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Naturally Occurring Background Levels of Arsenic in the Soils of Southwestern Oregon

Heather Ann Hurtado
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Naturally Occurring Background Levels of Arsenic
in the Soils of Southwestern Oregon

by

Heather Ann Hurtado

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science
in
Geology

Thesis Committee:
Scott F. Burns, Chair
Adam M. Booth
R. Benjamin Perkins

Portland State University
2016
Abstract

This study examines the natural background concentrations of arsenic in the soils of southwest Oregon, using new samples in addition to data collected from previous theses (Khandoker, 1997 and Douglas, 1999). The original 213 samples were run by ICPAES with a reporting limit of 20 ppm, and only three samples had detected values. The original samples were tested again (2013) at a detection limit of 0.20 ppm by ICP-MS, as were 42 new samples (2013), to better ascertain the natural levels of arsenic in undisturbed soils. The aim is to add to the existing DEQ data set, which has been used to establish new regulatory levels based on natural levels in the environment that are both safer and more economically viable than the former risk-based remediation levels (DEQ, 2013).

The maximum and mean concentrations, respectively, for each province (with high formation map unit) are 85.4 and 21.99 ppm for South Willamette Valley (Tfee), 45.4 and 5.42 ppm for the Klamath Mountains (Jub), 11.9 and 2.76 ppm for the Cascade Range (Tbaar), 10.6 and 5.15 ppm for the Coast Range (Ty), 2.32 and 1.29 ppm for the Basin and Range (Qba) and 1.5 and 1.20 ppm for the High Lava Plains (Tmv).

In addition, the distribution and variance of arsenic in the A and B soil horizons is assessed in this study; one of 18 new sites sampled for this study (distinguished with the HH prefix), site HH11, was randomly chosen for this purpose. Site HH11 is an Inceptisol soil above volcanic rock (KJdv map unit) located at 275 meters elevation in Douglas County within the Klamath province. Five samples were taken from the A and from the B
horizons at site HH11. The mean and standard deviation, respectively, was 3.74 ± 0.44 for the A horizon and 4.53 ± 0.39 for the B horizon. The consistency and low deviation within each horizon indicate that a single sample within a horizon is a good representative of that horizon and supports the field methodology used in this study of taking only one sample in the A horizon and one sample in the B horizon. The Wilcoxon Rank-Sum test (p-value: 0.76) determined that A and B horizons for the 119 sites that had data for both the A and B horizons were not statistically different. However, 47 sites (39.5%) are higher in arsenic in the A horizon while 63 sites (52.9%) are higher in the B horizon, with 9 sites (7.6%) having no value detected. This is strong support for sampling in both the A and B horizons to ensure a sample is collected from the horizon with the highest arsenic value, and critical for an accurate assessment of the maximum levels for naturally occurring arsenic in soils.

Lastly, this study statistically examines six potentially important environmental predictors of naturally occurring arsenic in southwestern Oregon: site elevation, geomorphic province, mapped rock type and age, and sample soil order and color (redness). A Classification and Regression Tree Model (CART) determined soil order, elevation and rock type to be of significant importance in determining arsenic concentrations in the natural environment. According to the regression tree, arsenic concentrations are greater within Alfisol and Ultisol/Alfisol and Vertisol soil orders, at lower elevations below 1,207 meters, and within soils from sedimentary, mixed volcanic/sedimentary and unconsolidated rock types.
The relationship between environmental factors and high levels of arsenic is complex and research is ongoing. However, soil order is likely to be a significant factor for predicting levels of arsenic since soil order is defined by its horizon development. Negatively charged arsenic ions adsorb to positively charged minerals, commonly iron, aluminum and magnesium oxides and clay. Any soils with a zone of mineral accumulation (B horizon) — such as Alfisol, Ultisol and Vertisol soils — are likely to attract, retain and concentrate arsenic in the soil.

The relationship between elevation and rock type to arsenic level is less clear. Arsenic values could be higher in lower elevations because weather and gravity have transported arsenic-bearing sediments to lower topography where it accumulates, or a result of more chemical processes in the more temperate climates at lower elevation, or is correlated with other factors such as depositional regime of the rock. Rock type as a predictive factor also requires more research; the degree of arsenic enrichment in rock and arsenic released through physical and chemical weathering are likely to have a high degree of local variability than will ultimately not allow definitive association of high arsenic levels by rock type.
Acknowledgements

Dr. Scott Burns, your encouragement and confidence has made the process of creating this Master’s thesis much more enjoyable than I imagined it could be. Also, I learned a lot from you! David Anderson from DEQ and Neil Morton from GeoEngineers, Inc. were both invaluable resources for questions I had regarding the DEQ data set. I thank Kassandra Lindsey and Aubrey Frimoth for being my post-surgery arms and legs with their physical contributions (digging many holes) and can-do attitude in the field. Classmates Traci Parker and Kimberly Yazzie joined me in playing with my data for a class project, helped troubleshoot appropriate analyses for the data and traded ideas for what the results may imply.

To my immediate family: thank you, parents, for emotional support and perspective, always. I also very much appreciate my dog, Daisy, who has kept my toes warm while snuggled under my desk during all of my higher education. My fantastic husband, Josh, with his patience of steel, earns my lifetime of gratitude; he has sacrificed many date-nights through both my Bachelor’s and Master’s education. Josh, without your sense of humor and support, I would not have had the fun and focus that I am grateful to have experienced through these degrees. Last but not least… Liam, welcome to the world, my son!
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CHAPTER I: INTRODUCTION

Some elements that are natural to the environment can lead to significant, even fatal health effects and so must be managed to ensure human health and safety. In Oregon a major element of concern is arsenic (As). Exposure and poisoning from this naturally occurring metalloid can occur from drinking water, inhaling dust, or ingesting foods grown in high-arsenic soils or irrigated with high-arsenic waters. Anthropogenic sources also contribute to elevated arsenic by introducing products with arsenic content, such as some pesticides and treated lumber. The Environmental Protection Agency has classified inorganic arsenic as a human carcinogen. Inorganic arsenic poisoning has also been linked to various cancers, skin lesions, and decreased function in the cardiovascular, neurological and respiratory systems (U.S. Department of Health, 2007).

Originally, the Department of Environmental Quality (DEQ) set remediation standards to one part per million (ppm) of arsenic, but Khandoker (1997) found natural values can be higher in Oregon. For northwest Oregon, Ricker (2013) showed many samples from undisturbed soils were higher in arsenic than one ppm. Khandoker’s southwest Oregon samples were originally tested for arsenic with a minimum reporting limit of 20 ppm. In this study, his arsenic samples were re-tested at a detection limit of <0.20 ppm to investigate the arsenic in soil to assess naturally occurring levels of arsenic in southwest Oregon. Soil nomenclature and a background of arsenic in soils is introduced in Chapter III.
1.1 PURPOSE AND SCOPE

The regulatory authority for setting standards and assuring compliance for environmental quality at the state level is the Department of Environmental Quality (DEQ). The maximum exposure levels for metal and metalloid elements, chosen by DEQ, have historically been established using risk-based concentrations (RBC’s) using data not specific to Oregon, where risk from exposure is defined as the product of a chemical’s toxicity and the degree of exposure to it (DEQ, 2003). The difference between the scenarios for exposure is the frequency of the exposure expected in a given year (DEQ, 2003).

Risk-based concentrations for arsenic in soils in Oregon were based on duration of exposure and ranged from 0.4 to 1.7 ppm for residential and occupational environments (Table 1). Studies in northwest Oregon (Ricker, 2013) have shown most natural soil samples are above that number. To move away from RBC’s and refine clean-up standards, an understanding of natural background levels of arsenic and other elements in soils is needed. Regional background elemental concentrations data will aid the design of standards that are more reasonable and therefore economically sustainable for cleanup. To accomplish this, the DEQ has compiled data from Portland State University, the United States Geological Survey, the National Geochemical Database, the Umatilla Chemical Depot and samples and analysis from GeoEngineers. The DEQ has recently completed the re-evaluation of background data for elements of concern in Oregon, and released a report (DEQ, 2013) with the project phase information and values based on background concentration data to replace the previous values. Concentrations
were grouped by physiographic province (Figure 1), and new standards dictate that metals require remediation when exceeding the regional 95% upper tolerance limit of the default background concentrations (Table 1).

The objective of this study is to determine the range of naturally occurring arsenic in southwest Oregon soils. The data in this thesis will add to the dataset that supports the evaluation of background levels of arsenic for Oregon. In addition, environmental factors were assessed to see if there are more readily measurable environmental parameters. A potential relationship may justify more research to determine if an environmental source may be used as a “red flag” indicator of potentially high soil arsenic content. Factors being assessed are rock type and age, soil order, soil color, elevation, and geomorphic region.

Table 1. Historic and new maximum limits of arsenic established by DEQ (2012, 2013).

<table>
<thead>
<tr>
<th>Risk-Based Concentration Method (DEQ, 2012)</th>
<th>Residential</th>
<th>Urban Residential</th>
<th>Occupational</th>
<th>Construction Worker</th>
<th>Excavation Worker</th>
</tr>
</thead>
<tbody>
<tr>
<td>soil (ppm)</td>
<td>0.4</td>
<td>1.0</td>
<td>1.7</td>
<td>13.0</td>
<td>370.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Regional 95% Upper Prediction Limit (UPL) Default Background Concentrations within Southwest Oregon (DEQ, 2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physiographic Province</td>
</tr>
<tr>
<td>soil (ppm)</td>
</tr>
</tbody>
</table>
1.2 STUDY AREA

The study area is from the Pacific Ocean on the west to the city of Bend on the east, the Oregon-California border on the south up to the city of Eugene on the north. The bounds of this study area were chosen to be consistent with a study by Khandoker (1997), since soil samples from Khandoker’s study were retested for arsenic for use in this study. The primary physiographic provinces in the study area (Figure 1) are the Klamath Mountains, the Coast Range and the Cascade Range (Orr and Orr, 2012). This study also includes the southernmost portion of Willamette Valley and a few sites within the westernmost portions of the High Lava Plains and Basin and Range provinces. The varied physiography within southwest Oregon is a result of tectonic accretion and deformation, volcanism and Quaternary glaciation. Detailed unit descriptions (Walker and MacLeod, 1991) are in Appendix B.
Figure 1. Physiographic provinces (Orr and Orr, 2012) within Southwest Oregon study area with sample locations. Physiographic provinces from lower left corner, clockwise, are the Klamath Mountains, Coast Range, South Willamette Valley, Cascade Range, High Lava Plains and Basin and Range. Province lines are from DEQ (2013).
CHAPTER II: BACKGROUND

2.1 PHYSIOGRAPHIC PROVINCES OF OREGON

Of Oregon’s ten physiographic provinces (Orr and Orr, 2012), six lie within the bounds of the southwest quadrant of Oregon. The Klamath Mountains dominate the study area while parts of the Coast Range, Cascade Range, Willamette Valley, Basin and Range and High Lava Plains stretch into it (Figure 1). Southwest Oregon was covered by ocean until about 150 Ma (Orr and Orr, 2006). The diverse geography we see today in southwest Oregon — with half of all Oregon geophysical provinces present in the southwest quadrant — illustrates the dynamic earth processes that formed them.

2.2 GEOLOGIC HISTORY OF SOUTHWEST OREGON

The Klamath Mountains are formed of accreted ocean crust from the Farallon and later Juan de Fuca plates, and volcanic island chains active in the Mesozoic era (Orr and Orr, 2012). Collision with the North American plate folded and thrust slabs of this material beneath each other, stacking successive terranes like shingles with the oldest terrane (~210 Ma) inland to the east. Various igneous plutons intruded all belts of the Klamath Mountains from 174-136 Ma, which bound the terranes together. Paleomagnetic data from these plutonic intrusions indicate the clockwise rotation of terranes was active during off-shore Jurassic deposition, prior to collision with North America and was mostly completed by about 100 Ma in the early Cretaceous Period (Orr and Orr, 2012).

About 140 Ma, uplift of the Klamath Mountains began (Orr and Orr, 2012). Uplift and an ocean transgressive period continued into the Cenozoic. The Willamette Valley
subsided in the late Cenozoic into a northward-dipping marine trough, collecting Klamath debris and sand, mud and silts consistent with marine deposition. The ocean receded, and Willamette Valley held lakes, meandering streams and swamp lands.

The Cenozoic era was dominated by volcanism and sedimentation (Orr and Orr, 2012). Eocene to Oligocene volcanism was brought on by the collision of the Farallon and North American plates. From 35-17 Ma plate subduction and rising plumes resulted in a volcanic arc that produced lavas and ash that created the Western Cascade Range, which is composed of andesites, basaltic andesites and dacites. Plate collision also created a north-south crustal fold that rotated and uplifted marine sediments and Klamath erosional debris and Tertiary ocean-bottom basalts to become the Coast Range. East-West crustal extension of the Basin and Range in the Miocene resulted in basaltic to rhyolitic flow of lavas across the Basin and Range and High Lava Plains (17-10 Ma), an elevated desert plateau. Crustal failure also resulted in northwest-trending faults for hundreds of miles, active until 7-8 Ma.

From the late Miocene to Holocene (10,000 BP), basaltic and basaltic-andesite lavas from stratovolcanoes and shield volcanoes formed the High Cascade peaks. Less than 2 Ma to 12,000 BP, glacial and interglacial periods resulted in massive geomorphic change in all provinces. Marine terracing occurred along the Oregon coast in the Coast Range and Klamath Mountains, and lahars flowed down High Cascade Mountain sides. Catastrophic flooding covered older bedrock with alluvial fans and gravel terraces and deposited thick silts in the Willamette Valley (Orr and Orr, 2012).
Klamath Mountains

The Klamath Mountains province is bordered by the Pacific Ocean on the west, the Western Cascades to the east, and extends 402 km (250 miles) south from the Coast Range into northwest California. Overall, the summits in this region are of uniform relief. Mount Ashland is the highest point in the Oregon Klamath Mountains at 2,295 m (7,530 feet). From Port Orford, coastal terrain is rocky headlands south to Ophir, then 18- to 24-m (59- to 79-feet) wide sandy beaches to Gold Beach at the mouth of the Rogue River. Cliffs dominate the remaining coastline into California, with occasional thin strips of coastal terraces. The Klamath, Rogue and Chetco rivers drain the province into the Pacific Ocean.

Early Paleozoic to Mesozoic ocean crust and volcanic island arcs accreted through collision and subduction under the North American plate. Successive slab collisions in late Mesozoic resulted in an east-dipping imbrication of terranes, bounded by thrust-faults, with the oldest terrane inland and progressively younger terranes westward to the Pacific Ocean (Figure 2). These terranes were delineated and further divided into subterranes and formations. Descriptions of the Klamath Mountain formations are summarized from Walker and MacLeod (1991) in Appendix A and listed in Table 2. Descriptions of the terranes in the text also list spatially concurrent formations or map units.

The western Paleozoic and Triassic belt was accreted in the mid- to late-Jurassic and rotated to its current position in the late Mesozoic to early Cenozoic. This 322 km
long and 80 km (200 by 50 miles) wide belt is divided into four terranes, two of which are in Oregon. The Rattlesnake Creek Terrane (Js, Ju, Jub, Jv, Kc, KJg, mc, Qal, Qt, TRPv, TRPzm) is described as an ophiolitic mélange overlain by ocean arc rocks (Jm, Js and Jv). The Western Hayfork volcanic terrane (Jm, Ju, Kc, KJg, Qal, Qf, Qt, TRPv, TRPzs) covered Rattlesnake Creek by the middle Jurassic and was then intruded by plutons (Orr and Orr, 2012).

Jurassic May Creek Terrane (mc) and Condrey Mountain Terrane (cm) are backarc basin remnants that were thrust beneath the Rattlesnake Creek and Western Hayfork terranes. May Creek Terrane is comprised of ophiolites metamorphosed to amphibolites. The Condrey Mountain Terrane is late-Jurassic schist that was then uplifted in the Miocene into a dome structure; the Condrey Mountain dome is believed to be the result of lateral pressure between the Juan de Fuca and North America plates (Orr and Orr, 2012).

The Western Klamath Terrane is composed of ophiolites, island arc volcanic rocks and deep ocean basin sediments (Orr and Orr, 2006) accreted in the late-Jurassic. The Western Klamath Terrane is to the west of the Western Paleozoic and Triassic belt, separated by the Orleans Fault. It runs 322 km (200 miles) along the western edge of the Oregon and California Klamath Mountains. From east to west, the Western Klamath Terrane includes the Smith River, Rogue Valley, Briggs Creek, Dry Butte and Elk subterranes (Figure 2).
The Smith River Subterrane (Js, Jss, JTRgd, Ju, Jub, Kc, KJg, Qal, Qf, Qt) consists of ophiolite, overlain by a thick layer of deep-water shales and turbidite sandstone known as the Galice Formation. The Josephine Ophiolite (160 Ma) developed in a back-arc basin between the Rogue-Chetco volcanic arc and the mainland. It is famous for being one of the world’s largest and most complete ophiolite sequences and for its rich economic mineral content, yielding gold, silver, copper, nickel and chromite. Galice Formation sediment sources include both accreted terrain and volcanic arc materials (Orr and Orr, 2012).

Northwest of the Smith River Subterrane are the Rogue Valley (Js, JTRgd, Ju, Jub, Jv, KJg, Qal), Briggs Creek (bc, Jv) and Dry Butte (JTRgd, Ju, Jv, Qls) subterranes.

Table 2. Description of geologic units sampled within Klamath Mountain Province. Unit description summarized from Walker and MacLeod (1991) and province boundary defined by DEQ (2013). Detailed descriptions are found in Appendix B.

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>Primary Rock Types/ Additional Rock Types</th>
<th>Description of Map Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>bc</td>
<td>amphibolite, quartzite, schist, chert</td>
<td>Amphibolite of Briggs Creek: amphibolite, micaceous quartzite, quartz schist and recrystallized manganiferous chert</td>
</tr>
<tr>
<td>cm</td>
<td>schist/ chert</td>
<td>Condrey Mountain Schist: a variety of schistose rocks; rare metachert and metagabbro</td>
</tr>
<tr>
<td>cs</td>
<td>pelitic schist/ meta-basalt</td>
<td>Colebrook Schist: metamorphosed sedimentary rocks; subordinate metamorphosed submarine pillow lavas and basaltic pyroclastics</td>
</tr>
<tr>
<td>Jm</td>
<td>melange: volcanic, metamorphic and sedimentary rocks</td>
<td>melange: complex mix of basaltic rocks, serpentinite, chert, argillite, conglomerate, silty sandstone and marble lenses</td>
</tr>
<tr>
<td>Jop</td>
<td>melange: greywacke, mudstone, siltstone, shale/ various metamorphic rocks</td>
<td>Otter Point Fm./Melange(?): highly sheared greywacke, mudstone, siltstone, shale; lenses of greenstone limestone, chert, blueschist and serpentine</td>
</tr>
<tr>
<td>Js</td>
<td>sedimentary rocks, tuff/ metamorphic rocks</td>
<td>mudstone, shale, siltstone, graywacke, andesitic to dacitic tuff; minor limestone, phyllite, slate</td>
</tr>
<tr>
<td>Jss</td>
<td>shale, mudstone, sandstone/ pebble conglomerate</td>
<td>sedimentary rocks with local lenses of pebble conglomerate</td>
</tr>
<tr>
<td>JTRgd</td>
<td>granite, diorite</td>
<td>felsic to intermediate granitoids: muscovite granodiorite, hornblende gabro, tonalite and quartz diorite</td>
</tr>
<tr>
<td>Ju</td>
<td>harzburgite, dunite/ serpentinite, gabbro</td>
<td>ultramafic and related rocks of ophiolite sequence</td>
</tr>
<tr>
<td>Jub</td>
<td>basalt, breccia/ shale, siltstone, mudstone</td>
<td>basaltic volcanic and sedimentary rocks: basalt flows, breccia, agglomerate, pillow basalt and breccia; lesser shale, chert siltstone and mudstone of ophiolitic complexes</td>
</tr>
</tbody>
</table>

(table continues on next page)
The Rogue Valley Terrane was deposited at the same time as the Galice Formation; it is eight km (5 miles) wide and composed of undersea volcanic flows and ash. The Galice Formation has been locally altered to slate which interfingers with the Rogue Formation volcanics. Briggs Creek Terrane is coarse-grained metamorphic rock, which includes chert, quartzite and folded and altered garnet amphibolites; this is the basement rock for the Rogue Valley volcanic arc. The late-Jurassic, Dry Butte Subterrane is an igneous batholith, thrust beneath Briggs Creek. The Briggs Creek and Dry Butte subterrane are

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>Primary Rock Types/ Additional Rock Types</th>
<th>Description of Map Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jv</td>
<td>andesite, basalt to rhyolite flows/ tuff, tuffaceous sedimentary rocks</td>
<td>volcanic rocks: lava flows, flow breccia and agglomerate dominantly andesite; flow rocks basaltic to rhyolitic; interlayered tuff and tuffaceous sedimentary rocks</td>
</tr>
<tr>
<td>Kc</td>
<td>sandstone, conglomerate</td>
<td>fossilsiferous clastic sedimentary rocks</td>
</tr>
<tr>
<td>KJds</td>
<td>sandstone, conglomerate, graywacke/ chert</td>
<td>sedimentary rocks related to Dothan Formation; chert lenses</td>
</tr>
<tr>
<td>KJdv</td>
<td>basalt</td>
<td>volcanic rocks related to Dothan Formation: basaltic pillow lavas, volcanic breccia and silicified basalt lava flows</td>
</tr>
<tr>
<td>KJg</td>
<td>tonalite, quartz diorite/ other granitoid rocks</td>
<td>granitic rocks</td>
</tr>
<tr>
<td>KJgu</td>
<td>gabbro/ pyroxene, pyroxene, peridotite, dunite, serpentinite</td>
<td>gabbro and ultramafic rocks associated with granitic plutons: hornblende gabbro, gabbro and olivine gabbro; includes pyroxenite, hornblende pyroxene; minor peridotite, dunite, serpentinite</td>
</tr>
<tr>
<td>KJm</td>
<td>conglomerate, sandstone, siltstone, limestone</td>
<td>Myrtle Group; locally fossilsiferous</td>
</tr>
<tr>
<td>Ks</td>
<td>graywacke, conglomerate, shale</td>
<td>marine graywacke and subgraywacke; conglomerate composed of volcanic, metavolcanic, metasedimentary and plutonic rocks</td>
</tr>
<tr>
<td>mc</td>
<td>amphibolite, schist, gneiss, quartzite</td>
<td>May Creek Schist</td>
</tr>
<tr>
<td>Qt</td>
<td>terrace/ alluvium</td>
<td>terrace, pediment and lag gravels: unconsolidated gravel, cobbles and boulders intermixed with clay, silt and sand</td>
</tr>
<tr>
<td>Tnss</td>
<td>sandstone, siltstone, mudstone</td>
<td>shallow marine sedimentary rocks; contains foraminifera</td>
</tr>
<tr>
<td>Ta</td>
<td>conglomerate, sandstone, siltstone, mudstone</td>
<td>nonmarine sedimentary rocks with abundant biotite and muscovite</td>
</tr>
<tr>
<td>TrPv</td>
<td>intermediate metavolcanic rock/ andesite, tuff, basalt</td>
<td>meta-andesite, meta-basalt, spilit, keratophyre, volcanic breccia; andesite flows, breccia, agglomerate, tuff, basalt flows and dacitic tuffs of Applegate Group</td>
</tr>
<tr>
<td>TrPzm</td>
<td>melange: metasedimentary and metavolcanic rocks</td>
<td>Melange of Dutchmans Peak: heterogeneous mix metamorphosed to upper greenschist, serpentinite, gabbro and metagabbro</td>
</tr>
<tr>
<td>TrPzs</td>
<td>shale, mudstone, sandstone, graywacke, conglomerate, tuff, chert, marble/ argillite, chert, phyllite, quartzite, limestone, marble</td>
<td>Applegate Group: partially metamorphosed, poorly bedded sedimentary rocks; impure limestone and marble</td>
</tr>
<tr>
<td>Tsr</td>
<td>basalt/ siltstone, sandstone, tuff, conglomerate</td>
<td>Siletz River Volcanics and related rocks: visicular pillow flows, tuff-breccias, massive lava flows and sills of tholeiitic and alkali basalt; upper part of sequence contains interbeds of basaltic sedimentary rocks</td>
</tr>
</tbody>
</table>
currently considered mid- to late-Jurassic components of the Rogue Valley Arc (Orr and Orr, 2012).

The Elk Subterrane (cs, Js, JTRgd, Ju, Ks, Qt, Tmsc) is composed of sandy turbidites, shales and andesitic lavas. Although this terrane is over 32 km (20 miles) north of the main Western Klamath Terrane, it is placed in the Western Klamath belt due to the thick sequences of Galice Formation submarine slides found within it. The Elk Subterrane is believed to be tectonically displaced 160 km (100 miles) northward from California by faulting (Orr and Orr, 2012).

Figure 2. The Klamath Mountain province is comprised of east-dipping terranes, imbricated by subduction and thrust faults. The oldest terrane is to the east with progressively younger terranes to the west (Orr and Orr, 2012).

The southwest Oregon terranes (Figure 2) are the Snow Camp (Jc, Ju, Jv, KJds, KJg, KJm, Qal, Qls, Qt, Tfe, Tut), Pickett Peak (Ju, KJds, KJm), Yolla Bolly (cs, Jc,
JTRgd, Ju, Jv, KJds, KJdv, Qls, Tia, Tmsc), Gold Beach (Jop, Ju, KJds, Qal, Tcs) and the Sixes River (cs, Ju, KJds Qt, Tmsc, Tmsm, Tt) terranes and are located on the southwest Oregon Coast and were displaced from the Western Klamath Terrane and transported from the south by early Cretaceous thrust faulting. Formations within the Snow Camp Terrane include the Coast Range ophiolite, late Jurassic Mule Mountain Volcanics, the Jurassic Riddle Formation and the Cretaceous Days Creek conglomerates, silts and sands.

The Oregon section of the Pickett Peak Terrane is made of blueschist; deep sea tuffs, cherts and pillow lavas were metamorphosed in the early Cretaceous into Colebrooke Schist. Late Jurassic to early Cretaceous Yolla Bolly Terrane is composed of forearc basin sands, muds and deep-water cherts. These sediments, known as the Dothan Formation, were transported by turbidity currents from continental and volcanic arc sources (Orr and Orr, 2012).

Gold Beach Terrane includes the late Jurassic Otter Point Formation, and late Cretaceous Cape Sebastian and Hunters Cove formations. The deep-water Otter Point Formation was part of an accretionary wedge at a subduction zone. Cape Sebastian Sandstone and Hunters Cove siltstone include turbidite-deposited deeper sands and shales as remnants from past storms. Sixes River Terrane includes Jurassic and Cretaceous mudstones, sandstones and conglomerates with blueschist and eclogite outsized clasts, as well as limestones, deep-water shales and pillow lavas.

The Klamath terranes were accreted, subject to faulting and clockwise rotation and intruded by plutons. According to paleomagnetic data, rotation occurred from late-
Triassic to early-Jurassic and continued into the early Cretaceous. The late Cretaceous brought a transgressing seaway that inundated most of Oregon. Cretaceous to Cenozoic uplift of the Klamath Mountains pushed the shoreline north and provided sedimentation to the surrounding basin. Fluctuating sea levels resulted in raised marine terraces, some of which are still intact along the southwest Oregon coast. See Appendix A, Figure A.1 for stratigraphy of this province (Orr and Orr, 2012).

**Coast Range**

The Coast Range extends south from the Columbia River to the Middle Fork of the Coquille River on the northern side of the Klamath Mountains, and west from the Willamette Valley into the Pacific Ocean (Figure 1). The heavy marine influence has extensively eroded the west slopes of the Cascade Range, and heavy precipitation has produced an intricate drainage system and dense forests. Coastal terrain includes abrupt headlands, sea stacks, marine terraces, bays, estuaries, small beaches, sand dunes and spits. Drainage within the province is provided by moderately-sized rivers (Orr and Orr, 2012).

The geologic history of the province includes submarine volcanism, subsidence, uplift and sedimentation (Orr and Orr, 2012). Oblique plate subduction of the Juan de Fuca plate under North America resulted in Eocene to Pleistocene clockwise rotation, faulting and uplift of the Coast Range. However, only the southern part of this province is included in the study area, with the north border of the study area extending from Eugene, Oregon to approximately Florence, Oregon at the coast. Descriptions of the
Coast Range formations within the study area are summarized from Walker and MacLeod (1991) in Table 3.

Table 3. Description of geologic units sampled within the Coast Range. Unit description summarized from Walker and MacLeod (1991) and province boundary defined by DEQ (2013). Detailed descriptions are found in Appendix B.

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>Primary Rock Types/ Additional Rock Types</th>
<th>Description of Map Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qal</td>
<td>sand, gravel, silt/ talus, slope wash</td>
<td>alluvial deposits; locally, thin peat beds and high in organic material</td>
</tr>
<tr>
<td>Qd</td>
<td>sand</td>
<td>dune sand; mostly feldspar and quartz minerals</td>
</tr>
<tr>
<td>Qls</td>
<td>landslide: basalt, andesite, tuff/ slope wash, colluvium</td>
<td>landslide and debris flow deposits are unstratified mixtures of fragments of adjacent bedrock; largest slides and flow occur where thick sections of basalt and andesite flows overlie clayey tuffaceous rocks</td>
</tr>
<tr>
<td>Qt</td>
<td>terrace/ alluvium</td>
<td>terrace, pediment and lag gravels; unconsolidated gravel, cobbles and boulders intermixed with clay, silt and sand</td>
</tr>
<tr>
<td>Ti</td>
<td>gabbro/ granitoid</td>
<td>mafic intrusions: sheets, sills and dikes of granophyric ferrogabbro</td>
</tr>
<tr>
<td>Tmsm</td>
<td>sandstone, siltstone, mudstone/ conglomerate</td>
<td>Roseburg Formation: marine sedimentary rocks with minor conglomerate; contains foraminifera</td>
</tr>
<tr>
<td>Tmss</td>
<td>sandstone, siltstone, mudstone</td>
<td>shallow marine sedimentary rocks; contains foraminifera</td>
</tr>
<tr>
<td>Tpb</td>
<td>basalt/ basaltic andesite, dacite</td>
<td>lava flows and breccia of porphyritic basalt, minor basaltic andesite and rare dacite</td>
</tr>
<tr>
<td>Tsr</td>
<td>basalt/ siltstone, sandstone, tuff, conglomerate</td>
<td>Siletz River Volcanics and related rocks: viscicular pillow flows, tuff-breccias, massive lava flows and sills of tholeiitic and alkali basalt; upper part of sequence contains interbeds of basaltic sedimentary rocks</td>
</tr>
<tr>
<td>Tss</td>
<td>mudstone, siltstone, sandstone/ tuff</td>
<td>tuffaceous marine sedimentary rocks; contains calcareous concretions and foraminiferous assemblage</td>
</tr>
<tr>
<td>TT</td>
<td>sandstone, siltstone/ dacite tuff</td>
<td>Tyee Formation: rhythmically-bedded marine sandstone and micaceous carbonaceous siltstone; minor interbeds of dacite tuff; foraminifera</td>
</tr>
<tr>
<td>Ty</td>
<td>siltstone, sandstone/ basalt, lapilli tuff</td>
<td>Yamhill Formation and related rocks: marine siltstone; thin interbeds of arkosic, glauconitic and basaltic SS; locally interlayered basalt lava flows and lapilli tuff; foraminiferous assemblages</td>
</tr>
</tbody>
</table>

The oldest Coast Range rocks in the south part of the range are Eocene pillow basalts and breccias, named the Roseburg Volcanics. These ocean-bottom flows were produced in the Siletzia Terrane, which was a Paleocene-Eocene coastal marine basin. The 644-kilometer-long (400 mile) Siletzia platform subsided into a forearc basin in the middle Eocene; deposition from deep-sea fans and deltas and subsequent uplift closed the seaway by late Miocene. This deposition covered Roseburg Volcanics with fluvial and marine deposits: the Lookingglass (Tmsc), Flournoy (Tmss) and Tyee (Tt) Formations. Slope deposits during sea transgression created the Lookingglass Formation. The
Flournoy Formation includes conglomerates, pebbly sandstones and siltstones deposited during the seaway retreat. The Tyee Formation, overlying the Flournoy, is composed of huge submarine fans from river-transported Klamath Mountain sediments. In the middle to late Eocene, inland streams provided sediments to the Elkton, Bateman and Coaledo formations (Tss). These sediments from the Western Cascade Range and northern Klamath Mountains settled in the forearc basin at Coos Bay. The Elkton Formation is mudstone, which coarsens up through the Bateman submarine fan to the Coaledo’s coarse delta sandstones. Ash and pyroclastics from the early Western Cascade eruptions provided sediment for the bathyal Bastendorff Shales (Tsd) and overlying marine embayment Tunnel Point Sandstones (Orr and Orr, 2012).

Oligocene marine sedimentation was limited to the central and north coast. Late Oligocene to mid-Miocene included regional uplift that shifted the shoreline near to its present-day location. The Western Cascades eruptions continued to deposit ash into the ocean. The Miocene Tarheel Formation is fossiliferous sandstone and is overlain by the sandstone of both the mid-Miocene Floras Lake Formation and late Miocene Empire Formation. The Empire Formation (Tm, not sampled) is an estuary deposit of silts and fine sands full of mollusks and marine vertebrate fossils. The Roseburg Formation (Tmsm) is composed of deep-sea turbidite mudstone and shales (Orr and Orr, 2012).

Erosion predominated in the Pliocene before Pleistocene glaciations widened coastal plains and rapidly down-cut estuaries and stream valleys. About 11,000 years ago, the climate reversed, and ocean levels rose and submerged the coastline. The Port Orford and Elk River Formations at Cape Blanco and the Coquille Formation at Bandon, Oregon
are shallow-water terrace deposits dominated with mollusks. See Appendix A, Figure A.2 for stratigraphy of this province.

**Cascade Range**

The Cascade Mountains extend north-south 966 km (600 miles) from British Columbia, through the entirety of Oregon (Figure 1). The Oregon Cascade Range is divided into the Western Cascades and the High Cascades. In contrast to the older, eroded Western Cascades (518 to 1,768 m), the younger High Cascades are near double the elevation at greater than 3,353 meters (Orr and Orr, 2012).

The major rivers in the Cascades drain west. Near the study area, the McKenzie River drains into the Willamette River just north of Eugene. Within the study area, the Middle Fork Willamette River also joins the Willamette River system. The Umpqua River drains 180 km (112 miles) from the Western Cascades, through Roseburg and the Coast Range to the Pacific Ocean at Reedsport. East-draining rivers are much smaller, averaging 48 to 56 km (30 to 35 miles) in length.

During the Eocene, a volcanic arc formed along the Pacific Ocean from the subduction of the Farallon Plate. From Eocene to Miocene (40 to 7.5 Ma), thick deposits of volcanic debris, intrusives and marine sediments built the Western Cascades. Volcanic activity prior to 17 Ma produced andesites, basaltic andesites and dacites, after which production lessened and transitioned to lava and ash. Tectonic tilting and folding ceased deposition about 5 Ma, and volcanic activity moved eastward. Basaltic and basaltic andesite lava and ash from the late-Miocene to Holocene stratovolcanoes and shield
volcanoes of the High Cascades obscured much of the Western Cascades and were active as recently as a few thousand years before present. Significant volcanic peaks within the study area include the Crater Lake stratovolcano, and the Mt. Bachelor, Mt. Thielsen and Mt. McLoughlin volcanoes (Orr and Orr, 2012).

The geology of the Cascade Range formations within the study area is summarized from Walker and MacLeod (1991) in Table 4. The Western Cascades shared the same depositional regimes as the Coast Range, and therefore include some of the same significant formations (Appendix A, Figure A.3) within the study area. The Umpqua and Lookingglass Formation (Tmsc) siltstone, sandstone and conglomerate present in the Coast Range as siltstone, sandstone and mudstone extends into the Western Cascades. The Roseburg Formation (Tmsm) is partly a shelf and slope facies, and Eugene and Fisher (Tfe, Tfee) Formations are marine and nearshore sands and tuffs, all present across provinces.

Volcanic activity produced the basaltic and andesitic rock Elk Lake and Nohorn Creek (Tbaa). Little Butte, Mehama, Breitenbush and Molalla Formations (Tv) are composed of flows and tuffs. The Sardine Formation (Trb) is described as having andesitic, basaltic andesite and dacitic lavas. In the High Cascades, Mount Mazama eruption resulted in rhyodacitic to andesitic ash-flow deposits (Qma), and more recently the Newberry and South Sister volcanoes (Qrd) produced rhyolite and dacite flow breccia. See Appendix A, Figure A.3 for stratigraphy of this province.
Table 4. Description of geologic units sampled within the Cascade Range Province. Unit description summarized from Walker and MacLeod (1991) and province boundary defined by DEQ (2013). Detailed descriptions are found in Appendix B.

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>Primary Rock Types/ Additional Rock Types</th>
<th>Description of Map Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qa</td>
<td>andesite, basaltic andesite/ dacite, basalt</td>
<td>andesite phenocrysts are principally pyroxene, olivine, plagioclase, few hornblende</td>
</tr>
<tr>
<td>Qal</td>
<td>sand, gravel, silt/ talus, slope wash</td>
<td>alluvial deposits; locally, thin peat beds and high in organic material</td>
</tr>
<tr>
<td>Qba</td>
<td>basaltic andesite, basalt</td>
<td>flows and flow breccia; basaltic andesite of plagioclase, olivine, pyroxene phenocrysts and olivine basalt</td>
</tr>
<tr>
<td>Qg</td>
<td>boulder gravel, sand, rock flour</td>
<td>glacial deposits in ground terminal and lateral moraines</td>
</tr>
<tr>
<td>Qgf</td>
<td>boulder gravel, sand, rock flour</td>
<td>partly sorted glaciofluvial deposits in ground terminal and lateral moraines</td>
</tr>
<tr>
<td>Qls</td>
<td>landslide: basalt, andesite, tuff/ slope wash, colluvium</td>
<td>landslide and debris flow deposits are unstratified mixtures of fragments of adjacent bedrock; largest slides and flow occur where thick sections of basalt and andesite flows overlie clayey tuffaceous rocks</td>
</tr>
<tr>
<td>Qma</td>
<td>rhyodacitic to andesitic ash-flow</td>
<td>Mount Mazama ash-flow deposits</td>
</tr>
<tr>
<td>Qmp</td>
<td>rhyodacitic pumice</td>
<td>Mount Mazama primary and reworked air-fall pumice deposits</td>
</tr>
<tr>
<td>Qrd</td>
<td>rhyolite, dacite</td>
<td>domes and related aphric and porphyritic flows and flow breccia on Newberry and South Sister volcanoes</td>
</tr>
<tr>
<td>Qs</td>
<td>clay, silt sand, gravel/ mudflow, fluvial deposits, peat</td>
<td>unconsolidated to semi-consolidated lacustrine and fluvial sedimentary rocks</td>
</tr>
<tr>
<td>Qta</td>
<td>andesite, basaltic andesite</td>
<td>flows and flow breccia; plagioclase, olivine, clinopyroxene, and lesser hypersthene and hornblende phenocrysts</td>
</tr>
<tr>
<td>QTba</td>
<td>basalt, basaltic andesite</td>
<td>flows, flow breccia and pyroclastic deposits; bytownite and labradorite, olivine, calcic augite and hypersthene phenocrysts</td>
</tr>
<tr>
<td>QTmv</td>
<td>basalt, basaltic andesite, andesite/ pyroclastic rocks</td>
<td>mafic vent complexes: plugs, dikes, breccia, cinders and agglutinate</td>
</tr>
<tr>
<td>QTp</td>
<td>basalt, andesite</td>
<td>basaltic and andesitic ejecta: scoriaceous cinders, bombs and agglutinate</td>
</tr>
<tr>
<td>Tbba</td>
<td>basalt, andesite</td>
<td>lava flows and flow breccia of hypersthene and olivine andesite, basaltic andesite with plagioclase and pyroxene phenocrysts, and basalt</td>
</tr>
<tr>
<td>Tfc</td>
<td>basaltic andesite, andesite/ dacite</td>
<td>undifferentiated flows and clastic rocks: lava flows, flow breccia, mudflows and volcanic conglomerates</td>
</tr>
<tr>
<td>Thi</td>
<td>diorite, quartz: diorite/ gabbro, biotite, quartz monzonite, granodiorite</td>
<td>hypabyssal intrusive rocks</td>
</tr>
<tr>
<td>Tmsc</td>
<td>conglomerate, sandstone, siltstone, mudstone</td>
<td>marine sedimentary rocks; foraminifera</td>
</tr>
<tr>
<td>Trb</td>
<td>basaltic andesite, olivine basalt</td>
<td>ridge-capping basalt and basaltic andesite flows and flow breccia</td>
</tr>
<tr>
<td>Tsv</td>
<td>rhyolite, dacite</td>
<td>silicic vent complexes</td>
</tr>
<tr>
<td>Tu</td>
<td>complexly interstratified epiclastic and</td>
<td>undifferentiated tuffs, tuffaceous sedimentary rocks, and basalt:</td>
</tr>
<tr>
<td>Tub</td>
<td>basalt, basaltic andesite</td>
<td>basaltic lava flows and breccia</td>
</tr>
<tr>
<td>Tus</td>
<td>sedimentary and volcanic rocks/ tuff</td>
<td>basaltic to dacitic sedimentary and volcaniclastic rocks; lapilli tuff,</td>
</tr>
<tr>
<td>Tut</td>
<td>ash-flow tuff</td>
<td>welded to unwelded vitric tuff; glass locally altered to clay, zeolites and secondary silica minerals</td>
</tr>
<tr>
<td>Qyb</td>
<td>basalt, basaltic andesite</td>
<td>youngest basalt and basaltic andesite; flows and associated breccia on slopes of Newberry Volcano</td>
</tr>
</tbody>
</table>

**Willamette Valley**

The Willamette Valley province is a synclinal valley bounded by the Cascade Mountains on the east and the Coast Range on the west, with up to 64 km (40 miles)
between the borders. The province is tapered at both ends, with Cottage Grove, Oregon at its southern point, and the Columbia River 130 miles to the north. The basin is a north-dipping syncline, with 122 meters (400 feet) of elevation at Eugene decreasing to near sea level at Portland. The Willamette River meanders north through alluvial plain from near Eugene to the Columbia River. Topography in the southern portion of the valley is fairly flat. This province supports 70 percent of Oregon’s population and a diverse agriculture (Orr and Orr, 2012).

Table 5. Description of geologic units sampled within the South Willamette Valley. Unit description summarized from Walker and MacLeod (1991) and province boundary defined by DEQ (2013). Detailed descriptions are found in Appendix B.

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>Primary Rock Types/ Additional Rock Types</th>
<th>Description of Map Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qs</td>
<td>clay, silt sand, gravel/ mudflow, fluvial deposits, peat</td>
<td>unconsolidated to semi-consolidated lacustrine and fluvial sedimentary rocks</td>
</tr>
<tr>
<td>Qt</td>
<td>terrace/ alluvium</td>
<td>terrace, pediment and lag gravels: unconsolidated gravel, cobbles and boulders intermixed with clay, silt and sand</td>
</tr>
<tr>
<td>Tfe</td>
<td>sandstone, siltstone/ lapilli tuff, breccia, ash</td>
<td>Fisher and Eugene Formations and correlative rocks; marine arkosic and micaceous sandstone and siltstone</td>
</tr>
<tr>
<td>Tfeb</td>
<td>basalt</td>
<td>basaltic rocks, Fisher Formation(?)</td>
</tr>
<tr>
<td>Tfee</td>
<td>marine sandstone/ tuffaceous SS, siltstone; pebbly conglomerate</td>
<td>Marine Eugene Formation</td>
</tr>
</tbody>
</table>

The environments and sediments of the Willamette Valley are the result of the same geologic influences as the Coast Range. The Siletzia Volcanic Island Terrane collided and accreted with the North America plate, subsided into a forearc basin in the middle Eocene and was buried by marine sediments through the Oligocene. Siletzia volcanics are the basement rock for both the Coast Range and Willamette Valley.

The Willamette Valley subsided into a trough concurrent with the late Cenozoic uplift and tilting of the Coast Range; uplift, tilting and increased sedimentation led to the
northward retreat of the ocean. Pleistocene melt-waters increased sediment transport and filled the valley with alluvial sediments. The Missoula Floods then covered the basin with thick silts from 18,000 to about 15,000 calendar years ago (Allen et al., 2009).

Descriptions of the South Willamette Valley formations within the study area are summarized from Walker and MacLeod (1991) in Table 5. The formations in the Willamette Valley province within the southwest Oregon study area are the Eugene Formation (Tfe, Tfee), Lacomb and Leffler Gravels (Qt), and the Rowland Formation (Qs) with overlying Holocene alluvium. The Eugene Formation consists of thick, shallow marine and non-marine sandstones and siltstones deposited during the late Eocene to Oligocene. In the mid- to late-Pliocene, glacio-fluvial sediments from the Cascades and Coast Range created the Lacomb and Leffler (2.5 to 0.5 Ma) gravels. The Rowland Formation (formerly Linn Formation) is composed of thick, glacial outwash gravel fans that invaded from the Cascades (420 ka) after further subsidence and river downcutting in the valley (Orr and Orr, 2012). See Appendix A, Figure A.4 for stratigraphy of this province.

**Basin and Range**

The Oregon Basin and Range is made of alternating north-south trending mountains and wide valleys, and it extends from the Cascade Mountains on the west to the Owyhee Uplands in the east. The north and south borders are the High Lava Plains and California, respectively. Overall, the elevation average is 1,219 m (3,999 ft.), with the highest elevations east of the study area at Steens Mountain (2,947 m; 9,669 ft.) and
Warner Peak (2,458 m; 8,064 ft.). All drainage is small and toward the interior, except the 31,080 km² (12,000 square miles) Klamath River watershed, which reaches the Pacific Ocean from Klamath Lake through northern California (Orr and Orr, 2012).

Regional uplift and crustal extension with consequent faulting and volcanism has resulted in horst and graben physiography by Miocene north-west strike-slip faults and Quaternary north-northeast normal faults. North American plate movement over a mantle plume produced flood basalts at Steens Mountain (17 Ma) and rhyolitic eruptions that prograded across the Oregon Basin and Range and High Lava Plains (Orr and Orr, 2012). Pleistocene cooling increased precipitation and introduced pluvial lakes in the valley lowlands. Descriptions of the Basin and Range formations within the study area are summarized from Walker and MacLeod (1991) in Table 6. The eastern border of the southwest Oregon study area is approximately 233 km (145 miles) west of Steens Mountain.

Significant stratigraphy in the west part of this province includes the Gearhart Mountain Volcanics (Tvm), the Yamsay Mountain Volcanics (Tob, Trh), and the Yonna Formation (Ts) (Appendix A, Figure A.5). Gearhart Mountain is a mid- to late-Miocene andesitic volcano. The Yamsay Mountain shield cone produced basalt, then rhyolitic lavas in the Pliocene (4.7 Ma), emitting a small amount of basalt at the end of its cycle. The Yonna Formation is lacustrine-deposited Pliocene ash and debris (Orr and Orr, 2012).

Both Tertiary and Quaternary deposition were dominated by volcanics, pyroclastics and sediments of basaltic and andesitic composition. Tertiary and Quaternary
geologic units sampled within the Basin and Range Province descriptions are summarized in Table 6. For the full description, see Appendix B. See Appendix A, Figure A.5 for stratigraphy of this province.

Table 6. Description of geologic units sampled within the Basin and Range Province. Unit description summarized from Walker and MacLeod (1991) and province boundary defined by DEQ (2013). Detailed descriptions are found in Appendix B.

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>Primary Rock Types/ Additional Rock Types</th>
<th>Description of Map Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qba</td>
<td>basaltic andesite, basalt</td>
<td>flows and flow breccia; basaltic andesite of plagioclase, olivine, pyroxene phenocrysts and olivine basalt is part of the volcanic sequence of the High Cascade Range</td>
</tr>
<tr>
<td>Qf</td>
<td>alluvial fan, slope wash, colluvium, talus/silt, basalt fragments</td>
<td>fanglomerate</td>
</tr>
<tr>
<td>Qma</td>
<td>rhyodacitic to andesitic ash-flow</td>
<td>Mount Mazama ash-flow deposits</td>
</tr>
<tr>
<td>QTb</td>
<td>olivine basalt/ palagonite tuff, breccia</td>
<td>basalt grades laterally through tuff and breccia into sedimentary rocks</td>
</tr>
<tr>
<td>QTs</td>
<td>sandstone, siltstone/ ashy and palagonitic sedimentary rocks, palagonitized basaltic debris, pebble conglomerate</td>
<td>semiconsolidated lacustrine and fluvial sedimentary rocks, mostly tuffaceous SS and siltstone</td>
</tr>
<tr>
<td>QTvm</td>
<td>basalt, andesite/ pyroclastic rocks</td>
<td>mafic vent deposits: agglomerate, breccia, scoria, cinder, ash, restricted flows and small basaltic intrusions</td>
</tr>
<tr>
<td>Tb</td>
<td>basalt/ andesite, tuff, tuffaceous sedimentary rocks</td>
<td>basalt flows, flow breccia and basaltic peperite; minor andesite flows; tuffaceous interbeds</td>
</tr>
<tr>
<td>Tob</td>
<td>olivine basalt/ andesite</td>
<td>basalt grades laterally through palagonite breccia and tuff into tuffaceous sedimentary rocks (Ts)</td>
</tr>
<tr>
<td>Tp</td>
<td>basalt, andesite</td>
<td>basaltic and andesitic ejecta: scoriaceous cinders, bombs and agglutinate</td>
</tr>
<tr>
<td>Tps</td>
<td>pyroclastic/ some lacustrine sedimentary rock interbeds</td>
<td>subaqueous pyroclastic rocks of basaltic cinder cones: bombs, breccia and mafic to intermediate tuff</td>
</tr>
<tr>
<td>Trh</td>
<td>rhyolite, dacite/ andesite breccia</td>
<td>ash-flow tuff, lava flows, pumice-lapilli tuff, coarse pumice, blow breccia and rhyolitic to dacitic domal complexes</td>
</tr>
<tr>
<td>Ts</td>
<td>various sedimentary rocks/ tuff</td>
<td>tuffaceous sedimentary rocks and tuff: tuffaceous SS, siltstone, mudstone, claystone, pumicite, diatomite, vitric ash, palagonitic tuff and tuff breccia, fluvial SS and conglomerate</td>
</tr>
<tr>
<td>Tvm</td>
<td>basalt, andesite/ pyroclastic rocks</td>
<td>mafic and intermediate vent deposits: agglomerate, breccia, scoria, cinder, flow and intrusive masses forming lava cones and shields</td>
</tr>
<tr>
<td>Tvs</td>
<td>rhyolite, rhyodacite, dacite</td>
<td>silicic vent rocks: near-vent flows, flow breccia, obsidian, perlite, pumice</td>
</tr>
</tbody>
</table>

**High Lava Plains**

The High Lava Plains province is an elevated desert plateau bordering five other provinces (Figure 1), extending 241 km (150 miles) to the east from central Oregon, and with about 80 km (50 miles) between the northern and southern border. Only the
southwestern portion of the High Lava Plains is within the study area, with the Cascade Range bordering to the west, and the Basin and Range to the south (Orr and Orr, 2012).

Topography is mostly level, with an average elevation of 1.6 km (1 mile) above sea level. Highest elevation is 2,434 m (7,984 feet) at Paulina Peak, located only about five km (three miles) east of the study area. Low rounded domes and steep, flat-topped ridges provide moderate relief between Paulina Peak and the Harney Basin on the east end of the province. Streams are seasonal, with water provided by modest precipitation and snowmelt from nearby mountains.

Descriptions of the High Lava Plains formations within the study area are summarized from Walker and MacLeod (1991) in Table 7. The High Lava Plains deposition is dominated by Tertiary and Quaternary bimodal lava flows. From the Harney Basin, eruptions progressed northwest to the Newberry Crater (Appendix A, Figure A.6); the oldest eruptions at Duck Creek Butte in Harney Basin are dated at over 10 million years, while the Newberry flows (Qyb) are as recent at 1,300 years ago. Within the study area, the oldest units sampled range from 4 to 10 Ma and include the Devine Canyon and Prater Creek (Tmv) ash-flow tuffs, overlain by Rattlesnake Tuff (Tat). Younger stratigraphy is predominantly basalt and basaltic andesite flows dated less than 6,800 year old ($^{14}$C), found on the flanks of the Newberry Volcano and to the northwest in the Bend, Oregon area. See Appendix A, Figure A.6 for stratigraphy of this province (Orr and Orr, 2012).
Table 7. Description of geologic units sampled within High Lava Plains Province. Unit description summarized from Walker and MacLeod (1991) and province boundary defined by DEQ (2013). Detailed descriptions are found in Appendix B.

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>Primary Rock Types/Additional Rock Types</th>
<th>Description of Map Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qb</td>
<td>basalt, andesite</td>
<td>basalt, basaltic andesite, olivine basalt</td>
</tr>
<tr>
<td>QTps</td>
<td>basalt, andesite</td>
<td>subaqueous basaltic and andesitic ejecta: scoriaceous cinders, bombs, breccia, minor agglutinate</td>
</tr>
<tr>
<td>QTst</td>
<td>rhyolitic to andesitic tuff/ mud flows, alluvium</td>
<td>tuffaceous sedimentary rocks and tuffs</td>
</tr>
<tr>
<td>Qyb</td>
<td>basalt, basaltic andesite</td>
<td>youngest basalt and basaltic andesite: flows and associated breccia on slopes of Newberry Volcano</td>
</tr>
<tr>
<td>Tat</td>
<td>rhyolitic to dacitic tuff/ tuffaceous sedimentary rocks</td>
<td>silicic ash-flow tuff; minor tuffaceous sedimentary rocks</td>
</tr>
<tr>
<td>Tmv</td>
<td>basalt, basaltic andesite, andesite/ pyroclastic rocks</td>
<td>mafic vent complexes: plugs, dikes, breccia, cinders and agglutinate</td>
</tr>
</tbody>
</table>

2.3 CLIMATE

Oregon is divided into nine climatic zones, six of which are represented in this southwest Oregon study area (Figure 3) (Taylor and Hannan, 1999). Zones were established by the National Climatic Data Center using average precipitation and temperature values from NOAA weather stations (Taylor and Hannan, 1999). The following descriptions of the climatic zones and climate 30-year normal averages (1961-1990) are summarized from Taylor and Hannan (1999).

The Coastal Area (zone 1) is characterized by wet winters, relatively dry summers and mild temperatures throughout the year. Annual precipitation averages 165 to 229 cm (65 to 90 inches) along the coast where elevations are lower, and up to 508 cm (200 inches) in the upper elevations of the west slopes in the Coast Range. Summer temperatures increase only about 8 °C (15 °F) above January temperatures. The study area includes the lower half of zone 1.
The Willamette Valley (zone 2) has a mild climate throughout the year with cool, wet winters and warm, dry summers. As with the coastal area, typically half the annual rainfall occurs in the winter months, from December to February. Annual precipitation varies in the valley, with more precipitation at higher elevations. Precipitation in Portland (6.4 m above sea level) averages below 102 cm (40 inches). Average precipitation in Eugene (109 m above sea level) is 117 cm (46 inches) and is greater than 203 cm (80 inches) in the Cascade and Coast Range foothills. Sample sites lie in the southernmost
part of this climate zone, near the city of Eugene. The stations local to Eugene are Eugene WSO (110 m, 360 ft.), Noti (137 m, 450 ft.), Cottage Grove (198 m, 650 ft.), Leaburg (207 m, 680 ft.) and Dorena Dam (250 m, 820 ft.). Precipitation averages for these stations are 125-, 154-, 116-, 163-, and 118-cm, respectively (49.25, 60.65, 45.54, 64.11 and 46.65 inches). Mean temperature in zone 2 ranges from about -1 °C to 5 °C (30 °F to 40 °F) during cold months and average from the low 10 °C to low 27 °C (50 °F to 80 °F) in the summer months (Taylor and Hannan, 1999).

All of the Southwestern Interior (zone 3) is included in the study area. The rugged terrain of high mountain ridges and incised river valleys results in precipitation averages from 48 cm (18.85 inches) in the Rogue Valley, to in excess of 305 cm (120 inches) in the Klamath Mountains. Temperature fluctuations in the southwestern interior are large. Mean temperature in zone 3 ranges from -1 °C (30 °F) to the mid-10s °C (~50 °F) during cold months and average from the low 10 °C to 32 °C (50 °F to 90 °F) in the summer months (Taylor and Hannan, 1999).

The lower quarter of the Northern Cascades (zone 4) is part of the study area. This zone encompasses high elevations west of the Cascade crest and includes average elevations over 2,743 m (9,000 ft.), extending from 43.5°N latitude to the Columbia River. The northern Cascades receive from 203 cm to over 381 cm (80- to 150-inches) of precipitation (mostly snow), where precipitation increases and temperature decreases with increasing elevation. The Oakridge station (1280 ft.) is the only station listed within the study area, and averages 114.8 cm (45.18 inches) of precipitation annually. The
minimum average temperature is -1.3 °C (29.7 °F), maximum average 28.3 °C (82.9 °F), and an average temperature range from a few degrees Celsius to 10 °C (high 30s °F to 50s °F) in the winter to about 18 °C (mid-60’s °F) in July (Taylor and Hannan, 1999).

The western half of the High Plateau climatic zone (zone 5) is within the study area. The Plateau has cool temperatures due to its largely high elevations, which average 1,676 m (5,500 ft.). The rain-shadow effect produced by the Cascades is less here than to the north of this zone, because the Cascade crest averages a lower elevation here, and the Plateau elevation is higher, allowing for less of a temperature difference. As a result, there is greater precipitation in zone 5 than the surrounding zone 7, with more than 165 cm (65 inches) in the west at Crater Lake and less than 30.5 cm (12 inches) to the east. The Crater Lake (1975 m, 6480 ft.), Odell Lake (1463 m, 4800 ft.) and Wickiup Dam (1329 m, 4360 ft.) stations are within the study area. Mean precipitation is 168-, 85- and 54-cm, respectively (66.28, 33.35 and 21.23 inches). The average temperature ranges from -3 °C (26 °F) to about 2 °C (mid-30s °F) in the winter and about 13 °C (mid-50s °F) at Crater Lake and about 14 °C to 17 °C (57 °F to 62 °F) in the summer for Odell Lake and Wickiup Dam (Taylor and Hannan, 1999).

The South Central Area (zone 7) is only partially represented in the study area; only Sisters (969 m, 3180 ft.), Bend (198 m, 650 ft.), Sprague River (1329 m, 4360 ft.), Klamath Falls (1250 m, 4100 ft.) and Malin (1411 m, 4630 ft.) stations are within the study area, which includes the westernmost part of the zone to the left of the “U” created by zone 5. This climate zone is defined by low precipitation. Annual precipitation for the
stations listed above is 36-, 30-, 43-, 34- and 34.5-cm, respectively (14.18, 11.70, 16.97, 13.47 and 13.59 inches). The average temperature ranges from -2.6 °C to about 6 °C (27.4 °F to low 40s °F) in the winter and 16.9 °C to 19.9 °C (62.5 °F to 67.9 °F) in the summer for these stations (Taylor and Hannan, 1999).

2.4 VEGETATION

To obtain the natural distribution of metals in the soil profiles, samples were collected from vegetated locations away from anthropogenic influences. Most sites were heavily forested with species of fir and pine prevailing. In drier climates, Pacific madrone and scrub oak were predominant. Pictures of foliage are included in Appendix C, and vegetation listed by sample site in Appendix E.
CHAPTER III: BACKGROUND WORK ON THE CONCENTRATION OF ARSENIC IN SOILS

3.1 SOILS

3.1.1 SOIL DEFINITION

The definition of soil varies by profession. To an engineer, soil is unconsolidated surficial material (Birkeland, 1999). As disciplines require more details about the soil to study-- for example, its chemistry, mechanical properties or pedogenesis-- the definition becomes more complex. For the purpose of this study, soil is defined as: “a natural body consisting of layers (horizons) of mineral and/or organic constituents of variable thicknesses, which differ from the parent materials in their morphological, physical, chemical, and mineralogical properties and their biological characteristics” (Birkeland, 1999). All soil terms and concepts discussed in this chapter are summarized from Birkeland (1999), unless cited otherwise.

3.1.2 SOIL PROFILES AND HORIZON NOMENCLATURE

The profile of a soil is a two-dimensional vertical arrangement of all the horizons down to the parent material. As soil forms (pedogenesis) and deposition occurs above the parent material, physical and chemical weathering result in horizons within the soil.

The major factors that influence soil formation were defined in a formula by Jenny (1941):

\[ \text{Soil} = f (c_l, o, r, p, t, \ldots) \]
The abbreviations within the parentheses represent the following factors: “cl” for climate, “o” for biota, “r” the topography, “p” the parent material and “t” the time. The ellipsis allows for the addition of unspecified factors that may have local or regional importance to soil formation. All factors despite real world influences on other factors are considered independent variables, where changing a factor will change the soil. By analyzing a single factor and holding the others constant, soil properties may be predicted.

Climate dictates rate of weathering, transport and changes in element species. Organisms recycle nutrients and provide pathways for water, while bacterial decomposition is known to affect the solubility (Banning and Rude, 2010), and therefore transportation of arsenic. Topography influences water flow, water storage and temperature; in the Northern Hemisphere, north-facing slopes, which have thicker A and B horizons, are generally cooler and wetter than south-facing slopes (Birkeland, 1999). Parent material affects the soil type and rate of development. Time is required for soil formation (Jenny, 1941) and allows the other factors to have greater influence on development.

Anthropogenic sources also contribute to elevated arsenic by introducing products with arsenic content, such as some pesticides (organic arsenic), mining and treated lumber, but samples were collected away from these potential human influences. The formation factors are relevant to this thesis only wherein topography, parent material and time were included in the analysis as potential influences on the levels of arsenic in soils.
Soil horizons are termed using capital letters for the master horizons, and lowercase letters to describe characteristics of the sub-horizons. Soil horizon nomenclature and characteristics common to profiles in southwest Oregon are listed in Table 8. The samples for this study were taken only in the A and B master horizons. The A horizon is found at the surface or near the surface beneath the O horizon. The A horizon is defined as having relatively high organic matter mixed with mineral fraction, where the mineral fraction dominates the humified organic matter (Birkeland, 1999). The B horizon is found beneath the A or an E horizon. The B horizon will develop characteristics from the influence of overlying horizons or its parent material; it accumulates clay translated from above horizons and metal compounds such as iron and aluminum, and is typically brown to red in color from iron released from the parent material.

Both horizons were sampled because Burns et al. (1991) found that sometimes the maximum concentration of a metal is found in the A horizon and in older soils it is found in the B horizon. The purpose of this project was to find the maximum concentration so both horizons were sampled.

3.1.3 FIELD SOIL CHARACTERISTICS AND PROPERTIES

Color, texture, organic matter, structure and soil pH are used as aids in the field to qualitatively determine soil materials and current or previous processes that are or have acted on the soil. Use of a Munsell soil color book allows for consistent soil color comparison using notation for the hue, value and chroma, where hue is the dominant color, value ranges from one (dark) to 8 (light), and chroma is the strength of the spectral color from one (least vivid) to 8 (most vivid). Soil with organic matter will present dark
brown to black in color with a low value and chroma, and value will decrease (get darker) as organic matter increases. Leaching of oxides and hydroxides above the B horizon,

**Table 8: Soil Horizon Nomenclature (Birkeland, 1999).**

<table>
<thead>
<tr>
<th>Master Horizons</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>O horizon</td>
<td>Surface accumulations of mainly organic material; may or may not be, or has been, saturated with water.</td>
</tr>
<tr>
<td>A horizon</td>
<td>Accumulation of humified organic matter mixed with mineral fraction; mineral fraction dominant. Occurs at the surface or below O horizon in forest soils.</td>
</tr>
<tr>
<td>E horizon</td>
<td>Usually underlies O or A horizon. Characterized by less organic matter and/or fewer sesquioxides iron and aluminum compounds) and/or less clay than underlying horizon; light in color.</td>
</tr>
<tr>
<td>B horizon</td>
<td>Underlies O, A, or E horizon. Shows little or no evidence of original sediment or rock structure. Subdivided by illuvial accumulations or residual concentrations of materials.</td>
</tr>
</tbody>
</table>

**B horizon subdivisions:**

- **Bt horizon**—Accumulation of silicate clay formed in situ or by clay translocation; greater amount of clay than assumed parent material and/or the overlying horizon.

- **Bw horizon**—Development of color (redder hue or higher chroma relative to C) or structure, or both, with little or no apparent illuvial accumulation or material.

| C horizon       | A subsurface horizon, excluding R, like or unlike material from which the soil formed, or is presumed to have formed. Lacks properties of A and B horizons, but includes materials in various stages of weathering. |
| R horizon       | Consolidated bedrock underlying soil. |
gibbsite within the B horizon in humid areas, and carbonate or gypsum below the B horizon in arid areas will result in a bleaching effect on the soil. Pedogenic iron will color the soil brown or red. Redoxymorphic conditions will result in mottled (red and gray) soils or gray soils if conditions are fully reduced (gleyed) in poorly drained soils.

![Figure 4: Approximate relations between texture class, grittiness, and wet consistence (Birkeland, 1999).](image)

The texture class is based on the proportion of sand, silt and clay with a particle size less than 2 mm in diameter in the soil. Texture can be determined in the field using Figure 4 and techniques outlined in Appendix 1 of Birkeland (1999). The variation of texture between horizons is a useful tool to interpret the pedogenic and geologic history of the soil. Clay variation with depth can be used to estimate age; the greater the clay
content, the older the soil is. Also, soils that are finer in texture will be more chemically active and weather faster (Birkeland, 1999).

Organic matter will be concentrated at the surface. It affects soil structures and reactions, increasing the soil’s ability to hold water and the cation-exchange capacity; the increase in chemical reactions results in carbonic acid buildup, a decrease in pH and an increase in weathering.

Structure is classified by the aggregated shape of soil particles. Since horizon formation and subsequent aggregation is a result of the past and active pedogenic processes which then create shapes favorable to the processes, the shapes can be related with particular horizons. A granular structure is indicative of high organic matter, or an A-horizon. B horizons have higher clay content, which is conducive to blocky, prismatic or columnar structures. Platy structures are the result of precipitation and cementation, and will be in an E or K horizon, or labeled as a subhorizon. Structure highly affects water movement and erosion; granular structure has more voids between aggregates, allowing for infiltration of surface water. As porosity decreases due to clay infilling or more compactable structures, the soil’s storage capacity will be exceeded and surface runoff will result in erosion. Structure was noted in the field but was not used in the total analysis (Birkeland, 1999).

Soil acidity or alkalinity, measured as pH, influences mineral solubility; dissolution and precipitation is reliant on the proportion of exchangeable ions present in the soil. In acidic soils (pH<7), the exchangeable ions of H\(^+\), Al\(^{3+}\) and aluminum
hydroxides dominate. In alkaline soils (pH > 7) the base cations of $K^+$, $Ca^{2+}$, $Mg^{2+}$ and $Na^+$ dominate. The pH varies within a soil and should only be used as an estimate of soil weathering and mineral stability (Adriano, 2001).

The pH can also be used to help identify diagnostic soil horizons for soil classification. Base saturation, the percentage of exchangeable base ions (non-hydrogen) that make up the total available cations, is defined to classify soils. However, since base saturation and pH have a positive correlation, and pH is easier to obtain, the pH can be used as a proxy for base saturation for classification. A regional pH-base saturation relationship should be established, but in general 50% base saturation occurs between pH 5 and 6 (Birkeland, 1999). Neither the base saturation nor pH was collected for samples in this study but are discussed as important properties for soil classification.

3.1.4 SOIL CLASSIFICATION

Within the United States, soil is typically classified using the scheme in Keys to Soil Taxonomy (USDA, 2010). Using soil characteristics in the field and laboratory settings, a soil can be grouped into one of eleven soil orders: Entisols, Inceptisols, Aridisols, Mollisols, Alfisols, Spodosols, Andisols, Ultisols, Oxisols, Vertisols and Histosols (USDA, 2010). The soil orders in this study region include Entisols, Inceptisols, Mollisols, Alfisols, Spodosols and Ultisols.

The 11 orders of Soil Taxonomy (USDA, 2010) are generally grouped from least to most developed, where a young soil may begin high in nutrients, then develop and increase in clay, and eventually be leached of nutrients (old soil). However, not all orders
are classified by development. The 11 soil orders can be further broken down into 47 suborders and 230 great groups based on more detailed characteristics beyond the scope of this study (Birkeland, 1999).

For the soil orders represented in this study, we focus only on the degree of soil and clay development (Birkeland, 1999). Entisols are young soils with a very mild degree of weathering and slight degree of soil development. Inceptisols are recent soils with mild weathering and a slight degree of soil development. Alfisols consist of mildly acidic clays and have an intermediate degree of weathering and soil development. Ultisols are old, well-developed and leached soils that consist of strongly acid clays with intermediate to strong degree of weathering and soil development. Mollisols are soft, dark, and fertile soils with an intermediate degree of weathering and soil development. Spodosols are commonly found in cool, wet and sandy environments and have an intermediate to strong degree of weathering and soil development. Parent material is bedrock in which soil horizons form from; its physical and chemical composition plays an important role in early soil development.

For analysis, two categories were created that are not technically soil orders. An Alfisols/Ultisols category was assigned to samples where base saturation, the distinguishing characteristic between those two orders, was not determined; physical characteristics between these orders are too similar to make an accurate differentiation without lab testing. This combined Alfisol/Ultisol category shows an intermediate to strong degree of weathering and soil development. The Parent Material category represents sample sites where no soil horizon has developed.
3.2 SOURCES OF NATURALLY OCCURRING ARSENIC

Globally, arsenic concentrations in uncontaminated topsoil (5.1 to 20 cm) can range from 1-100 ppm (McLaren et al., 2006). In the U.S., the range of arsenic in soil and other surficial materials is <0.1–97 ppm, with a mean of 7.2 ppm (USDH, 2007). The range of background arsenic concentrations in soils has been attributed to differences in the soils parent material and its degree of weathering. Typical arsenic concentrations in general rock types were compiled from various sources by Ravenscroft et al. (2009) (Table 9).

Arsenic exists in primary arsenic-bearing minerals which are found in high concentrations in sulfide deposits (Adriano, 2001), or adsorbed onto various mineral phases (Ravenscroft et al., 2009). The common mineral phases — iron, manganese and aluminum oxides — are discussed in the geochemistry section (3.3). Sedimentary rocks have been shown to reach much higher levels of arsenic concentrations than igneous and metamorphic rocks (Table 9). Enrichment of arsenic in rock is attributed to hydrothermal activity in igneous and metamorphic rock; sedimentary rock enrichment is due to pyrite accumulation in swamps for coal and iron hydroxide adsorption in oxic conditions for ironstone (Ravenscroft et al., 2009).

While outside the scope of this study, atmospheric deposition is another source of arsenic accumulation in soils. Despite the large influence of anthropogenic sources on arsenic emissions and subsequent deposition, natural sources of arsenic from volcanic activity and low-temperature volatilization still contribute from 30 to 60% of total global arsenic emissions to the atmosphere (McLaren et al., 2006).
3.3 GEOCHEMISTRY: ARSENIC SPECIES AND TRANSPORTATION

The fate and transport of arsenic in soil can be simplified by Figure 5. In this study, we are concerned with arsenic retained in the solid phase of uncontaminated soil.

In the near-surface environment in soils, the chemical species of arsenic primarily occurs as As(V) or As(III); corresponding primary arsenic compounds are arsenate (AsO$_4^{3-}$) and arsenite (AsO$_3^{3-}$). Retention (adsorption) of arsenic by soils and release (desorption) from
soils is influenced by its oxidation state, the surface charge of minerals, the pH of the soil and redox potential. Arsenite is more soluble, mobile and toxic than arsenate, whereas arsenate is generally more readily attracted to and retained by soils and sediments (Adriano, 2001). The negatively charged arsenite and arsenate ions adsorb to positively charged mineral surfaces, most commonly iron, aluminum and magnesium oxides, or to clay due to its high surface area (Ravenscroft et al., 2009). Iron oxides dominate arsenic adsorption, retaining arsenic on the surface of clay particles or as microaggregates (McLaren et al., 2006). The pH affects the charge of oxides; at low pH oxides are positively charged and allow adsorption. In general, as pH increases, adsorption of arsenate will decrease and adsorption of arsenite will increase (Adriano, 2001).

![Figure 5: Simplified fate of arsenic in the soil environment (McLaren et al., 2006).](image)

To predict the stability of the arsenic species in different environments, pe-pH diagrams can be used. Redox potential, shown as pe or $E_\text{h}(\text{mV})$, is a measure of a species ability to acquire electrons and be reduced. As shown in Figure 6, arsenate is more stable
under oxidized conditions, while arsenite is more stable at moderate to low redox potentials below the limits for arsenate (Inskeep et al., 2002).

![Figure 6: Simplified pe-pH diagram for the As-S-H2O system at 25°C (Inskeep et al., 2002).]

**3.4 PREVIOUS WORK: ARSENIC IN SOILS IN SOUTHWEST OREGON**

Khandoker (1997) sampled 118 sites throughout southwest Oregon in the A and B horizons and found only three samples above the reporting limit of 20 ppm; the B horizon at site R13 had 29.4 ppm, and site KL21 had 36.4 and 46.5 ppm in the A and B horizons, respectively. Locations of these sites are in Figure 1 and characteristics in Appendix E. When retested with the lower detection limit of 0.20 ppm, site R13 was 13.6 ppm, and site KL21 had 32.6 and 26.1 ppm in the A and B horizons, respectively. Both sites are in the Klamath Mountain province. The sample from site R13 is from basaltic volcanic and sedimentary rock unit (Jub) and an Ultisol/Alfisol soil. The samples from site KL21 are from the Condrey Mountain Schist formation (cm) and are Alfisol soils.
DEQ has more recently released a report of the maximum limits permissible by physiographic province (DEQ, 2013). The DEQ analyzed default background concentrations collected by regulatory and educational institutions and consultants; summary statistics and background statistics were used to calculate a regional default background concentration at the 95-percent upper limit (Table 1).

No other current studies were found specific to naturally occurring levels of arsenic in soils in southwest Oregon outside of those related to the Oregon DEQ reports (2013), although there is a study assessing arsenic in groundwater that attributes higher arsenic values to aquifers within specific rock units (Hinkle and Polette, 1999).
CHAPTER IV: METHODOLOGY

4.1 GEOGRAPHIC INFORMATION SYSTEMS

The geologic map of Oregon created by the United States Geological Survey (Walker and MacLeod, 1991) was used as a base map for this study to ensure consistency with arsenic studies done in Oregon previous to this study (Khandoker, 1997; Douglas, 1999). The map was obtained online, and ArcGIS software was used to isolate the lithologic polygons in the southwest Oregon study area. Lithologic units on the map were assumed to be correctly labeled for this analysis. The mapped units were used to ensure good sample coverage in the soils overlying them. In drier climates, such as in eastern Oregon, eolian processes have a much higher influence on arsenic distribution. However, for this study area, it is assumed that soil development is influenced by the weathering of the underlying bedrock.

ArcGIS software was then used to assess the lithologic units (Appendix E: geologic unit) to determine where additional field sampling should be done to maximize sample coverage within the study area. First, the sum of area for each lithologic unit in southwest Oregon was calculated using analysis tools in ArcGIS. The largest units by total area that were not sampled by previous studies (Khandoker, 1997; Douglas, 1999) were selected for sampling: Qyb, Tvm, Thi, Tfeb, Tvs, KJdv, QTa, and Ti. In addition, the previously sampled Tfee unit in Eugene, which had the largest arsenic concentration in Khandoker’s study (1997), was selected for resampling. Ultimately, the sum of the area of all lithologic units underlying soil sample sites within the PSU data set represent over 99% of the mapped bedrock in the study area. GIS was also used to determine what
formations are within terranes in much of the study area by orthorectifying and digitizing Figure 2, then spatially joining geologic units within the terrane polygons.

4.2 FIELD METHODS

Forty-two samples from soils overlying the nine selected units were acquired July 21-23, 2013. Field sampling was done exactly the same way as was done by Douglas (1999) and Khandoker (1997). Samples from the A and B horizons were collected from uncontaminated, remote and undisturbed soils to avoid anthropogenic influences and obtain the natural distribution of metals in the soil profiles. Once the location was selected, a soil pit was dug with a shovel to reveal the A horizon, and some of the B horizon. A horizons were sampled within the top 4 cm of soil, and B horizons sampled from different locations around the walls of the pit where soil was the most red in color.

To both assess the variability of arsenic within each horizon and validate the consistency of ICP-MS analysis, five samples from the A horizon and five samples from the B horizon were collected for testing. Samples were taken from site HH 11 at different locations around the pit wall within each horizon to test the validity of taking only one sample from the A and B horizons. This one site was chosen randomly for this analysis; additional samples from different pits above this unit, or from other sites, would have added statistical robustness but were not collected because additional sample analysis was cost prohibitive.

The location of each pit was determined by Garmin GPS, using the WGS84 datum with horizontal accuracy of ± 3 meters. Soil properties were recorded using
techniques outlined by Birkeland (1999, Appendix 1). Photographs of soil pits and local vegetation at each site were taken (Appendix C). Samples were then placed in a labeled zip-lock bag, and pits filled back in.

4.3 LABORATORY METHODS

In the Portland State University soil lab, the 42 new samples were air dried and soil classifications (USDA, 2010) determined using field notes of soil texture, consistency, and dry Munsell color. Samples were disaggregated using a mortar and pestle, then sieved with a number 10 sieve. Approximately 300 grams were repackaged into labeled zip-lock bags and delivered to Apex Laboratory for testing; however, Apex Laboratories only requires a maximum of 2 grams for ICP-MS analysis.

Soil samples from former studies (Khandoker, 1997; Douglas, 1999) had also been prepared by air drying after the original collection. They were then disaggregated, shaken through a #10 sieve and approximately 300 grams of soil for each sample was bagged for later machine testing. Arsenic concentrations were originally determined by inductively coupled plasma-atomic emission spectrometry (Khandoker, 1997) at a minimum reporting limit of 20 ppm.

For this study, Apex Labs used U.S. Environmental Protection Agency’s Method 6020A (EPA, 2007b) for analysis by inductively coupled plasma-mass spectrometry (ICP-MS). Prior to analysis sediments were prepared using acid digestion Method 3051A (EPA, 2007a, which dissolves almost all elements that could become “environmentally available.” See Appendix G for partial copies of Apex Labs reports. Samples by work
order, quality control sample results, sample preparation information and notes and
definitions used in Apex reports are included. Results pages are omitted; these reports are
for all samples used for Oregon metals evaluation, only some of which are samples
collected by PSU. Results of arsenic for PSU-collected samples are in Appendix D.

All 118 former soil samples (Khandoker, 1997; Douglas, 1999) were re-tested in
2010 by Apex Laboratories in Tigard using ICP-MS with a detection limit of 0.20 ppm,
which allows for a more accurate exploration of the true background levels of arsenic in
soils of southwest Oregon. Arsenic concentrations of the 42 new samples from July 2013
field work were also tested by Apex Laboratories in October 2013 using the same method
and detection limit.

4.4 GROUPINGS FOR STATISTICAL ANALYSES

The statistical analysis started with an examination of the data. Statistical tests
used were the Shapiro-Wilk test for normality, Fisher’s F-ratio for variance and the
Welch t-test for comparison of means between the groups. Wilcoxon Rank-Sum was used
for comparison of medians when data was not normally distributed. Horizons were
compared to determine if the arsenic in the A horizon (Table 12) should be analyzed
separate from the B horizon (Table 13). The detection limit for arsenic is 0.20 ppm. Non-
detect samples were assigned a value of 0.001 ppm half the detection limit of the
originally reported 0.002 ppm; this method is commonly used for analysis (Helsel, 2006).

A comparison between the samples collected by Portland State University (PSU)
students for this study area and a modified DEQ data set was conducted. The samples
collected by Douglas (1999) and Khandoker (1997) were first removed from the DEQ data set. The maximum concentration of arsenic measured in samples from each PSU site (136 total sites) was used to compare to the remaining 673 sites from the DEQ data for the provinces in southwest Oregon. Summary statistics and estimates for the two data sets were run using ProUCL Version 4.1.

The maximum arsenic concentrations at each site were then evaluated by their relationship to the following predictors: soil color, soil order, elevation, geomorphic province, and rock age and rock type. The highest value per sample site was used for analysis following the industry standard for determining maximum background levels (Burns et al., 1991). For sites where both the A horizon and B horizon were ND but soil color or order differed, the B horizon was selected for use in analyses. This was done because high arsenic concentrations are often associated with iron oxides and sulfide minerals on clay surfaces (McLaren et al., 2006), which typically concentrate in the B horizon.

To assess a potential relationship with color (or soil development), dry Munsell data were converted to the Buntley-Westin color index (Buntley and Westin, 1965), which indicates the redness of the soil. This color index has assigned values for each hue in the Munsell Color Book and is calculated by multiplying the hue value with chroma. Soil order as recorded by former studies (Khandoker, 1997; Douglas, 1999) was combined with field observations from this study.
Rock analyses in this study include dominant rock type and rock age. The variety of dominant rock types (i.e., sandstone, shale) mapped by the USGS (Walker and MacLeod, 1991) have been simplified to the process that formed them (i.e., sedimentary, metamorphic). The categories were assigned using lithologies described by USGS (Walker and MacLeod, 1991) and the Oregon Department of Geology and Mineral Industries, or DOGAMI (McCloughry et al., 2010). Where mixed lithology did not clearly indicate a primary rock type, assignment was dictated by the parameters listed in Table 10. Descriptions for rocks that included verbiage such as “minor interbeds” and “locally includes” were not considered a primary rock type. For category assignments and lithologic descriptions of each unit, see Appendix B. The reclassification includes the following categories: Metamorphic, Plutonic, Volcanic, Sedimentary, mixed Volcanic/Sedimentary and Unconsolidated sediments (Table 10). Elevation from USGS metadata (Walker and MacLeod, 1991) was converted from feet to meters.

To analyze rock age, the minimum and maximum ages according to the rock unit description (Walker and MacLeod, 1991) were averaged. This was done to provide a single number for relative comparison while taking the duration of deposition into account. For example, a Cretaceous rock unit (65.5 Ma to 145.5 Ma) has a value of 105.5, and a Mesozoic and Paleozoic rock unit (65.5 Ma to 542 Ma) a value of 303.75. A Paleozoic rock unit (251 Ma to 542 Ma) has a value of 396.5. This assigns rocks of similar age but longer duration of deposition a higher value, while maintaining a higher ranking for older deposition. Rock unit ages and ranking are included in Appendix F.
Table 10. Description of rock type categories; mixed lithologies were discerned following these descriptors within the unit descriptions by Walker and MacLeod (1991).

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>Metamorphic: primary rocks are metamorphic, or mixed lithologies are described as mélange, highly sheared or altered.</td>
</tr>
<tr>
<td>P</td>
<td>Igneous Plutonic: primary rocks are granite, diorite.</td>
</tr>
<tr>
<td>V</td>
<td>Igneous Volcanic: primary rocks are basalt, andesite.</td>
</tr>
<tr>
<td>S</td>
<td>Sedimentary: primary rocks are sandstone, siltstone, mudstone, limestone.</td>
</tr>
<tr>
<td>VS</td>
<td>Mixed Volcanic and Sedimentary: primary rocks are described as volcanic and sedimentary, tuffaceous sedimentary, undifferentiated or undivided volcanic and sedimentary, or as having one lithology (volcanic or sedimentary) as part of the sequence.</td>
</tr>
<tr>
<td>U</td>
<td>Unconsolidated sediments of any lithology not falling under “VS.”</td>
</tr>
</tbody>
</table>

Statistical analyses were done to test the validity of the splits in the regression tree using the Shapiro-Wilk Test for normality, Fisher’s F-ratio for variance, and the Wilcoxon Rank-Sum Test to compare the center of data between the two groups defined by the split. A regression forest was then done to check the predictions of the regression tree, since forests have been shown to produce better predictions than a single tree (Shih, 2011).
CHAPTER V: RESULTS

5.1 ARSENIC CONCENTRATIONS IN SOUTHWEST OREGON

A total of 255 samples from 136 sites were collected by PSU and used in this study; 123 samples are from the top of the A horizon (Table 12) and 132 samples were taken from within the B horizon (Table 13). The highest arsenic concentrations measured in samples from the A and B horizons, respectively, are 63.2 ppm and 85.4 ppm. These maximum values are both from the Eugene Formation, a marine sedimentary deposit exposed along the eastern margin of the Willamette Valley from Creswell on the south to north of the study area in Scio, Oregon (McLaughry et al., 2010). Of the 255 samples, arsenic was not detected (ND) in 20 (7.8%) of the samples tested at a minimum detection limit of 0.20 ppm; of the ND samples, 11 were from the A horizon and 9 from the B horizon.

Maximum concentrations of arsenic for the 136 PSU-collected sites were mapped using ArcGIS and classed using Jenks natural breaks (Figure 7). The Jenks method clusters data to minimize the average deviation from the mean within each class and maximize the deviation from the means of other classes. The Jenks class with the lowest arsenic concentrations (0.00 to 2.82 ppm) includes 60.3% of the maximum arsenic concentrations, 8.1% of which have no arsenic detected. The second class includes 24.3% of the data. The third, fourth and fifth arsenic classes constitute 13.2%, 1.5% and 0.7% of the data, respectively.
5.2 DISTRIBUTION OF ARSENIC IN A AND B SOIL HORIZONS

To test whether the concentration of arsenic was greater in the A or B horizon, the two groups were compared using the results in Table 12 and Table 13. Of 136 sites, 119
sites had samples for both the A and the B horizon; 17 sites were omitted for not having a representative sample in the adjacent horizon. The Shapiro-Wilk normality test (Ellison and Gotelli, 2013) concluded that arsenic levels in both A and B horizons deviated from normality (p-values both <2.2e-16). Fisher’s F-ratio (Ellison and Gotelli, 2013) was used to interpret variation. The F-ratio (0.5436) indicates the variance among arsenic samples in the A and B horizon groups is small relative to the variation within the groups A and B (Figure 8).

Figure 8. Cube root transformed variance of arsenic within the A and the B horizons for the 119 sites that had samples for both the A and B horizons.

Since the groups deviate from normality, the Wilcoxon rank sum test (Ellison and Gotelli, 2013) was used to compare the median between groups. The center of data for each horizon does not differ significantly (p-value: 0.7567) at a 95% confidence level. The W value (W: 6915.5) is large, so results are less likely to have occurred by chance. Although 47 sites (39.5%) are higher in arsenic in the A horizon while 63 sites (52.9%)

52
are higher in the B horizon, with 9 sites (7.6%) having no value detected, the A and B horizons are not statistically different (Table 11).

Table 11: Comparison on A and B horizon indicates center of data between horizons is not significantly different.

<table>
<thead>
<tr>
<th>Data Type: A vs. B horizon</th>
<th>Statistical Test</th>
<th>Test Result</th>
<th>p-value (α=0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Arsenic Values</td>
<td>Shapiro-Wilk</td>
<td>W = 0.4099</td>
<td>&lt;2.2e-16 (A horizon)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W = 0.3696</td>
<td>&lt;2.2e-16 (B horizon)</td>
</tr>
<tr>
<td></td>
<td>F-test</td>
<td>F = 0.5436</td>
<td>0.001044</td>
</tr>
<tr>
<td></td>
<td>Wilcoxon Rank Sum</td>
<td>W = 6915.5</td>
<td>0.7567</td>
</tr>
</tbody>
</table>

Site HH11 was randomly chosen to compare arsenic between A and B horizons and to assess variation within a horizon. Site HH11 is an Inceptisol soil above volcanic rock (KJdv map unit) located at 275 meters elevation in Douglas County within the Klamath province. Five samples were taken from the A and from the B horizons at site HH11. The Shapiro-Wilk normality test concluded that arsenic levels in both A and B horizons have a normal deviation with p-values 0.8981 and 0.8596 for A and B horizons, respectively. Fisher’s F-ratio was used to interpret variation. The F-ratio (1.2997) indicates the variance between arsenic samples in the A and B horizon groups is larger relative to the variation within the groups A and B (Figure 9). Since the groups are normally distributed, the Welch Two-Sample t-test was used to compare the median between groups. The test results (Table 14) indicate that with 95% confidence there is a significant difference between the center of data for each horizon subset (p-value: 0.01699).
Table 12. Arsenic concentrations for samples collected in the A horizon, in order of increasing concentration.

<table>
<thead>
<tr>
<th>Sample</th>
<th>As</th>
<th>Sample</th>
<th>As</th>
<th>Sample</th>
<th>As</th>
<th>Sample</th>
<th>As</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH01</td>
<td>0.001</td>
<td>LM11</td>
<td>0.957</td>
<td>LM04</td>
<td>2.1</td>
<td>HH11.2</td>
<td>3.95</td>
</tr>
<tr>
<td>HH02</td>
<td>0.001</td>
<td>LM22</td>
<td>0.965</td>
<td>LM12</td>
<td>2.1</td>
<td>LC12</td>
<td>4.27</td>
</tr>
<tr>
<td>HH03</td>
<td>0.001</td>
<td>KLO2</td>
<td>0.995</td>
<td>EO27</td>
<td>2.15</td>
<td>HH17</td>
<td>4.28</td>
</tr>
<tr>
<td>HH04</td>
<td>0.001</td>
<td>R15</td>
<td>1.0</td>
<td>KL18</td>
<td>2.22</td>
<td>HH11.1</td>
<td>4.38</td>
</tr>
<tr>
<td>HH07</td>
<td>0.001</td>
<td>LM21</td>
<td>1.03</td>
<td>LC17</td>
<td>2.28</td>
<td>HH18</td>
<td>4.54</td>
</tr>
<tr>
<td>HH08</td>
<td>0.001</td>
<td>EO33</td>
<td>1.07</td>
<td>LM16</td>
<td>2.32</td>
<td>LC10A</td>
<td>4.58</td>
</tr>
<tr>
<td>HH09</td>
<td>0.001</td>
<td>EO22</td>
<td>1.12</td>
<td>KL13</td>
<td>2.36</td>
<td>HH05</td>
<td>4.88</td>
</tr>
<tr>
<td>HH10</td>
<td>0.001</td>
<td>EO34</td>
<td>1.15</td>
<td>LM15</td>
<td>2.38</td>
<td>KL19</td>
<td>4.88</td>
</tr>
<tr>
<td>HH12</td>
<td>0.001</td>
<td>EO24</td>
<td>1.22</td>
<td>LC13</td>
<td>2.52</td>
<td>LC08</td>
<td>4.96</td>
</tr>
<tr>
<td>HH15</td>
<td>0.001</td>
<td>KL24</td>
<td>1.22</td>
<td>KL03</td>
<td>2.57</td>
<td>LC11</td>
<td>4.96</td>
</tr>
<tr>
<td>HH16</td>
<td>0.001</td>
<td>LC14</td>
<td>1.25</td>
<td>LM20</td>
<td>2.57</td>
<td>LM02</td>
<td>5.04</td>
</tr>
<tr>
<td>KL28</td>
<td>0.1085</td>
<td>LM05</td>
<td>1.26</td>
<td>LC20</td>
<td>2.58</td>
<td>KL08</td>
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</tr>
<tr>
<td>LC06</td>
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<td>KL26</td>
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<td>KL11</td>
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<td>5.14</td>
</tr>
<tr>
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<td>EO16</td>
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<td>KL05</td>
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</tr>
<tr>
<td>KL23</td>
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<td>KL14</td>
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<td>LM01</td>
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</tr>
<tr>
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<td>KL17</td>
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<td>KL12</td>
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<tr>
<td>LM09</td>
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<td>KL20</td>
<td>1.44</td>
<td>KL25</td>
<td>2.88</td>
<td>LC18</td>
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</tr>
<tr>
<td>EO01</td>
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<td>EO07</td>
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<td>LM07</td>
<td>2.99</td>
<td>HH06</td>
<td>7.29</td>
</tr>
<tr>
<td>EO21</td>
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<td>3.09</td>
<td>LC09</td>
<td>7.36</td>
</tr>
<tr>
<td>EO18</td>
<td>0.718</td>
<td>KL01</td>
<td>1.49</td>
<td>LM17</td>
<td>3.13</td>
<td>KL27</td>
<td>7.48</td>
</tr>
<tr>
<td>EO20</td>
<td>0.724</td>
<td>EO32</td>
<td>1.5</td>
<td>KL10</td>
<td>3.19</td>
<td>R01</td>
<td>7.94</td>
</tr>
<tr>
<td>KL30</td>
<td>0.761</td>
<td>EO08</td>
<td>1.57</td>
<td>HH11.3</td>
<td>3.24</td>
<td>KL04</td>
<td>7.97</td>
</tr>
<tr>
<td>EO30</td>
<td>0.762</td>
<td>EO36</td>
<td>1.57</td>
<td>LC22</td>
<td>3.29</td>
<td>LC05</td>
<td>8.74</td>
</tr>
<tr>
<td>KL07</td>
<td>0.765</td>
<td>KL22</td>
<td>1.57</td>
<td>KL06</td>
<td>3.43</td>
<td>R14</td>
<td>10</td>
</tr>
<tr>
<td>EO15</td>
<td>0.776</td>
<td>EO35</td>
<td>1.62</td>
<td>R02</td>
<td>3.47</td>
<td>LC02</td>
<td>10.1</td>
</tr>
<tr>
<td>LC19</td>
<td>0.799</td>
<td>LM14</td>
<td>1.63</td>
<td>HH11.4</td>
<td>3.48</td>
<td>HH13</td>
<td>13.5</td>
</tr>
<tr>
<td>EO31</td>
<td>0.821</td>
<td>KL16</td>
<td>1.7</td>
<td>KL09</td>
<td>3.5</td>
<td>R13</td>
<td>13.6</td>
</tr>
<tr>
<td>EO23</td>
<td>0.845</td>
<td>R03</td>
<td>1.72</td>
<td>LC07</td>
<td>3.64</td>
<td>LC01</td>
<td>17.2</td>
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<tr>
<td>EO14</td>
<td>0.869</td>
<td>LM13</td>
<td>1.81</td>
<td>HH11.5</td>
<td>3.65</td>
<td>KL21</td>
<td>32.6</td>
</tr>
<tr>
<td>EO25</td>
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<td>LM03A</td>
<td>1.92</td>
<td>LM08</td>
<td>3.71</td>
<td>HH14</td>
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</tr>
<tr>
<td>LM06</td>
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<td>LC03</td>
<td>2.08</td>
<td>LC16</td>
<td>3.73</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The values for site HH11 in the A horizon were 4.38, 3.95, 3.24, 3.65 and 3.48 with a mean of 3.74 and standard deviation of ±0.44. Values in the B horizon were 4.99, 4.83, 4.51, 4.29 and 4.04 with a mean of 4.53 and standard deviation of ±0.39. Variation within each Site 11 horizon is low (Figure 9); variation is 0.1949 for the A horizon and 0.1499 for the B horizon. Standard deviation for Site 11 A and B horizons is 0.4414 and
0.3872, respectively. Although this should be verified with more pits, the consistency and low deviation within each horizon support that a single sample within a horizon is a good representative of that horizon. This supports the field methodology used in this study of taking only one sample in the A horizon and one sample in the B horizon.

Table 13. Arsenic concentrations for samples collected in the B horizon, in order of increasing concentration.

<table>
<thead>
<tr>
<th>Sample</th>
<th>As</th>
<th>Sample</th>
<th>As</th>
<th>Sample</th>
<th>As</th>
<th>Sample</th>
<th>As</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH03</td>
<td>0.001</td>
<td>EO18</td>
<td>0.923</td>
<td>LM09</td>
<td>1.79</td>
<td>HH11.2</td>
<td>4.83</td>
</tr>
<tr>
<td>HH04</td>
<td>0.001</td>
<td>EO12</td>
<td>0.941</td>
<td>LM12</td>
<td>1.86</td>
<td>LC04</td>
<td>4.9</td>
</tr>
<tr>
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<td>0.001</td>
<td>EO17</td>
<td>0.965</td>
<td>KL17</td>
<td>1.9</td>
<td>LC12</td>
<td>4.98</td>
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<td>LM11</td>
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<td>LM03B</td>
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<td>HH11.3</td>
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</tr>
<tr>
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<td>LM06</td>
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<td>LM20</td>
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<td>KL08</td>
<td>5.04</td>
</tr>
<tr>
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<td>1</td>
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<td>KL10</td>
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</tr>
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<td>EO16</td>
<td>1.01</td>
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<td>KL11</td>
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<td>EO14</td>
<td>1.02</td>
<td>LM04</td>
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</tr>
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<td>LC20</td>
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<td>R12</td>
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<td>KL03</td>
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<td>KL12</td>
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<td>1.29</td>
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<td>8.63</td>
</tr>
<tr>
<td>EO34</td>
<td>0.757</td>
<td>LM22</td>
<td>1.48</td>
<td>LC10B</td>
<td>3.79</td>
<td>KL04</td>
<td>8.71</td>
</tr>
<tr>
<td>EO23</td>
<td>0.783</td>
<td>LM14</td>
<td>1.52</td>
<td>KL06</td>
<td>3.82</td>
<td>LC05</td>
<td>10.3</td>
</tr>
<tr>
<td>EO20</td>
<td>0.806</td>
<td>KL02</td>
<td>1.56</td>
<td>KL14</td>
<td>3.84</td>
<td>LC09</td>
<td>10.6</td>
</tr>
<tr>
<td>LM16</td>
<td>0.809</td>
<td>R05</td>
<td>1.61</td>
<td>HH11.4</td>
<td>4.04</td>
<td>HH13</td>
<td>11.5</td>
</tr>
<tr>
<td>KL07</td>
<td>0.814</td>
<td>KL01</td>
<td>1.62</td>
<td>LC11</td>
<td>4.11</td>
<td>R01</td>
<td>11.9</td>
</tr>
<tr>
<td>EO33</td>
<td>0.826</td>
<td>R15</td>
<td>1.64</td>
<td>HH11.5</td>
<td>4.29</td>
<td>R14</td>
<td>12.9</td>
</tr>
<tr>
<td>EO25</td>
<td>0.83</td>
<td>LC21</td>
<td>1.67</td>
<td>HH11.1</td>
<td>4.51</td>
<td>LC01</td>
<td>17.5</td>
</tr>
<tr>
<td>EO01</td>
<td>0.846</td>
<td>KL20</td>
<td>1.73</td>
<td>LM08</td>
<td>4.74</td>
<td>KL21</td>
<td>26.1</td>
</tr>
<tr>
<td>KL30</td>
<td>0.884</td>
<td>LC03</td>
<td>1.73</td>
<td>HH05</td>
<td>4.78</td>
<td>R13</td>
<td>45.4</td>
</tr>
<tr>
<td>KL23</td>
<td>0.915</td>
<td>LC14</td>
<td>1.74</td>
<td>LM02</td>
<td>4.8</td>
<td>HH14</td>
<td>85.4</td>
</tr>
</tbody>
</table>
Figure 9. Variance of raw arsenic values within the A and the B horizons at Site 11. The boxplot shows two distinct populations.

Table 14. Comparison on Site 11 A and B horizons indicates center of data between horizons is significantly different.

<table>
<thead>
<tr>
<th>Statistical Tests</th>
<th>Raw Values Test Result</th>
<th>p-value (α=0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shapiro-Wilk</td>
<td>W = 0.9737</td>
<td>0.8981 (A horizon)</td>
</tr>
<tr>
<td></td>
<td>W = 0.9676</td>
<td>0.8596 (B horizon)</td>
</tr>
<tr>
<td>F-test</td>
<td>F = 1.2997</td>
<td>0.8056</td>
</tr>
<tr>
<td>Welch Two Sample</td>
<td>t = -3.0161</td>
<td>0.01699</td>
</tr>
</tbody>
</table>

5.3 DISTRIBUTION OF ARSENIC IN SOUTHWEST OREGON BY PROVINCE

The Oregon Department of Environmental Quality (DEQ) reported new maximum levels by province. Maximum concentration of arsenic at each PSU site (136 total sites) was compared to the modified DEQ data set (673 sites after PSU sites were removed) for the provinces in southwest Oregon. Summary statistics and background calculations for the two data sets are listed in Table 15 and Table 16, which mirror the
format of the DEQ report (2013) for easy comparison. The DEQ data set used in this study only includes data for provinces covered in this study, and does not include the sites collected by former PSU students. As such, these DEQ results differ slightly from the Oregon statewide report by DEQ (DEQ, 2013). It is also important to note that DEQ averaged the concentrations of arsenic for each site to calculate statistics—PSU studies used the maximum value for each site—to define maximum levels.

Summary statistics report detectable arsenic in 92.8% of DEQ data and 87.6% in PSU data. Both DEQ and PSU data sets report Willamette Valley to have the highest average concentrations. All other rankings differ. The maximum detected concentration and also the largest standard deviation was in the Cascades for DEQ data and Willamette Valley for PSU data. The lowest detection was in the Basin and Range for DEQ data but is in the Klamath Mountains for PSU data. For the PSU data, the highest and average concentrations with standard deviation for each province, respectively, are: South Willamette Valley, 85.4 and 21.99 ± 10.5 ppm; Klamath Mountains, 45.4 and 5.42 ± 3.0 ppm; Cascade Range, 11.9 and 2.76 ± 1.2 ppm; Coast Range, 10.6 and 5.15 ± 3.0 ppm; Basin and Range, 2.32 and 1.29 ± 0.5 ppm; High Lava Plains, 1.5 and 1.20 ± 0.2 ppm. The geological units with the maximum concentration for each province for PSU data are Tfee for Willamette Valley, Jub for Klamath Mountains, Tbaa in the Cascade Range, Ty in the Coast Range, Qba in the Basin and Range and Tmv in the High Lava Plains.

Nonparametric background statistics for data sets with non-detects was run using ProUCL, v4.1.1 to compute reliable upper percentiles of background arsenic
concentrations, upper tolerance limits (UTLs) and upper prediction limits (UPLs). See Table 16 for background calculation results.

DEQ is currently using 95% UPLs as the new not-to-exceed values (DEQ, 2013). Background calculation ranks the 95% Upper Prediction Limit (UPL) from highest to lowest for the DEQ data set as Cascades (20.5), South Willamette Valley (17.9), Basin and Range (12.8), Coast Range (12.7), Klamath Mountains (9.9) and High Lava Plains (20.5). For PSU data, provinces are ranked South Willamette Valley (70.1), Klamath Mountains (19.0), Coast Range (10.6), Cascades (7.0), Basin and Range (2.1) and High Lava Plains (1.7). The 95% UPL set for the state of Oregon (DEQ, 2013) by province is Cascades (19), South Willamette Valley (18), Basin and Range (12), Coast Range (12), Klamath Mountains (12) and High Lava Plains (7.2). Removing the PSU data from the DEQ data set resulted in 95% UPLs greater than the Oregon limit for Basin and Range, Cascades Coast Range and High Lava Plains in the new DEQ data set and in higher UPLs in the Klamath Mountains and South Willamette Valley for the PSU data set. There are 31 detected values (4.6% of data set) in the DEQ data and 4 values (3.2% of data set) in the PSU data that are greater than the new Oregon limits.
Table 15. Summary statistics for the DEQ and PSU data sets were run for comparison using ProUCL v4.1.

<table>
<thead>
<tr>
<th>Province</th>
<th>Number of Detects</th>
<th>Number Non-Detects</th>
<th>Detection Frequency</th>
<th>Minimum Detected Concentration</th>
<th>Maximum Detected Concentration</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Calculation Method (Mean and SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DEQ Summary Statistics: All Concentrations in ppm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basin and Range</td>
<td>111</td>
<td>80</td>
<td>58.12%</td>
<td>0.7</td>
<td>43</td>
<td>4.29</td>
<td>5.13</td>
<td>Kaplan-Meier</td>
</tr>
<tr>
<td>Cascades</td>
<td>143</td>
<td>2</td>
<td>98.62%</td>
<td>0.288</td>
<td>73.4</td>
<td>6.17</td>
<td>8.64</td>
<td>Kaplan-Meier</td>
</tr>
<tr>
<td>Coast Range</td>
<td>119</td>
<td>0</td>
<td>100.00%</td>
<td>0.9</td>
<td>16.4</td>
<td>5.72</td>
<td>3.44</td>
<td>Standard</td>
</tr>
<tr>
<td>High Lava Plains</td>
<td>89</td>
<td>10</td>
<td>89.90%</td>
<td>1.28</td>
<td>14</td>
<td>3.67</td>
<td>2.21</td>
<td>Kaplan-Meier</td>
</tr>
<tr>
<td>Klamath Mountains</td>
<td>59</td>
<td>2</td>
<td>96.72%</td>
<td>1.38</td>
<td>12.8</td>
<td>5.14</td>
<td>2.80</td>
<td>Kaplan-Meier</td>
</tr>
<tr>
<td>Willamette Valley</td>
<td>58</td>
<td>0</td>
<td>100.00%</td>
<td>1.96</td>
<td>58.9</td>
<td>9.64</td>
<td>8.20</td>
<td>Standard</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Province</th>
<th>Number of Detects</th>
<th>Number Non-Detects</th>
<th>Detection Frequency</th>
<th>Minimum Detected Concentration</th>
<th>Maximum Detected Concentration</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Calculation Method (Mean and SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PSU Summary Statistics: All Concentrations in ppm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basin and Range</td>
<td>15</td>
<td>4</td>
<td>78.95%</td>
<td>0.496</td>
<td>2.3</td>
<td>1.29</td>
<td>0.49</td>
<td>Kaplan-Meier</td>
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<tr>
<td>Cascades</td>
<td>37</td>
<td>2</td>
<td>94.87%</td>
<td>0.349</td>
<td>11.9</td>
<td>2.76</td>
<td>1.21</td>
<td>Kaplan-Meier</td>
</tr>
<tr>
<td>Coast Range</td>
<td>19</td>
<td>0</td>
<td>100.00%</td>
<td>0.799</td>
<td>10.6</td>
<td>5.15</td>
<td>2.97</td>
<td>Standard</td>
</tr>
<tr>
<td>High Lava Plains</td>
<td>6</td>
<td>2</td>
<td>75.00%</td>
<td>0.762</td>
<td>1.5</td>
<td>1.20</td>
<td>0.22</td>
<td>Kaplan-Meier</td>
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<tr>
<td>Klamath Mountains</td>
<td>42</td>
<td>1</td>
<td>97.67%</td>
<td>0.301</td>
<td>45.4</td>
<td>5.42</td>
<td>2.97</td>
<td>Kaplan-Meier</td>
</tr>
<tr>
<td>Willamette Valley</td>
<td>6</td>
<td>2</td>
<td>75.00%</td>
<td>2.08</td>
<td>85.4</td>
<td>22.00</td>
<td>10.47</td>
<td>Kaplan-Meier</td>
</tr>
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Table 16. Background calculation for the DEQ and PSU data sets were run for comparison using ProUCL v4.1.

<table>
<thead>
<tr>
<th>Province</th>
<th>90th Percentile</th>
<th>95th Percentile</th>
<th>Calculation Method (Percentiles)</th>
<th>90% UTL</th>
<th>90% UPL</th>
<th>Calculation Method</th>
<th>95% UPL</th>
<th>Calculation Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DEQ Background Calculations: All Concentrations in ppm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basin and Range</td>
<td>10.87</td>
<td>12.74</td>
<td>Nonparametric KM(z)</td>
<td>11.5</td>
<td>10.9</td>
<td>90% UTL 90% Coverage; 90% KM UPL(t)</td>
<td>12.8</td>
<td>95% KM UPL(t)</td>
</tr>
<tr>
<td>Cascades</td>
<td>17.24</td>
<td>20.37</td>
<td>Nonparametric KM(z)</td>
<td>18.6</td>
<td>17.3</td>
<td>90% UTL 90% Coverage; 90% KM UPL(t)</td>
<td>20.5</td>
<td>95% KM UPL(t)</td>
</tr>
<tr>
<td>Coast Range</td>
<td>10.49</td>
<td>12.16</td>
<td>Nonparametric</td>
<td>11.4</td>
<td>10.9</td>
<td>90% UTL 90% Coverage; 90% UPL</td>
<td>12.7</td>
<td>95% UPL</td>
</tr>
<tr>
<td>High Lava Plains</td>
<td>6.50</td>
<td>7.31</td>
<td>Nonparametric KM(z)</td>
<td>6.9</td>
<td>6.5</td>
<td>90% UTL 90% Coverage; 90% KM UPL(t)</td>
<td>7.4</td>
<td>95% KM UPL(t)</td>
</tr>
<tr>
<td>Klamath Mountains</td>
<td>8.73</td>
<td>9.75</td>
<td>Nonparametric KM(z)</td>
<td>9.4</td>
<td>8.8</td>
<td>90% UTL 90% Coverage; 90% KM UPL(t)</td>
<td>9.9</td>
<td>95% KM UPL(t)</td>
</tr>
<tr>
<td>Willamette Valley</td>
<td>16.12</td>
<td>17.53</td>
<td>Nonparametric</td>
<td>17.5</td>
<td>16.9</td>
<td>90% UTL 90% Coverage; 90% UPL</td>
<td>17.9</td>
<td>95% UPL</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Province</th>
<th>90th Percentile</th>
<th>95th Percentile</th>
<th>Calculation Method (Percentiles)</th>
<th>90% UTL</th>
<th>90% UPL</th>
<th>Calculation Method</th>
<th>95% UPL</th>
<th>Calculation Method</th>
</tr>
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<tbody>
<tr>
<td><strong>PSU Background Calculations: All Concentrations in ppm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basin and Range</td>
<td>1.81</td>
<td>2.00</td>
<td>Nonparametric KM(z)</td>
<td>2.1</td>
<td>1.9</td>
<td>90% UTL 90% Coverage; 90% KM UPL(t)</td>
<td>2.1</td>
<td>95% KM UPL(t)</td>
</tr>
<tr>
<td>Cascades</td>
<td>5.88</td>
<td>6.80</td>
<td>Nonparametric KM(z)</td>
<td>6.7</td>
<td>6.0</td>
<td>90% UTL 90% Coverage; 90% KM UPL(t)</td>
<td>7.0</td>
<td>95% KM UPL(t)</td>
</tr>
<tr>
<td>Coast Range</td>
<td>8.41</td>
<td>10.33</td>
<td>Nonparametric</td>
<td>10.3</td>
<td>10.3</td>
<td>90% UTL 90% Coverage; 90% UPL</td>
<td>10.6</td>
<td>95% UPL</td>
</tr>
<tr>
<td>High Lava Plains</td>
<td>1.51</td>
<td>1.62</td>
<td>Nonparametric KM(z)</td>
<td>1.8</td>
<td>1.6</td>
<td>90% UTL 90% Coverage; 90% KM UPL(t)</td>
<td>1.7</td>
<td>95% KM UPL(t)</td>
</tr>
<tr>
<td>Klamath Mountains</td>
<td>15.59</td>
<td>18.5</td>
<td>Nonparametric KM(z)</td>
<td>18.0</td>
<td>15.9</td>
<td>90% UTL 90% Coverage; 90% KM UPL(t)</td>
<td>19.0</td>
<td>95% KM UPL(t)</td>
</tr>
<tr>
<td>Willamette Valley</td>
<td>50.9</td>
<td>60.5</td>
<td>Nonparametric</td>
<td>75.7</td>
<td>56.7</td>
<td>90% UTL 90% Coverage; 90% KM UPL(t)</td>
<td>70.1</td>
<td>95% KM UPL(t)</td>
</tr>
</tbody>
</table>
CHAPTER VI: DISCUSSION

The primary purpose of this study was to measure the range of naturally occurring arsenic concentrations in southwestern Oregon soils. I will now discuss the distribution of arsenic within horizons, why the DEQ and PSU data differ, as well as what natural factors may be contributing to those levels. Regression tests were applied to assess potential causal relationships between arsenic and environmental factors.

6.1 LEVELS OF ARSENIC IN SOUTHWEST OREGON SOILS

6.1.1 DISTRIBUTION OF ARSENIC IN A AND B HORIZONS

The box plot (Figure 8) for Site HH11 samples illustrates that the A and B horizons are separate populations, and demonstrates the necessity of sampling separate horizons in order to correctly determine the largest concentration of arsenic at a site. The A and B horizon comparisons for the 119 PSU sites taken as a whole set of numbers did not show the horizons to be statistically different. However, if only the A horizon was sampled (Table 12), 53% of the higher concentrations found in the B horizon (Table 13) would have been missed. Likewise, if only the B horizon was sampled, 40% of the samples would have been incorrectly assessed. This practice would result in the interpretation that naturally occurring arsenic concentrations are lower than is actually the case. It is clear that sampling both horizons is important to increase the probability that the highest value within the profile is collected.

6.1.2 COMPARISON BETWEEN DEQ AND PSU DATA SETS

Mapped arsenic concentrations (Figure 7) of the PSU samples show that arsenic
from the Cascade Range, and eastward within the study area, only contain low levels of arsenic (<2.82 ppm). This finding is not in agreement with the 95% limit of upper concentrations (7.2 and 12 mg/kg, respectively) set by the Oregon DEQ for the High Lava Plains and Basin and Range provinces. The DEQ data set includes sites that are outside the study area. To obtain the 95% limit used as the DEQ standard (DEQ, 2013), sites to the east of the study area must have much higher concentrations of arsenic in soils. No other spatial relationship is evident between arsenic concentrations and province; west of the Cascade Range, low to moderate soil arsenic concentrations (0-17.5 ppm) were measured.

The difference from the new set standard (DEQ, 2013) in the modified DEQ data set was not large but the 95% UPL calculated for the PSU data set was significantly different from the standard (Table 16). For the PSU data set, UPLs in the Klamath Mountains and South Willamette Valley were higher than the new standard (DEQ, 2013) but much lower for all other provinces. The PSU data set is small enough that it may not be representative of the spectrum of arsenic concentrations in Oregon. Also, the sites in the PSU data set are constrained to the study area, whereas the modified DEQ data set includes all sites within the listed provinces; spatial data was not a part of the DEQ data set and so sites outside the study area could not be removed. This means that sites from formations that are not found within the study area are represented in the modified DEQ data set. Another probable factor contributing to these differences is that DEQ used an average of all values collected at each site to calculate maximum background levels; PSU
used the maximum value. In any event, the relationship of arsenic in soils is much more complex than can be defined by the province it is located in.

6.1.3 COMPARISON WITH A FORMER PSU DATA SET

In a study of arsenic concentrations in northwest Oregon, Ricker (2013) evaluated 186 samples from both the A and B horizons. The northwest Oregon study area also included the Coast Range, Cascade Range and Willamette Valley provinces. Results for mean and standard deviation for A and B horizons, respectively, are $6.09 \pm 2.65$ and $10.26 \pm 4.65$ for the Coast Range, $3.59 \pm 3.72$ and $3.25 \pm 2.23$ for Willamette Valley and $2.45 \pm 4.29$ and $3.12 \pm 4.47$ for the Cascade Range.

In comparison, southwest Oregon results for mean and standard deviation for the set of 136 maximum values are $5.15 \pm 2.97$ for the Coast Range, $21.99 \pm 10.47$ for South Willamette Valley and $2.76 \pm 1.21$ for the Cascade Range. The difference in values between studies can be explained by differences in geology in different parts of these provinces. For example, mid-Miocene Columbia River Basalt volcanics occur in the central and northern extent of the Coast Range, but do not extend into the southern part of the range which is dominated by both fluvial and marine deposits of the Umpqua Group — Roseburg (Tmsm), Lookingglass (Tmsc) and Flournoy (Tmss) Formations — and the Tyee (Tt) Formation. Eugene Formation silts and sands (Tfe, marine Tfee) and Fisher Formation tuffs and conglomerates (Tfe) are marine and nearshore deposits (Orr and Orr, 2012) from the late Eocene, when the eastern border of what became Willamette Valley was ocean shoreline (Orr and Orr, 2012). In the late Quaternary, the Missoula Floods brought silts from Montana into Willamette Valley to Eugene (McClaughry et al, 2010);
samples in this study were taken south of Eugene. Samples and statistics by Ricker (2013) for the Willamette Valley likely reflect Missoula Flood deposits. In contrast, the Eugene and Fisher Formations exposed in South Willamette Valley have long been known to have high arsenic (Ravenscroft et al., 2009; Hinkle and Polette, 1999). The values for the Cascade Range are similar because the Cascades are younger soils; the soils have not had enough time to develop a B horizon where oxides accumulate and can adsorb and concentrate higher levels of naturally occurring arsenic.

6.2 RELATIONSHIP OF ARSENIC WITH ENVIRONMENTAL FACTORS

6.2.1 REGRESSION TREE

Regression analysis was done to assess the relationship of six environmental factors to arsenic concentrations: rock type, rock age, soil order, soil color, elevation and geomorphic province. Rock and soil factors were chosen because former studies have stated correlations with rock type (Ravenscroft et al., 2009; Hinkle and Polette, 1999) or with clays (Ravenscroft et al., 2009) to high arsenic. Elevation and province were chosen to investigate potential spatial relationships, since new DEQ limits are delineated by province.

Using a statistical regression tree produced the root, node 1: soil order, node 2: elevation and node 3: rock type as the strongest influences on arsenic concentrations (Figure 10). Each node was looked at individually and tested for normality and variance using the Shapiro-Wilk test and the F-Test, respectively (Ellison and Gotelli, 2013). The leaves of the tree report the number of observations and mean of arsenic concentrations.
Node 1, soil order, splits the data at the mean of arsenic ($\mu=4.31$). This splits the data into groups Node 1L and Node 1R. Node 1L (n=114) consists of soil order groups Entisols, Inceptisols, Mollisols, Parent Material, Spodosols and Ultisols. Node 1R (n=22) consists of Alfisols, Ultisols/Alfisols and Vertisols. Node 2, the left split from Node 1L, is based on the elevation of the 114 samples that do not include Alfisol or Vertisol orders. Node 2L consists of elevations greater than or equal to 1,207 meters (n=53). Node2R contains elevations less than or equal to 1,207 meters (n=61). Node 3 splits Alfisols, Ultisol/Alfisols and Vertisols by rock type into Node 3L (n=10) and Node 3R (n=12). Node 3L includes metamorphic, plutonic and volcanic rock types, and Node 3R includes sedimentary, unconsolidated sediments and mixed volcanic/sedimentary units.
6.2.2 FOREST REGRESSION

The random forest was performed on the data set multiple times using the R Party Package; a conditional permutation scheme provides unbiased variable selection and variable importance for predictor variables of different types, as well as reduces the appearance that correlated predictor variables are more important than uncorrelated ones (Strobl et al., 2009). Conditional variable importance is calculated by randomly shuffling the values of a given independent variable thereby “breaking” the variable’s bond to the response. Then, the difference of the model accuracy before and after the random permutations, averaged over all trees in the forest, tells us how important that predictor is for determining the outcome (Shih, 2011; Strobl et al., 2009).

At 2,000 trees, the results were consistent between forests with different random seeds set (Table 17). The variable importance plot ranked elevation high, followed by soil order and rock type (Figure 11). The forest regression predicts the same three variables as the regression tree for significant predictors of arsenic, however, the regression tree ranked soil order as more significant than elevation. Predictors in the forest regression are considered significant when they rank larger than the absolute value of the largest negative value in the variable importance test.
Figure 11: Variable importance plot showing the predictive ranking of variables using a 2,000 trees forest and random seed of 729.

Table 17. Using the Party Package in R, forest regressions were done with increasing tree numbers until ranking for significant predictors did not vary with different seeds.

<table>
<thead>
<tr>
<th>Seed</th>
<th>Elevation</th>
<th>Soil Order</th>
<th>Rock Type</th>
<th>Province</th>
<th>Soil Color</th>
<th>Age Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>729</td>
<td>2.6674</td>
<td>1.1541</td>
<td>0.3470</td>
<td>-0.0632</td>
<td>-0.1080</td>
<td>-0.1564</td>
</tr>
<tr>
<td>1052</td>
<td>2.8072</td>
<td>1.4535</td>
<td>0.3697</td>
<td>-0.1224</td>
<td>-0.1390</td>
<td>-0.2547</td>
</tr>
<tr>
<td>2594</td>
<td>2.6708</td>
<td>1.2964</td>
<td>0.3773</td>
<td>-0.1837</td>
<td>-0.1018</td>
<td>-0.1484</td>
</tr>
</tbody>
</table>

6.2.3 RELATIONSHIP OF ARSENIC TO SOIL ORDER

The box plot for Node 1 (Figure 12) shows the variance within each sub-group. A comparison between the soil order sub-groups indicates that Alfisol and Vertisol soils have a much higher variation. The Shapiro-Wilk normality test shows that neither Node 1R nor Node 1L has a normal distribution (p-values: 1.2e-06 and 5.8e-09, respectively). Box-Cox analysis was completed to see if a normal distribution could be obtained through transformation ($\lambda = 0.2626$ at 95% confidence interval), and indicated cube root
transformation would convert raw data to a distribution closer to normal. Cube
transformation resulted in a normal distribution for Node 1R, only (Shapiro-Wilk p-
values: 0.125 versus 1.59e-4 for Node 1L) so node data was not transformed for
regression tests. Data were cube root transformed for variance plots for visual clarity. The
means of the two groups are widely separated compared to within each group (F-ratio:
55.8534), so variance in Node 1R is unequal to the variance in Node 1L.

![Figure 12: Cube root transformed variance of Alfisols, Ultisols/Alfisols and Vertisols (Node 1R)
varying Entisols, Inceptisols, Mollisols, Parent Material, Spodosols and Ultisols.](image)

To determine if there is a significant difference between soil order groups a
nonparametric test was used, since it does not require normal distributions or equal
variance to be valid. The Wilcoxon rank sum test (Ellison and Gotelli, 2013), which is
moderately robust for non-normal distributions and unequal variance, was used and the
results indicate that the means of arsenic concentrations in the two soil order groups are
significantly different (p-value = 0.01463). The F-ratio and Wilcoxon test support that
Node 1R and Node 1L are statistically different; the arsenic concentrations for soil orders
that include Alfisols and Vertisols are significantly different than arsenic concentrations for soil orders that do not include Alfisols and Vertisols. This is a reasonable division; Alfisols, Ultisols and Vertisols are older than the other soils, and therefore have had more time to accumulate the oxides and clays that retain and concentrate arsenic. Statistical results are listed in Table 18.

Table 18: Summary of statistical tests run on Node 1 of the regression tree for soil order by split: orders that include Alfisols and Vertisols versus other orders.

<table>
<thead>
<tr>
<th>Data Type: Node 1</th>
<th>Statistical Test</th>
<th>Test value</th>
<th>p-value ($\alpha=0.05$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Arsenic Values</td>
<td>Shapiro -Wilk</td>
<td>W = 0.5957</td>
<td>1.193e-06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Alfisols, Ult/Alfs and Vertisols)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wilcoxon Rank Sum</td>
<td>W = 0.8605</td>
<td>5.814e-09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(non-Alfisol and Vertisol soils)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F-test</td>
<td>F = 55.8534</td>
<td>&lt; 2.2e-16</td>
</tr>
<tr>
<td></td>
<td>Wilcoxon Rank Sum</td>
<td>W = 1667.5</td>
<td>0.01463</td>
</tr>
<tr>
<td>Cube Root Arsenic Values</td>
<td>Shapiro -Wilk</td>
<td>W = 0.9304</td>
<td>0.125</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Alfisols, Ult/Alfs and Vertisols)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wilcoxon Rank Sum</td>
<td>W = 0.9456</td>
<td>1.59e-4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(non-Alfisol and Vertisol soils)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F-test</td>
<td>F = 3.6943</td>
<td>6.837e-06</td>
</tr>
<tr>
<td></td>
<td>Wilcoxon Rank Sum</td>
<td>W = 1667.5</td>
<td>0.01463</td>
</tr>
</tbody>
</table>

6.2.4 RELATIONSHIP OF ARSENIC TO ELEVATION

The two subsets from Node 2 of the regression tree were split based on elevation. Higher arsenic concentrations occur in the lower elevation subset which also has more variability as can be seen in the box plots that were created to graphically represent these two subsets (Figure 13). The Shapiro-Wilk normality test indicates that arsenic concentrations in the low elevation subset (Node 2R) is not normally distributed, but data at elevations greater than 1,207 meters are normally distributed (p-values: 2.759e-16 and 0.0797, respectively). To see if normality could be attained by transforming the data, Box-Cox analysis (Gotelli and Ellison, 2013) was conducted ($\lambda = 0.2626$ at 95%
confidence interval). The lambda ($\lambda$) value from the Box-Cox indicates that a cube root transformation of arsenic data may show normal distributions for arsenic concentrated in samples collected from low elevation. Results from the Shapiro-Wilk normality test show that subsets defined by Node 2R and Node 2L are not normally distributed despite cube root transformation of the data, so raw data were again used for further analysis (Shapiro-Wilk p-values: 9.5e-06 and 6.7e-08, respectively). The cube root transformed data were again used for variance plots for visual clarity and for comparability.

Figure 13: Box plots for subsets created by the regression tree at Node 2. Node 2L contains the data set with elevations above 1,207 m. while Node 2R is the data set below 1,207 m.

The F-ratio test indicates that the two data sets do not have equal variance (F-ratio: 238.4). Since distribution is not normal, the Wilcoxon test was again used; the means of Node2R and Node 2L are statistically different (p-value: 4.4e-13). Higher soil arsenic concentrations are found at elevations lower than 1,207 meters. Statistical results are listed in Table 1.
Table 19: Summary of statistical tests run on Node 2 of the regression tree for both elevation splits: less than or equal to 1,207 m. and greater than or equal to 1,207 m.

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Statistical Test</th>
<th>Test value</th>
<th>p-value ($\alpha=0.05$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Arsenic Values</td>
<td>Shapiro-Wilk</td>
<td>W = 0.4275</td>
<td>2.759e-16 (1,207 m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W = 0.9614</td>
<td>0.0797 (1,207 m)</td>
</tr>
<tr>
<td></td>
<td>F-test</td>
<td>F = 238.4135</td>
<td>&lt; 2.2e-16</td>
</tr>
<tr>
<td></td>
<td>Wilcoxon Rank Sum</td>
<td>W = 3842.5</td>
<td>4.4e-13</td>
</tr>
<tr>
<td>Cube Root Arsenic</td>
<td>Shapiro-Wilk</td>
<td>W = 0.8997</td>
<td>9.483e-06 (1,167 m)</td>
</tr>
<tr>
<td>Values</td>
<td></td>
<td>W = 0.7655</td>
<td>6.718e-08 (1,167 m)</td>
</tr>
<tr>
<td></td>
<td>F-test</td>
<td>F = 2.8591</td>
<td>7.891e-05</td>
</tr>
<tr>
<td></td>
<td>Wilcoxon Rank Sum</td>
<td>W = 3842.5</td>
<td>4.4e-13</td>
</tr>
</tbody>
</table>

6.2.5 RELATIONSHIP OF ARSENIC TO ROCK TYPES

Node three of the regression tree separated subsets based on rock type. The most variability of all the subsets analyzed occurs in the group containing sedimentary and mixed volcanic and sedimentary rock types and unconsolidated sediments. The highest arsenic concentrations are also in this subset (Node 3R) as can be seen by the box plots that were created to graphically present both subsets of Node 3 (Figure 14).

Figure 14: Box plots of arsenic values for the subsets created by the regression tree at Node 3. Node 3R contains sedimentary, mixed volcanic/ sedimentary rock types and unconsolidated sediments while Node 3L contains metamorphic, plutonic and volcanic rock types.
Results of the Shapiro-Wilk normality test (Table 20) indicate that arsenic concentrations in both splits of Node 3 do not have normal distributions (p-values: 3.6e-14 and 1.1e-14, respectively). Box-Cox analysis indicates that the two subsets may show normal distributions after cube root transformation of the data ($\lambda = 0.2626$ at a 95% confidence interval). The Shapiro-Wilk normality test was conducted on the cube transformed data, and the results for the rock type groups defined by Node 3R and Node 3L (p-values: 1.3e-06 and 2.8e-04, respectively) still show that the data sets are not normally distributed. Therefore, raw data were preserved for regression analyses, and again, cube root transformed data were used for variance plots for visual clarity and comparability.

Table 20: Summary of statistical tests run on Node 3 subsets for both rock type origin splits: sedimentary with mixed sedimentary/volcanic and unconsolidated sediments versus metamorphic, plutonic and volcanic rock types.

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Statistical Test</th>
<th>Test value</th>
<th>p-value ($\alpha=0.05$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Arsenic Values</td>
<td>Shapiro-Wilk</td>
<td>W = 0.4079</td>
<td>3.637e-14 (Sedimentary, Volcanic/Sed, Unconsolidated)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W = 0.4984</td>
<td>1.087e-14 (Metamorphic, Plutonic, Volcanic)</td>
</tr>
<tr>
<td></td>
<td>F-test</td>
<td>F = 238.4135</td>
<td>&lt; 2.2e-16</td>
</tr>
<tr>
<td></td>
<td>Wilcoxon Rank Sum</td>
<td>W = 3326.5</td>
<td>4.527e-06</td>
</tr>
<tr>
<td>Cube Root Arsenic Values</td>
<td>Shapiro-Wilk</td>
<td>W = 0.8373</td>
<td>1.315e-06 (Sedimentary, Volcanic/Sed, Unconsolidated)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W = 0.9264</td>
<td>0.0002829 (Metamorphic, Plutonic, Volcanic)</td>
</tr>
<tr>
<td></td>
<td>F-test</td>
<td>F = 1.166</td>
<td>0.5267</td>
</tr>
<tr>
<td></td>
<td>Welch’s T-Test</td>
<td>t = 4.7053</td>
<td>6.751e-06</td>
</tr>
</tbody>
</table>

The F-ratio test was conducted and shows that there is not equal variance between the two subsets (F-ratio: 238.4) and indicates there is a large separation in the means of these groups compared to within each group. Since the two subsets failed to show normal distributions the Wilcoxon rank sum test was used to see if arsenic concentrations
are significantly different between rock type subsets. The test results (Table 20) indicate that there is a significant difference between the two subsets (p-value: 4.5e-06).

6.2.6 SUMMARY OF TOP THREE PREDICTORS

Statistical analyses of 255 soil samples were studied to determine any relationships that exist between six environmental predictors and arsenic concentrations in southwestern Oregon. Initial analysis included a Classification and Regression Trees (CART) model, which determined that three of the six environmental predictors are influential on arsenic levels: soil order, elevation and rock type. Validation of the CART model with random forest analysis resulted in the same three variables selected as important predictors. Non-parametric analysis using the Wilcoxon test was used as the raw data for three predictors did not show equal variance or normal distribution. For all three predictors, the null hypothesis was rejected as there is a significant difference between the median within each subgroup. This validates the logic of the splits in the CART models.

According to Ravenscroft et al. (2009), high soil-As or inorganic arsenic is associated with carbonaceous shales and volcanic materials and rocks, with silt and clayey soils generally containing more arsenic than sandy soils. This study was found to concur that soil with more clay contain higher arsenic; percent clay was not tested, however soil orders defined as having a well-developed B-horizon, which accumulates clay minerals, were grouped as having a higher mean of arsenic concentrated in soil. Sedimentary rocks showed the highest arsenic levels; soils collected from sample sites
underlain by sedimentary, mixed sedimentary and volcanic or unconsolidated rock had the highest mean of arsenic (µ = 16.85).

The first important predictor of arsenic levels was soil order. The few soil orders that do contain Alfisol, Ultisol/Alfisol and Vertisol soils (n = 22), showed greater variation and higher arsenic levels ranging from 0.001-85.4 ppm (Figure 12). Entisols, Inceptisols, Mollisols, Spodosols, Ultisols, and Parent Material, (n = 114), have less variation in arsenic levels, 0.001-11.9 ppm. In general, Alfisols, Ultisols and Vertisols have increased weathering, soil and clay development and support literature that arsenic levels are greater in soil orders with increased clay development (Ravenscroft et al., 2009). Despite Ultisol being the most well developed soil, it was grouped by the regression tree with less developed soils. The mean for Ultisol soils was 3.52 and 3.94 for the A and B horizons, respectively. The Ult/Alf order had a higher mean of 8.2 for the A horizon and 15.12 for the B horizon. The pH and reclassification of the Ult/Alf samples to Ultisol or Alfisol orders would be necessary to determine if these higher values would raise the mean arsenic for Ultisols enough to fit with the other well developed soils in the regression analysis.

Elevation was a second important predictor of arsenic levels (the most important predictor by forest regression). Samples taken from lower elevation 1,207 m, (n = 61), have higher levels of arsenic between 0.001-85.4 ppm, while samples collected at higher elevation 1,207 m, (n = 53), were found to contain lower levels of arsenic, 0.001-3.12 ppm (Figure 13). The highest values were in Eugene, Oregon at only 292 meters.
Rock weathering is a natural process leading to the release of arsenic and its introduction to the aquatic environment (Mitsunobu et al., 2006). The mountain ranges of this study area receive a considerable amount of rain, where arsenic is carried downstream in water or sediments and accumulates in low-lying areas. These findings may indicate that biota and communities at lower elevations are at a greater risk for exposure to arsenic but to what degree is not a part of this study.

Node 3 split arsenic concentrations by rock type. Study of rock type revealed that variation in arsenic levels with mixed volcanic and sedimentary, sedimentary and unconsolidated rock (n=12) is greater with a range of 0.496-85.4 ppm, compared to arsenic levels in Metamorphic, Plutonic and Volcanic origins (n=10), with a range of 0.001-32.6 ppm (Figure 14). The split by the CART model again seems logical; volcanic activity and rock weathering release arsenic, hydrologic processes transport arsenic from high mountain ranges to areas below where sediments accumulate, then arsenic adsorbs to sediments. The highest arsenic concentrations in this study are within a region where the high arsenic concentration in aquifers is associated with volcanic and sedimentary rock (Hinkle and Polette, 1999). Lastly, the map scale of 1:500,000 (Walker and MacLeod, 1991) only provides for the dominant rock type where the sample was taken, so error may be introduced if it is not the parent material for that soil.

A potential issue in the study of arsenic concentration is how non-detect samples are reported for analyses. Helsel (2006) indicates that replacing the detection limit with an arbitrary fraction results in inaccurate analyses of regression slopes, correlation coefficients, means and standard deviation. As further research on arsenic concentration
is conducted, this must be factored into the analysis. R packages (NADA) are available to help analyze non-detects (Helsel, 2006), and the ProUCL software has tests specifically for data sets that include non-detect samples.

Caution was exercised when creating the data set for our CART model to avoid inflating predictors; the maximum sample from each site was selected instead of including all data and treating each sample as independent despite being taken from the same site. Development of proximal horizons certainly share the same environmental influences, however, the degree of influence on one horizon from another is difficult to measure and beyond the scope of this study.

Power is a factor that must be considered when performing data analysis. As data are reformatted and transformed away from their original format, power is lost. When data have unequal variance and non-normal distribution, non-parametric tests like the Wilcoxon Rank Sum test are used. This statistic ranks data, thereby lowering the power. The lower the power of the test, the higher will be the probability of a type II error as power is the probability of rejecting the null hypothesis when it is false (Crawley, 2007).

Further, caution is imperative when studying real world problems. Arsenic concentrations have dire effects on the health of our ecosystem and therefore human consumption. While this study only shows sample location and arsenic concentration, and the investigation of potential arsenic sources does not prescribe remediation, the potential for error was still heavily taken into account. In this analysis, we are claiming that we are
95% confident that the hypothesis is true while we are okay with a 5% chance of making a type I or type II error, where a test statistic of \( \alpha = 0.05 \), was used.

A type I error using the Shapiro-Wilk test as an example would occur if the null hypothesis that arsenic concentrations are normally distributed is rejected when it is true. The fact that arsenic concentrations are higher at lower elevations may not be addressed, thereby undermining the importance of elevation as a predictor of arsenic. On the other hand, a type II error would occur if the null hypothesis that ranked medians of arsenic are not different at high and lower elevations is not rejected when the difference is significant. Either type of error could result in wasted resources in research time and false claims by investigating a predictor variable that does not have a true effect on the level of arsenic, or by undermining the importance of an environmental predictor.

The findings from this study are in general agreement with literature (Ravenscroft et al., 2009) where arsenic levels are higher in soils with increased weathering and clay development, in this case Alfisols, Ultisol/Alfisols and Vertisols. Samples taken from lower elevations than 1,207 m were found to contain higher levels of arsenic as natural weather events carry arsenic downstream and is adsorbed to and concentrates within sediments (Mitsunobu et al., 2006). Further, samples of sedimentary rock origin were also found to have higher levels of arsenic by Hinkle and Polette (1999).
CHAPTER VII: CONCLUSIONS

There are 255 total samples from 136 sites in this study; 123 samples are from the A horizon (Table 12) and 132 samples were taken from the B horizon (Table 13). The highest value in the A and B horizons, respectively, are 63.2 ppm and 85.4 ppm. These maximum values are both from the Eugene Formation (Tfe, or Tfee where mapped separately as marine).

Comparison of arsenic between the A and B horizons at site HH11 showed arsenic to be centered on different means with low deviation. This supports that collection of one sample per horizon is a reliable representation of the level of arsenic within that horizon. This also demonstrates the necessity of sampling separate horizons in order to correctly determine the largest concentration of arsenic at a site.

Comparison of A and B horizons for all 119 PSU sites that had arsenic in both A and B did not show a statistical difference. In this study arsenic was not found to be higher in the A or the B horizon; if just the A or just the B horizon were sampled, the maximum concentration would not have been collected half the time. In this study 39.5% of sites are higher in arsenic in the A horizon while 52.9% are higher in the B horizon, with 7.6% of sites having no detectible arsenic (at minimum detection limit of 0.20 ppm). Collection from both horizons ensures the site is better represented and that the sample of maximum value is used for analysis.

Regression analysis of six environmental factors was done to assess for potential predictors for arsenic in undisturbed soils. The regression tree indicated soil order, elevation and rock type to have the strongest relationship with arsenic. In this study area
arsenic concentrations were found in greater levels within Alfisol and Ultisol/Alfisol and Vertisol soil orders, at lower elevations below 1,207 meters, and within soils from sedimentary, mixed volcanic/sedimentary and unconsolidated rock types. The regression forest confirmed the same factors as environmental predictors with elevation the strongest predictor, followed by soil order and rock type. Province, soil color and the age ranking of rock deposition were not considered significant.

Marine sediments have higher arsenic values than other lithologies. Data with the highest value and highest mean are in the South Willamette Valley. This site was mapped as the Eugene Formation, a marine sedimentary deposit, by both Walker and MacLeod (1991) and McClaughry et al. (2010). Marine sediments were also found to have the highest (>7 ppm) concentrations of arsenic in the northwest Oregon study area (Ricker, 2013).

The map units associated with the maximum values for each province are all described as either having a marine sediment composition (Jub, Tfe, Tfee, Ty), or as basaltic (Jub, Tbaa, Qba) or mafic (Tmv) by Walker and MacLeod (1991). This is in keeping with other research that sedimentary rocks reach much higher levels of arsenic than igneous and metamorphic sources (Ravenscroft et al., 2009), although basalt can also have a large range (0.18 – 113 ppm) for arsenic concentration (Ravenscroft et al., 2009).

A summary of the three important factors for each of the high-value samples and the mean arsenic of each province are listed in Table 21. Factor descriptions for these representative sites are in alignment with the results of the regression analyses. Rock
types for the highest value sites include sedimentary and mixed igneous volcanic and sedimentary rock types, as well as igneous volcanic. The sedimentary and mixed rock types are the highest by mean concentration (5.15 – 21.99 ppm) with all igneous volcanic sites lower by mean (1.20 – 2.76 ppm). The soil orders for the two highest value sites are the Alfisol or Ultisol soils; these soils are older and have had time to concentrate higher levels of arsenic. Lastly, arsenic is higher in lower elevations and less concentrated at higher elevations. Weathering, gravity and topography result in sediment transportation and accumulation in sinks or valleys, however, topographical influences were outside the scope of this study.

Table 21. Summary of results for arsenic level and three important factors by province.

<table>
<thead>
<tr>
<th>Province</th>
<th>Highest Value (ppm)</th>
<th>Map Unit</th>
<th>Rock Type</th>
<th>Soil Order</th>
<th>Elevation (meters)</th>
<th>Mean (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. Willamette Valley</td>
<td>85.4</td>
<td>Tfe, Tfee</td>
<td>Sedimentary</td>
<td>Alfisol</td>
<td>292</td>
<td>21.99</td>
</tr>
<tr>
<td>Klamath Mountains</td>
<td>45.4</td>
<td>Jub</td>
<td>Mixed Volc./ Sed.</td>
<td>Alf/Ult</td>
<td>730</td>
<td>5.42</td>
</tr>
<tr>
<td>Cascade Range</td>
<td>11.9</td>
<td>Tbaa</td>
<td>Volcanic</td>
<td>Inceptisol</td>
<td>803</td>
<td>2.76</td>
</tr>
<tr>
<td>Coast Range</td>
<td>10.6</td>
<td>Ty</td>
<td>Sedimentary</td>
<td>Mollisol</td>
<td>134</td>
<td>5.15</td>
</tr>
<tr>
<td>Basin and Range</td>
<td>2.32</td>
<td>Qba</td>
<td>Volcanic</td>
<td>Mollisol</td>
<td>1289</td>
<td>1.29</td>
</tr>
<tr>
<td>High Lava Plains</td>
<td>1.5</td>
<td>Tmv</td>
<td>Volcanic</td>
<td>Entisol</td>
<td>1891</td>
<td>1.20</td>
</tr>
</tbody>
</table>
CHAPTER VIII: FUTURE WORK

This study tested for arsenic in undisturbed soils, increasing the coverage of arsenic data from different rock types found in southwest Oregon. The purpose of this study was to provide location and arsenic concentration data to DEQ to increase the current data set. While Oregon coverage is now fairly robust, the causes driving the concentration of arsenic are still being explored.

In order to study environmental variables as potential causes or predictors of arsenic, it first would be necessary to verify the accuracy each environmental variable in the field and lab. Elevation and geomorphic region are easy to verify, but soil order and rock type should be verified at the site and with lab testing (pH for soils and X-ray diffraction to determine parent material) as the site could vary from the mapped soil order and unit, which are generally mapped over a much larger area. In the lab, percent clay content should be determined to hone its relationship as and adsorber of arsenic. Also, enough samples should be collected per site in order to make statistical analyses valid. Further analysis could also be done using separate CART models for the A and B horizons for a comparison of important predictor variables between horizons.
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APPENDIX A: Stratigraphy of Provinces within Southwest Oregon

Figure A.1. The stratigraphy of the Klamath Mountains. Copied from Orr and Orr (2012).
Figure A.2. The stratigraphy of the Coast Range province. Coos Bay and SW Oregon formations are within the study area. Copied from Orr and Orr (2012).
Figure A.3. The stratigraphy of the Cascade Range province. Copied from Orr and Orr (2012).
Figure A.4. The stratigraphy of the Willamette Valley province. Copied from Orr and Orr (2012).
Figure A.5. The stratigraphy of the Basin and Range province. Copied from Orr and Orr (2012).

Figure A.6. The stratigraphy of the High Lava Plains province. Copied from Orr and Orr (2012).
APPENDIX B: Description of Geologic Units (Walker and MacLeod, 1991) by Province (DEQ, 2013) that Correlate with Sample Locations

Basin and Range

Qba  **Basaltic andesite and basalt (Holocene? and Pleistocene)**—Flows and flow breccia dominantly of basaltic andesite containing plagioclase, olivine, and pyroxene phenocrysts and olivine-bearing basalt representing part of the volcanic sequence of the High Cascade Range. Unit mostly forms small shield volcanoes, gentle-sided lava cones, and, in places, intracanyon flows.

Qf  **Fanglomerate (Holocene? and Pleistocene)**—Poorly sorted and poorly stratified alluvial fan debris, slope wash, colluvium, and talus; composed mostly of silt and fragments of basalt, basaltic andesite, and andesite. In places includes small areas of pediment gravels and colluvium.

Qma **Mazama ash-flow deposits (Holocene)**—Rhyodacitic to andesitic ash-flow deposits related to climactic eruptions of Mount Mazama about 6,845 yr B.P. ($^{14}$C).

QTb **Basalt (Pleistocene and Pliocene)**—Thin flows and minor flow breccia of open-textured (diktytaxitic) olivine basalt in southeastern part of map area. Locally contains thin interbeds of sedimentary rocks. Grades laterally through palagonite tuff and breccia into sedimentary rocks (unit QTs).

QTs **Sedimentary rocks (Pleistocene and Pliocene)**—Semiconsolidated lacustrine and fluvial ashy and palagonitic sedimentary rocks, mostly tuffaceous sandstone and siltstone; locally contains abundant palagonitized basaltic debris and some pebble conglomerate. In places, grades laterally through palagonite tuff and breccia into basalt flows (Qtb).

QTvm **Mafic vent deposits (Pleistocene, Pliocene, and Miocene?)**— Mostly in small stratovolcanoes or shield volcanoes and lava cones of basalt and andesite.
Includes agglomerate, breccia, scoria, cinder, ash, restricted flows, and small basaltic intrusive bodies. Transitional into pyroclastic rocks of cinder cones (QTp). May also include rocks of late Miocene (?) age.

**Tb**  **Basalt (upper and middle Miocene)**—Basalt flows, flow breccia, and basaltic peperite; minor andesite flows; some interbeds of tuff and tuffaceous sedimentary rocks. Basalt is aphyric to moderately porphyritic with phenocrysts of plagioclase and olivine and exhibits both subophitic and diktytaxitic textures.

**Tob**  **Olivine basalt (Pliocene and Miocene)**—Thin, commonly open-textured (diktytaxitic), subophitic to intergranular olivine basalt flows, intercalated with and grades laterally through palagonite breccia and tuff into tuffaceous sedimentary rocks (unit Ts). In places includes flows of platy olivine andesite or basaltic andesite.

**Tp**  **Basaltic and andesitic ejecta**—Mostly unconsolidated, oxidized, fine to coarse, scoriaceous cinders, bombs, and agglutinate deposited in subaerial environment.

**Tps**  **Subaqueous pyroclastic rocks of basaltic cinder cones**—Deposits of bombs, breccia, and mafic to intermediate tuff occurs as palagonitic tuff and breccia cones, rings, and ridges. In places interbedded with lacustrine sedimentary rocks.

**Trh**  **Rhyolite and dacite (Pliocene? and Miocene)**—Ash-flow tuff, lava flows, pumice-lapilli tuff, coarse pumicite, blow breccia, and domal complexes of rhyolitic, rhyodacitic, and dacitic composition; in places includes peralkaline rhyolite and some andesite and andesite breccia. Locally porphyritic with phenocrysts of alkali feldspar, plagioclase, and minor augite, ferro-hedenbergite, hornblende, hypersthene, or biotite. Commonly flow banded; locally glassy. Many of the ash-flow tuffs exhibit flow features and only obscure vitro-clastic textures.

**Ts**  **Tuffaceous sedimentary rocks and tuff (Pliocene and Miocene)**—Semiconsolidated to well-consolidated mostly lacustrine tuffaceous sandstone,
siltstone, mudstone, concretionary claystone, pumicite, diatomite, air-fall and water-deposited vitric ash, palagonitic tuff and tuff breccia, and fluvial sandstone and conglomerate. Palagonitic tuff and breccia grade laterally into altered and unaltered basalt flows of unit Tob. In places includes layers of fluvial conglomerate and, in parts of the Deschutes-Umatilla Plateau, extensive deposits of fanglomerate composed mostly of Miocene basalt debris and silt. Also includes thin, welded and nonwelded ash-flow tuffs.

Tvm Mafic and intermediate vent rocks (Pliocene? and Miocene)—Basaltic and andesitic agglomerate, breccia, scoria, cinders, flow, and intrusive masses forming lava cones and small shields.

Tvs Silicic vent rocks (Pliocene, Miocene, Oligocene, and Eocene?)—Plugs and domal complexes of rhyolitic, rhyodacitic, and dacitic composition; includes related near-vent flows, flow breccia, and deposits of obsidian, perlite, and pumice. Locally includes resurgent domes related to caldera complexes.

Cascade Range

Qa Andesite (Holocene and Pleistocene)—Forms major stratovolcanoes dominantly of aphyric to porphyritic basaltic andesite and andesite; phenocrysts are principally pyroxene, olivine, plagioclase, and, rarely, hornblende. Locally includes dacite and minor basalt.

Qal Alluvial deposits (Holocene)—Sand, gravel, and silt forming flood plains and filling channels of present streams. In places includes talus and slope wash. Locally includes soils containing abundant organic material, and thin peat beds.

Qba Basaltic andesite and basalt (Holocene? and Pleistocene)—Flows and flow breccia dominantly of basaltic andesite containing plagioclase, olivine, and pyroxene phenocrysts and olivine-bearing basalt representing part of the volcanic
sequence of the High Cascade Range. Unit mostly forms small shield volcanoes, gentle-sided lava cones, and, in places, intracanyon flows.

Qg **Glacial deposits (Pleistocene)**—Unsorted boulder gravel, sand, and rock flour in ground, terminal, and lateral moraines. Locally include: glaciofluvial deposits (Qgf).

Qgf **Glaciofluvial deposits**—Partly sorted.

Qls **Landslide and debris-flow deposits (Holocene and Pleistocene)**—Unstratified mixtures of fragments of adjacent bedrock. Locally includes slope wash and colluvium. Largest slides and debris flow occur where thick sections of basalt and andesite flows overlie clayey tuffaceous rocks. May include some deposits of late Pliocene age.

Qma **Mazama ash-flow deposits (Holocene)**—Rhyodacitic to andesitic ash-flow deposits related to climactic eruptions of Mount Mazama about 6,845 yr B.P. ($^{14}$C).

Qmp **Mazama pumice deposits (Holocene)**—Primary and reworked air-fall rhyodacite pumice related to climactic eruptions of Mount Mazama about 6,845 yr B.P. ($^{14}$C). Mapped only where it extensively covers older units. Thickness shown by isopachs (in meters).

Qrd **Rhyolite and dacite (Holocene and Pleistocene)**—Domes and related flows and flow breccia of aphyric and plagioclase and hornblende porphyritic rhyolite and dacite. Includes rhyolite and dacite on Newberry volcano and at South Sister volcano in the Cascade Range that are younger than Mazama ash deposits (Qma, Qmp; radiometrically dated by $^{14}$C methods at approximately 6,800 yr old).

Qs **Lacustrine and fluvial sedimentary rocks (Pleistocene)**—Unconsolidated to semiconsolidated lacustrine clay, silt, sand, and gravel; in places includes mudflow and fluvial deposits and discontinuous layers of peat.
Qta **Andesite (Pleistocene and Pliocene)**—Flows and flow breccia in the High Cascade Province composed dominantly of aphyric to porphyritic basaltic andesite and andesite. Mostly represents remnants of moderately to deeply eroded stratovolcanoes. Phenocrysts are mostly plagioclase, olivine, clinopyroxene, and lesser hypersthene and hornblende.

QTba **Basalt and basaltic andesite (Pleistocene and Pliocene)**—Flows, flow breccia, and pyroclastic deposits of the High Cascades Province. Flows are aphanitic to finely crystalline, commonly diktytaxitic, and aphyric to porphyritic. Textures are mostly intergranular grading to intersertal; some andesite flows are finely trachytic and a few basalt flows are subophitic. Phenocrysts, mostly unaltered, include bytownite and labradorite, olivine, calcic augite, and hypersthene. Flows and breccia form shields, lava cones, and valley fill; in places greatly dissected and modified by glacial and fluvial erosion.

QTmv **Mafic vent complexes (Pleistocene, Pliocene, and Miocene?)**—Plugs, dikes, and related near-vent flows, breccia, cinders, and agglutinate of basalt, basaltic andesite, and andesite; commonly in the form of either little-modified lava cones or partly eroded piles of reddish, iron-stained thin flows and fragmental ejecta cut by mafic intrusions. May also include rocks of late Miocene(?) age.

QTp **Basaltic and andesitic ejecta**—Mostly unconsolidated, oxidized, fine to coarse, scoriaceous cinders, bombs, and agglutinate deposited in subaerial environment.

Tbaa **Basaltic and andesitic rocks (upper and middle Miocene)**—Lava flows and flow breccia of hypersthene and olivine andesite, basaltic andesite containing plagioclase and pyroxene phenocrysts, and basalt; many flows contain phenocrysts of both hypersthene and augite. Includes interbedded volcaniclastic and epiclastic rocks mostly of andesitic composition, but partly of dacitic or rhyodacitic composition. Includes areally restricted flows of silicic andesite or dacite. Upper part of unit mostly unaltered, although olivine crystals are locally altered to clay minerals. Lower parts commonly altered; secondary minerals
include nontronite and saponite, chalcedony, calcite, and zeolites. Older parts of this unit locally are propylitically altered adjacent to larger intrusions. Erupted mostly from widespread, northwest- and north-trending dikes and dike swarms and related plugs and lava cones.

Tfc **Flows and clastic rocks, undifferentiated (Miocene)**—Chiefly basaltic andesite and andesite lava flows and flow breccia containing plagioclase and pyroxene (hypersthene and augite) phenocrysts, mudflows (lahars), and volcanic conglomerates; locally includes some dacite flows. Includes lesser, coarse- to fine- grained epiclastic volcanic sedimentary rocks and ash-flow and air-fall tuffs. Partly equivalent in age to unit Tba and may be partly coeval with younger parts of unit Tstb. Locally altered adjacent to larger intrusions.

Thi **Hypabyssal intrusive rocks (Miocene)**—Hypabyssal, medium-grained, hornblende diorite and quartz diorite in small stocks and large dikes; includes intrusions of medium- to fine-grained gabbro and plugs and small stocks of commonly porphyritic biotite quartz monzonite and leucocratic granodiorite. Many of these intrusive bodies are moderately to intensely propylitized, as are wallrocks they intrude; locally, along shears, the rocks also are sericitized.

Tmsc **Marine siltstone, sandstone, and conglomerate (lower Eocene)**—Cobble and pebble conglomerate, pebbly sandstone, lithic sandstone, siltstone, and mudstone; massive to thin bedded; shelf and slope depositional setting. Contains foraminiferal faunas referred to the Penutian Stage of early Eocene age.

Tn **Nonmarine sedimentary rocks (Eocene)**—Continentially derived conglomerate, pebble conglomerate, sandstone, siltstone, and mudstone containing abundant biotite and muscovite, Dominantly nonvolcanic; clastic material derived from underlying older rocks.

Trb **Ridge-capping basalt and basaltic andesite (Pliocene and upper Miocene)**—Flows and flow breccia of basaltic andesite and lesser diktytaxitic to intergranular
olivine basalt. Includes some dense, aphyric flows, commonly with either cryptocrystalline of pilotaxitic to trachytic texture, and porphyritic flows with phenocrysts and glomerocrysts of olivine, hypersthene, and labradorite. A few flows contain both hypersthene and calcic augite phenocrysts. Olivine mostly fresh or slightly altered to iddingsite in flows high in section; flow low in section show some alteration to clays (nontronite and saponite), secondary silica minerals, and calcite; pinkish-brown glass in some flows unaltered. Locally includes some andesite and dacite.

**Tsv**  
**Silicic vent complexes (Pliocene, Miocene, and upper Oligocene)**—Large, rhyolitic to dacitic vent areas in the Cascade Range that commonly include multiple intrusions and much associated silicic eruptive breccia and erosional debris and some flows.

**Tu**  
**Undifferentiated tuffaceous sedimentary rocks, tuffs, and basalt (Miocene and Oligocene)**—Heterogeneous assemblage of continental, largely volcanogenic deposits of basalt and basaltic andesite, including flows and breccia, complexly interstratified with epiclastic and volcaniclastic deposits of basaltic to rhyodacitic composition. Includes extensive rhyodacitic to andesitic ash-flow and air-fall tuffs, abundant lapilli tuff and tuff breccia, andesitic to dacitic mudflow (lahar) deposits, poorly bedded to well-bedded, fine- to coarse-grained tuffaceous sedimentary rocks, and volcanic conglomerate. In places subdivided into: sedimentary and volcaniclastic rocks (Tus), tuff (Tut) and basaltic lava flows (Tub).

**Tub**  
**Basaltic lava flows**—Basaltic and basaltic andesite lava flows and breccia; grades laterally into rare bedded palagonitic tuff and breccia.

**Tus**  
**Sedimentary and volcaniclastic rocks**—Lapilli tuff, mudflow deposits (lahars), flow breccia, and volcanic conglomerate, mostly of basaltic to dacitic composition; rare iron-stained palagonitic tuff and breccia of basaltic and andesitic composition; and ash-flow, air-fall, and water-laid tuff of dacitic to
rhyolitic composition. The palagonite tuff and breccia grade laterally into peperite and into lava flows of basalt and basaltic andesite.

**Tut**  
**Tuff**—Welded to unwelded, mostly vitric crystal and vitric ash-flow tuff of several ages. Glass in tuff locally altered to clay, zeolites, and secondary silica minerals.

*Coast Range*

**Qal**  
**Alluvial deposits (Holocene)**—Sand, gravel, and silt forming flood plains and filling channels of present streams. In places includes talus and slope wash. Locally includes soils containing abundant organic material, and thin peat beds.

**Qd**  
**Dune sand (Holocene)**—Large areas of windblown sand composed of rock-forming minerals, mostly feldspar and small amounts of quartz.

**Qls**  
**Landslide and debris-flow deposits (Holocene and Pleistocene)**—Unstratified mixtures of fragments of adjacent bedrock. Locally includes slope wash and colluvium. Largest slides and debris flow occur where thick sections of basalt and andesite flows overlie clayey tuffaceous rocks. May include some deposits of late Pliocene age.

**Qt**  
**Terrace, pediment, and lag gravels (Holocene and Pleistocene)**—Unconsolidated deposits of gravel, cobbles, and boulders intermixed and locally interlayered with clay, silt, and sand. Mostly on terraces and pediments above present flood plains.

**Ti**  
**Mafic intrusions (Oligocene)**—Sheets, sills and dikes of massive granophyric ferrogabbro; some bodies strongly differentiated and include pegmatitic gabbro, ferrogranophyre, and granophyre.

**Tmsm**  
**Marine sandstone, siltstone and mudstone (lower Eocene and Paleocene?)**—Rhythmically interbedded sandstone, siltstone, and mudstone with minor
conglomerate; deposited in deep-sea fan depositional setting on submarine basalts of the Siletz River Volcanics.

Tmss  **Marine sandstone and siltstone (middle Eocene)**—Thin- to thick-bedded, crossbedded, well-sorted, fine- to medium-grain sandstone, siltstone, and mudstone; characterized by sparse fine white mica; shallow marine depositional setting at least partly of deltaic origin.

Tpβ  **Porphyritic basalt (upper Eocene)**—Subaerial lava flows and breccia of porphyritic basalt, minor basaltic andesite, and rare dacite.

Tsr  **Siletz River Volcanics and related rocks (middle and lower Eocene and Paleocene)**—Aphanitic to porphyritic, vesicular pillow flows, tuff-breccias, massive lava flows and sills of tholeiitic and alkali basalt. Upper part of sequence contains numerous interbeds of basaltic siltstone and sandstone, basaltic tuff, and locally derived basalt conglomerate. Rocks of unit pervasively zeolitized and veined with calcite. Most of these rocks are of marine origin and have been interpreted as oceanic crust and seamounts.

Tss  **Tuffaceous siltstone and sandstone (upper and middle Eocene)**—Thick- to thin-bedded marine tuffaceous mudstone, siltstone, and sandstone; fine to coarse grained. Contains calcareous concretions and, in places, is carbonaceous and micaceous.

Tt  **Tyee Formation (middle Eocene)**—Very thick sequence of rhythmically bedded, medium- to fine-grained micaceous, feldspathic, lithic, or arkosic marine sandstone and micaceous carbonaceous siltstone; contains minor interbeds of dacite tuff in upper part.

Ty  **Yamhill Formation and related rocks (upper and middle Eocene)**—Massive to thin-bedded concretionary marine siltstone and thin interbeds of arkosic, glauconitic, and basaltic sandstone; locally contains interlayered basalt lava flows and lapilli tuff.
High Lava Plains

Qb Basalt and basaltic andesite (Holocene and Pleistocene)—Thin flows of aphyric and porphyritic basalt and basaltic andesite, and open-textured (diktytaxitic), generally nonporphyritic, subophitic olivine basalt that commonly is highly feldspathic. Also includes some dissected intracanyon flows of porphyritic basalt and related vent complexes. Pressure ridges and tumuli on upper surfaces well preserved. Occurs principally along crest of Cascade Range; also in areas near and east of Newberry volcano, along southeast margin of Harney Basin, and in Rome Basin.

QTps Subaqueous basaltic and andesitic ejecta of basaltic and andesitic cinder cones (Holocene, Pleistocene, Pliocene, and Miocene?)—Partly consolidated, palagonitized, fine to coarse, scoriaceous altered cinders, bobs, breccia, and minor agglutinate, mostly deposited in subaqueous environment. Commonly with some interlayers and intermixed lacustrine sedimentary rocks. Forms palagonitic tuff and breccia cones and rings (maars) and, in places, palagonitic tuff ridges.

QTst Tuffaceous sedimentary rocks and tuffs (lower? Pleistocene or Pliocene)—Rhyolitic to andesitic ash-flow tuffs, pumice-fall deposits, minor mud flows, and older alluvium on the flanks of Newberry volcano.

Qyb Youngest basalt and basaltic andesite (Holocene)—Little-modified flows and associated breccia of basaltic andesite and some basalt on slopes of Newberry Volcano. Relations to Mazama pumice deposits indicate most of these rocks are less than 6,800 yr old \(^{14}C\); isotopic ages on flows range from about 1,000 to 6,000 yr B.P. \(^{14}C\).

Tat Silicic ash-flow tuff (lower Pliocene and upper Miocene)—Ash-flow tuff and associated pumiceous air-fall tuff mostly of rhyolitic and rhyodacitic composition; includes minor tuffaceous sedimentary rocks. Grades laterally through less-
densely welded tuff to nonwelded ash-flow tuff and interlayered tuffaceous sediments of unit Ts.

Tmv **Mafic vent complexes (Miocene)**—Intrusive plugs and dike swarms and related near-vent flows, breccias, cinders, and agglomerate of basaltic andesite, basalt, and andesite; commonly in the form of eroded piles of red, iron-stained thin flows, cinders, and agglomerate cut by mafic intrusions.

*Klamath Mountains*

bc **Amphibolite of Briggs Creek (Mesozoic or Paleozoic)**—Consists of amphibolite, micaceous quartzite, quartz schist, and recrystallized manganiferous chert. Includes structurally complex amphibole schist and quartz-rich hornblende gneiss of unknown age exposed at and near Chetco Peak west of Cave Junction.

cm **Condrey Mountain Schist (Triassic? and Paleozoic?)**—Consists of a variety of schistose rocks characterized by different proportions of muscovite, quartz, graphite, chlorite, actinolite, and epidote, rare thin layers of metachert, and clinozoisite-actinolite-albite-garnet metagabbro.

cs **Colebrooke Schist (Mesozoic or Paleozoic)**—Metamorphosed politic sedimentary rocks and subordinate metamorphosed submarine pillow lavas and pyroclastic beds of basaltic composition. Metamorphic age is Early Cretaceous (about 130 Ma).

Jm **Mélange (Jurassic)**—Structurally complex mixture of basaltic rocks, serpentine, chert, argillite, conglomerate, silty sandstone, and lenses of marble composing the mélange of the Takilma area.

Jop **Otter Point Formation of Dott (1971) and related rocks (Upper Jurassic)**—Highly sheared greywacke, mudstone, siltstone, and shale with lenses and pods of sheared greenstone, limestone, chert, blueschist, and serpentine. Identified as mélange by some investigators.
Sedimentary rocks (Jurassic)—Black and gray mudstone, shale, siltstone, graywacke, andesitic to dacitic water-laid tuff, porcelaneous tuff, and minor interlayers and lenses of limestone and fine-grained sediments metamorphosed to phyllite or slate. Locally includes some felsite, andesite and basalt flows, breccia, and agglomerate. Marine invertebrate fauna indicates age range from Early Jurassic (Hettangian) to early Late Jurassic (Oxfordian). In Klamath Mountains of southwest Oregon, includes Galice Formation and unnamed, hornblende- and (or) pyroxene-bearing clastic rocks of Jurassic age.

Shale, mudstone, and sandstone (Jurassic)—Black to gray shale, mudstone, and sandstone with local lenses of pebble conglomerate. Overlies Josephine ophiolite (unit Ju).

Granite and diorite (Jurassic and Triassic)—Felsic to intermediate, granitoid intrusive rocks. Includes Jurassic muscovite granodiorite, hornblende gabbro, tonalite, and quartz diorite of southwest Oregon.

Ultramafic and related rocks of ophiolite sequences (Jurassic)—Predominantly harzburgite and dunite with both cumulate and tectonite fabrics. Locally altered to serpentinite. Includes gabbroic rocks and sheeted diabasic dike complexes. Comprises Josephine ophiolite, ophiolites of Onion Mountain, Sexton Mountain, Pearsoll Peak, Rogue River, and Riddle areas and Coast Range ophiolite and serpentinite mélangé. In southwest Oregon, locally includes small bodies of early Mesozoic or late Paleozoic serpentinized and sheared ultramafic rocks, mostly in shear zones. Locally, volcanic and sedimentary rocks shown separately.

Basaltic volcanic and sedimentary rocks—Basalt flows, flow breccia, agglomerate, pillow basalt and pillow breccia, and lesser shale, chert siltstone, and mudstone of ophiolitic complexes.
Jv  **Volcanic rocks (Jurassic)**—Lava flows, flow breccia, and agglomerate dominantly of plagioclase, pyroxene, and hornblende porphyritic and aphyric andesite. Includes flow rocks that range in composition from basalt to rhyolite as well as some interlayered tuff and tuffaceous sedimentary rocks. Commonly metamorphosed to greenschist facies; locally foliated, schistose or gneissic. Includes the Rogue Formation and volcanic rocks commonly assigned to the Galice Formation. Considered to be accreted island-arc terrane.

Kc  **Clastic sedimentary rocks (Upper and Lower Cretaceous)**—Locally fossiliferous sandstone and conglomerate; marine fossils indicate Early Cretaceous (Albian) age.

KJds  **Sedimentary rocks related to the Dothan Formation (Lower Cretaceous and Upper Jurassic)**—Sandstone, conglomerate, graywacke, rhythmically banded chert lenses. Includes western Dothan and Otter Point Formations.

KJdv  **Volcanic rocks related to the Dothan Formation (Lower Cretaceous and Upper Jurassic)**—Basaltic pillow lavas, volcanic breccia, and silicified basalt lava flows.

KJg  **Granitic rocks (Cretaceous and Jurassic)**—Mostly tonalite and quartz diorite but including lesser amounts of other granitoid rocks. Potassium-argon ages determined on hornblende indicates plutons range in age from 143 to 166 Ma.

KJgu  **Gabbro and ultramafic rocks associated with granitic plutons (Cretaceous and Jurassic)**—Predominantly hornblende gabbro, gabbro, and olivine gabbro, but includes pyroxenite, hornblende pyroxene, and minor peridotite, dunite, and serpentinite.

KJm  **Myrtle Group (Lower Cretaceous and Upper Jurassic)**—Conglomerate, sandstone, siltstone, and limestone. Locally fossiliferous. As shown, includes Riddle and Days Creek Formations.
Ks  **Sedimentary rocks (Cretaceous)**—Marine graywacke, subgraywacke, conglomerate, and shale. Pebbles and cobbles in conglomerate are well-rounded volcanic and metavolcanic rocks, low-grade metasedimentary rocks, quartzite, chert, and minor silicic and intermediate plutonic rocks, Shales are gray to black and are fissile to blocky, Sandstones commonly display graded bedding; conglomerate beds are commonly thick and poorly bedded. Shales, near Mitchell, have yielded latest Early Cretaceous (Albian) fossils’ some earliest Late Cretaceous (Cenomanian) fossils occur in beds southeast of Mitchell.

mc  **May Creek Schist (Paleozoic)**—Layered amphibolite, schist, gneiss, and quartzite. Protolith considered to be of Paleozoic age.

Qt  **Terrace, pediment, and lag gravels (Holocene and Pleistocene)**—Unconsolidated deposits of gravel, cobbles, and boulders intermixed and locally interlayered with clay, silt, and sand. Mostly on terraces and pediments above present flood plains. Includes older alluvium in the Klamath Mountains and both high- and low-level terraces along Oregon coast.

Tmss  **Marine sandstone and siltstone (middle Eocene)**—Thin- to thick-bedded, crossbedded, well-sorted, fine- to medium-grain sandstone, siltstone, and mudstone; characterized by sparse fine white mica; shallow marine depositional setting at least partly of deltaic origin. Contains foraminiferal and molluscan faunas of early middle Eocene age.

Tn  **Nonmarine sedimentary rocks (Eocene)**—Continentially derived conglomerate, pebble conglomerate, sandstone, siltstone, and mudstone containing abundant biotite and muscovite, dominantly nonvolcanic; clastic material derived from underlying older rocks.

TrPv  **Volcanic rocks (Triassic and Permian)**—Massive flows of porphyritic metaandesite, metabasalt, spilite, and keratophyre, volcanic breccia, and subordinate amounts of fine-grained volcaniclastic rocks. In southwest Oregon includes
hornblende, pyroxene, and plagioclase porphyritic andesite flows, breccia, agglomerate, tuff, and locally, some basalt flows and dacitic tuffs of the Applegate Group.

TrPzm **Mélangé of Dutchmans Peak (Triassic or Paleozoic)**—Heterogeneous mixture of interlayered metasedimentary and metavolcanic rocks metamorphosed to upper greenschist and (or) almandine-amphibolite facies, and serpentinite, gabbro, and metagabbro.

TrPzs **Sedimentary rocks, partly metamorphosed (Triassic and Paleozoic)**—Poorly bedded argillite, chert, phyllite, phyllitic quartzite, calc-phyllite, impure limestone, and marble. In places rocks are strongly foliated. In Klamath Mountains of southwest Oregon, includes shale, mudstone, volcaniclastic sandstone, graywacke, conglomerate, tuff, and minor radiolarian chert and marble of the Applegate Group.

Tsr **Siletz River Volcanics and related rocks (middle and lower Eocene and Paleocene)**—Aphanitic to porphyritic, vesicular pillow flows, tuff-breccias, massive lava flows and sills of tholeiitic and alkali basalt. Upper part of sequence contains numerous interbeds of basaltic siltstone and sandstone, basaltic tuff, and locally derived basalt conglomerate. Rocks of unit pervasively zeolitized and veined with calcite. Most of these rocks are of marine origin and have been interpreted as oceanic crust and seamounts.

*Willamette Valley*

Qs **Lacustrine and fluvial sedimentary rocks (Pleistocene)**—Unconsolidated to semiconsolidated lacustrine clay, silt, sand, and gravel; in places includes mudflow and fluvial deposits and discontinuous layers of peat.

Qt **Terrace, pediment, and lag gravels (Holocene and Pleistocene)**—Unconsolidated deposits of gravel, cobbles, and boulders intermixed and locally interlayered with clay, silt, and sand. Mostly on terraces and pediments above
present flood plains. Includes older alluvium in the Klamath Mountains and both high- and low-level terraces along Oregon coast.

Tfe **Fisher and Eugene Formations and correlative rocks (Oligocene and upper Eocene)**—Thin to moderately thick bedded, coarse-to fine-grained arkosic and micaceous sandstone and siltstone, locally highly pumiceous, of the marine Eugene Formation; and coeval and older andesitic lapilli tuff, breccia, water-laid and air-fall silicic ash of the continental Fisher and Colestin Formations; upper parts of the Fisher Formation apparently lap onto ad interfingers with the Eugene Formation.

Tfeb **Basaltic rocks**—Probably part of Fisher Formation.

Tfeе **Marine Eugene Formation, where mapped separately.**
APPENDIX C: Site and soil Pit Images for HH Sites. (Rock units in parentheses.)

Site HH01 and HH02 are both from the south edge of the Newberry Lava Flow (Qyb).
Site HH03 (QTa)
Site HH04 (QTa)
Site HH05 (Thi)
Site HH06 (Thi)
Site HH07 (upper left) and HH08 had the same vegetation (Tvs)
Site HH09 (upper left) and HH10 had the same vegetation (Tvm)
Site HH11 (KJdv)
Site HH14 (Tfée)
Site **HH15** (Tfeb)
Dr. Burns points to a demarcation in the Bt (20-60+ cm) horizon at Site HH17 (Ti), where below the soil is a darker red.
## APPENDIX D: Soil Data

### A Horizon

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<tr>
<th>Sample</th>
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## APPENDIX D: Soil Data, A Horizon (cont.)

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### APPENDIX D: Soil Data, A Horizon (cont.)

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### APPENDIX D: Soil Data, B Horizon (cont.)

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## APPENDIX D: Soil Data, B Horizon (cont.)

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## APPENDIX E: SAMPLING SITE CHARACTERISTICS

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APPENDIX E: Sampling Sites Characteristics (cont.)

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Appendix E Key
MRC = Map Reference Code
Vegetation: a alder, b blackberry, br brush, c cedar, cs citrus spruce, cw cottonwood, df Douglas fir, f fir, frn fern, g grass, gf ground, h hemlock, hz hazelnut, lp lodgepole pine, m maple, mb myrtle bush, md madrone, mgc mossy ground cover, ml mountain laurel, o oak, p pine, pi poison ivy, po poison oak, pp ponderosa pine, sb scotch broom, s salal, ss sitka spruce, w willow, wmb wax myrtle bush, wp wetland and prairie plants.
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**Appendix F Key:**

Rock type defined in Table 10.

Age Rank is the average of minimum and maximum deposition age as defined by Walker and MacLeod (1999).
APPENDIX G: Apex Labs Sample ID and Control Data

This appendix contains sample identification, quality control results, sample preparation information and notes and definitions used in Apex Labs reports for the following work orders:

- A10D053
- A10D059
- A10D066
- A10D071
- A10D077
- A10E125

These samples were tested for concentrations of various metals for Oregon, but only arsenic results were used in this study. The pages reporting results from different metals are not included, but results for arsenic concentrations in soils collected by PSU are in Appendix D.
Thursday, May 13, 2010

Neil Morton
GeoEngineers - Seattle
600 Stewart St. Suite 1700
Seattle, WA 98101

R.E. Oregon Metals Evaluation / 2787 069-000

Enclosed are the results of analyses for work order A1000062, which was received by the laboratory on 4/20/2010 at 3:35:00PM.

Thank you for using Apex Labs. We appreciate your business and strive to provide the highest quality services to the environmental industry.

If you have any questions concerning this report or the services we offer, please feel free to contact me by email at pmorton@apex-labs.com, or by phone at 503-718-2323.

Apex Laboratories

[Signature]

Philip Neustein, For Darvin Thomas, Business Development Director
### SAMPLE INFORMATION

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Philip Neuringer, For Darwin Thomas, Business Development Director
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QUALITY CONTROL (QC) SAMPLE RESULTS

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**Batch 1004114 - EPA 3051A**

**EPA 6010**

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**LCS (200414-EPSH)**

**EPA 6010**

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**Duplicate (1004114-EPSH)**

**EPA 4000**

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Matrix Spike (1004114-MSE)

**EPA 4000**

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Apex Laboratories

The results in this report apply to the samples analyzed in accordance with the chain of custody document. Any analytical results reported are representative of the sample.
QUALITY CONTROL (QC) SAMPLE RESULTS

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**Batch 1004114: EPA 3051A**

**Matrix Spike (1004114-MSK)**

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**Matrix Spike (1004114-MSK)**

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**Batch 1004114: EPA 3051A**

**Matrix Spike (1004114-MSK)**

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[Signature]

Philip Neuberg, For Darwin Thomas, Business Development Director

Page 37 of 33
QUALITY CONTROL (QC) SAMPLE RESULTS

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**Batch 1004123- EPA 3051A**

**Soil**

**Blank (1004123-HLC1)**

Prepared: 04/09/00 08:49  Analyzed: 04/09/00 19:29

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Prepared: 04/09/00 08:49  Analyzed: 04/09/00 19:44

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**Matrix Spike (1004123-MSP)**

Prepared: 04/09/00 08:49  Analyzed: 04/09/00 19:47

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Philip Nurnberg, For Darwin Thomas, Business Development Director
### QUALITY CONTROL (QC) SAMPLE RESULTS

#### Total Metals by EPA 6010 (ICPMS)

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| Antimony | 18.0 | 0.109 | 1.09 | mg/kg dry | 10 | 27.2 | 0.176 | 68 | 75-125% | -- | -- | QM
| Arsenic | 0.015 | 2.10 | * | * | | | | | | | | |
| Boron | 25.0 | 0.109 | 1.09 | * | * | 27.2 | 0.325 | 69 | 40-160% | -- | -- | |
| Cadmium | 52.0 | 0.109 | 1.09 | * | * | 54.4 | 0.375 | 64 | 40-160% | -- | -- | |
| Lead | 0.015 | 2.10 | * | * | | | | | | | | |
| Selenium | 25.0 | 0.109 | 1.09 | * | * | 27.2 | 0.351 | 75 | 90-110% | -- | -- | |
| Silver | 25.0 | 0.109 | 1.09 | * | * | NO | NO | 61 | 40-160% | -- | -- | |
| Thallium | 24.0 | 0.109 | 1.09 | * | * | 0.145 | 85 | 61 | 40-160% | -- | -- | |
| **Post Spike** | **BR04123-P51** | | | | | | | | | | | |
| QC 5 source sample | 40 AFA | (AAB063-75) |
| **ETA 6010** | | | | | | | | | | | | |
| Antimony | 18.0 | ugl | 10 | 126 | 5.57 | 98 | 80-130% | -- |

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The results in this report apply to the samples analyzed in accordance with the chain of custody document. This analytical report must be reproduced in its entirety.

Philip Neumark, For Dianne Thomas, Business Development Director
## QUALITY CONTROL (QC) SAMPLE RESULTS

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The results in this report apply to the samples analyzed in accordance with the data of

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Apex Laboratories

Philip Neumark, President, Business Development Director
### QUALITY CONTROL (QC) SAMPLE RESULTS

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The results in this report apply to the samples analyzed in accordance with the data of this document. This analysis report shall be reproduced in its entirety.

[Signature]

Philip Neumark, For Darwin Thomason, Business Development Director

Page 42 of 54
# QUALITY CONTROL (QC) SAMPLE RESULTS

## Total Metals by EPA 6010B (ICPMS)

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The results in this report apply to the samples analyzed in accordance with the sieve of existing methods. Any analytical errors must be reported to the laboratory.
### QUALITY CONTROL (QC) SAMPLE RESULTS

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The results in this report are the samples analyzed in accordance with the claim of custody document. This analytical report is to be reproduced in its entirety.
QUALITY CONTROL (QC) SAMPLE RESULTS

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Batch 1001144 EPA 3051A


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LSC (200144-1001) - Prepared: 09/12/2010 10:32 - Analyzed: 09/14/2010 14:00

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Post Spikes (H00144-PS1) - Prepared: 09/14/2010 16:46 - Analyzed: 09/14/2010 16:46

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Post Spikes (H00144-PS2) - Prepared: 09/14/2010 16:46 - Analyzed: 09/14/2010 16:51

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Philip Neumark, For David Thomas, Business Development Director

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QUALITY CONTROL (QC) SAMPLE RESULTS

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Apex Laboratories

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Philip Newman, Site Manager, Business Development Director
## QUALITY CONTROL (QC) SAMPLE RESULTS

### Percent Dry Weight by D2216

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Reported: 05/15/03 22:21

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Philip Neumann For Darwin Thomas, Business Development Director
### SAMPLE PREPARATION INFORMATION

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### SAMPLE PREPARATION INFORMATION

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**Batch 100123**

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Apex Laboratories

The results in this report apply to the samples analyzed in accordance with the stated methods. This analytical report will be reproduced in its entirety.

Philip Newman, For Darwin Thomas, Business Development Director

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### SAMPLE PREPARATION INFORMATION

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Apex Laboratories

The results in this report apply to the sample(s) analyzed in accordance with the data shown in this document. This analysis report must be retained in its entirety.

Philip Rosenberg, For Darwin Tooman, Business Development Director

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Thursday, May 13, 2010

Neil Morton
GeoEngineers - Seattle
800 Stewart St. Suite 1700
Seattle, WA 98101

R.E. Oregon Metals Evaluation J 2787-550-000

Enclosed are the results of analyses for work order A00652, which was received by the laboratory on 4/2/2010 at 3:35:00PM.

Thank you for using Apex Labs. We appreciate your business and strive to provide the highest quality services to the environmental industry.

If you have any questions concerning this report or the services we offer, please feel free to contact me by email at: mleitenberg@apex-labs.com, or by phone at 503-718-2323.
## SAMPLE INFORMATION

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## Analytical Report for Samples

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*Note: The results in this report apply to the samples analyzed in accordance with the chain of custody documents. This analytical report is reproduced in its entirety.*

Philip Neumayr, Vice President, Business Development Director
## Analytical Report for Samples

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Apex Laboratories

The results in this report apply to the samples analyzed in accordance with the details of the attached document. This analytical report must be considered in its entirety.
## QUALITY CONTROL (QC) SAMPLE RESULTS

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### QUALITY CONTROL (QC) SAMPLE RESULTS

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Prepared: 9/12/03 10:30  Analyzed: 9/12/03 7:56
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Philip Newberg, Jr., Darwin Thomas, Business Development Director

Page 167 of 25
QUALITY CONTROL (QC) SAMPLE RESULTS

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## QUALITY CONTROL (QC) SAMPLE RESULTS

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### Soil

**Batch 100456 - EPA 3051A**

**Block (00456-HL1)**

**Proposed:** 04/13/00 09:56  **Analyzed:** 04/14/00 15:00

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| Batch 100456-HS1 | Proposed: 04/13/00 09:56 | Analyzed: 04/14/00 15:06 |

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### EPA 0456

**Block (00456-HS1)***

**Proposed:** 04/13/00 09:56  **Analyzed:** 04/14/00 15:06

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**Proposed:** 04/13/00 09:56  **Analyzed:** 04/14/00 15:29

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**Apex Laboratories**

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The results in this report apply to the samples analyzed in accordance with the criteria of

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Philip Neuenberg, For Darwin Homan, Business Development Director
QUALITY CONTROL (QC) SAMPLE RESULTS

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The results in this report apply to the samples analyzed in accordance with the state of Oregon's consultant agreements. This analytical report must be reproduced in its entirety.

Philip Neuberg, For Darwin Thomas, Business Development Director
QUALITY CONTROL (QC) SAMPLE RESULTS

### Total Metals by EPA 8030 (ICPMS)

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### LCS (100187-B61)

| **EPA 610** | | | | |
| **Analyte** | **Result** | **MDL** | **Reporting Limit** | **Units** | **Dil.** | **Amendment** | **Source** | **Detection** | **%RSD** | **Limits** | **RSD** | **LSD** | **Note** |
| Antimony | 257 | 0.100 | 0.100 | mg/kg wet | 10 | 25.0 | -- | 103 | 82-120% | -- | -- | -- | -- |
| Arsenic | 480 | 0.200 | 0.200 | * | -- | -- | -- | 96 | -- | -- | -- | -- | -- |
| Beryllium | 217 | 0.200 | 0.200 | * | -- | -- | -- | 95 | -- | -- | -- | -- | -- |
| Cadmium | 49.2 | 0.100 | 0.100 | * | -- | -- | -- | 98 | -- | -- | -- | -- | -- |
| Lead | 48.3 | 0.100 | 0.100 | * | -- | -- | -- | 97 | -- | -- | -- | -- | -- |
| Selenium | 213 | 0.400 | 0.400 | * | -- | -- | -- | 93 | -- | -- | -- | -- | -- |
| Silver | 24.6 | 0.100 | 0.100 | * | -- | -- | -- | 98 | -- | -- | -- | -- | -- |
| Thallium | 22.6 | 0.100 | 0.100 | * | -- | -- | -- | 94 | -- | -- | -- | -- | -- |

### Duplicate (100187-D45)

| **EPA 610** | | | | |
| **Analyte** | **Result** | **MDL** | **Reporting Limit** | **Units** | **Dil.** | **Amendment** | **Source** | **Detection** | **%RSD** | **Limits** | **RSD** | **LSD** | **Note** |
| Antimony | 0.477 | 0.165 | 1.65 | mg/kg dry | 10 | -- | -- | 0.502 | -- | -- | 30 | 40% | -- |
| Arsenic | 1.65 | 0.339 | 3.39 | * | -- | -- | -- | 1.71 | -- | -- | 16 | 40% | -- |
| Beryllium | ND | 0.165 | 1.65 | * | -- | -- | -- | ND | -- | -- | -- | -- | -- |
| Cadmium | 0.153 | 0.165 | 1.65 | * | -- | -- | -- | 0.319 | -- | -- | 19 | 40% | -- |
| Lead | 179 | 0.165 | 1.65 | * | -- | -- | -- | 186 | -- | -- | 6 | 40% | -- |
| Selenium | ND | 0.618 | 6.18 | * | -- | -- | -- | 0.805 | -- | -- | -- | -- | -- |
| Silver | ND | 0.165 | 1.65 | * | -- | -- | -- | ND | -- | -- | -- | -- | -- |
| Thallium | ND | 0.165 | 1.65 | * | -- | -- | -- | ND | -- | -- | -- | -- | -- |

### Match Spike (100187-M58)

| **EPA 610** | | | | |
| **Analyte** | **Result** | **MDL** | **Reporting Limit** | **Units** | **Dil.** | **Amendment** | **Source** | **Detection** | **%RSD** | **Limits** | **RSD** | **LSD** | **Note** |
| Antimony | ND | 0.165 | 1.65 | mg/kg dry | 10 | -- | -- | -- | -- | -- | -- | -- | -- |
| Arsenic | ND | 0.339 | 3.39 | * | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Beryllium | ND | 0.165 | 1.65 | * | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Cadmium | ND | 0.153 | 1.65 | * | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Lead | ND | 0.165 | 1.65 | * | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Selenium | ND | 0.618 | 6.18 | * | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Silver | ND | 0.165 | 1.65 | * | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Thallium | ND | 0.165 | 1.65 | * | -- | -- | -- | -- | -- | -- | -- | -- | -- |

The results in this report apply to the samples analyzed in accordance with the basis of the EPA document. The analytical report must be reproduced in its entirety.
### QUALITY CONTROL (QC) SAMPLE RESULTS

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| **Water** |        |     |                 |       |      |              |               |      |       |        |           |       |
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| Matrix Spike (1004157-158) | | | | | | | | | | | |
| QC Source Sample: MI0457 (A110059-49) | | | | | | | | | | | |
| Antimony | 22.3 | 0.104 | 104 | µg/g dry | 10 | 26.1 | 0.116 | 86 | 75.122% | — | — | |
| Arsenic | 49.7 | 0.209 | 209 | | | | | | | | | |
| Beryllium | 25.0 | 0.209 | 104 | | | | | | | | | |
| Cadmium | 30.4 | 0.104 | 104 | | | | | | | | | |
| Lead | 49.3 | 0.104 | 104 | | | | | | | | | |
| Selenium | 22.9 | 0.438 | 209 | | | | | | | | | |
| Silver | 25.3 | 0.104 | 104 | | | | | | | | | |
| Thallium | 22.9 | 0.104 | 104 | | | | | | | | | |

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Philip Neurenberg, For Daniell Thomas, Business Development Director

Page 11 of 35
### QUALITY CONTROL (QC) SAMPLE RESULTS

#### Total Metals by EPA 8020 (ICPMS)

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#### QC Source spike: M1206a (6010456-87)

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The results in this report apply to the samples analyzed in accordance with the chain of custody document. This analysis sheet must be reproduced in its entirety.

Philip Hennberg, Director of Business Development Director
QUALITY CONTROL (QC) SAMPLE RESULTS

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Apex Laboratories

Philip Neuburger, For Darren Thomas, Business Development Director

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# QUALITY CONTROL (QC) SAMPLE RESULTS

## Total Metals by EPA 6010B (ICPMS)

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Apex Laboratories

The results in this report apply to the samples analyzed in accordance with the criteria of the applicable standard. This analytical report should be reviewed in its entirety.

Philip Neumark, For Darwin Thomas, Business Development Director

Page 44 of 50
## Quality Control (QC) Sample Results

### Total Metals by EPA Method 8080 (ICP-MS)

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**Matrix Spikes (M05300-MS2)**

**QC Source Sample: M7240 (A11008-56-3S)**

**EPA 6000**

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The results in this report apply to the samples analyzed in accordance with the guidelines of the testing document. This analytical report must be reviewed by the customer.
### QUALITY CONTROL (QC) SAMPLE RESULTS

#### Total Metals by EPA 6020 (ICPMS)

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#### LCS (1004214-351E)

|       |        |     |                 |       |      |       |        |        |      |      |        |           |       |
|-------|--------|-----|-----------------|-------|------|-------|--------|        |      |      |        |           |       |
| Soil  |        |     |                 |       |      |       |        |        |      |      |        |           |       |
|       |        |     |                 |       |      |       |        |        |      |      |        |           |       |
| Antimony | 25.3 | 0.100 | 100 | mg/kg wet | 10 | 250 | --- | 301 | 80.12% | --- | --- | --- | --- | --- |
| Arsenic | 46.3 | 0.300 | 200 | " | " | 500 | --- | 93 | " | --- | --- | --- | --- |
| Barium | 23.5 | 0.200 | 100 | " | " | 250 | --- | 94 | " | --- | --- | --- | --- |
| Cadmium | 47.5 | 0.100 | 100 | " | " | 500 | --- | 95 | " | --- | --- | --- | --- |
| Lead | 45.2 | 0.100 | 100 | " | " | 250 | --- | 91 | " | --- | --- | --- | --- |
| Selenium | 23.9 | 0.400 | 200 | " | " | 250 | --- | 95 | " | --- | --- | --- | --- |
| Silver | 23.6 | 0.100 | 100 | " | " | 250 | --- | 95 | " | --- | --- | --- | --- |
| Thallium | 22.8 | 0.100 | 100 | " | " | 91 | " | 91 | " | --- | --- | --- | --- |

*The results in this report apply to the samples analyzed in accordance with the methods of analysis documented. This analytical report must be reproduced in its entirety.*

---

*Apex Laboratories, 12232 S.W. Garden Place, Tigard, OR 97223, 503-718-2323 Phone, 503-718-0933 Fax*
### QUALITY CONTROL (QC) SAMPLE RESULTS

#### Percent Dry Weight by B2216

<table>
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#### Batch B204-177 - Dry Weight

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**SpectroChemometrics**

- The results in this report apply to the samples analyzed in accordance with the claims of nature document. Any analysis statement must be reproduced in its entirety.

---

Phil Weaverg, For Darwin Thomas, Business Development Director
## QUALITY CONTROL (QC) SAMPLE RESULTS

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Apex Laboratories

Philip Neeburg, For Darwin Thomas, Business Development Director
<table>
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**Sample Preparation Information**

**Total Metals by EPA 6020 (ICPMS)**

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**Notes:**

*The results in this report apply to the sample analyzed in accordance with the protocol described in the study document. The analytical report must be read in its entirety.*

Philip Neumberg, President & CEO, Business Development Director
### SAMPLE PREPARATION INFORMATION

**Prop: EPA 3051A**

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*Note: The results in this report apply to the samples analyzed in accordance with the terms of the contract.*

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Philip Nienberg, Business Development Director
## SAMPLE PREPARATION INFORMATION

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**Note:** The results in this report apply to the samples analyzed in accordance with the data of the sample document. This analytical report must be reproduced in its entirety.

**Philip Neuremburg**, For Darwin Trobon, Business Development Director

Page 51 of 55
Thursday, May 13, 2010

Neil Morton
GeoEngineers - Seattle
600 Stewart St. Suite 1700
Seattle, WA 98101

RE: Oregon Metals Evaluation / 2787-050-000

Enclosed are the results of analyses for work order A100005, which was received by the laboratory on 4/6/2010 at 3:35:00PM.

Thank you for using Apex Labs. We appreciate your business and strive to provide the highest quality services to the environmental industry.

If you have any questions concerning this report or the services we offer, please feel free to contact me by email at: memster@apexlabs.com, or by phone at 503-718-2523.
## ANALYTICAL REPORT FOR SAMPLES

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Apex Laboratories

The results in this report apply to the samples analyzed in accordance with the terms of a written agreement. This analytical report must be returned to its originator.
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Apex Laboratories

The results in this report apply to the sample analyzed in accordance with the terms of this document. This analytical report must be reproduced in its entirety.

[Signature]

Philip Nauwers, For Darwin Thomas, Business Development Director
## ANALYTICAL REPORT FOR SAMPLES

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The results in this report apply to the samples analyzed in accordance with the terms of the contract document. This analytical report must be considered as its entirety.
# QUALITY CONTROL (QC) SAMPLE RESULTS

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*The results of this report apply to the samples analyzed in accordance with the criteria of the method document. This analytical report will be reproduced in its entirety.*

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Apex Laboratories

Philip Neurnberg, For Darwin Thomas, Business Development Director

Page 33 of 37
# QUALITY CONTROL (QC) SAMPLE RESULTS

**Total Metals by EPA HZ211 (ICPMS)**

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**Batch #1104214 - EPA 3051A**

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The results in this report apply to the samples analyzed in accordance with the criteria of the test method. This analytical report must be reproduced in its entirety.
## QUALITY CONTROL (QC) SAMPLE RESULTS

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**User Notes:** The results in this report apply to the samples analyzed in accordance with the stated quality control measures. Analytical reports must be reproduced in full entirety.
QUALITY CONTROL (QC) SAMPLE RESULTS

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Philip Neuman, For Darwin Thomas, Business Development Director
Page 10 of 37
## QUALITY CONTROL (QC) SAMPLE RESULTS

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**Analysis**

- **Antimony**: ND 0.100 1.00 mg/kg wet 10 -- -- -- -- -- --
- **Arsenic**: ND 0.200 2.00 -- -- -- -- -- --
- **Barium**: ND 0.200 1.00 -- -- -- -- -- --
- **Calzium**: ND 0.100 1.00 -- -- -- -- -- --
- **Lead**: ND 0.100 1.00 -- -- -- -- -- --
- **Selenium**: ND 0.100 1.00 -- -- -- -- -- --
- **Thallium**: ND 0.100 1.00 -- -- -- -- -- --

**Analysis**

- **Antimony**: 27.0 0.100 1.00 mg/kg wet 10 25.0 108 82 100% -- --
- **Arsenic**: 49.3 0.200 2.00 -- 30.0 200 99 -- --
- **Barium**: 24.4 0.200 1.00 -- 20.0 98 90 -- --
- **Calcium**: 20.1 0.100 1.00 -- 100 97 -- --
- **Lead**: 48.4 0.100 1.00 -- 97 95 -- --
- **Selenium**: 24.2 0.100 1.00 -- 94 95 -- --
- **Silver**: 21.2 0.100 1.00 -- 85 95 -- --
- **Thallium**: 23.8 0.100 1.00 -- 95 95 -- --

**Analysis**

- **Antimony**: ND 0.126 1.26 mg/kg dry 10 -- ND -- -- 400
- **Arsenic**: 1.39 0.252 2.52 -- 1.46 3 400 T
- **Barium**: 0.577 0.252 1.26 -- 0.407 8 400 T
- **Calcium**: 0.47 0.126 1.26 -- 0.407 8 400 T
- **Lead**: 4.24 0.126 1.26 -- 7.36 3 400 T
- **Selenium**: ND 0.533 1.26 -- ND -- -- 400 T
- **Silver**: ND 0.126 1.26 -- ND -- -- 400 T
- **Thallium**: 0.009 0.126 1.26 -- 0.302 9 400 T

Apex Laboratories

The results in this report apply to the samples analyzed in accordance with the criteria of the standard document. This analytical report shall be reproduced in its entirety.

Philip Neuenberg, For Darwin Thomas, Business Development Director

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QUALITY CONTROL (QC) SAMPLE RESULTS

## Total Metals by EPA 6020 (ICPMS)

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Apex Laboratories

The results in this report apply to the samples analyzed in accordance with the criteria of the contract. This analytical report shall be reproduced in its entirety.
### QUALITY CONTROL (QC) SAMPLE RESULTS

#### Total Metals by EPA 8030 (ICPMS)

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| **Matrix Spike (100001-10050)** | Prepared: 04/23/01 12:27 | Analyzed: 04/26/01 12:42 |        |     |     |              |        |               |      |          |          |       |       |
| Soil         |        |     |                 |      |      |              |        |               |      |          |          |       |       |
| Antimony     | 26.0   | 0.108| 2.16 mg/kg dry | 10   | 27.0 | ND           | 96     | 75-125%       | --   | --       |          |       |       |
| Arsenic      | 51.9   | 0.216| 2.16            | *    | *    | 54.0         | 0.977  | 94            |     | --       |          |       |       |
| Barium       | 25.5   | 0.216| 1.08            | *    | *    | 27.0         | ND     | 94            |     | --       |          |       |       |
| Cadmium      | 53.1   | 0.108| 1.08            | *    | *    | 54.0         | 0.160  | 96            |     | --       |          |       |       |
| Lead         | 51.6   | 0.108| 1.08            | *    | *    | 51.6         | 0.189  | 96            |     | --       |          |       |       |
| Selenium     | 23.9   | 0.432| 2.16            | *    | *    | 27.0         | ND     | 96            |     | --       |          |       |       |
| Silver       | 26.0   | 0.108| 1.08            | *    | *    | ND           | 96     |               |     | --       |          |       |       |
| Tellurium    | 54.9   | 0.108| 1.08            | *    | *    | ND           | 96     |               |     | --       |          |       |       |

*Note: The results in this report apply to the sample analyzed in accordance with the chain of custody documents. This analytical summary must be reproduced in this entirety.*

Philip Hennberg, For Darwen Thomas, Business Development Director
## QUALITY CONTROL (QC) SAMPLE RESULTS

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The results in this report apply to the samples analyzed in accordance with the details of the sample. This analysis report must be reproduced in its entirety.
# QUALITY CONTROL (QC) SAMPLE RESULTS

## Total Metals by EPA 8020 (ICPMS)

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### Batch 1004367 - EPA 3051A

**Matrix:** Soil

**QC Source Sample:** L101562 (A1310005-41)

**Prepared:** 06/25/10 16:36, **Analyzed:** 06/27/10 13:15

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### QUALITY CONTROL (QC) SAMPLE RESULTS

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The results in this report apply to the samples analyzed in accordance with the data of this document. The analytical report must be reproduced in its entirety.

Philip Neuenberg
Press Darwin Thomas, Business Development Director
QUALITY CONTROL (QC) SAMPLE RESULTS

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Matrix Spikes (1047 A-1058)

QC Source angle: RD 1643 (A134066-89)

The results in this report apply to the samples analyzed in accordance with the chain of custody document. This analysis is complete and is reported to its accuracy.

Philip Nurnberg, For Darwin Thomas, Business Development Director
## QUALITY CONTROL (QC) SAMPLE RESULTS

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The results in this report apply to the sample analyzed in accordance with the chain of custody document. This analytical report may be reproduced in its entirety.

Philip Nemenberg, For Devon Thomas, Business Development Director
QUALITY CONTROL (QC) SAMPLE RESULTS

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Apex Laboratories

Philip Neurenberg, PE, Darwin Thomas, Business Development Director

The results in this report apply to the samples analyzed in accordance with the terms and conditions outlined in the engagement agreement.
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### SAMPLE PREPARATION INFORMATION

#### Total Metals by EPA 6020 (ICPMS)

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**Plots 1004087**

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**Plots 1004087**

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## SAMPLE PREPARATION INFORMATION

**Total Metals by EPA 6020 (ICP-MS)**

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**Apex Laboratories**

The results in this report apply to the samples analyzed in accordance with the data of the attached document. This statement is made to be reproduced in its entirety.

Philip Neuberg, P.E., Darwin Thomas, Business Development Director
Thursday, May 13, 2010

Neil Norton
GeoEngineers -Seattle
600 Stewart St. Suite 1700
Seattle, WA 98101

RE: Oregon Metals Evaluation /2787-050-000

Enclosed are the results of analyses for work order #100071, which was received by the laboratory on 4/2/2010 at 3:35:00PM.

Thank you for using Apex Labs. We appreciate your business and strive to provide the highest quality services to the environmental industry.

If you have any questions concerning this report or the services we offer, please feel free to contact me by email at: person@email.com, or by phone at 503-718-2323.

Apex Laboratories

[Signature]

Philip Neumark, Business Development Director
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The results in this report are subject to the terms and conditions of sale. Apex Laboratories is not responsible for the accuracy of this report.
## ANALYTICAL REPORT FOR SAMPLES

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## LC 120 (100-4215-ABSI)

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## Matrix Spike (100-4215-MS1)

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## Analyte: Antimony

The results in this report apply to the samples analyzed in accordance with the chain of custody documents. This analytical report has been reviewed and is correct.
### QUALITY CONTROL (QC) SAMPLE RESULTS

**Total Metals by EPA 6020 (ICPMS)**

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| Batch 1004205 EPA 3051A Soil
Matrix Spike (1804205-10505) Preparied: 04/10/04 Analyzed: 04/19/04 19A47
QC Source: Sample ID 112.2.3.4.4 EPA 4000
Antimony    | 25.1   | 0.025 | 1.25             | mL   | 10   | 31.2         | ND           | 95   | 75%  |       |     |       |
| Arsenic     | 63.1   | 0.259 | 1.69             |       |      |              | 62.4         | 2.15 | 98   | *     |     |       |
| Barium      | 25.1   | 0.025 | 1.25             |       |      |              | 31.2         | 0.251| 92   | *     |     |       |
| Cadmium     | 32.2   | 0.125 | 1.25             |       |      |              | 63.2         | 0.313| 96   | *     |     |       |
| Lead        | 70.0   | 0.125 | 1.25             |       |      |              | 16.7         | 55   | *    |       |     |       |
| Selenium    | 33.8   | 0.010 | 2.49             |       |      |              | 31.2         | ND   | 96   |       |     |       |
| Silver      | 21.0   | 0.125 | 1.25             |       |      |              | 9.12          | ND   | 93   |       |     |       |
| Thallium    | 27.3   | 0.125 | 1.25             |       |      |              | 0.201         | 87   |       |       |     |       |

Matrix Spike (1804205-10505) Preparied: 04/10/04 Analyzed: 04/19/04 19A41
QC Source: Sample ID 112.2.3.4.4 EPA 4000
Antimony    | 21.8   | 0.100 | 1.00             | mL   | 10   | 25.1         | 0.100         | 96   | 75%  |       |     |       |
| Arsenic     | 41.8   | 0.010 | 2.01             |       |      |              | 50.1         | 3.10 | 95   |        |     |       |
| Barium      | 26.1   | 0.010 | 1.00             |       |      |              | 25.1         | 0.393| 95   |        |     |       |
| Cadmium     | 46.4   | 0.010 | 1.00             |       |      |              | 50.1         | ND   | 96   |        |     |       |
| Lead        | 56.6   | 0.100 | 1.00             |       |      |              | 10.5         | 92   | *    |        |     |       |
| Selenium    | 22.2   | 0.010 | 2.01             |       |      |              | 25.1         | ND   | 89   |        |     |       |
| Silver      | 23.7   | 0.100 | 1.50             |       |      |              | ND           | 95   | *    |        |     |       |
| Thallium    | 22.7   | 0.100 | 1.50             |       |      |              | 0.141         | 90   | *    |        |     |       |

Apex Laboratories

The results in this report apply to the samples analyzed in accordance with the state of the practice for environmental monitoring. Any analytical results are subject to error.
## QUALITY CONTROL (QC) SAMPLE RESULTS

### Total Metals by EPA 6020 (ICP-MS)

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**Batch 10/19/18 - EPA 6051A**  
Soil

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**CS-1105-07-1SA**  
Prepared: 04/26/2018  
Analyzed: 04/26/2018  
RSD 4.9%

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Prepared: 04/26/2018  
Analyzed: 04/26/2018  
RSD 4.9%

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**QC Source Sample 1C99A1 (180486-19)**

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Apex Laboratories  
The results in this report apply to the samples analyzed in accordance with the limits of

Philip Neumann  
For Darwyn Thomas, Business Development Director

Page 21 of 30
QUALITY CONTROL (QC) SAMPLE RESULTS

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Matrix Spike (100-693-555)  

QC Source 6: L1167  (6.1009/7-39)

The results in this report apply to the samples analyzed in accordance with the chain of custody documents. The analytical report must be reproduced in its entirety.

Philip Nemesh, For Darwin Thomas, Business Development Director
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The results in this report are the samples analyzed in accordance with the limits of customary practice. This analysis report cannot be reproduced in its entirety.
### QUALITY CONTROL (QC) SAMPLE RESULTS

#### Percent Dry Weight by D2216

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Apex Laboratories

The results in this report apply to the samples analyzed in accordance with the stated of analysis. The analysis results are reported to one decimal.

Philip Neuberg, For Damaro Thomas, Business Development Director
## SAMPLE PREPARATION INFORMATION

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The results in this report only on the samples collected in accordance with the data of the sample document. This analytical report shall be reproduced in its entirety.

Philip Neuman, For Darwin Thomas, Business Development Director
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*Note: The results in this report apply to the samples analyzed in accordance with the claims of the report document. The analytical report must be reproduced in its entirety.*
Thursday, May 13, 2010

Neil Morton
GeoEngineers - Seattle
600 Stewart St. Suite 1700
Seattle, WA 98101

RE: Oregon Metals Evaluation As/2727-069-00

Enclosed are the results of analyses for work order #100077, which was received by the laboratory on 4/2/2010 at 3:35:00PM.

Thank you for using Apex Labs. We appreciate your business and strive to provide the highest quality services to the environmental industry.

If you have any questions concerning this report or the services we offer, please feel free to contact me by email at: pmorton@apex-labs.com, or by phone at 503-718-2323.

Philip Morton
GeoEngineers, Business Development Director
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QUALITY CONTROL (QC) SAMPLE RESULTS

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Apex Laboratories

The results in this report apply to the samples analyzed in accordance with the chain of custody document. This analytical report must be reproduced in its entirety.

Philip Neumann, For Darren Thomas, Business Development Director
QUALITY CONTROL (QC) SAMPLE RESULTS

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The results in this report apply to the samples analyzed in accordance with the details of the study document. This analytical report may be reproduced in its entirety.

Philip Newberg
For Darwin Thomas, Business Development Director
# QUALITY CONTROL (QC) SAMPLE RESULTS

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The results in this report apply to the samples analyzed in accordance with the criteria of this standard. This analysis has been performed to the standards outlined in this analysis.

Philip Neumeier, Business Development Director
## QUALITY CONTROL (QC) SAMPLE RESULTS

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Apex Laboratories

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Duplicate (300-2232-DUPE)
Prepared: 04/28/10 09:49
Analyzed: 04/29/10 09:18

QC Sample: L1012 (A100877-02)
22326

Apex Laboratories

Philip Neuberg, For Danwin Thomas, Business Development Director
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Apex Laboratories

The results in this report apply to the samples analyzed in accordance with the terms of the custody document. This analytical report may be reproduced in its entirety.

Philip Noremberg, For Damon Thomas, Business Development Director
## SAMPLE PREPARATION INFORMATION

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*Note: The results in this report apply to the samples analyzed in accordance with the outline of the sampling protocol. The data presented are meant to be representative of the samples.*
Thursday, May 27, 2010

Neil Morton
Geology
15055 SW Sequoia Pkwy, #140
Portland, OR 97224

R.E. Oregon Metals Evaluation / 002787-06000

Enclosed are the results of analyses for work order ALOE125, which was received by the laboratory on 5/13/2010 at 2:05:00PM.

Thank you for using Apex Labs. We appreciate your business and strive to provide the highest quality services to the environmental industry.

If you have any questions concerning this report or the services we offer, please feel free to contact me by email at: ADineen@Apex-Labs.com, or by phone at 503-719-2323.
## ANALYTICAL REPORT FOR SAMPLES

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QUALITY CONTROL (QC) SAMPLE RESULTS

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Batch 1005303, EPA 3051A

Soil

Prepared: 05/19/12 12:14  Analyzed: 05/29/12 16:02

**EPA 0610**

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Allison Obermier For Devon Thomas, Business Development Director

Page 3 of 9
## QUALITY CONTROL (QC) SAMPLE RESULTS

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No Client related Batch QC’s samples analyzed for this batch. See notes page for more information.
## SAMPLE PREPARATION INFORMATION

### Total Metals by EPA 6020 (ICPMS)

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<th>Sample Initial/Final</th>
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The results in this report apply to the samples analyzed in accordance with the chain of custody document. This analysis report must be reproduced as is and not reproduced in its entirety.
Notes and Definitions

Qualifiers:

B Analyte detected in an associated blank at a level above the MRL. (See Notes and Conventions below)
H-01 This sample was analyzed outside the EPA recommended holding time.
H-06 This sample was received outside the EPA recommended holding time.
I External Result: Result detected below the lowest point of the calibration curve, but above the specified MQL.
Q-01 Percent recovery and/or RPD outside acceptance limits.
Q-25 Analytes not controlled on RPD values from sample or duplicate concentrations measured below the reporting level.

Notes and Conventions:

BET Analyte DETECTED
ND Analyte NOT DETECTED at or above the reporting limit
NR Not Reported
Sample results reported on dry weight basis. Results listed in "<" without "d" designation are not dry weight corrected.
RPD Relative Percent Difference
MQL If MQL is met, data has been evaluated to the Method Reporting Limit only.
WMTQC Water Monitoring Section Quality Control has been applied to Results and MRLs for volatile and semi volatile samples per EPA 8000C.
Batch QC Unless specifically requested, the report contains only results for Batch QC derived from client samples included in this report. All analyses were performed with the appropriate Batch QC (including 5 sample duplicates, Matrix 5 plus added Matrix 5 plus duplicates) in order to meet current method and regulatory requirements. Any exceptions to this will be qualified in this report. Complete Batch QC results are available upon request. In cases where there is no sufficient sample provided (i.e. sample duplicates and Matrix 5 plus, a Lab Control sample duplicates (LC5 Dup) is analyzed to demonstrate accuracy and precision of the extraction and analysis.
Batch QC Policy A sample represents blank data for potential high bias from a level equal to 5% the method reporting limit (MRL), except for conventional chemistry and ICP/MS analyses which are assessed only to the MQL. Sample results flagged with B or B-02 qualifier are potentially biased. High if they are less than ten times the level found in the blank for nonorganic analyses.
For accurate comparison of results to the level found in the blank, matrix sample ratios should be divided by the dilution factor and actual sample results should be divided by 100 of the sample dilution to account for the sample prep factor.
Results qualified as reported above the MRL may include a potential high bias if associated with a B or B-02 qualified blank. B and B-02 qualifications are not applied to I qualified results reported below the MRL.

Apex Laboratories

Philip Neurenberg, For Darwin Thomas, Business Development Director

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