outwash channels;

stratigraphically overlies Vashon-age till. It is not a primary aggregate source despite its high quality sand and gravel, due to the long, sinuous nature of the deposits. It becomes an economically viable deposit when adjacent to other aggregate-rich units that expand the square acreage of a deposit.

Qgik **Vashon Stade ice-contact kame deposits**—Includes both kame deposits of pebble gravel and sand in irregular mounds and kame terrace deposits of sand and pebble to cobble gravel in terraces whose surfaces locally are deformed by post-emplacement settling. The unit is prevalent on the eastern side of the Puyallup River channel and along South Prairie Creek. The unit provides an aggregate source locally, though the variable nature of the unit limits deposit certainty over relatively short distances. Five mines are currently producing from this unit, and one mine and nine pits produced from this unit historically.

Qga **Vashon Stade advance outwash**—Pebble to cobble gravel composed mostly of polycrystalline quartz, plutonic rock, and minor metamorphic rock; additionally 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; compact and resistant to erosion, except where 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 unit Qgt along a sharp, unconformable contact. This unit may occasionally be subdivided into unit Qga_s in areas where sand is the dominant constituent of the unit. Unit Qga is second in terms of production, with 7 mines and 1 pit active and 28 mines and 41 pits historically.

Qpg **pre-Fraser glacial deposits**—Weakly to moderately oxidized sand and gravel, lacustrine sediments containing local peat layers, and moderately to strongly oxidized diamicton composed of silty matrix and rounded gravel clasts. Concentrated deposits of sand and gravel locally occur in pre-Fraser outwash. The unit may also include nonglacial deposits of approximately the same age. Oxidation and weathering generally make this unit unsuitable for aggregate resources; however, economically viable deposits of less weathered materials exist locally. Mining of this unit is extensive in localized areas of minor weathering adjacent to deposits of unit Qga. At sample site 1 (*see* map sheet and Appendix D) in the hillside north of the Port of Tacoma, this unit passed both LA abrasion and degradation tests and has proved an excellent local source of aggregate. This unit had historic production from 4 mines and 13 pits.

Quaternary Igneous Rocks

Qva_{mr} **Andesite of Mount Rainier**—Late Pleistocene; chiefly gray porphyritic hypersthene-augite-pyroxene andesite; exposures of this unit near Hwy 165 are the northwestern extent of thick intra-canyon flows from an early stage of Mount Rainier; flows form massive 300-foot-high cliffs and expose columnar and platy jointing along the Mowich and Puyallup Rivers. Though only two pits have produced from this unit, this relatively fresh volcanic unit should provide adequate-quality rock for aggregate use. Although a DNR-sampled test (site 9) did not pass WSDOT specification for degradation, it is not uncommon for basalt and basaltic andesite samples to have widely variable degradation factors. For this reason, a single negative test does not preclude the unit from a speculative aggregate resource designation.

Qvb_c **Basalt of Canyon Creek**—Light-gray olivine basalt; locally vesicular. Olivine phenocrysts are partially altered with iddingsite rims and occur within an intergranular groundmass of plagioclase microlites, clinopyroxene, opaque minerals, and olivine.

Pliocene Igneous Rocks

Pvb_{dr} **Basalt of Dalles Ridge**—Light gray pilotaxitic basalt flows. Phenocrysts of olivine are partially to completely altered to iddingsite and occur within a groundmass of plagioclase, clinopyroxene, olivine, and opaque minerals.

Miocene Igneous Rocks

Mia$_{tr}$ **Tatoosh pluton**—Undifferentiated diorite, quartz diorite, granodiorite, and quartz monzonite porphyries with subordinate amounts of microgranite, porphyritic granophyre, and felsite; aphanitic to medium-grained, commonly porhyritic and granophyric and is locally hydrothermally altered; occurs as swarms of sills, dikes, and irregular small intrusive bodies clustered mainly near the borders of the Tatoosh pluton and associated stocks; also concentrated along contact between Ohanapecosh-Stevens Ridge Formations; sill near Chinook Pass is 25.8 Ma (zircon U-Pb).

Mian **Intrusive andesite**—Dark to medium gray, aphanitic to porphyritic pyroxene and hornblende andesite and basaltic andesite; forms numerous dikes, sills, small plugs, and stocks. No production has occurred with this unit to date, nor is test data available; however, lithologic description and proximity to developing areas suggest it may be favorable for rock and aggregate use.

Migd$_{cr}$ **Carbon River stock**—Early Miocene; chiefly pale greenish-gray uralitized equigranular to porphyritic biotite-hypersthene-augite granodiorite; bordered by a zone of pyroxene quartz diorite (tonalite) and an aureole of pyroxene andesite dikes; related to the Tatoosh pluton. Though it has never been mined, the physical properties of this unit indicate that it would make an excellent source of aggregate. This is confirmed by a DNR-collected sample (site 8) that passed the LA abrasion and degradation tests.

Mii **Intermediate intrusive rocks**—Sills and dikes of light gray to creamy tan flow-banded latite; xenoliths are common; well jointed, breaks into platy fragments; plagioclase is dominantly oligoclase, and quartz is absent; intrudes the Northcraft Formation.

Mit **Tonalite**—Uralitic pyroxene tonalite with hypersthene and clinopyroxene; rarely grades to granodiorite or quartz diorite. Most outcrops are plagioclase-pyroxene phyric and have fine-grained hypidiomorphic granular texture; quartz is interstitial and commonly mesostasic. Some outcrops are texturally transitional to pyroxene andesite porphyry. Small intrusions on Dalles Ridge are quartz-bearing olivine-pyroxene gabbro. Many small tonalite masses may be satellites of the Snoqualmie or Tatoosh batholiths. Tonalite bodies may also grade into dacite porphyry. Some areas mapped as tonalite may be made up of closely spaced dikes.

Mva$_{fp}$ **Fifes Peak Formation**—Basaltic andesite, basalt flows, and flow breccia; flows are generally dark red, dark green to dark gray, or black; locally contains flow banding, columnar jointing, vesicular tops, scoriaceous and amygdaloidal zones, and minor zones of drusy quartz. The unit also contains massive to well-bedded polymictic tuff and breccia and rare monomict tuff and breccia with andesite clasts. Textures are trachytic, intersertal, or intergranular. Porphyritic to microporphyritic andesite contains plagioclase (20–30%), hypersthene (5–15%), and clinopyroxene in a reddish brown glass. The glass contains plagioclase microlites, pyroxene, opaque minerals, and secondary smectites, hematite, calcite, and quartz. Black basalt contains plagioclase ± pyroxene microphenocrysts and altered olivine in the groundmass. Rocks of the Fifes Peak Formation locally contain some heulandite, clay, chlorite, and quartz alteration products. This alteration is especially prevalent in areas proximal to the intrusions of the rhyolite of Clear West Peak (see below). Nineteen pits have produced from this unit for construction of local forest roads. Test results from DNR-collected samples (sites 5 and 7) indicate that a fresh, unweathered exposure of basalt–basaltic andesite narrowly failed the LA abrasion test; a separate moderately weathered and hydrothermally altered sample passed the abrasion test, but did not pass the degradation test. It is common for basalt and basaltic andesite samples to have widely variable degradation factors. For this reason, a single negative test does not preclude the unit from a speculative aggregate resource designation, particularly when both LA abrasion tests and one degradation test passed.

Mir$_{fp}$ **Fifes Peak Formation, rhyolite of Clear West Peak**—Rhyolite dikes, sills, plugs, domes, and shallow stocks; commonly white to tan fine-grained felsite; may contain welded tuffs; mostly grey to purple, highly altered, sparsely plagioclase-phyric, and devitrified rhyolite with vertical banding. This unit has not been used for production of rock or aggregate, and test results on a DNR-collected sample (site

6) indicate that the unit does not pass degradation tests. The sample was taken from an exposure near the rim of an exposed intrusion; better quality rhyolite may be available closer to the intrusive core. Though no passable roads provided the opportunity to confirm this, we tentatively consider this unit a speculative aggregate resource.

Mvba$_1$ **Basaltic andesite flows**—Chiefly dark-colored augite-hypersthene andesite flows; fresh platy non-vesicular flows occasionally display columnar jointing. Though only one pit has produced from this unit, test results from a DNR-collected sample (site 10) indicate that the unit passes both LA abrasion and degradation requirements and should provide an excellent source of aggregate in the future.

Miocene–Oligocene Igneous Rocks

MΦiad **Intrusive andesite and dacite**—Dacite dikes, sills, or plugs; plagioclase-quartz-hornblende-phyric and fine-grained chloritized and silicified andesite or dacite; cuts rocks of Eocene through lower Oligocene age; may have been feeders for Miocene volcanic rocks. Weathering and chloritization may limit use of the unit for aggregate. Two pits have historically mined this unit.

MΦian **Intrusive andesite**—Andesite and andesite porphyry dikes, sills, or plugs; abundant dark-colored plagioclase-pyroxene and hornblende-phyric andesite dikes, small plugs, and sills; grades locally into andesite porphyry and pyroxene diorite; commonly chloritized and argillitized; cuts rocks of Eocene through lower Oligocene age; may have been feeders for Miocene volcanic rocks. Two mines are actively producing from this unit and there are 16 historical pits.

MΦid **Intrusive diorite**—Diorite dikes, sills, or plugs; augite and (or) augite-hypersthene diorite dikes, sills, or plugs with fine- to medium-grained phaneritic texture; cuts Eocene rocks of the Puget Group and Northcraft Formation; may have been feeders for Miocene volcanic rocks. No mining or test data exists; however, the general physical characteristics of this unit indicate that it is a potentially useful aggregate source.

Oligocene–Eocene Igneous Rocks

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. The unit potentially provides a source of aggregate, though the interbedded marine and volcaniclastic layers may limit its usefulness. This unit is the most heavily mined bedrock resource and has 3 active mines, 9 historic mines, and 30 pits.

Appendix D. Field Notes from DNR Test Sites

The following is a list of locations that were visited to collect samples, perform competency tests, and improve existing geologic descriptions. Each site lists the age, geologic name, location, and a detailed hand sample and outcrop description. LA abrasion and degradation test results, where performed, are also listed. A full listing of county-wide competency test results is provided in the companion Microsoft Excel file.

Table D1. Field notes and degradation test results. ––– indicates no data.

Site and geologic unit	Location (lat/long)	Nearest town; access road	Geologic description	Degradation test sample number	Degradation sample notes	LA abrasion test result	LA wet degradation test result
Site 1 Qpg	North 47.297583 East -122.422251	Tacoma; Marine View Dr, just east of Heron Ridge Dr E	Pleistocene Possession outwash gravel—Consists of grain-supported clean gravel and sand with variable lithology; weak to moderate localized weathering; <10% silt. Cliff contains several minor sand beds or lenses between thick deposits of coarse gravel with crossbedding noted in several locations.	DNR-101	Sampled from cliff face with a shovel after the first couple inches of face material was removed. This removed abundant silts that clearly flowed down the face from overlying deposits during storm events and were not representative of the underlying deposit.	14.2	34
Site 2 Qga	North 47.299001 East -122.424163	Tacoma; Marine View Dr just east of Heron Ridge Dr E	Pleistocene Vashon Stade advance outwash—Consists of grain-supported clean sand and gravel of variable lithology with <5% silt. No notable weathering of clasts or matrix material observed. Exposure consists almost entirely of coarse gravel with only one bed/lens of sand.	–––	–––	–––	–––
Site 3 Qpg	North 47.298176 East -122.423168	Tacoma; Marine View Dr just east of Heron Ridge Dr E	Pleistocene Possession outwash gravel—Similar lithology to site 1, but with a higher degree of weathering; very clean clast-supported gravel with lenses of fine to medium sand.	–––	–––	–––	–––
Site 4 Qga, Qgic	North 47.221607 East -122.259093	Sumner; inside of mine CB-B-277, off West Valley Hwy East	Pleistocene Vashon Stade recessional outwash—Thick exposure of unit Qga in mine pit is similar to site 2. Possession-age unit Qpg mapped on south side of pit could not be sampled due to reworking and spread of reclamation grasses and volunteer alder. Vashon Stade ice-contact deposits (unit Qgic) exposed in lower pit wall along entry road have highly variable lithology with pods of matrix-bound coarse sand and gravel, fine sandy crossbeds, and massive to platy clay/silt. Unit Qgic was not sampled due to its high lithologic variability. While it could provide a locally important source of sand and gravel, the variability makes it unsuitable for the scope of this aggregate study.	–––	–––	–––	–––

Site and geologic unit	Location (lat/long)	Nearest town; access road	Geologic description	Degradation test sample number	Degradation sample notes	LA abrasion test result	LA wet degradation test result
Site 5 Mva$_{fp}$	North 47.148612 East -121.964327	Buckley; Hancock Forest Management Rd 9	Miocene basaltic andesite of Fifes Peak—Samples represent unweathered extrusive basaltic andesite that is phaneritic with plagioclase and pyroxenes; crystals are <1 centimeter and euhedral. Outcrop is predominately an entablature–colonnade portion (chaotic columnar jointing) of a lava flow with each column measuring 1 to 2 feet in diameter.	DNR-105	Sampled from crushed/shot rock pile inside of pit.	36.4	51
Site 6 Mir$_{fp}$	North 47.130022 East -121.808858	Greenwater; Hancock Forest Management Rd 6000	Miocene intrusive rhyolite of Fifes Peak—Rhyolite has platy jointing with abundant microfractures filled with secondary quartz. Contains porphyritic quartz, feldspar, and minor amphibole and biotite(?) with the biotite altered to epidote. Several hand samples include <3 centimeter xenocrysts of highly altered basaltic andesite/dacite. All samples show laminar flow structures. Outcrop is moderately weathered with planes of increased weathering and weakness along platy jointing.	DNR-106	Sampled from roadcut exposure along a forest road.	27.9	3
Site 7 Mva$_{fp}$	North 47.16721 East -121.796178	Greenwater; Hancock Forest Management Rd 6002	Miocene basaltic andesite of Fifes Peak—Sample is lithologically similar to sample at site 5; however, this location has experienced a high degree of hydrothermal alteration. Alteration seems prevalent in areas proximal to intrusive rhyolite (unit Mir$_{fp}$) and was noted along much of the haul road between sites 5 and 6. Alteration includes breakdown of mafic minerals to an epidote-rich groundmass that is partially replaced by silica (silicification).	DNR-107	Sampled from crushed/shot rock pile inside of forest road pit.	21.7	16
Site 8 Migd$_{cr}$	North 46.999732 East -121.917853	Carbonado; National Forest Rd 7810	Miocene granodiorite of the Carbon River stock—granodiorite is texturally massive, with abundant phaneritic euhedral plagioclase, minor amphibole, and biotite; contains large (0.5–2 feet) inclusions of altered aphanitic basalt to basaltic andesite. These mafic inclusions likely represent host rock or minor amounts of melt entrained by the stock. Crushed sample includes a manmade mixture of granodiorite and basaltic andesite (70:30) that represents the local ratio of these materials, but whether this is representative of the entire stock is unknown.	DNR-108	Sampled from pit. Crushed rock in the pit likely originated from processing of talus slopes from the main stock body.	15.7	57
Site 9 Qva$_{mr}$	North 46.928367 East -121.920149	Carbonado; Mowich Lake Rd	Quaternary andesite flow of Mount Rainier—Pit predominantly exposes texturally massive andesite with some entablature–colonnade jointing in upper portion (unreachable for measurement). Hand samples are weakly weathered aphanitic andesite.	DNR-109	Sample from crushed/shot rock pile in pit.	19.9	9
Site 10 Mvba$_1$	North 46.763126 East -122.19121	Elbe; Hwy 706	Miocene basaltic andesite flow—Roadcut exposes fresh texturally massive porphyritic basaltic andesite with 3 millimeter plagioclase and pyroxene glomerocrysts.	DNR-110	Sampled from a roadcut.	23.3	41