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Arsenic in the Soils of Northwest Oregon

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Arsenic in the Soils of Northwest Oregon

by

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ABSTRACT

One hundred and eighty-six soil samples from Northwest Oregon were tested for arsenic content. The highest values measured were 13.9 ppm in the A horizon (site C4) and 20.4 ppm in the B horizon (Site P4). Arsenic was not detected in 28 A horizon samples and 23 B horizon samples.

Data are grouped based on the age and rock type of underlying bedrock. Lithologic groups with six or more data points were compared statistically to ascertain if groups are distinct. Analysis of Variance (ANOVA) multiple comparison tests indicate that the arsenic content of the Marine Sediments and Sedimentary Rocks group samples is distinguishable from the Quaternary Basalts group in the A horizon and all other groups in the B horizon. Kruskal-Wallis multiple comparison tests indicate that the arsenic content of the Marine Sediments and Sedimentary Rocks group is distinguishable from the Quaternary Basalts, Quaternary/ Tertiary Sediments and Sedimentary Rocks and Volcanic Sediments groups in both the A and B soil horizons.

The ANOVA and Kruskal-Wallis tests compared A and B horizon data by lithologic group. The ANOVA shows the Marine Sediments and Sedimentary Rocks group in the A horizon is distinct from the Quaternary Basalts in the A and B horizon. The Kruskal-Wallis test yielded the same result. Per the ANOVA, the Marine Sediments and Sedimentary Rocks in the B horizon are distinct from all other tested groups. The Kruskal-Wallis test shows the Marine Sediments and Sedimentary Rocks group in the B

horizon as distinct from the Quaternary Basalts, Quaternary/ Tertiary Sediments, and Volcanic Sediments groups in the A and B horizon.

A K-means cluster analysis was used to group all available data independent of underlying bedrock. Three, four, and five group analyses were conducted, and the results of these tests were compared to the data grouped by underlying rock type. No correlation between the groups resulting from the K-means cluster analysis and groups based on underlying lithology was found.

This analysis supports the creation of a map distinguishing arsenic content in the soils above Marine Sediments and Sedimentary Rocks group units from arsenic content in all other tested lithologic groups. The mean and standard deviations of these groups (in ppm) are: A horizon: Marine Sediments (6.09 ±2.66); other groups (3.10 ±3.19); B horizon: Marine Sediments (10.26 ±4.65); other groups (3.13, ±2.52). This analysis indicates that geologic context must be taken into account when determining background levels of naturally occurring arsenic in soils.

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CHAPTER 1: INTRODUCTION

This study aims to further characterize the natural background level of arsenic in northwest Oregon soils, establish statistical connections between the measured arsenic content of the soil and the underlying bedrock, and explore other data trends in soil arsenic values when possible. The study area lies between the Columbia River in the north and the city of Eugene in the south. The Pacific Ocean defines the western boundary of the study area, with the city of Bend defining the eastern boundary (Figure 1). Understanding naturally occurring arsenic in the soils of the northwest quadrant of the state is particularly important from a public health standpoint, as this area is home to the majority of the state's population.

Oregon, along with many other states and government entities, regulates exposure to anthropogenic arsenic in soils. These levels are regulated by individual studies using risk-based concentrations (RBC's) and a default background concentration of arsenic (Oregon DEQ, 2002; 2009; 2010). The determination of background concentration levels and risk-based concentrations, as well as the enforcement of cleanup requirements, is the responsibility of the Oregon Department of Environmental Quality (Oregon DEQ, 2009; 2010). Risk-based concentration levels are derived from equations combining exposure assumptions with toxicity data. Remediation is mandated for public health purposes to ensure that anthropogenic arsenic contamination is diminished or eliminated.

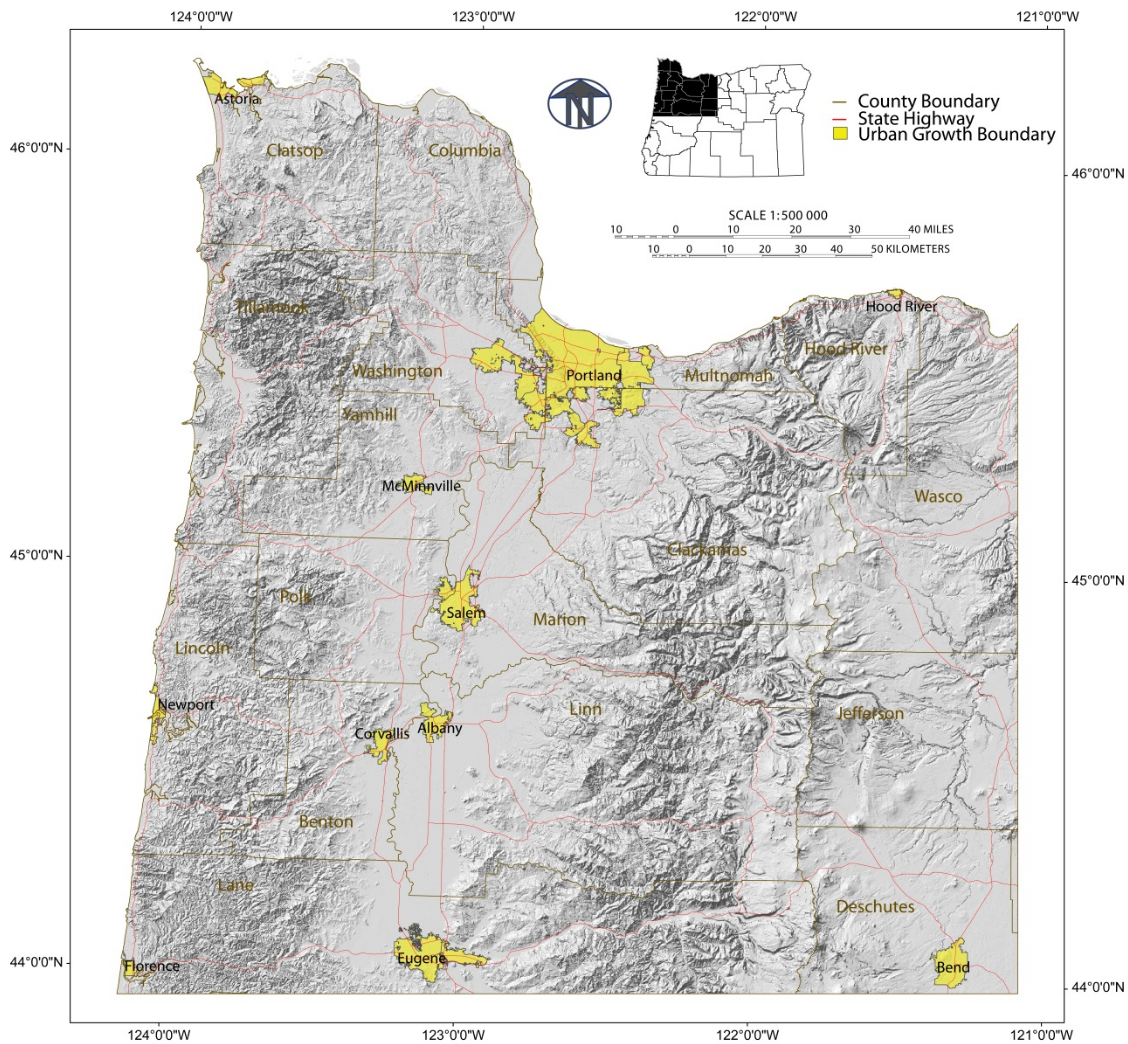


Figure 1: The study area is defined by the Pacific Ocean in the west, the city of Eugene in the south, the city of Bend in the east, and the Columbia River in the north.

Oregon differentiates risk based concentrations of arsenic by exposure pathway (water, soil, etc.) and exposure environment (residential, occupational, etc.) These RBC's are under 2 ppm for all circumstances excepting construction and excavation workers (Oregon DEQ, 2009). The default background concentration of arsenic in Oregon soils has been determined by the Oregon DEQ to be 7 mg/kg statewide (Oregon DEQ, 2002, 2010). This default background level is of primary interest to this study and is currently under evaluation and subject to change by the Oregon DEQ.

Three previous studies suggest that the amount of naturally occurring arsenic in the study area's soils may be higher than the 7 mg/kg default background level set by the Oregon DEQ (Ashbaugh, 1995; Boschmann, 2008; Ricker and Shepker, 2009; Oregon DEQ, 2002; 2010). Approximately 11% of soil samples collected for Ashbaugh's 1995 study and tested for arsenic by Boschmann (1998) had measurable levels of arsenic above the 20 ppm detection limit of the available test (Ricker and Schepker, 2009). This analysis raised significant questions, as it suggested the values the Oregon DEQ use to evaluate sites for the remediation of soil arsenic may be too low (Oregon DEQ, 2002, 2010). Fully understanding the natural background level of soil arsenic is critical to determining if the cleanup protocols currently being used by the Oregon DEQ are reasonable and effective. Without accurately describing this background level, there is a risk of allowing too much anthropogenic arsenic in the environment, a significant health risk. A lack of understanding in this area also risks the cleanup requirements being too stringent, legally mandating that landowners remediate large amounts of naturally occurring arsenic and creating economic hardship. For these reasons, a balanced and reasonable policy based on good scientific information and analysis is required.

AIMS AND OBJECTIVES:

Goal: Add to the knowledge background soil arsenic content in the northwest Oregon study area. The following steps were taken to attain this goal:

1. Obtained soil samples from above as many major geologic formations within the study area as possible. Soils were sampled pedologically by sampling from the surface A horizon and the underlying B horizon. Previous studies suggest arsenic levels are likely higher in the B horizon in well-developed soils (Burns et al., 1991).
    a. Samples collected for Ashbaugh's (1995) radionuclide study were tested for arsenic content (step 2).
    b. Used a geographic information system (GIS) to determine major formations in the study area from which samples were not previously obtained by Ashbaugh (1995) (Walker and MacLeod, 1991). The eight units which covered the largest area within the study area were chosen for additional sampling.
    c. Conducted additional field work to sample soils from above the formations identified through step 1b. Sampling procedures were modeled after those used by Ashbaugh (1995) for continuity.

2. Determined the arsenic content of the sampled soils (step 1). A commercial laboratory (Apex Laboratories) tested the soil samples for arsenic content using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Tests were run to Oregon DEQ and Environmental Protection Agency (EPA) Standards.
3. Produced a database of soil arsenic values including measured A and B horizon arsenic values in parts per million, location of sampling, and underlying geologic unit per Walker and MacLeod (1991).
4. Statistically analyzed the data for significant trends.
    a. Statistically evaluate data to determine connections between the measured level of arsenic in soils above similar rock types
    b. Statistically evaluate the data to determine connections between the measured arsenic level of soils in the A and B horizon.
5. Mapped the arsenic values using GIS in a scientifically appropriate manner based on the conducted statistical analysis.

CHAPTER 2: BACKGROUND

2.1: ARSENIC AND HUMAN HEALTH

It is well documented that a variety of human health problems are linked to arsenic exposure. Health problems associated with arsenic exposure include vascular diseases such as blackfoot disease and high blood pressure (IPCS, 2001). Diabetes and forms of nerve damage have been linked to long term arsenic exposure (IPCS, 2001). Arsenic has also been linked to severe reproductive problems such as low birth weight, stillbirth, and birth defects (IPCS, 2001). Acute arsenic exposure has been known to result in death.

Arsenic is a known carcinogen. Although the exact method by which arsenic exposure causes cancer is not clearly known, Hughes (2002) discusses possible mechanisms. These include protein inhibition, promotion of tumor growth, and the deletion of genetic material resulting in mutations (Hughes, 2002). Arsenic may impede levels of oxygen in the body, diminishing a damaged cell's healing capability (Hughes, 2002). Arsenic is primarily connected to lung, bladder, kidney, and skin cancers (IPCS, 2001).

2.2: DEFAULT BACKGROUND CONCENTRATIONS AND RISK BASED CONCENTRATIONS

Due to the severe negative human health effects associated with arsenic exposure, many government institutions regulate arsenic exposure from soils and water. In the United States, these regulations are typically determined by the individual states. An overview of action levels for arsenic throughout the United States and internationally is compiled in Appendix A: Overview U.S. and International Arsenic Cleanup Levels. These levels are commonly determined by the exposure levels that are believed to cause significant health risks.

The United States Environmental Protection Agency (EPA) has set Regional Screening Levels (RSLs) (formerly referred to as Preliminary Remediation Goals, or PRG's). These are risk-based levels that combine what is known about how the contaminant interacts with the human body to what is known about the contaminant's toxicity (EPA, 2012). These values are used for prioritizing contaminated sites for cleanup, setting RBC's, identifying when a cleanup is required, and determining the desired level of cleanup at a contaminated site along with other determinations. (EPA, 2012). The RSL for residential soil is .39 mg/kg and is 1.6 mg/kg for industrial soils (EPA, 2012).

In Oregon, the DEQ's Environmental Cleanup and Tanks program regulates environmental contaminants. The DEQ has published risk based concentrations (RBCs) for a variety of contaminants, including arsenic (Table 1). The DEQ distinguishes between arsenic content in soil and groundwater (Oregon DEQ, 2009).

Table 1: Oregon DEQ Risk Based Concentrations for Arsenic in Soils. These values are differentiated by the exposure pathway in which the arsenic is encountered: through skin contact, inhalation, or ingestion (Oregon DEQ, 2009).

Receptor Scenario	Soil Arsenic Content in Parts Per Million (PPM)
Residential	.39
Urban Residential	1.0
Occupational	1.7
Construction Worker	13
Excavation Worker	370

The Oregon DEQ has set the default background value of arsenic in soils statewide at 7 mg/kg (Oregon DEQ, 2002, 2010). This value is of primary interest to this study. It is currently subject to change and has recently been under evaluation. Per the Oregon DEQ (2006), “Contaminants found above background levels are compared to [the EPA’s RSLs] and DEQ’s risk-based concentrations (RBCs) to evaluate whether these contaminants pose unacceptable risks to current or future site users, construction and/or excavation works, or surrounding properties.” Because these risk-based values are compared with background levels to determine cleanup requirements, a full understanding of the background level is required.

2.3: BACKGROUND STUDIES OF ARSENIC IN NORTHWEST OREGON SOILS

This project builds upon the thesis of Stuart Ashbaugh (1995), a Portland State University student who worked under Dr. Scott Burns. Ashbaugh collected soil samples from as many different bedrock formations as possible, per the geologic map of Oregon, as part of a radionuclide study (Ashbaugh, 1995; Walker and

MacLeod, 1991). Both A and B horizon samples were taken at each site. Sites were chosen in wooded areas that had no indication of significant anthropogenic contamination (Ashbaugh, 1995). The arsenic values resulting from these samples are therefore expected to reflect the background arsenic content of these soils.

Darek Boschmann (2008), also a Portland State University student, tested 170 of the samples collected by Ashbaugh (1995) for arsenic content. The analytical test method used in Boschmann's study detected soil arsenic levels above 20 ppm. Nineteen of the 170 samples (11%) measured arsenic above the 20 ppm minimum detection limit. These 19 samples were collected at 13 sites and measured arsenic between 21.2 and 167 ppm. Seven of the 19 samples were B horizon soils, with the remaining 12 samples being A horizon samples. The samples tested for Boschmann's (2008) study were retested for arsenic content as part of this study, and these new values were used in favor of the values tested by Boschmann (2008). Nonetheless, Boschmann's (2008) work is critical to the inception of this project. The number of samples in Boschmann's (2008) study containing arsenic above the 20 ppm detection limit of the test used raised significant questions about the level of background arsenic in the soils within this project's study area.

Ricker and Shepker (2009) reevaluated the arsenic data generated by Boschmann (2008) from the samples collected by Ashbaugh (1995). The 2009 study by Ricker and Shepker was conducted as part of a graduate level Environmental Geology course taught by Dr. Burns and utilized a significant Geographic Information Systems (GIS) component. The study's primary premise, based on background literature, was that the level of naturally occurring arsenic in a soil is closely related to the lithology of underlying bedrock (Yan-Chu, 1994; Naidu and Bhattacharya, 2006). Based on this knowledge, a map was made highlighting geologic units whose overlying soils tested above 20 ppm arsenic. This was done making the underlying assumption that additional soils in these areas would have similarly high levels of arsenic. In doing this, Ricker and Schepker determined areas within Oregon that were at risk for having naturally occurring soil arsenic levels in excess of 20 ppm. The Ricker and Schepker (2009) study found that the bedrock underneath the samples that contained arsenic in excess of 20 ppm covered 35% of Oregon's total area.

2.4: ARSENIC IN THE ENVIRONMENT

To understand the levels of arsenic found in the soils tested for this study, it is necessary to understand how arsenic functions in the natural environment. This understanding requires ascertaining the original source of natural arsenic in soils. Natural arsenic content of soils is believed to be linked to the arsenic content of underlying bedrock, therefore the arsenic content of bedrock is discussed in detail (Yan-Chu, 1994; Naidu and Bhattacharya, 2006). How arsenic behaves once it is in the soil is also relevant and is therefore discussed here.

2.4.1. ORIGIN OF ENVIRONMENTAL ARSENIC

2.4.1.1. SOURCE OF ARSENIC AND ASSOCIATED MINERALOGY

Arsenic content of rocks is closely connected to mineralogy. Arsenic is primarily linked with sulfide minerals and iron oxides, and rocks that contain these minerals in significant quantities generally contain the largest amounts of arsenic (Boyle and Jonasson, 1973). The correlation between iron and arsenic suggests that the highest amounts of soil arsenic are typically found in the reddest soils. These are usually B horizon soils where elements such as iron and arsenic have collected over time through leaching processes due to moisture and weathering processes (Birkeland, 1999; Burns et al., 1991). Some studies, particularly in the Bengal Basin of India, suggest a correlation between the weathering of micas and high arsenic levels (Dowling et al., 2002). Realgar (AsS), orpiment (As_2S_3) and arsenopyrite (FeAsS) are three common examples of arsenic bearing sulfides (Manning and Goldberg, 1997). Arsenopyrite is a particularly well known example and constitutes the primary arsenic bearing mineral found in the environment (Boyle and Jonasson, 1973; Francesconi and Kuehnelt, 2002).

2.4.1.2. ARSENIC CONTENT OF ROCKS

Arsenic content of rocks can be generalized in terms of lithology (Onishi and Sandell, 1955; Boyle and Jonasson, 1973; Tanaka, 1988). Although there is some variability in the arsenic content found in different types of igneous lithologies, these values are typically very close to each other and tend to be comparatively low (Onishi and Sandell, 1955; Boyle and Johnasson, 1973). Sedimentary rocks tend to have higher arsenic levels compared to igneous rocks (Tanaka, 1988). Some sedimentary processes allow for increased arsenic content, and some minerals that are conducive to high arsenic content are found primarily in sedimentary rocks (Boyle and Jonasson, 1973; Tanaka, 1988). Data on arsenic content in metamorphic rocks suggests that arsenic content in the daughter rock is correlated with the arsenic content of the parent rock (Tanaka, 1988). In some cases, metamorphic processes are believed to decrease the amount of arsenic in the rock (Onishi, 1970). The decrease of arsenic during the metamorphism of slates and graywackes is one example, as well as the leaching of arsenic out of sedimentary rocks that contain hematite (Onishi, 1970).

Data published in Onishi and Sandell (1955), Boyle and Jonasson (1973), and Tanaka (1988) connecting lithology to arsenic content is reprinted verbatim in Appendix B: Overview of Arsenic Content by Rock. The presentation of this table is based on Tanaka (1988) because it is a synthesis of data from both previous works. This presentation also includes the number of samples, average arsenic content and range of each group (Tanaka, 1988). More recent data published by Mandal and Suzuki (2002) is also presented (Appendix B: Overview of Arsenic Content by Rock). These data are presented as ranges of arsenic content and do not include averages (Mandal and Suzuki, 2002). Because more detailed information about the groups is unavailable, these data are included as additional information only and are not used further in this discussion.

The presented data on arsenic in igneous rocks are differentiated by composition and texture (Tanaka, 1988; Appendix B: Overview of Arsenic Content by Rock). These data support the assertion that the arsenic content of igneous rocks is fairly similar when these data are grouped by composition and texture (Appendix B: Overview of Arsenic Content by Rock). The average arsenic content of each group of igneous rock samples is relatively low. The highest of these averages is 4.3 mg/kg, with many of the averages in the 1 to 2 mg/kg range. The extrusive rocks of each composition have a higher average arsenic content than their intrusive counterparts, with the exception of Onishi and Sandell's (1955) mafic data. Here, both the intrusive and extrusive rock samples have the same average arsenic content (Onishi and Sandell, 1955; Appendix B: Overview of Arsenic Content by Rock).

The data on sedimentary rocks and arsenic content support that sedimentary rocks have generally higher average amounts of arsenic than igneous and metamorphic rocks (Appendix B: Overview of Arsenic Content by Rock). The average arsenic content for these groups ranges between and 2.3 mg/kg (Onishi and Sandell's 1955 clastic rocks group) and 33.7 mg/kg (Boyle and Jonasson's 1973 ocean sediments group)(Appendix B: Overview of Arsenic Content by Rock). Relatively high levels of arsenic tested in the recent sedimentary rock groups, iron-bearing rock group, and phosphates are unsurprising based on the correlation between arsenic and oxide and phosphate minerals (Boyle and Jonasson, 1973).

The metamorphic rock data describe the arsenic levels of these rocks differentiated by mode of metamorphism (Appendix B: Overview of Arsenic Content by Rock). These data do not support large decreases of arsenic in metamorphic rocks, and in fact, many metamorphic rocks tested contain significant amounts of arsenic (Appendix B: Overview of Arsenic Content by Rock). The lowest average value of arsenic in metamorphic rocks, 1.1 mg/kg for the schists tested by Boyle and Jonasson (1973), is similar to the low arsenic averages of igneous rock groups. Boyle and Jonasson (1973) tested the highest average arsenic content for metamorphic rocks; their slate and phyllite group averages 18.1 mg/kg arsenic (Appendix B: Overview of Arsenic Content by Rock).

2.4.2. ARSENIC BEHAVIOR IN SOILS

Once arsenic enters the soil environment, it takes one of four paths (McLaren et al., 2006): 1) Arsenic is leached into groundwater from both bedrock and soils. 2) Arsenic is taken in by plants as they intake water. 3) Arsenic can be removed from soils through other biological processes besides plant uptake. When this happens, the arsenic is typically volatized into the atmosphere. 4) Arsenic can also be adsorbed into the soil. It is this final pathway that is of particular interest in this study.

Arsenic in the soil environment is typically found in one of two oxidation states. Trivalent arsenite (AsIII), and pentavalent arsenate (AsV), are known to behave differently in soils depending on environmental factors. The oxidation state of arsenic found in soils is largely determined by the redox state of the soil environment (Manning and Goldberg, 1997). In oxidizing conditions, arsenate is prevalent primarily as $H_2AsO_4^-$, $HAsO_4^{2-}$, or AsO_4^{3-} (Sadiq, 1995; Manning and Goldberg, 1997; Mandal and Suzuki, 2002). In reducing conditions, arsenite is prevalent in the form of $H_3AsO_3^0$, $H_2As0_3^-$ or $HAsO_3^{2-}$ (Manning and Goldberg, 1997; Mandal and Suzuki, 2002). A common chemical reaction by which arsenic acid (an oxidizing agent) is reduced to arsenous acid is:

$$H_3As^{V}O_4 + 2H^+ + 2e^- \leftrightarrow H_3As^{III}O_3 + H_2O$$

(Naidu and Bhattacharya, 2006)

Arsenite is known to be more mobile through the soil environment than arsenate, as well as more toxic to human health (Mandal and Suzuki, 2002; Naudu and Bhattcharya, 2006). At pH levels common in natural waters, arsenite tends to exhibit a neutral charge, while arsenate exhibits a negative charge (Manning and Goldberg, 1997). This difference in surface charge at common environmental pH's is believed responsible for arsenite's mobility and toxicity. Because of its lack of charge, arsenite adsorbs less readily onto soils as compared to arsenate and is therefore more mobile and more toxic (Manning and Goldberg, 1997).

Arsenic amounts measured in soils are heavily dependent on how much arsenic attaches, or adsorbs, onto soil particles. Smith et al. (1999) studied the adsorption of arsenic into soils and found that, at various pH levels, more arsenate was generally adsorbed into soils than arsenite. Iron oxides are a primary class of minerals that readily adsorb both forms of arsenic (Smith et al., 1999). Aluminum hydroxide and phyllosilicates are known to encourage adsorption of arsenite

(Manning and Goldberg, 1997; Smith et al., 1999; Smith and Naidu, 2002). Other minerals that encourage adsorption of arsenic include manganese, alluminosillicates, phosphates, and ferrihydrite (Smith et al., 2002). The oxidation state of the arsenic, the pH of the soil environment, and the minerals available for the arsenic to adsorb onto are all factors which influence how much arsenic will adsorb into the soil. Arsenic adsorption onto iron oxides and aluminum oxides was studied by Goldberg (2002) and exhibit how the factors of pH, mineralogy and arsenic's oxidation state play a role in the adsorption of arsenic.

The adsorption of arsenite and arsenate onto iron oxides as illustrated by Goldberg (2002) is shown as Figure 2. Goldberg's (2002) study illustrates how in the presence of iron oxides, the amount of arsenate adsorbing onto iron oxides in the acidic and neutral environment is relatively stable. At approximately pH 8, significant amounts of the arsenate begin to desorb from the iron oxide. The amount of arsenite adsorbed onto the iron oxide does slightly increase with increasing pH, but overall, changes very little as pH changes according to this study.

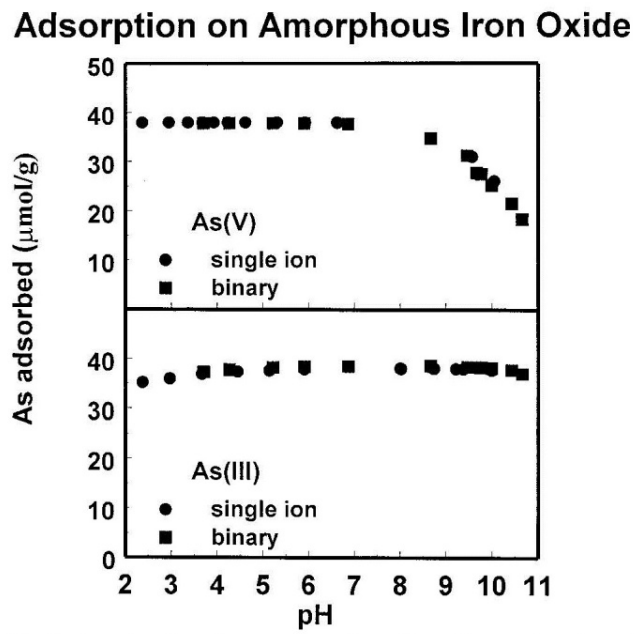


Figure 2: Goldberg (2002); Description verbatim: Arsenic adsorption on amorphous Fe oxide as a function of pH and As redox state: (a) arsenate; (b) arsenite.
Single ion systems: As_T = 20 µM. Binary systems: $As(III)_T$ = As(V)T = 20µM. Suspension density: 0.5 g L^{-1}.

The result of Goldberg's (2002) study of arsenic adsorption onto aluminum oxides is shown as Figure 3. Similar to arsenic adsorption onto iron oxides, the amount of arsenate adsorbed onto aluminum oxides drops off when the pH of the environment becomes basic. In this case, this drop in amount of adsorbed arsenate begins at a pH of approximately 9.5 and continues as pH rises. Unlike the adsorption of arsenite onto iron oxides, the adsorption of arsenite onto aluminum oxides was found to vary significantly with pH (Goldberg, 2002). Goldberg's (2002) results show very low amounts of arsenite adsorbing onto the aluminum oxide when the environment is acidic (pH 4 and below). The amount of arsenite adsorbing onto the aluminum oxide begins to rise at this pH and peaks at approximately pH 8. A significant decrease in the amount of arsenic adsorbed onto the aluminum oxide is noted from this point as pH continues to rise.

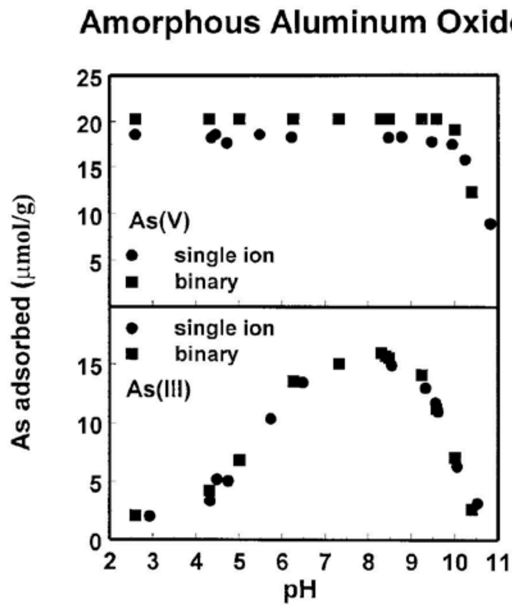


Figure 3: Goldberg (2002); Description verbatim: Arsenic adsorption on amorphous Al oxide as a function of pH and As redox state: (a) arsenate; (b) arsenite.
Single ion systems: As_T = 20 µM. Binary systems: $As(III)_T$ = As(V)T = 20µM.
Suspension density: 0.5 g L^{-1}.

In addition to pH playing a role in arsenic adsorption, the oxidation/reduction state of the environment plays a role in how arsenic functions in the natural environment. As previously stated, the REDOX state of the environment primarily affects the oxidation state of the arsenic present. An Eh-pH diagram depicting stable forms of arsenic in the presence of sulfur as pH (x-axis) and oxidation potential (Eh) (y-axis) change is shown as Figure 4. For oxidation potential values, positive values indicate an oxidizing environment, with negative numbers representing a reducing environment (Krauskopf and Bird, 1995; Misra, 2012). Figure 4 illustrates how these two factors of oxidation potential and pH together affect which arsenic compounds are found in the natural environment.

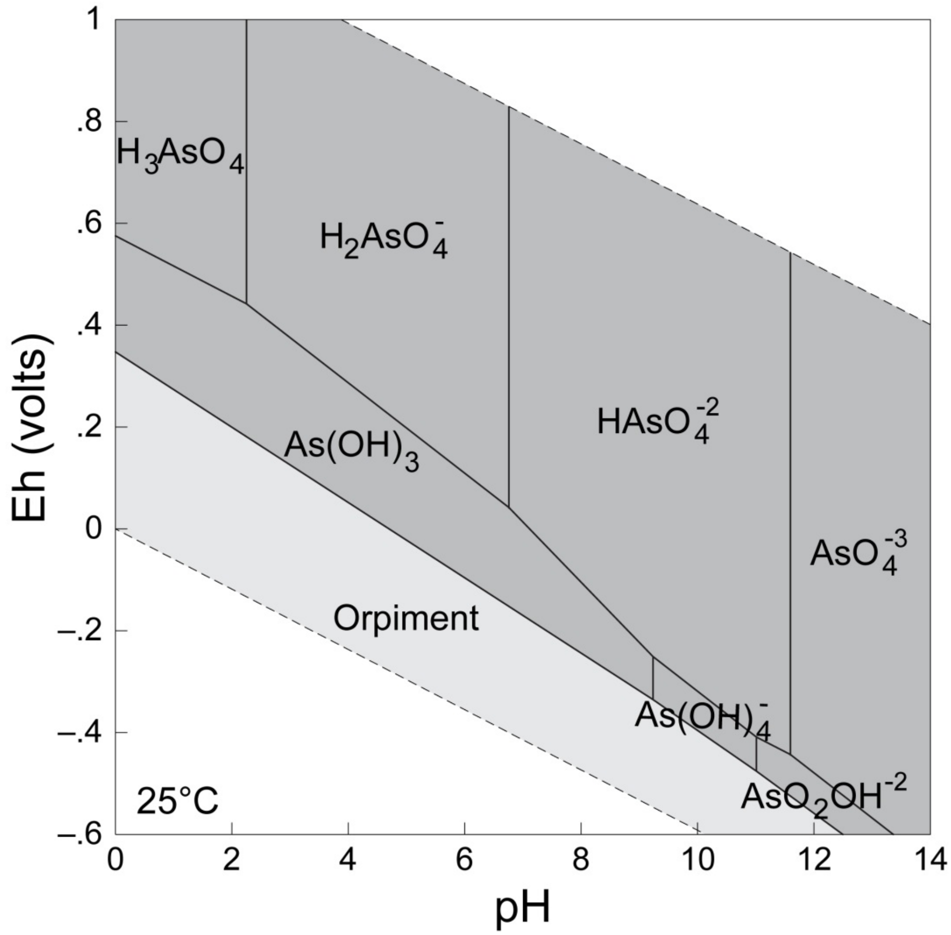


Figure 4: Generalized Eh-pH diagram for arsenic in the presence of sulfur at 25C and 1 atm pressure. Assumes activity of As = 10^-6 and activity of S = 10^-3. Note that the realgar mineral field is suppressed.

CHAPTER 3: SITE ENVIRONMENT

3.1: GENERAL GEOLOGY

The geologic history of the study area as reported here relies heavily on Orr and Orr's (1999) work. Unless otherwise noted, the following text was liberally extracted from their work. In this section, the general tectonic history of the project's study area is discussed, followed by a description of the geology found in each of the three physiographic provinces in the study area (Figure 5). Detailed descriptions of the major geologic units in the study area are included in Appendix I: Descriptions of Lithology by Lithologic Group.

The study area ranges from 43.95° through 46.25° north latitude and 124.15° through 121.1° west longitude (Figure 1). The study area covers three physiographic provinces in Oregon, the Coast Range, the Willamette Valley, and the Cascade Mountains (Figure 5). The climate of the study area is defined by proximity to the Pacific Ocean (Ashbaugh, 1995). Winters throughout the study area are primarily cool and wet, while summers are short, dry and warm.

3.1.1: GEOLOGIC HISTORY OF OREGON

The geology of the study area is heavily characterized by volcanic events beginning in the early Eocene (approximately 44 Ma) (Orr and Orr, 1999). The subduction of the offshore Farallon Plate underneath the North American Plate is responsible for the onset of this significant period of volcanism (Orr and Orr, 1999).

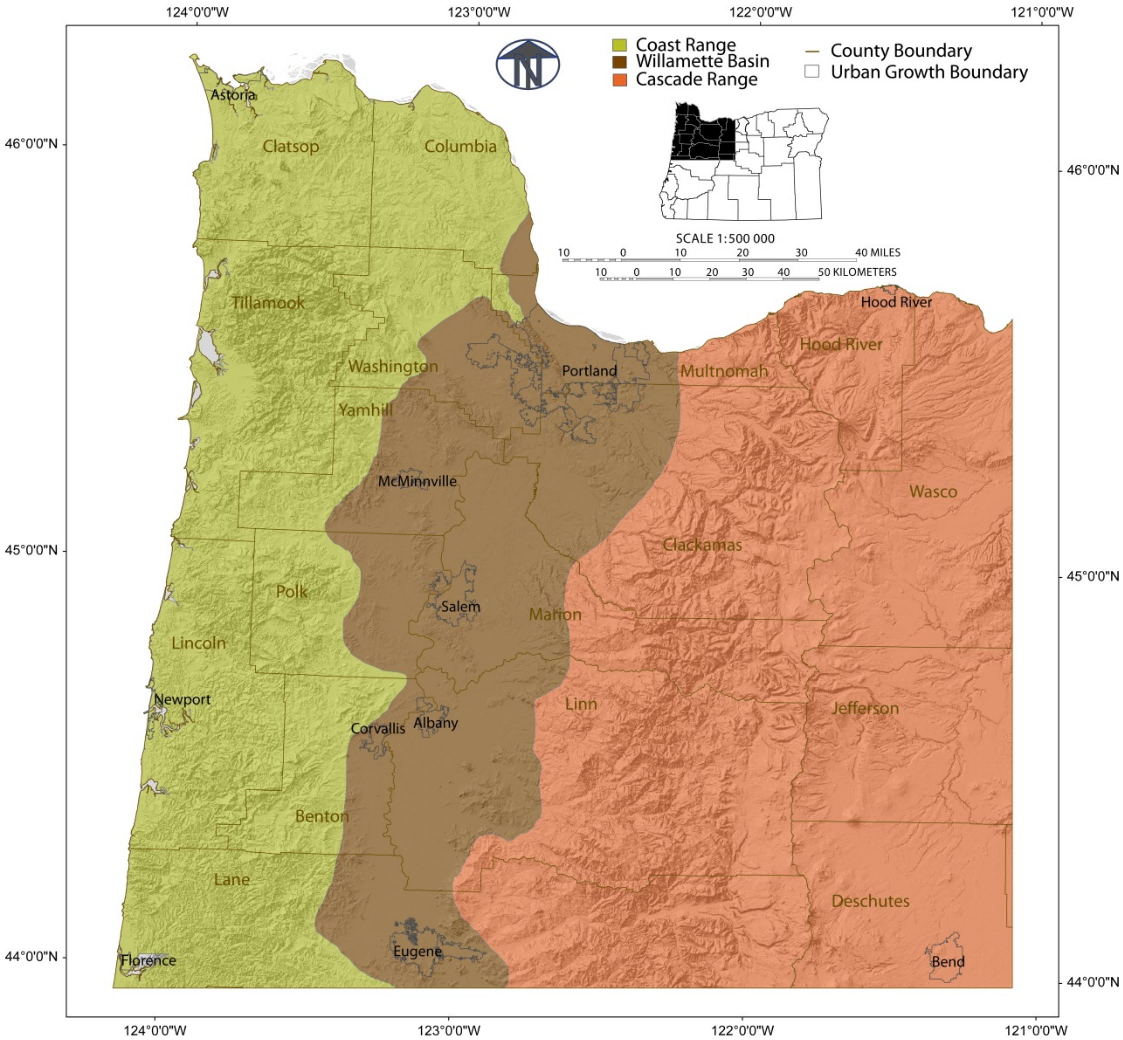


Figure 5: The physiographic provinces of northwest Oregon (NASA 2012)

As evidenced by an unconformity between 38 and 35 Ma, this Cascade volcanism stopped at this time and subsidence occurred in the study area (Orr and Orr, 1999). This subsidence allowed for the creation of offshore basins just off the coast approximately 37 Ma. These basins are associated with the deposition of basalts, basaltic sandstones and conglomerates (Orr and Orr, 1999).

A long period of volcanism began at approximately 35 Ma and continued through the early Miocene until approximately 20 Ma (Orr and Orr, 1999). Eruption of silicic volcanics, including ash flows, tuffs, and lavas, was common throughout the study area during this period. Deposition of felsic siltstones and sandstones is also noted during this period (Wells et al., 1983; Orr and Orr, 1999). felsic siltstones and sandstones (Orr and Orr, 1999).

Between 16.5 and 9 Ma, regional uplift throughout the study area occurred and coincided with the eruption of the Columbia River basalt flows throughout northeastern Oregon, eastern Washington, and western Idaho (Orr and Orr, 1999). These basalts cover a significant portion of the study area (Orr and Orr, 1999).

In the last 4.6 Ma, the study area has seen periods of volcanism and glaciation. Extensional tectonics and faulting are associated with this volcanism (Orr and Orr, 1999). The Willamette Basin was covered by Missoula Flood sediments between 18,000-15,000 calendar years B.P. (Allen et al., 2009).

3.1.2: THE COAST RANGE

3.1.2.1: COAST RANGE GEOGRAPHY

The Coast Range Province extends from the Pacific Ocean through approximately 123.2° west longitude (Figure 5). The Coast Range also includes the offshore continental shelf, continental slope, and offshore subduction zone (Orr and Orr, 1999). The Coast Range province is characterized by a series of coastal mountains with a maximum elevation just over 1000 meters in the east and typical coastal features such as dune fields, estuaries, sand spits and bays in the west (Orr and Orr, 1999).

Because the climate is heavily influenced by the Pacific Ocean, this province is known to have the most temperate climate in Oregon including the warmest average winter temperatures, the coolest average summer temperatures, and the largest rainfall values in the state (Orr and Orr, 1999).

3.1.2.2: COAST RANGE GEOLOGY

The stratigraphy of the Coast Range province, as illustrated by Orr and Orr (1999) is reprinted here as Figure 6. This stratigraphic column is drawn for three Coast Range areas: Coos Bay, the Central Coast Range, and Columbia County. The Columbia County column is referred to as the northern Coast Range for this discussion. The Central Coast Range and Columbia County portions of this stratigraphic column are of interest to this study and should be consulted for this discussion.

Marine volcanics and marine sedimentary rocks were deposited in the central and northern Coast Range province throughout the Eocene. The oldest volcanic rocks in the central and northern Coast Range stratigraphy are the lower Eocene Siletz River Volcanics (Figure 6). This volcanism is the result of the Farallon plate subducting under the North American plate (Orr and Orr, 1999). The pillow structures found in these basalts are indicative of eruption in a marine environment (Walker and MacLeod, 1991).

The overlying Eocene marine stratigraphic sequence in the central Coast Range continues with the Yamhill, Nestucca, and Yachats formations. Marine silts and muds characterize the Yamhill Formation (Orr and Orr, 1999). The Nestucca Formation, composed of mud, sand, and siltstones, indicates a deeper ocean environment in the late Eocene central Coast Range (Orr and Orr, 1999). The Nestucca Formation muds are interspersed with the marine Yachats basalts (Orr and Orr, 1999). The Eocene marine environment evident in the Central Coast Range predictably dominates the northern Coast Range Eocene stratigraphic sequence as well. The Cowlitz Formation, shallow sea conglomerates, sands and shales, are evidence of this marine environment (Orr and Orr, 1999).

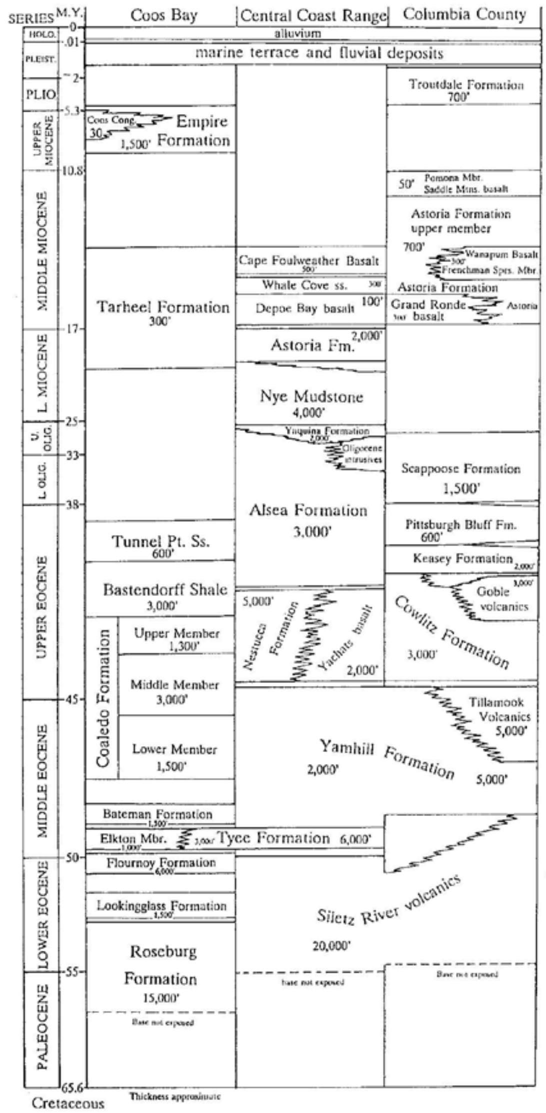


Figure 6: The stratigraphy of the Coast Range.
After Orr and Orr, 1999

As the Eocene ended and Oligocene commenced, a marine environment continued to predominate in both the central and northern Coast Range. In the central Coast Range, this time period is characterized by the deposition of the Alsea and Yaquina formations (Orr and Orr, 1999). Both of these formations are composed of marine silts and sands with layers of volcanic ash (Orr and Orr, 1999).

During the Oligocene, the northern Coast Range stratigraphic column also indicates a marine environment. The Pittsburg Bluff Formation tuffaceous sands and the arkosic Scappoose Formation deposited during this period are both shallow sea formations (Orr and Orr, 1999). The sediments comprising the Scappoose Formation have been linked to the eroding Idaho batholith by the presence of white mica (Orr and Orr, 1999).

The lower Miocene Nye mudstones of the central Coast Range are comprised of silt and mud and contain microfossils characteristic of the marine environment (Orr and Orr, 1999). The subsequent deposition of the Astoria Formation, composed primarily of sandstones and siltstones, is seen in the upper Miocene in the Central Coast Range and the middle Miocene in the northern Coast Range (Orr and Orr, 1999). The Astoria Formation is known for containing fossils characteristic of the marine environment, including mollusks, corals and brachiopods (Orr and Orr, 1999).

During the middle Miocene, the Columbia River basalts, one of the largest lava flows seen on Earth, engulfed the central Coast Range. These lava flows include the Depoe Bay Basalts, Cape Foulweather Basalts, and Grande Ronde Basalts as show in Figure 6 (Orr and Orr, 1999).

In the northern Coast Range, the Pliocene includes the deposition of thick Troutdale Formation gravels (Orr and Orr, 1999). This formation is indicative of a terrestrial environment, and these sediments were deposited when the Columbia River and other nearby rivers moved significant amounts of gravel into the Portland area (Trimble, 1963).

3.1.3: THE WILLAMETTE VALLEY

3.1.3.1: WILLAMETTE VALLEY GEOGRAPHY

The Willamette Valley is a structural trough that has been and is still being altered by erosion and sedimentation. The valley trends from north to south and extends from approximately 123.2° through 122.6° west longitude. It is approximately 160 km long and 60 km wide (Orr and Orr, 1999). The southern end of the valley lies at approximately 122 meters above sea level (Orr and Orr, 1999). The elevation of the basin steadily decreases northward, and the Portland area lies at sea level (Orr and Orr, 1999). Oregon's largest cities, Portland and Salem, and 70 percent of the state's population reside in this province (Orr and Orr, 1999).

Low rolling hills and alluvial flats are characteristic of this province (Orr and Orr, 1999). The northern part of the valley is hilly, with the Eola, Ankeny, and Waldo hills in the Salem area and the Tualatin and Chehalem Mountains in the Portland area (Orr and Orr, 1999). The Willamette River flows north throughout the length of the valley to its confluence with the Columbia River. The Clackamas, Sandy, and Tualatin rivers are major tributaries of the Willamette River.

3.1.3.2: WILLAMETTE VALLEY GEOLOGY

Figure 7 illustrates the stratigraphy of the Willamette Valley per Orr and Orr (1999) and should be consulted for the discussion below. The stratigraphy of the valley is illustrated at three places: in Eugene (the southern Willamette Valley), Sheridan and McMinnville (the central Willamette Valley), and Oregon City and Molalla (the northern Willamette Valley).

In the Willamette Valley, as in the Coast Range, the earliest rocks noted are the Siletz River Volcanics (Orr and Orr, 1999). Some Eocene marine environment formations noted in the Coast Range Province are also seen in the Willamette Valley. These include the middle Eocene Yamhill and late Eocene Nestucca formations in the central portion of the Willamette Valley.

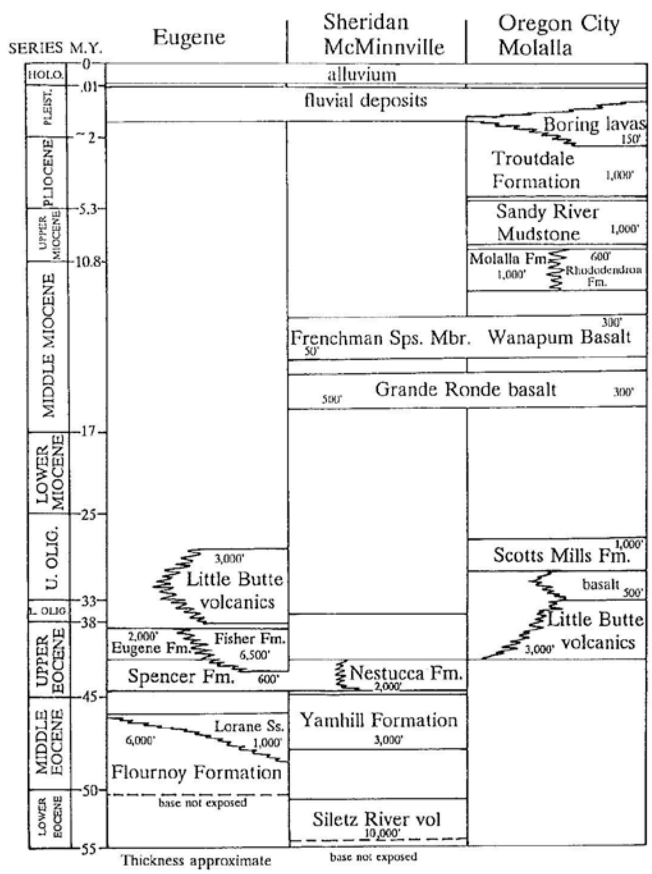


Figure 7: The stratigraphy of the Willamette Basin.
After Orr and Orr, 1999

During the Eocene, the Klamath Mountains and Idaho batholith eroded and subsidence resulted in the creation of the trough shape that defines this physiographic province. The thick sandstones of the middle Eocene Flournoy and Lorane formations were deposited in the southern Willamette Basin during this time (Orr and Orr, 1999). These formations are marine in origin as evidenced by their rhythmic bedding and microfossils (Orr and Orr, 1999).

Subsequently, in the southern part of the basin, the shallow marine sediments of the Spencer Formation were deposited (Orr and Orr, 1999). These were followed by deposition of the tuffs and conglomerates of the Fisher Formation and siltstones and sandstones of the Eugene Formation in the upper Eocene (Orr and Orr, 1999). The Fisher Formation contains fossils indicating a warm, wet, nearshore climate. Aquifers in both the Fisher and Eugene Formations have a known association with high levels of arsenic (Hinkle and Polette, 1999).

In the northern portion of the Willamette Valley, the stratigraphic sequence begins with the volcanic rocks of the Little Butte Volcanic Series in the upper Eocene and lower Oligocene (Orr and Orr, 1999). These were locally covered by the upper Oligocene Scotts Mill Formation's marine sediments and coals (Orr and Orr, 1999).

Plate tectonics resulted in the tilting of these Scotts Mill Formation sediments, along with a significant gap in deposition during the upper Oligocene and lower Miocene, (Orr and Orr, 1999). This hiatus of deposition ended during the middle Miocene when extensional tectonics resulted in the eruption of the Columbia River flood basalts in Eastern Oregon. The middle Miocene Grand Ronde basalts in the central and north Valley represents the onset of this volcanism, along with the overlying Wanapum Basalts and Frenchman Springs Member (Orr and Orr, 1999). In the northern Willamette Valley, the mudflows, clastics, and volcaniclastic sediments of the middle Eocene Molalla Formation overly the Columbia River Basalt group and represent a terrestrial environment of deposition (Orr and Orr, 1999).

During the upper Miocene, the Sandy River Mudstones, comprised of silts, conglomerates, and sandstones, were deposited in the northern Basin as fine-grained fluvial and lake sediments as tributaries of the Willamette River transported sediment into the Basin (Orr and Orr, 1999). This fluvial environment is associated with the late Pliocene Troutdale gravels (Orr and Orr, 1999).

The recent geologic history of the Willamette Basin is represented by the deposition of the Boring Lavas and ice age flood processes, as evidenced by Missoula Flood deposits. The Pliocene-Quaternary Boring Lavas were erupted during the Pliocene from the numerous volcanic vents across the northern Basin (Orr and Orr, 1999). The Missoula Flood deposits were deposited during the late Pleistocene between 18,000-15,000 years B.P. as Glacial Lake Missoula broke through its ice dam flooding this region over 40 times (Allen et al., 2009).

3.1.4: THE CASCADE RANGE

3.1.4.1: CASCADE RANGE GEOGRAPHY

The north-south trending Cascade Mountain Province extends between 122.6° and 121.1° west longitude. It is characterized by volcanic high peaks, some in excess of 3400 meters (Orr and Orr, 1999). Mount Hood is arguably the most prominent volcanic peak within this province and is among other separate volcanic vents including stratovolcanoes, shield volcanoes, lava domes and cinder cones. The Cascades are comprised of two mountain chains, in the east and in the west, based on age of volcanism. The Western Cascades are older, with volcanism starting approximately 37 Ma. Most present-day Cascade volcanoes are less than 2 million years old.

Glacial influence on this province is significant, with both active glaciers and glacial landforms present throughout the province. This province experiences significant rainfall, and the geomorphology of this province is heavily influenced by erosion caused by this precipitation (Orr and Orr, 1999).

3.1.4.2: CASCADE RANGE GEOLOGY

The stratigraphic column of the Cascade Mountain Range, as illustrated by Orr and Orr (1999) is provided in Figure 8. As with the stratigraphic columns describing the geologic units in the Coast Range and Willamette Valley, this stratigraphic column is separated by location. As with the Coast Range and Willamette Valley provinces, the stratigraphy of the Cascade Range begins with the Farallon Plate subducting under the North American plate over the last 37 Ma (Orr and Orr, 1999). The lithologies that comprise the geology of this province are primarily basalts, basaltic andesites, and other volcanics.

The Miocene Rhododendron and Sardine Formations are found in this province and are of particular interest to this study. The early to middle Miocene Sardine Formation is comprised of basaltic and andesitic flows and lahars, dacitic tuffs, intermediate lavas, breccias and tuffs (Orr and Orr, 1999). The Rhododendron Formation, which is middle to late Miocene in age, contains pyroclastic tuff breccias, laharic breccias, conglomerates, sandstones, mudstones, tuffs and andesite flows (Gullixson, 2006).

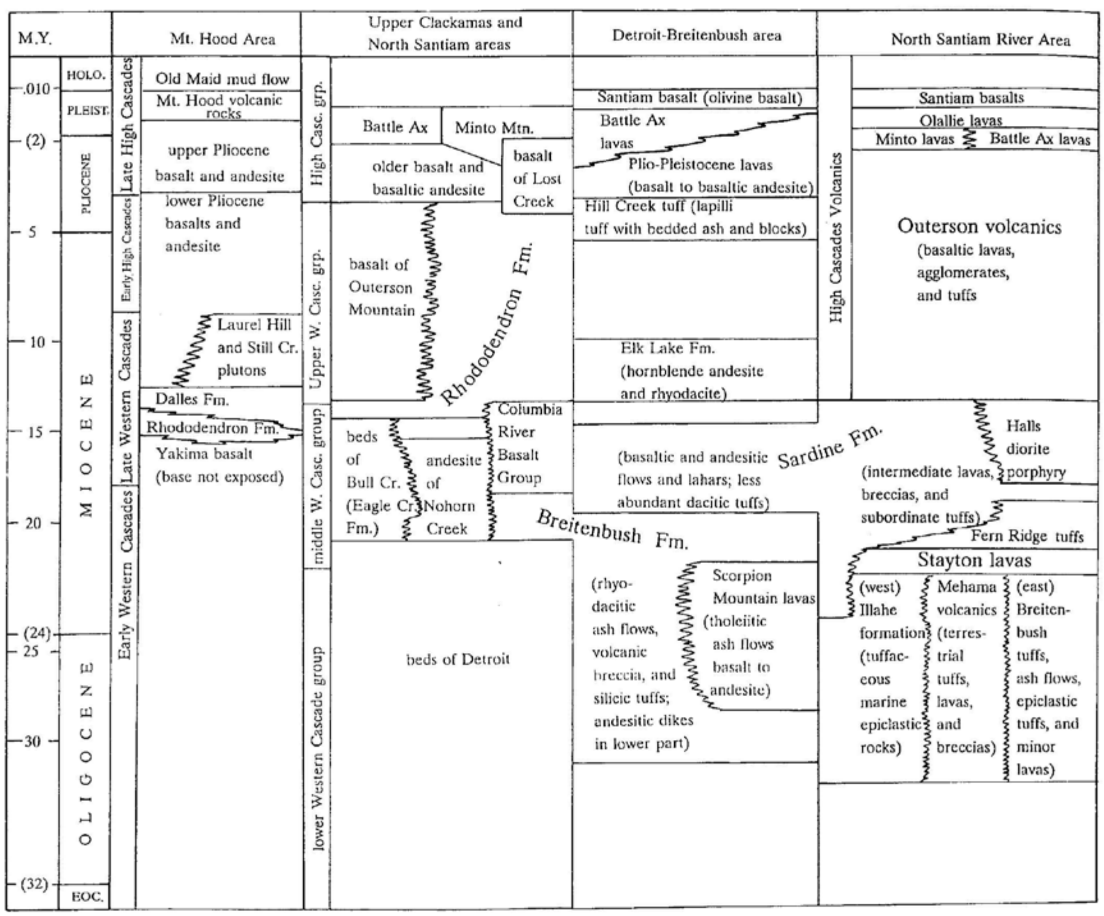


Figure 8: The Stratigraphy of the Cascade Mountain Range Province After Orr and Orr, 1999

3.2: SITE CHARACTERIZATIONS

Each site sampled during Phase I fieldwork for the Ashbaugh (1995) study is described in Appendix C: Site Observations for Phase I (1995) Sites (Ashbaugh, 1995). The soil samples collected during this phase are described in Appendix D: Description of Phase I Soil Samples (Ashbaugh, 1995). Sites and soil samples collected during Phase II fieldwork in August 2010 are described in Appendix E: Site Observations for Phase II (2010) and Appendix F: Description of Phase II Soil Samples (2010) respectively. Photographs of the soil pit and site environment for each Phase II site are included in Appendix G: Site and Soil Pit Images from Sites Sampled During Phase II Sampling (2010).

3.2.1: VEGETATION

All soil pits from which samples were taken for this project were dug at sites judged to have minimal anthropogenic input of arsenic. These consisted primarily of forested areas. The primary foliation at these sites consists of western hemlock and Douglas fir trees. Maple, cedar, and alder trees were also commonly noted. Other types of vegetation noted include sagebrush, grasses, and ferns.

3.2.2: SOIL CHARACTERIZATION

The following summarizes the soil characteristics of soil samples collected during Phase II sampling (Appendix F: Description of Phase II Soil Samples (2010). The thickness of the A horizon at the pits dug varied from 2 to 15 cm, most being less than 12 cm. B horizon samples were taken from depths primarily between 35 and 45 cm. Most pits were not deep enough to reach the bottom of the B horizon. The majority of sites exhibited Bw soils, suggesting these soils are relatively young. Sites where Bt horizons are present exhibit older and more developed soils (Birkeland, 1999). Sampled soils exhibited similar loamy textures. Samples exhibited weak to well-developed subangular blocky texture. All sites exhibited well-drained soils. B-horizon samples were collected from the zone of maximum red color when possible. Few sampled soils were very red, or iron-inundated, and most were characterized as primarily brown in color. This lack of wide spread iron-inundation is most likely due to the young age of many of these soils (Burns et al., 1991; Birkeland, 1999)

CHAPTER 4: METHODS

4.1: USING GEOGRAPHIC INFORMATION SYSYSTEMS (GIS) TO DETERMINE UNSAMPLED GEOLOGIC MAP UNITS

The geologic base map used for this study was obtained online from the United States Geological Survey (Walker and MacLeod, 1991). This map was downloaded as an ESRI shapefile, and ArcGIS version 10.0 was used throughout the analysis.

The study area was first isolated within ArcGIS (Figure 1). Areas representing the same geologic unit were combined for reasons of map usability. Areas labeled with a geologic unit and including a question mark signifying the area's bedrock geologic unit classification was unsure were assumed to be the unit that they were labeled. These areas were combined with the other areas where that unit was mapped.

The process of choosing geologic units for sampling during Phase II sampling was conducted within an Arc geodatabase. The geologic units whose overlying soils were not sampled during Phase I sampling were manually selected and separated into a new feature class. The total area within this project's study area that these remaining units covered was calculated. The eight of these geologic units that covered the largest amount of area were chosen for sampling during Phase II Sampling and are illustrated in Figure 9.

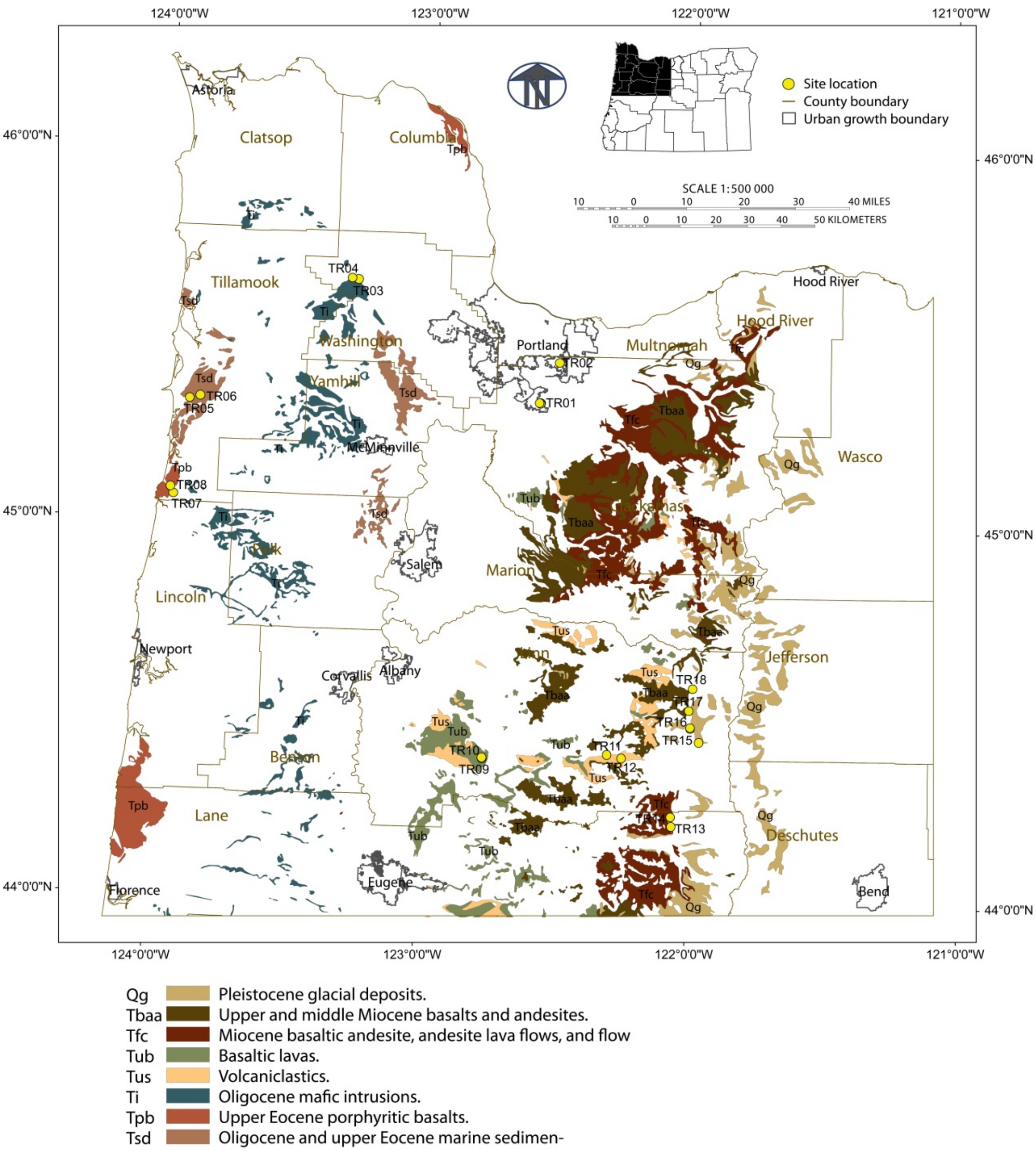


Figure 9: Location of sites sampled during Phase II (2010) fieldwork along with geologic unit associations. Unit labels and descriptions after Walker and MacLeod, 1991.

4.2: FIELDWORK

Fieldwork for this project was done in two phases, the first being conducted in 1995 and the second in 2010. Seventy five sites were sampled during Phase I, and eighteen sites were sampled during Phase II. The methods used during the 2010 phase of fieldwork were modeled from the methods used in 1995 for purposes of continuity. Sampling for Phase II took place over the course of two days in August 2010. The underlying geologic unit at each site could not be independently verified, and locations were determined to be within a given unit based on the geologic map (Figure 9). To minimize the amount of anthropogenic arsenic in the collected samples, sites were chosen in wooded areas away from roads.

Once specific sites were chosen, soil pits were dug using shovels to approximately 60 centimeters deep. One-half to three-quarters of a gallon bag (approximately 1 kg) of soil from the A and B horizons were collected, placed in sealable plastic bags, and labeled with the site label and horizon. The A horizon was sampled in the top 4 cm of soil over an area approximately 35 cm by 35 cm. B horizon samples are composite samples taken from all walls of the pit at the zone of maximum red color.

Site locations were taken with a Garmin GPS. The techniques of Birkeland (1999) were used to compile notes about the soil itself including color, texture, and structure (Appendix E: Site Observations for Phase II (2010) Sites; Appendix F: Description of Phase II Soil Samples (2010)). The Munsell Color Book was used to determine the color of the dry soil samples. Digital photographs of each soil pit and the surrounding site were taken in part to help document the vegetation at the site (Appendix G: Site and Soil Pit Images from Sites Sampled During Phase II Sampling (2010)). Each site was restored to its previous condition after sampling.

4.3: LABORATORY ANALYSIS

The soil samples discussed in this study were prepared, inspected, and analyzed in the following manner.

Phase II samples were dried through the Portland State University lab by spreading them onto newspaper and leaving them for one to three days to ensure complete drying. These samples were sieved using a number 10 sieve. Approximately 340 grams of the sieved sample was placed into a labeled sealable bag for transport to the commercial laboratory. No formal splits from Phase I or Phase II samples were taken because the samples were considered well homogenized through composite sampling at collection, drying, and sieving.

Samples that had been collected during Phase I also required preparation for laboratory testing. Some samples had already been sieved, and approximately 340 grams ounces of soil per sample were placed into labeled and sealed bags. Samples collected during Phase I sampling that had not yet been sieved were sieved using a number 10 sieve, then bagged and labeled in a manner consistent with the Phase II samples.

A comprehensive list of samples was compiled in preparation for testing. Sites that did not have samples from both the A and B horizon were excluded from testing. Samples were boxed and transported to Apex Labs in Tigard, Oregon for testing. A total of 186 samples from 93 sites were tested for arsenic content.

Apex Labs used Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to determine the amount of arsenic in each sample. Environmental Protection Agency method EPA 6020 was used (EPA, 2007). This method utilizes nitric acid (HNO_3) as the solute for sample preparation. Although a total of seven metals, including lead, were tested for, only the arsenic levels are discussed in this project so that these measurements could be focused on in more detail. The benefit of using ICP-MS in this study is its low detection limit of .01 ppm for arsenic (Personal communication, David Jack, Apex Labs, October 2012).

The accuracy of the results returned by APEX Laboratories is summarized in Appendix H: Example page from APEX Laboratory's . This appendix is referred to throughout this discussion on laboratory accuracy and is an example of approximately 15 analyses that were conducted throughout the laboratory analysis. Every morning, the ICP-MS is calibrated over the course of two hours. After every ten samples, three control samples are run for quality assurance purposes. The first sample is a blank for which all values should return ND, or nondetect. This sample is run to ensure no cross-contamination in the analytical methodology. The first analyte (sample 1004105-BLK1) reported in Appendix H: Example page from APEX Laboratory's Quality Control Sample Results detects no arsenic and is an example of this. Second, a check standard with known amounts is run to check for analytical accuracy. Per sample two in Appendix H: Example page from APEX Laboratory's

Quality Control Sample Results (sample 1004105-B51), the known amount of arsenic was 50 ppm and the reported value 48.9 ppm, a difference of 1.1 ppm. This represents a 98% recovery, well within the laboratory's 80-120% recovery limit. Lastly, to check for precision, a previously run sample is retested. In the case of the third sample in Appendix H: Example page from APEX Laboratory's Quality Control Sample Results, the original reported value was 2.81 ppm arsenic and the retest measured a value of 2.69 ppm arsenic, a difference of .12 ppm. This represents a relative percent difference (RPD) of 5%, well within the laboratory's QAQC limit of 40%.

In order to ensure that the laboratory analysis was returning consistent values, five A and five B horizon samples from pit TR6 were analyzed as a measure of precision. For this analysis, A and B horizon soil was sampled from around the pit per the composite sampling method used at all sites. Five homogonized samples from each were analyzed from these composite samples (Mason, 1992). According to Mason (2002), this composite type of sampling is known to result in large standard deviations and should be used cautiously. The benefit of this method is that it is a cost effective way of determining where arsenic levels require further analysis (Mason, 1992; Oregon DEQ, 2006). The results of the analysis from this pit, along with means and standard deviations, are included in Table 2 below. The standard deviations here are under 30% for the A horizon data, and under 5% for the B horizon data. These results suggest that the variability within the A and B horizon composite samples at site TR6 is low, much more so than the differences between similar soils from different locations (as discussed in 5.1: GENERAL OVERVIEW OF DATA), lending validity to this method of sampling and sample processing at this site.

Table 2: Measured arsenic values and basic statistics for pit TR6.

Sample Number	A Horizon As Value	B Horizon As Value
TR6-1	6.04	11.3
TR6-2	4.64	10.9
TR6-3	6.48	10.2
TR6-4	3.39	11
TR6-5	3.54	11.4
Mean	4.82	10.96
Standard Deviation	1.41	0.47

4.4: GROUPINGS FOR STATISTIC ANALYSIS

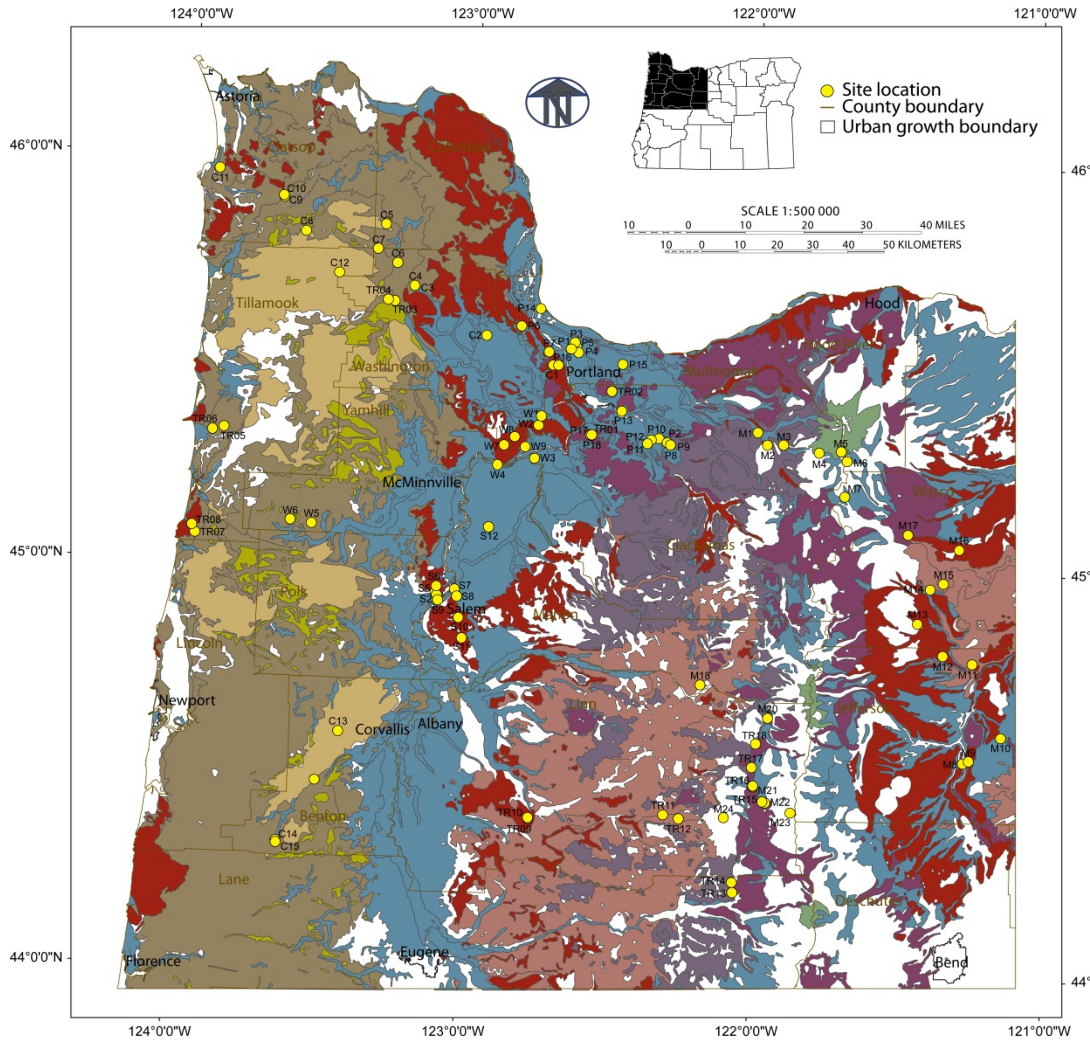
Prior to statistical tests being run, the data were aggregated into groups based on underlying bedrock (Walker and MacLeod, 1991). The rock types described in the Geologic Map of Oregon were used to group these data (Appendix I: Descriptions of Lithology by Lithologic Group; Walker and MacLeod, 1991). Groups were formed primarily based on age and lithology criteria in order to minimize differences in the arsenic content of the overlying soil based on these factors. These groupings are referred to as lithologic groups and are described in Table 3. A table of measured A and B horizon arsenic, underlying geologic unit and assigned lithologic group is found in Appendix J: Soil Arsenic Data from Northwest Oregon. Table 3 also includes the units that comprise each group. The lithologic groups are titled Quaternary/ Tertiary Sediments and Sedimentary Rocks (QTS), Marine Sediments and Sedimentary Rocks (MS), Mafic Intrusions (MI), Coast Range Basalts (CORB), Columbia River Basalts (CRB), Quaternary Basalts (QB), Andesites (A), Rhododendron/Sardine Formation (RS), and Volcanic Sediments (VS) (Table 3; Appendix I: Descriptions of Lithology by Lithologic Group). The geographic distribution of these lithologic groups together with sample locations from both Phase I and Phase II sampling are shown in Figure 10.

In addition to having common age and similar rock types, the lithologic groups have additional noteworthy traits. The Quaternary/ Tertiary Sediments group includes Missoula Flood deposits, the Troutdale Formation, alluvium, glacial till, stream terraces, and loess. The Marine Sediments and Sedimentary Rocks group includes sandstones and shales primarily found in the Coast Range Province. The Mafic Intrusions units are also primarily found in the Coast Range and include basalt dikes and sills. Coast Range Basalts are older basalt flows, primarily from the Eocene. These early Tertiary basalts are in contrast to the Columbia River Basalts, which flow mostly from eastern Oregon and are Miocene in age. The Quaternary Basalt and Andesite groups consist of the young volcanic units of the Cascade Range Province. The Rhododendron/ Sardine Formation group is made of rocks of these lithologic units and is comprised of volcaniclastic sediments of early Cascade volcanism.

Table 3: Lithologic Groups

GROUP NAME[1]	UNIT LABEL[2]	GROUP DESCRIPTION
Quaternary / Tertiary Sediments and Sedimentary Rocks	Qal; Qs; Qg; QTs; Ts; Qgs	The Quaternary/ Tertiary sediments group is characterized by sediments and sedimentary rock from recent geologic time periods, primarily the quaternary.
Marine Sediments and Sedimentary Rocks	Tco; Tms; Tmst; Tsd; Tss; Tt;Ty	The Marine Sediments and Sedimentary Rocks group is characterized by sedimentary rocks deposited in a marine environment. Each of the groups is Tertiary in age.
Mafic Intrusions	Ti	The Mafic Intrusion group is Oligocene in age and made up only of unit Ti.
Coast Range Basalt	Tsr; Ttv	The Coast Range Basalts group is composed of basalts deposited during the Tertiary. Geographically, these basalts are found in the Coast Range physiographic province.
Columbia River Basalts	Tc; Tcg; Tob; Tpb;Tub	The Columbia River Basalts are extensive geographically and were deposited during the Tertiary.
Quaternary Basalts	QTb; QTba; Qyb	The Quaternary basalts group is defined by a Quaternary period of deposition and a basaltic lithology.
Andesites	Qa	The Andesite unit was deposited during the Quaternary geologic time period.
Rhododendron / Sardine Formations	Tbaa; Tfc	The Rhododendron/ Sardine Formation rocks are of primarily basaltic and andesitic lithology and were deposited during the Tertiary time period.
Volcanic Sediments	Tca; Tus; Tsfj; Tu	The Volcanic Sediments group is comprised of sedimentary rocks deposited during the Tertiary. These rocks are comprised of sediments that are volcanic in origin.

1. Informal Designation
2. See Appendix I: Descriptions of Lithology by Lithologic Group for full unit descriptions.



- Marine sediments/Sedimentary rocks
- Coast Range basalts
- Columbia River basalts
- Volcanic sediments
- Mafic intrusions
- Rhododendron/Sardine Fm.
- Quaternary basalts
- Quaternary/Tertiary sediments/ Sedimentary Rocks
- Andesites
- Unsampled unit

Figure 10: Geographic extent of lithologic groups and all site locations (Walker and MacLeod, 1991; Ashbaugh, 1995).

CHAPTER 5: ANALYSIS

5.1: GENERAL OVERVIEW OF DATA

The levels of arsenic measured in each sample, the underlying bedrock unit, and assigned lithologic group of each data point are included in Appendix J: Soil Arsenic Data from Northwest Oregon. A table of high and low values tested in each horizon and number of samples in each horizon from which no arsenic was detected, grouped by underlying geologic unit, is included as Appendix K: High and Low Values for Samples by Mapping Unit. The mean arsenic level and standard deviations of five lithologic units tested in five or more pits are noted in Table 4 and Table 5 (Appendix J: Soil Arsenic Data from Northwest Oregon). The mean arsenic level and standard deviations of five lithologic groups containing six or more data points are noted in Table 6 and Table 7 (Appendix J: Soil Arsenic Data from Northwest Oregon). Four lithologic groups (the Andesites, Mafic Intrusions, Rhododendron/ Sardine Formations and Coast Range Basalts groups) are not included due to low sample size.

Table 4: Overview of arsenic data in the A horizon by unit.

Lithologic Unit	A Horizon Mean (ppm)	A Horizon Median (ppm)	A Horizon Standard Deviation (ppm)	Number of Samples per Horizon
Qal	3.04	3.08	2.654	7
Qgs	6.94	9.20	5.17	5
Qs	4.5	3.45	3.33	12
QTba	1.67	1.45	1.77	12
Tc	4.02	4.69	2.01	6

1. Units here are those sampled in five or more pits. Other units were sampled, but included less than five points of data. These units are excluded from this chart, as the groups are too small for mean and standard deviation calculations to be meaningful.
2. A complete list of values, including minimum and maximum for each lithologic unit, is included in Appendix J: Soil Arsenic Data from Northwest Oregon and Appendix K: High and Low Values for Samples by Mapping Unit.

Table 5: Overview of arsenic data in the B horizon by unit.

Lithologic Unit	B Horizon Mean (ppm)	B Horizon Median (ppm)	B Horizon Standard Deviation (ppm)	Number of Samples per Horizon
Qal	2.97	2.79	2.80	7
Qgs	3.87	3.53	1.64	5
Qs	4.59	4.91	1.21	12
QTba	1.79	1.25	1.94	12
Tc	5.24	5.02	1.70	6

1. Units here are those sampled in five or more pits. Other units were sampled, but included less than five points of data. These units are excluded from this chart, as the groups are too small for mean and standard deviation calculations to be meaningful.
2. A complete list of values, including minimum and maximum for each lithologic unit, is included in Appendix J: Soil Arsenic Data from Northwest Oregon and Appendix K: High and Low Values for Samples by Mapping Unit.

Table 6: Overview of arsenic data in the A horizon by lithologic group

Lithologic Group	A Horizon Mean (ppm)	A Horizon Median (ppm)	A Horizon Standard Deviation (ppm)	Number of Samples per Horizon
Quaternary/ Tertiary Sediments and Sedimentary Rocks	3.59	3.25	3.72	32
Marine Sediments/ Sedimentary Rocks	6.09	5.44	2.65	12
Columbia River Basalts	3.75	4.54	2.31	15
Quaternary Basalts	1.67	1.80	1.68	15
Volcanic Sediments	2.45	0.00	4.29	6

1. Lithologic groups here are those sampled by six or more pits. The Rhododendron/ Sardine Formation, Mafic Intrusions, and Andesites groups included less than six points of data. These groups are excluded from this chart, as the groups are too small for mean and standard deviation calculations to be meaningful.
2. A complete list of values, including minimum and maximum for each lithologic group, is included in Appendix J: Soil Arsenic Data from Northwest Oregon.

Table 7: Overview of arsenic data in the B horizon by lithologic group.

Lithologic Group	B Horizon Mean (ppm)	B Horizon Median (ppm)	B Horizon Standard Deviation (ppm)	Number of Samples per Horizon
Quaternary/ Tertiary Sediments and Sedimentary Rocks	3.25	3.43	2.23	32
Marine Sediments/ Sedimentary Rocks	10.26	10.73	4.65	12
Columbia River Basalts	4.28	4.99	2.33	15
Quaternary Basalts	1.75	1.26	1.86	15
Volcanic Sediments	3.12	1.24	4.47	6

1. Lithologic groups here are those sampled by six or more pits. The Rhododendron/ Sardine Formation, Mafic Intrusions, and Andesites groups included less than six points of data. These groups are excluded from this chart, as the groups are too small for mean and standard deviation calculations to be meaningful.
2. A complete list of values, including minimum and maximum for each lithologic group, is included in Appendix J: Soil Arsenic Data from Northwest Oregon.

5.2: ANALYSIS OF VARIANCE AND MULTIPLE COMPARISON ANALYSIS

Using soil arsenic measurements to make maps of expected background arsenic levels for soil types above different bedrock lithologies requires that the soils are statistically distinguishable. This is evaluated with an Analysis of Variance (ANOVA) test and a multiple comparison procedure which are used to compare means between the lithologic groups (Davis, 2002; Mathworks, 2012c). The soil data are grouped in two ways to test this project's motivating hypothesis. Data from individual sites are grouped according to underlying lithology, as discussed in the Methods section and Table 3. The data are alternatively considered as a single group. These groupings allow for the calculation of mean and standard deviation. This grouping strategy also allows conclusions to be drawn regarding the data in the absence of error estimates on individual sample sites.

The Analysis of Variance (ANOVA) test is used to determine if the five lithologic groups that have six or more samples in each horizon are statistically different from each other (Table 3, Table 6, Table 7). The procedure utilized here is chosen to avoid type I statistical errors that can occur when a T-test is used to directly compare two groups of data. The ANOVA analysis compares the variances both within and between the groups using an F-test. The null hypothesis states that there is no statistically distinguishable difference between the groups. The analysis is completed using lithologic groups for which six or more samples were tested: Quaternary/ Tertiary Sediments (QTS), Marine Sediments and Sedimentary Rocks (MS), Columbia River Basalts (CRB), Quaternary Basalts (QB), and Volcanic Sediments (VS). In addition to the typical assumptions underlying the ANOVA test, including that the data exhibit a normal distribution, specific assumptions made in this analysis include:

1. Samples are representative of both the bulk soil and the pit from which they were taken. (Because only one sample was taken in each horizon at most sites, the representative nature of the samples cannot be verified, and therefore must be assumed.

2. Lithology of underlying bedrock at different locations are drawn from the same populations; making the grouped soils drawn from a single population for the purpose of the motivating hypothesis of this test.

The critical value for this test at the 95% confidence level is approximately 2.72 (Davis, 2002). If the F-test value for the A and B horizon tests are above this critical value, the null hypothesis is rejected, indicating that at least one group is statistically distinguishable from the rest (Davis, 2002). The results are provided in Table 8 and Table 9.

Table 8: A Horizon data ANOVA

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F-Test Value	P-Value
Groups	138.06	4	34.51	3.63	.0093
Error	713.38	75	9.51		
Total	851.43	79			

Table 9: B Horizon data ANOVA

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F-Test Value	P-Value
Groups	566.41	4	141.60	17.26	4.45×10^{-10}
Error	615.22	75	8.20		
Total	1181.63	79			

In order to determine which group or groups are statistically distinguishable, a multiple comparison test is required. This test is also conducted to diminish the possibility of a type II error given the large standard deviations within the lithologic groups. In this analysis, the MS group is found to be statistically distinguishable from the QB group in the A horizon, and all groups in the B horizon (Figure 13, Figure 14).

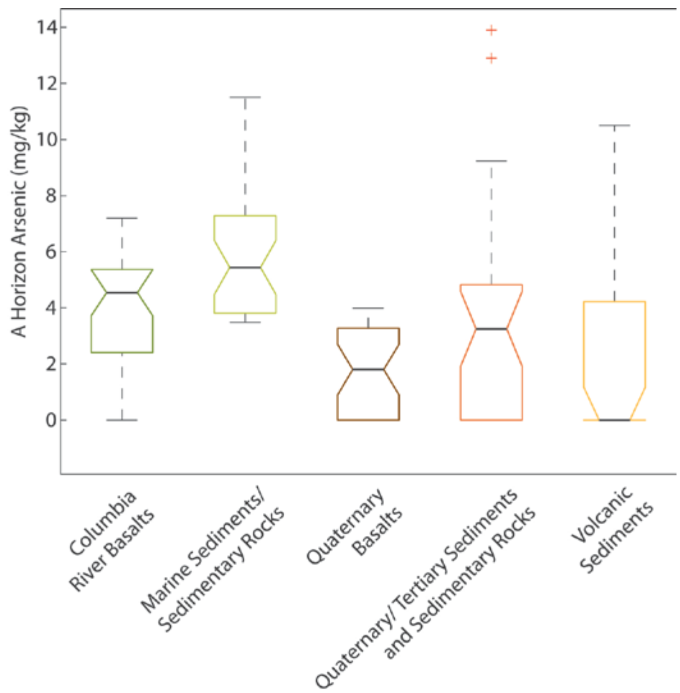


Figure 11: Stem-box plot showing mean, upper and lower quartile, data range, and outliers for the A horizon values of the five tested groups.

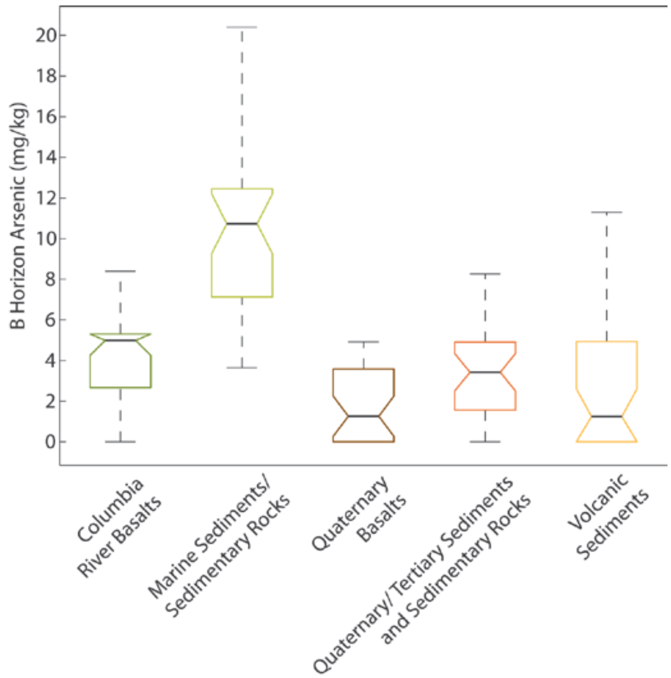


Figure 12: Stem-box plot showing mean, upper and lower quartile, data range, and outliers for the B horizon values of the five tested groups.

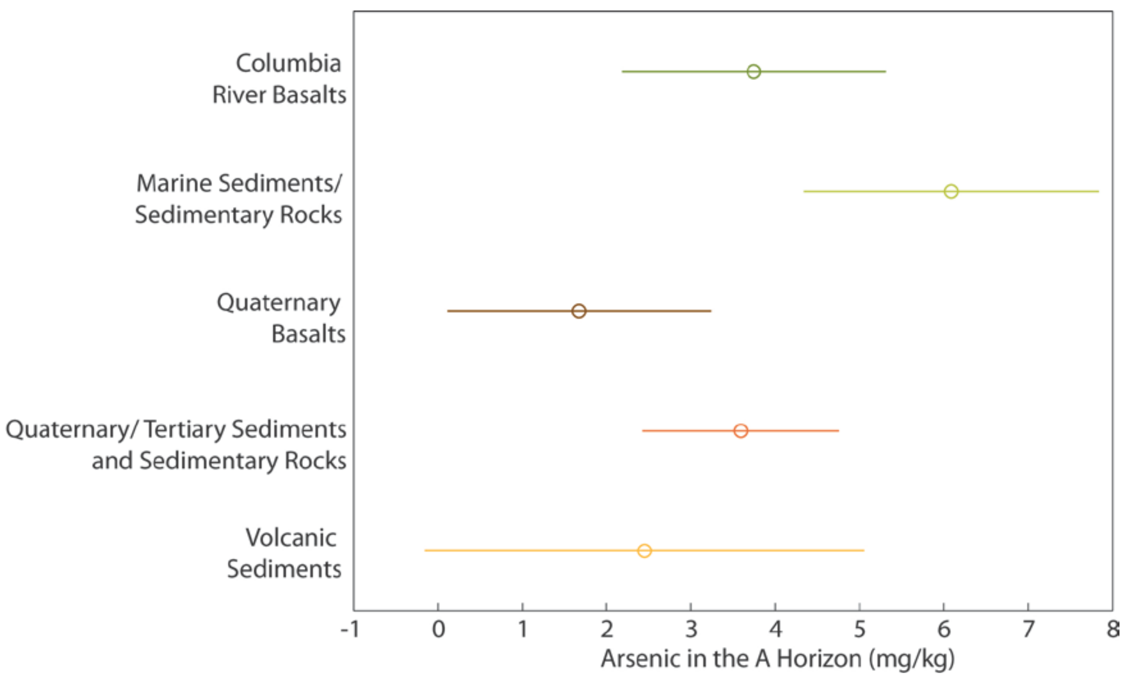


Figure 13: Multiple comparison of A horizon arsenic concentrations finds that group MS is distinct from group QB in this horizon.

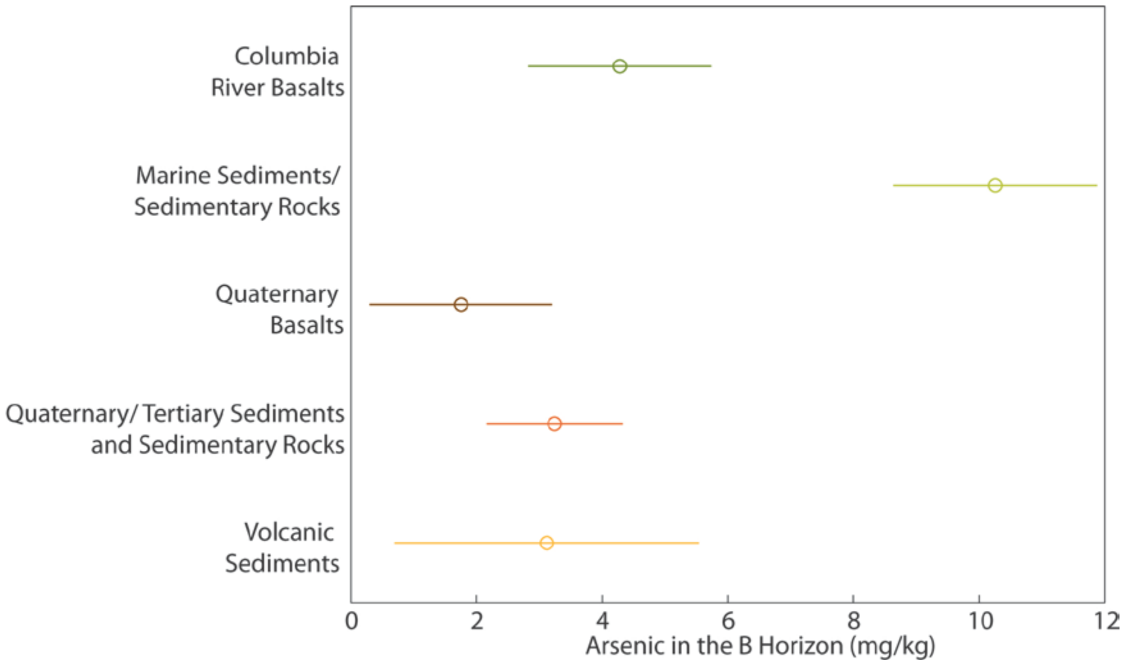


Figure 14: Multiple comparison of B horizon arsenic concentrations finds that group MS is distinct from all other tested groups in this horizon.

5.3: KRUSKAL-WALLIS TEST

The standard ANOVA assumption that the data are drawn from a normal distribution may not be appropriate here. A nonparametric alternative is the Kruskal-Wallis analysis of variance (Davis, 2002; Mathworks, 2012b). As in the standard ANOVA analysis, the null hypothesis states that the different sample sets are drawn from the same distribution. The Kruskal-Wallis test compares the median of the samples in each group using the Chi-squared test. Values are ranked for comparison.

The critical value of the Chi-squared test with 4 degrees of freedom is approximately 9.49. The Chi-squared value is higher than this critical value in both the A and B horizon test (Table 10, Table 11). These results indicate a rejection of the null hypothesis and that at least one group is statistically distinct from another (Table

10, Table 11). A multiple comparison analysis is again required to determine which group or groups are distinct (Figure 15, Figure 16).

Table 10: A Horizon Data Kruskal-Wallis Analysis

Source	Sum of Squares	Degrees of Freedom	Mean Squares	Chi-Squared Value	P-Value
Groups	9736.9	4	2434.21	18.53	.001
Error	31772.6	75	423.64		
Total	41509.5	79			

Table 11: B Horizon Kruskal-Wallis Analysis

Source	Sum of Squares	Degrees of Freedom	Mean Squares	Chi-Squared Value	P-Value
Groups	15878.5	4	3969.63	29.74	$5.52X10^{-6}$
Error	26295	75	350.6		
Total	42173.5	79			

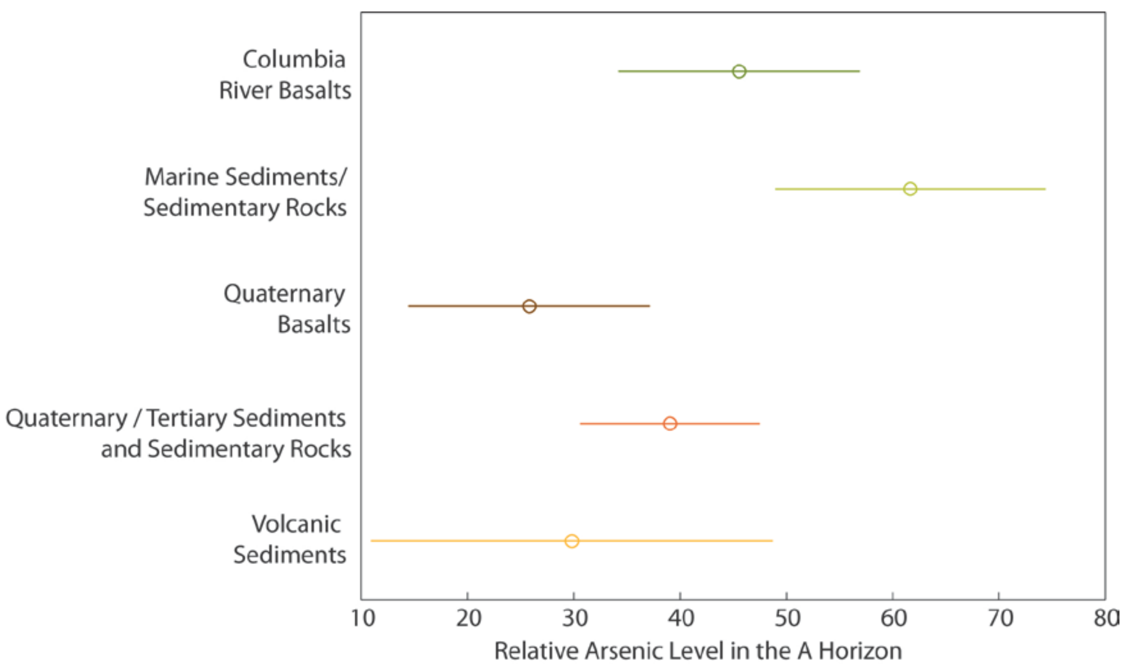


Figure 15: Multiple comparison test of A horizon data based on the Kruskal-Wallis analysis. This test shows the arsenic levels of group MS are statistically different from those of groups QB and QTS in the A horizon. The X axis values represent the mean and standard deviation of the group's ranks.

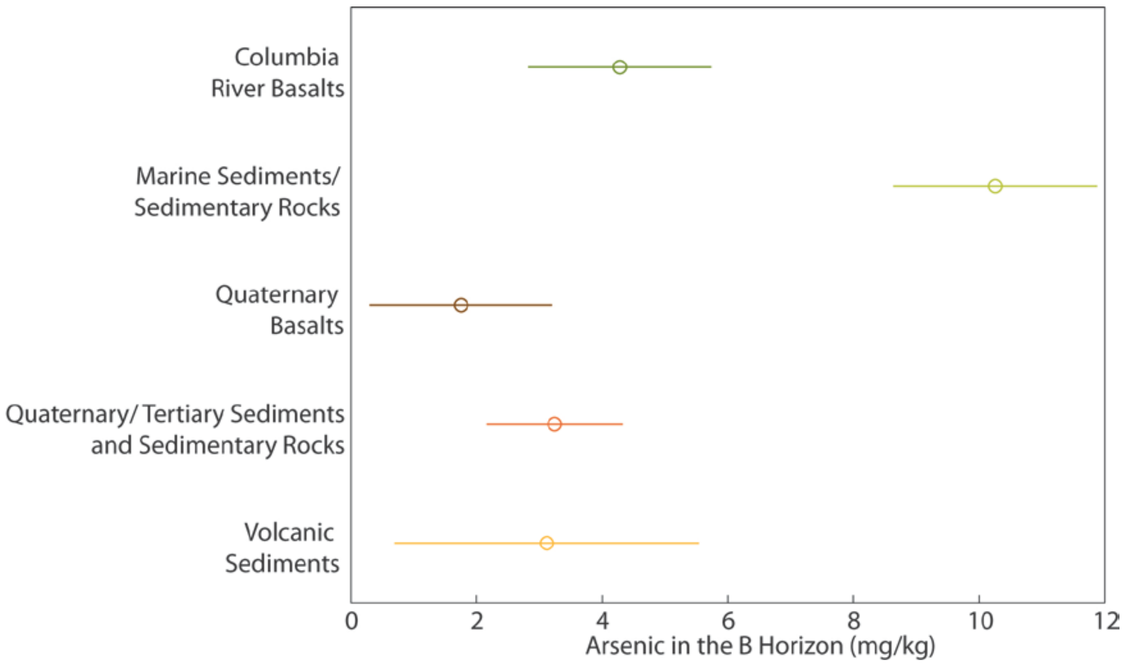


Figure 16: Multiple comparison test of B horizon data based on the Kruskal-Wallis analysis. This test shows the arsenic levels of group MS are statistically different from those of groups QB, QTS and VS in the B horizon. The X-axis values represent the mean and standard deviation of the group's ranks.

The multiple comparison test conducted from the Kruskal-Wallis analysis indicates, as in the standard ANOVA, that group MS is the only group that is statistically different from another group. In both the A and B horizon samples, group MS is statistically distinguishable from groups QB, QTS, and VS. This analysis supports the standard ANOVA test results.

For the purposes of making a map correlating underlying bedrock to arsenic content, the results of the standard ANOVA and Kruskal-Wallis tests indicate that the Marine Sediments and Sedimentary Rocks group should be considered one unit, and the other lithologic groups that were tested should be combined into a single separate unit. Lithologic groups that were not tested due to low sample size are distinguished from unsampled units for the purposes of this map. The basic mean and standard deviation of both tested horizons for these groups are noted in Table 12. The map correlating these underlying geologic units to the arsenic content of overlying soils is shown as Figure 17.

Table 12: Basic arsenic statistics of groups mapped based on analysis

	Group containing all tested data not in the Marine Sediments and Sedimentary Rocks Group		Marine Sediments and Sedimentary Rocks Group	
	A Horizon	B Horizon	A Horizon	B Horizon
Mean	3.10	3.13	6.09	10.26
Standard Deviation	3.19	2.52	2.66	4.65
Number of Samples	68		12	

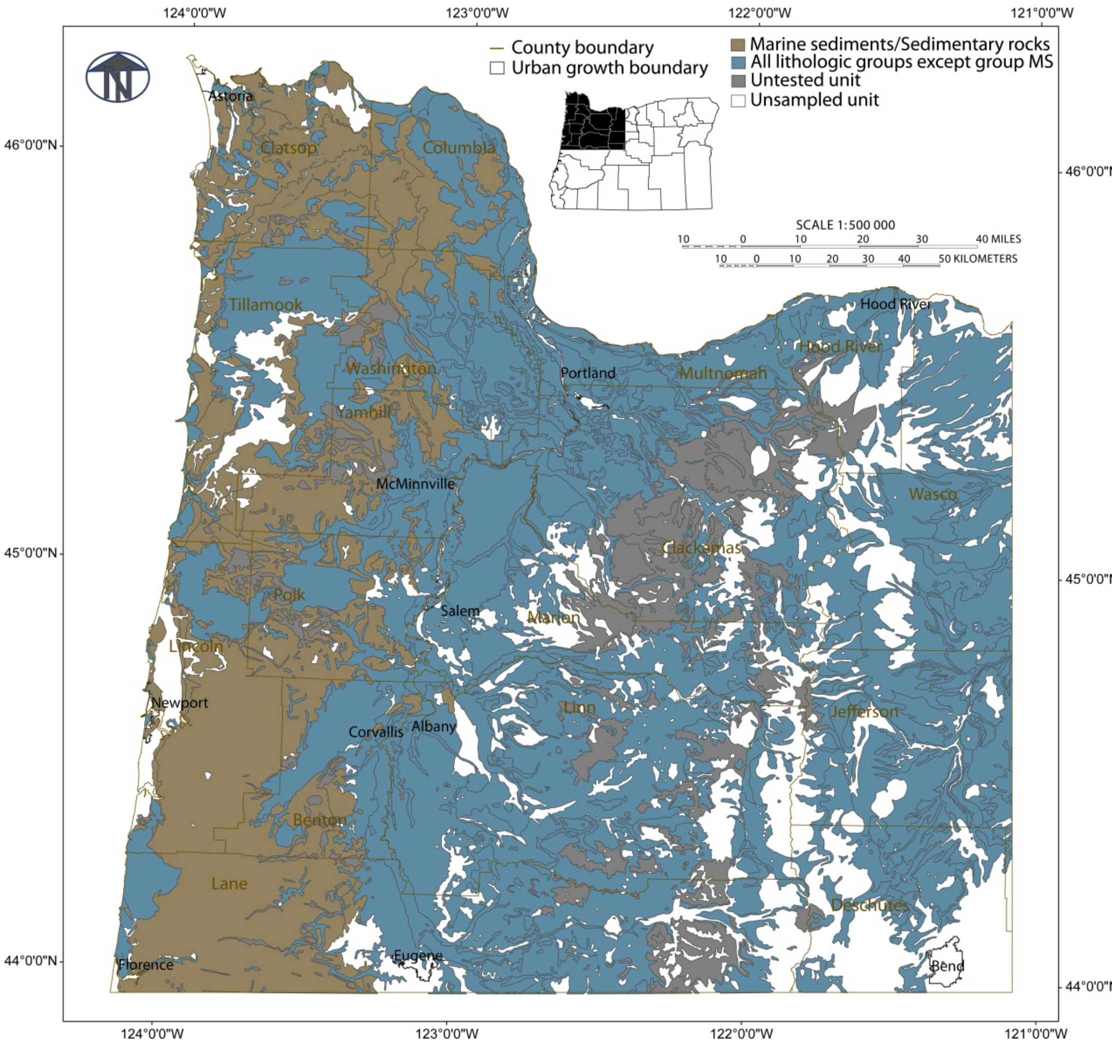


Figure 17: Map showing the distribution of Marine Sedimentary and Sedimentary Rocks group units and the other tested lithologic groups throughout the northwest Oregon study area. This map illustrates areas where soil arsenic content is statistically distinct (Walker and MacLeod, 1991).
Mean, standard deviation and number of samples in each of these mapped groups are found in Table 12. Untested units are those from which overlying soils were sampled but for which the resulting data was unable to be used in the standard ANOVA or Kruskal-Wallis test due to these samples being a part of lithologic groups that had fewer than six samples. Unsampled units are those from above which soil samples were not collected and tested for arsenic content.

5.4: A VS B HORIZON ANALYSIS

The A and B horizon arsenic data was looked at together to determine which, if any, groups were statistically distinguishable when data from both horizons was compared. An initial assessment of the data indicates that more arsenic was measured in the A horizon sample at 31 sites, more arsenic was measured in the B horizon sample at 31 sites, and A and B horizon samples measured equal amounts of arsenic at 20 sites. In order to ascertain if A horizon data are statistically distinguishable from B horizon data, the standard ANOVA and Kruskal-Wallis tests are again implemented. Data are again grouped by lithologic group (Table 3, Table 6, Table 7). Both A and B horizon data are assessed together to compare data between horizons (Figure 18).

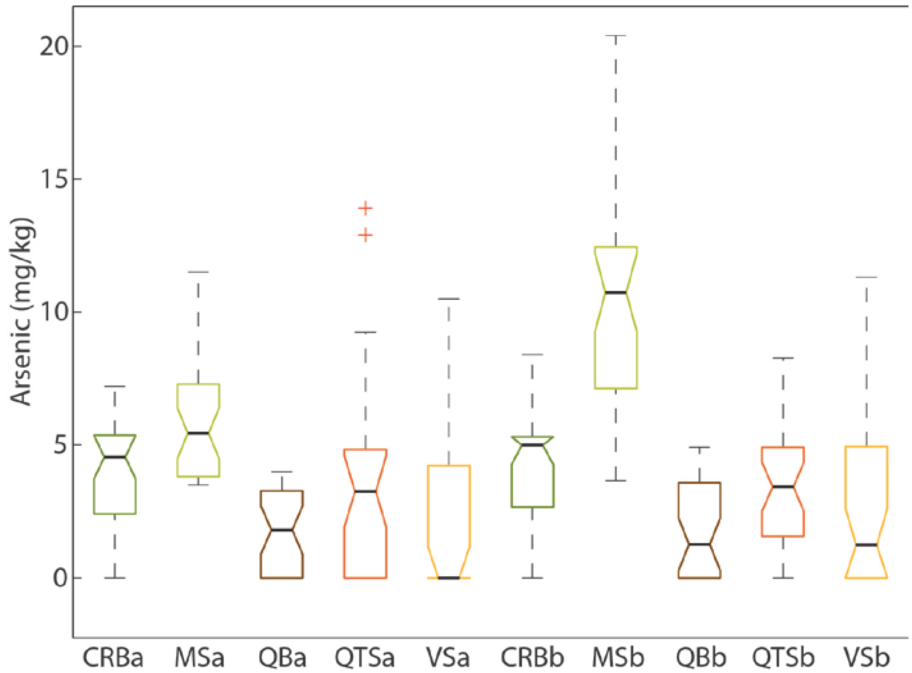


Figure 18: Stem-box plot showing mean, upper and lower quartile, data range, and outliers for A and B horizon data by lithologic group. X-Horizon labels indicate lithologic group and horizon.

The critical value of the standard ANOVA F-test used is approximately 1.94 at the 95% confidence level (Davis, 2002). The reported F-test value of 7.03 indicates a rejection of the null hypothesis (Table 13). The critical value of the Kruskal-Wallis Chi-squared test used is approximately 16.92 at the 95% confidence level (Davis, 2002). The Chi-squared value of 40.88 again indicates a rejection of the null hypothesis (Table 14). The results of both tests indicate that at least one group is statistically distinguishable from another. Multiple comparison tests are required in both cases to determine which group or groups are distinct (Figure 19, Figure 20).

Table 13: A vs B Horizon data ANOVA

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F-Test Value	P-Value
Groups	608.35	9	67.59	7.03	$1.89X10^{-8}$
Error	1441.7	150	9.61		
Total	2050.05	159			

Table 14: A vs B Horizon Kruskal-Wallis Analysis

Source	Sum of Squares	Degrees of Freedom	Mean Squares	Chi-Squared Value	P-Value
Groups	86160.7	9	9573.42	40.88	$5.27X10^{-6}$
Error	248983.8	150	1659.89		
Total	335144.5	159			

The standard ANOVA multiple comparison test indicates that the A horizon MS group is distinct from group QB in the A and B horizon. In the B horizon, the MS group is distinct from all other tested groups (Figure 19). The Kruskal-Wallis multiple indicates that the MS group is distinct from group QB in the A and B horizon. In the B horizon, the MS group is distinct from groups QB, QTS, and VS in both the A and B horizons (Figure 20). These results are consistent with the previously discussed standard ANOVA and Kruskal-Wallis test. Group MS is shown to be distinct from other lithologic groups.

The lack of statistically significant distinguishability between A and B horizon data is most likely due to the young age of many of the soils tested (Burns et al., 1991; Birkeland, 1999). In this dataset, 31 of the high values at a given site would not have been detected if only A horizon soils were sampled.

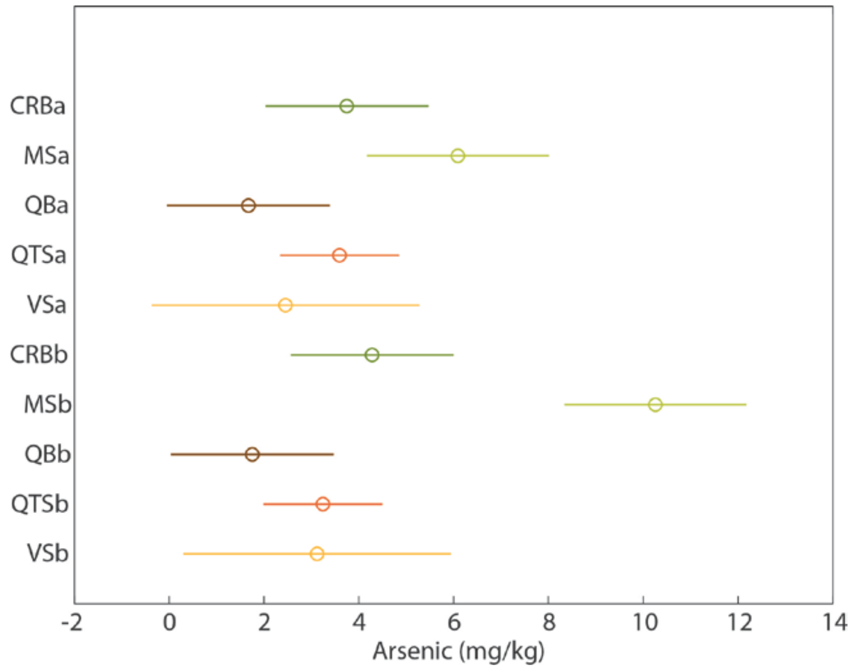


Figure 19: The standard ANOVA multiple comparison test indicates that group MS in the A horizon is distinct from group QB in the A and B horizon. Group MS in the B horizon is distinct from all other tested groups.

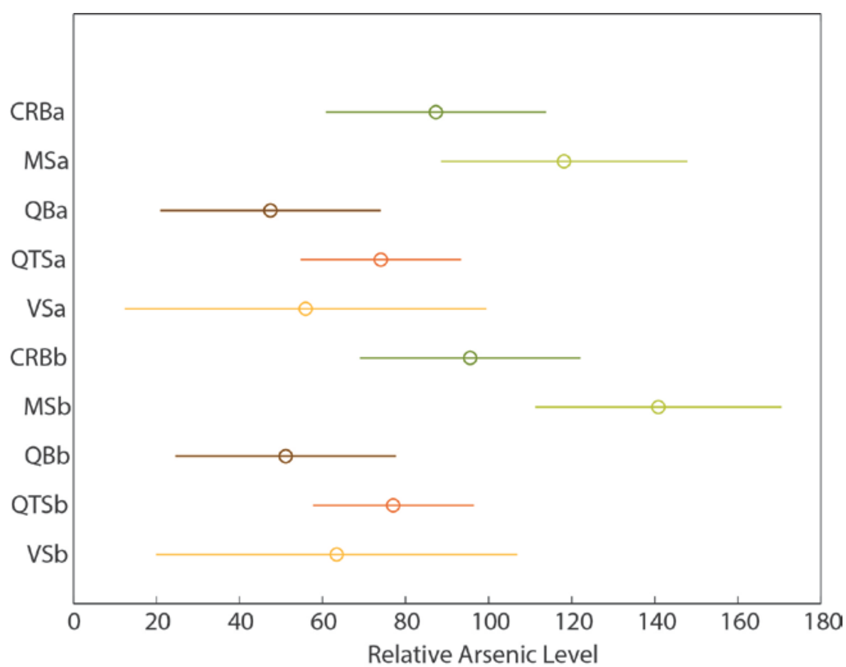


Figure 20: The Kruskal-Wallis multiple comparison test indicates group MS in the A horizon is distinct from group QB in both the A and B horizon. Group MS in the B horizon is distinct from groups QB, QTS and VS in the A and B horizons.

5.5: K-MEANS CLUSTER ANALYSIS

5.5.1: RATIONALE

Cluster analysis is a procedure for grouping data so that members of a given group are more similar to each other than they are to members of other groups. A centroid-based approach called K-means clustering, in which K represents the number of groups, is used here (Davis, 2002; Mathworks, 2012a). The resulting groups can be used for additional analyses, and in this case will be used to test the motivating hypothesis that soil arsenic content reflects underlying bedrock geology. If the hypothesis is correct, clusters will be comprised of samples with similar underlying bedrock lithologies. If this hypothesis is true for these soils, the bedrock type underlying the soil might then be used as an indicator of the background level of arsenic in soil.

5.5.2: METHOD

This clustering method is iterative and begins with the identification of centroids around which individual data points are grouped. The means of these groups are calculated and used to identify new centroids which better fit the data and new groupings are assigned. The process is repeated until individual data points remain assigned to the same group throughout subsequent iterations. A K-means clustering algorithm in the Statistics Toolbox of Matlab software is used in this analysis (Mathworks, 2012a). Three, four and five group cluster analyses are presented here. Calculations with K values greater than 5 did not converge.

The ratio of normalized A and B horizon arsenic values was used to identify clusters. Natural arsenic may accumulate in soils as they age, a process that, if occurring, will be reflected across the soil profile. This accumulation first occurs through leaching processes as bedrock degrades into soils. In later stages of soil development, this accumulation occurs as A and B horizons become well-developed and water and other weathering processes leach elements from the A to B horizon as the soil ages (Burns et al., 1991). Using the A to B horizon ratio allows soils of different ages to be compared. The arsenic concentrations are normalized to the maximum arsenic concentration measured in the respective horizon so that data from different soil pits can be treated as one dataset.

The quality of the groups formed by the cluster analysis is determined by comparing individual arsenic values to the mean of their assigned group. This comparison is shown graphically as a silhouette graph of the goodness of fit of each sample in its assigned cluster (Figure 22, Figure 24, Figure 26). Points with silhouette values approaching 1 are strong members of their assigned cluster, while points with a negative silhouette value are poor members of their assigned cluster (but do not fit elsewhere). The quality of the cluster analysis is determined by the mean of these silhouette values, with means closer to 1 indicating strong clusters, distinct from each other.

5.5.3: RESULTS

The three group cluster analysis yielded the strongest result, though the difference between the three, four and five cluster analyses were small. The three clusters are characterized by 1) low arsenic values in the A and B horizons, 2) moderate arsenic values in the A and B horizons, and 3) high arsenic values in either the A or B horizon (Figure 21, Figure 22). The four cluster analysis yields similarly arranged groups, with the low and mid A and B horizon clusters, more or less, separated into three clusters (Figure 23, Figure 24). The five cluster analysis further divides the high A/low B horizon values from the low A/high B horizon values (Figure 25, Figure 26). The mean silhouette values for the three, four and five cluster analysis are 0.6872, 0.7116, and 0.6398 respectively. The negligible difference between the mean silhouette values indicates that the subgroups resulting from the four and five group cluster analysis are not strongly defined.

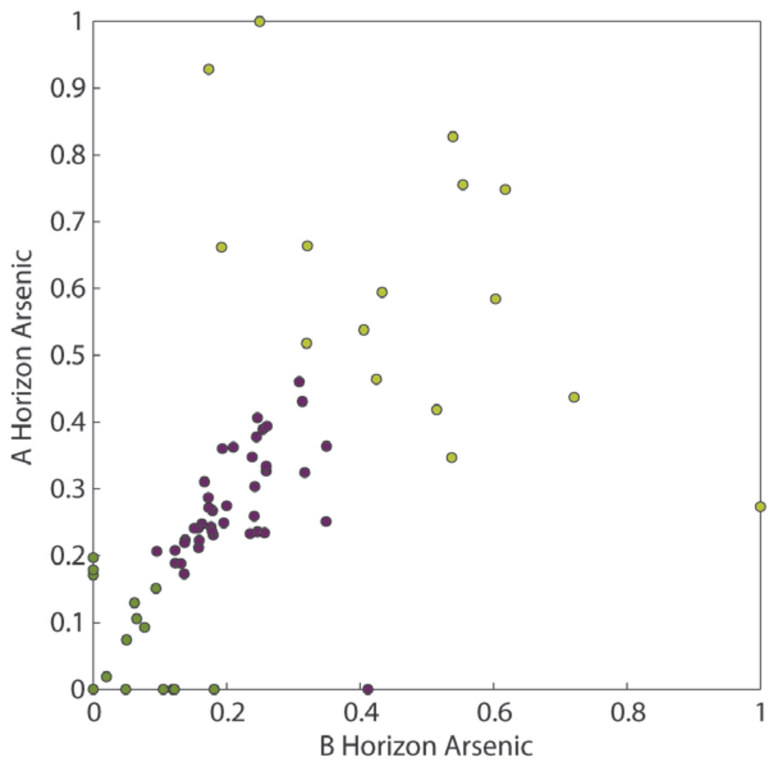


Figure 21: Scatterplot illustrating the results of the three group cluster analysis. Points with common color symbology are assigned to the same cluster.

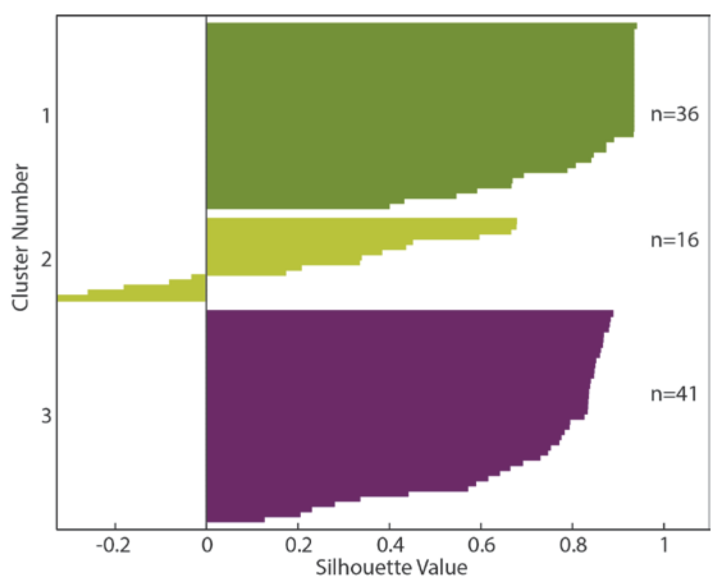


Figure 22: Silhouette graph illustrating the strength of the three cluster analysis results.
Color symbology represents cluster. Color of groups in Figure 22 match groups in Figure 21.

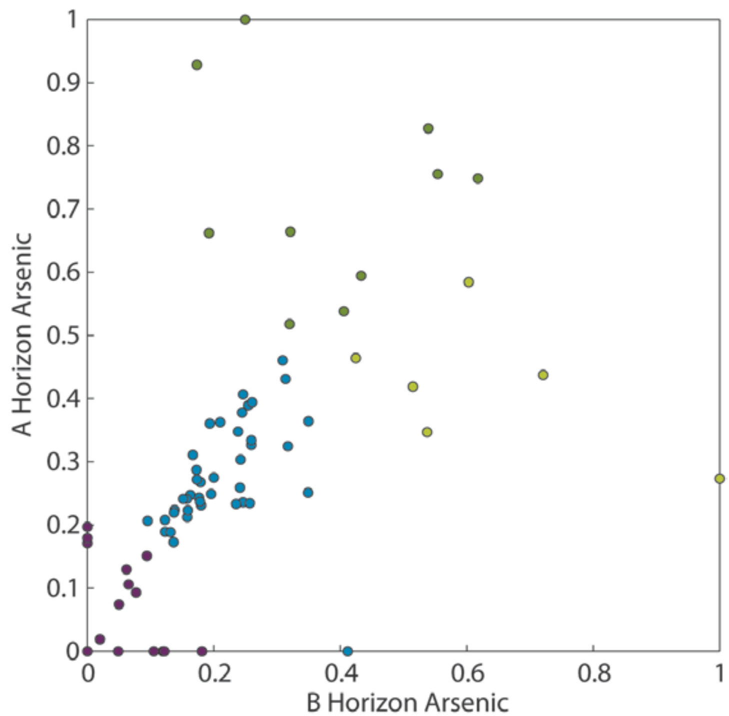


Figure 23: Scatterplot illustrating the results of the four group cluster analysis. Points with common color symbology are assigned to the same cluster.

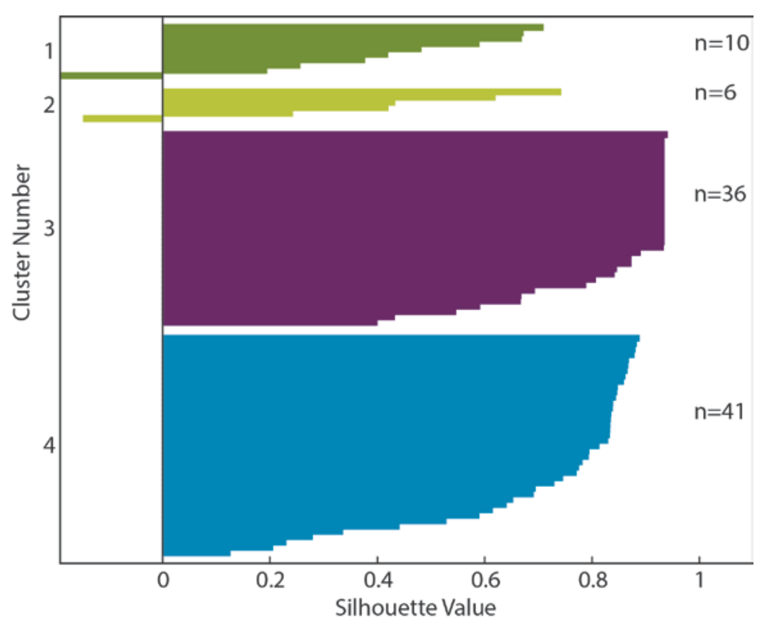


Figure 24: Silhouette graph illustrating the strength of the four cluster analysis results.
Color symbology represents cluster. Color of groups in Figure 24 match groups in Figure 23.

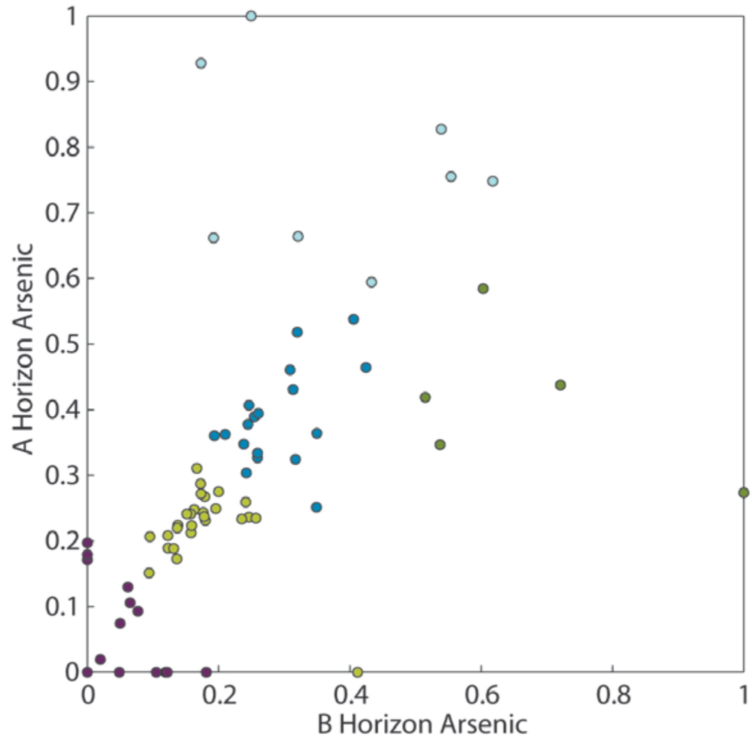


Figure 25: Scatterplot illustrating the results of the five group cluster analysis. Points with common color symbology are assigned to the same cluster.

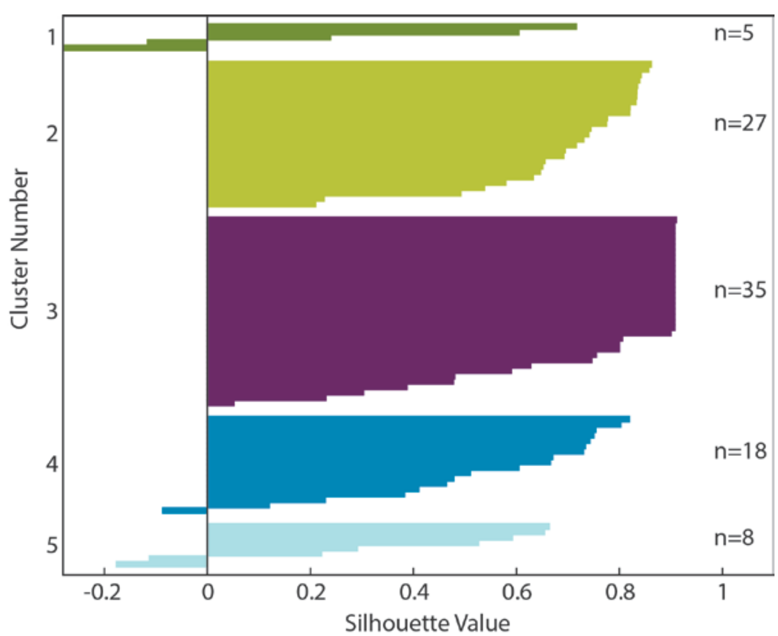


Figure 26: Silhouette graph illustrating the strength of the five cluster analysis results.
Color symbology represents cluster. Color of groups in Figure 26 match groups in Figure 25.

The hypothesis motivating the creation of a background soil arsenic map is tested by comparing the results of the cluster analyses with the lithologic groups discussed in the Methods section of this report and Table 3. To do this, the samples in each lithologic group are coded by color based on assigned cluster (Figure 27, Figure 28, Figure 29). For this analysis, lithologic group size is not a consideration, and all nine lithologic groups are included. In no case is a lithologic group strongly associated with a specific cluster, the exception being the lithologic groups comprised of low sample numbers such as the Andesite group. When the number of samples in a lithologic group rises, for example the Columbia River Basalt or Quaternary/ Tertiary Sediment groups, the samples from these lithologic groups are distributed into multiple clusters.

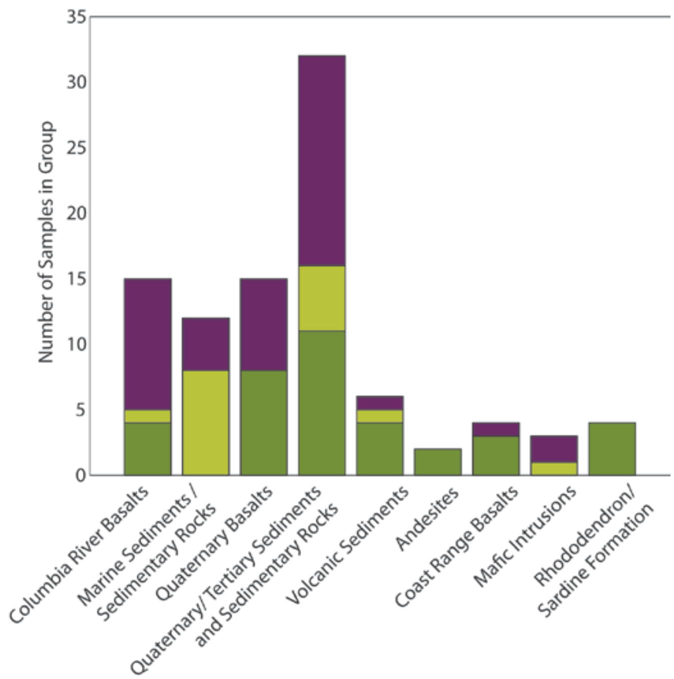


Figure 27: Bar graph connecting lithologic groups (X-axis) to the groups resulting from the three group cluster analysis (color symbology). Color symbology reflects clusters noted in Figure 21 and Figure 22.

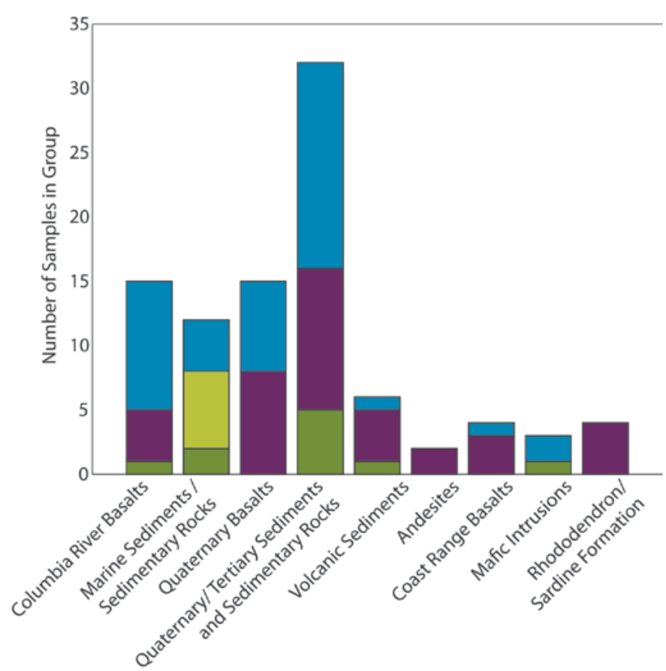


Figure 28: Bar graph connecting lithologic groups (X-axis) to the groups resulting from the four group cluster analysis (color symbology). Color symbology reflects clusters noted in Figure 23 and Figure 24.

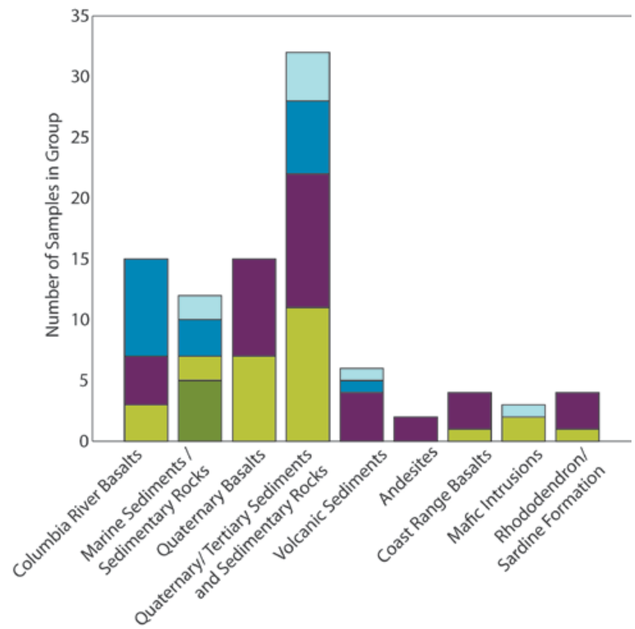


Figure 29: Bar graph connecting lithologic groups (X-axis) to the groups resulting from the five group cluster analysis (color symbology). Color symbology reflects clusters noted in Figure 25 and Figure 26.

CHAPTER 6: DISCUSSION AND CONCLUSIONS

For this project, 186 A and B horizon soil samples collected from 93 sites were tested for arsenic. Inductively Coupled Plasma Mass Spectrometry was used with a detection limit for arsenic of .01 ppm (Personal communication, David Jack, Apex Labs, October 2012). Soil pits that were sampled are above 31 geologic units per Walker and MacLeod's (1991) geologic map of Oregon. The resulting data are presented in Appendix J: Soil Arsenic Data from Northwest Oregon. A comprehensive outline linking the desired goals stated in the introduction of this project to their outcomes as illustrated by the tables and graphs included in this work is provided in Appendix L: Outline Illustrating Outcomes of Stated Goals.

High and low values measured and number of samples not registering values are grouped by geologic unit, presented by horizon, and seen in Appendix K: High and Low Values for Samples by Mapping Unit. The highest value measured in the A horizon is 13.90 ppm at site P4. These soils overly geologic unit Qs, Missoula Flood sediments, and are part of the Quaternary/ Tertiary Sediments and Sedimentary Rocks lithologic group. In the B horizon, the highest value measured is 20.4 ppm at site C4. This soil overlies geologic unit Tmst and is part of the Marine Sediments and Sedimentary Rocks lithologic group. Twenty-eight A horizon samples and 23 B horizon samples had unmeasurable amounts of arsenic.

6.1: CONCLUSIONS

The statistical analysis completed for this project indicates that soils sampled from above the Marine Sediments and Sedimentary Rocks (MS) group have statistically distinguishable, and higher, arsenic levels when compared to other lithologic groups (Table 12). These groups are shown to be distinct from each other based on the standard ANOVA and Kruskal-Wallis tests comparing the data by lithologic group both within and between each soil horizon. The mean arsenic levels of the MS group soils are 6.09 ±2.66 ppm in the A horizon and 10.26 ±4.65 in the B horizon. The other groups tested were not distinct from each other and were therefore grouped together. This group has mean arsenic levels of 3.10 ±3.19 ppm in the A horizon and 3.13 ±2.52 ppm in the B horizon.

Testing the A and B horizon soils for arsenic should be done for two reasons: first, to find the highest amount of arsenic within the horizons of the soil profile, and second, to characterize the variable distribution of arsenic throughout the vertical extent of the soil profile. When the A horizon and B horizon data analyzed for this project were compared to each other by lithologic group, the only groups that were statistically distinct were MS group values in the A and B horizon. In no other case were A and B horizon data statistically distinguishable from each other (5.4: A VS B HORIZON ANALYSIS). According to Burns et al. (1991), the level of arsenic in B horizon soils is expected to be higher in well developed soils. In many cases, the A horizon values of the soils tested for this project may be higher because they are young soils (Burns et al., 1991; Birkeland, 1999). Because neither the A nor B horizon samples tested for this project had statistically higher levels of arsenic, both horizons had to be tested to find the higher tested arsenic value. This demonstrates that surface sampling only may not accurately represent the soil, and both horizons should be sampled.

The specific reasons why there are comparatively elevated arsenic levels seen in soils above MS group units are beyond the scope of this project. However, this elevated arsenic content could be linked to both the prevalence of arsenic-linked minerals in these units and this lithologic group including formations that are known to be associated with elevated arsenic levels (eg., the Fisher and Eugene Formations). It is noteworthy that these results are consistent with the bedrock arsenic data of Onishi and Sandell (1955), Boyle and Jonasson (1973) and Mandal and Suzuki (2001) (Appendix B: Overview of Arsenic Content by Rock). Their work indicates that higher amounts of arsenic are commonly found in sedimentary rocks compared to igneous rocks. The MS lithologic group exemplifies the sedimentary rock types listed in Appendix B: Overview of Arsenic Content by Rock, while the other tested groups are volcanic in origin and exemplify igneous rock types listed in Appendix B: Overview of Arsenic Content by Rock.

The MS group includes the previously mentioned Fisher and Eugene Formations, both known to be associated with elevated arsenic levels (Hinkle and Polette, 1999). This association is apparent in the relatively high amounts of arsenic found in the aquifers underlying these units (Hinkle and Polette, 1999). The origin of the elevated arsenic content associated with these formations is environmental and may be linked to mineralogy of these rocks. For example, many of these rocks contain micas and these formations also include tuff units (Walker and MacLeod, 1991).

The MS group also includes significant amounts of additional tuffaceous sedimentary rock units. These rocks, formed primarily from the sediments of silicic volcanics, are known to be linked with high arsenic content (Hinkle and Polette, 1999).

The Scappoose Formation in the Coast Range Province is included in the MS group. This formation is known to be highly micaceous; this mineralogy provides a connection between the sediments of this formation and the Idaho Batholith from which its sediments are weathered (Orr and Orr, 1999). Weathered micas are known to be associated with elevated levels of naturally occurring arsenic (Dowling et al., 2002). The presence of elevated arsenic in Scappoose Formation rocks and their overlying soils would be consistent with the mineralogy of this Formation.

In the Bengal Basin, organic matter is believed to play an important role in the dangerous levels of naturally occurring arsenic found in the groundwater there (Ahmed et al., 2006). This elevated organic content may also play a role in the arsenic content of MS group soils, as rock types deposited in the marine environment are generally enriched in organic content.

This project has implications for establishing the background level of arsenic in soils. The arsenic content of soils is affected by geologic setting, as illustrated by the statistically distinguishable, and higher, levels of arsenic in soils above MS group lithologies (Table 12). Currently, the Oregon DEQ has one background level for naturally occurring arsenic in soils for the entire state. That the soils of the MS group are shown to be distinct from the other groups that were tested indicates this single value for a large geographic area may not be appropriate. The background levels of arsenic in soils may vary within a region and should be determined within a geologic context.

6.2: FUTURE WORK

A review of Appendix J: Soil Arsenic Data from Northwest Oregon suggests that the soil samples taken from above Unit Tus in the Cascades exhibit unexpectedly high arsenic values based on rock type and location. Many of the soils in this area exhibited relatively low or non-detectable amounts of arsenic. The two soil samples taken from above Unit Tus tested 4.22 ppm and 4.94 ppm in the A horizon, values which are higher than the mean of the MS group in the A horizon. In the B horizon, these pits measured 10.50 ppm and 11.30 ppm, again values that are higher than the mean of the MS group data in the B horizon. Further testing of the soils above this unit is required to ascertain if these values are representative of the soils from above this geologic unit and, if so, why these values are comparatively high.

A particularly interesting characteristic of the scatterplots (Figure 21, Figure 23, Figure 25) generated for the K-Means Cluster Analysis included in this project is the generally linear nature of the A vs B horizon arsenic values for sites, where A and B horizon normalized arsenic values are lower than 0.6. At these relatively low arsenic levels, the normalized A and B horizon arsenic values at a given site are very close to each other. When either horizon's normalized arsenic value is above this normalized 0.6 value, no apparent correlation between A and B horizon arsenic content is apparent at these sites. Future work would explore this observation to determine if this characteristic is true for other soil arsenic datasets. If so, further study would also ascertain why arsenic in A and B horizon soils at a given site are close to each other when arsenic content is low and more disparate at higher arsenic values.

In future studies, additional sampling where multiple samples are taken from multiple pits will allow additional statistical tests to be run. This type of dataset will also allow for a greater understanding of variability both within a single pit and between pits dug over the same bedrock lithology. A greater understanding of within pit variability would allow for outliers to be identified and managed, as well as a constraint of standard deviations. This type of additional sampling will additionally provide information on arsenic transport and host phase associations in soil profiles..

Additional work on this project would continue to explore the control of bedrock on soil arsenic levels. Statistics would be used to further ascertain the connection between bedrock and arsenic content. Exploring these controls would entail a more constrained sampling approach where samples would be taken from a smaller geographic area and from above a smaller number of geologic units. Sampling from above units that are distinct lithologically would ensure that if arsenic content of soils are not distinguishable based on underlying bedrock, that result is not due to the rock types being overly similar to each other.

In addition to exploring the connection between bedrock and the arsenic content of overlying soils, additional types of data would be collected to explore the effects of these other environmental factors on arsenic content. These additional types of data include pH, age, moisture content, and grain size. Additional data on pH would ascertain how this environmental factor is affecting the arsenic values measured. This type of data would also help constrain how pH needs to be considered during environmental assessments and other studies. Additional data on soil age and developmental stage would illuminate how arsenic levels vary by horizon in a soil depending on age, and could possibly illuminate important information regarding ratios of A to B horizon soil arsenic.

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Appendix A: Overview U.S. and International Arsenic Cleanup Levels

LOCATION	AGENCY	EXPOSURE PATHWAY	RELEVANT ARSENIC LEVEL	SOURCE
New Jersey, United States	New Jersey Department of Environmental Protection (NJDEP)	Residental and non-residental soils	20 mg/kg	Chen et al., 2001
Florida, United States	Florida Department of Environmental Protection (FDEP	Residential Soils	.80 mg/kg	Chen et al., 2001
		Non-residential Soils	3.7 mg/kg	
Montana, United States	Montana Department of Environmental Quality	Surface Soil (<2' deep)	40 mg/kg	Montana DEQ Arsenic Policy (http://deq.mt.gov/StateSuperfund/PDFs/ArsenicPositionPaper.pdf)
		Subsurface Soil (>2' deep)	300 mg/kg	http://deq.mt.gov/StateSuperfund/frequentlyaskedquestions.mcpx
Washington, United States	State of Washington Department of Ecology (for Tacoma Smelter Plume)		20 ppm	https://fortress.wa.gov/ecy/publications/publications/1109095.pdf
Wisconsin	Wisconsin Department of Natural Resources, 2009	Residential /Unrestricted Use	0.039	Teaf et al., 2010
California	California Environmental Protection Agency, 2005	Residential /Unrestricted Use	0.07	Teaf et al., 2010
Maine	Main Department of Environmental Protection, 2009	Residential /Unrestricted Use	1.4	Teaf et al., 2010
Ohio	Ohio Environmental Protection Agency, 2008	Residential / Unrestricted Use	6.7	Teaf et al., 2010

Appendix A: Overview of Mandatory Cleanup Levels (Continued)

LOCATION	AGENCY	EXPOSURE PATHWAY	RELEVANT ARSENIC LEVEL	SOURCE
Alabama, Colorado, Delaware, Idaho, Louisiana, Maryland, Missouri, North Carolina, Oklahoma, Oregon, Virginia, West Virginia, Wyoming	Alabama Department of Environmental Management, 2008; Colorado Department of Public Health, 2007; Delaware Department of Natural Resources and Environmental Control, 2007; Idaho Department of Environmental Quality, 2004; Louisiana Department of Environmental Quality, 2003; Maryland Department of the Environmenta, 2008; Missouri Risk Based Corrective Action, 2006; North Carolina Department of Environment and Natural Resources, 2005; Oklahoma Department of Environmental Quality, 2007; Oregon Department of Environmental Quality, 2005; Virginia Department of Environmental Quality, 2009; West Virginia Department of Environmental Protection, 2009; Wyoming Department of Environmental Quality, 2009	Residential/ Unrestricted Use	.38 to .41	Teaf et al., 2010
Florida	Florida Department of Environmental Protection, 2005	Residential/Unrestricted Use	2.1	Teaf et al., 2010
New Mexico	New Mexico Environment Department, 2009	Residential/Unrestricted Use	3.59	Teaf et al., 2010
Indiana	Indiana Department of Environmental Management, 2009	Residential/ Unrestricted Use	3.9	Teaf et al., 2010

Appendix A : Overview of Mandatory Cleanup Levels (Continued)

LOCATION	AGENCY	EXPOSURE PATHWAY	RELEVANT ARSENIC LEVEL	SOURCE
Texas	Texas Commission on Environmental Quality, 2009	Residential/ Unrestricted Use	24	Teaf et al., 2010
Arizona, Iowa, Kansas, Kentucky, Massachusetts, Minnesotta, Missouri, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Washington	Arizona Department of Environmental Quality, 2002; Iowa Department of Natural Resources, 2004; Kansas Department of Health and Environment, 2007; Code of Massachusetts Regulation Department of Environmental Protection, 2003; Montana Department of Environmental Quality, 2005; Missouri Risk Based Corrective Action, 2006; New Hampshire Department of Environmental Services, 2007; New Jersey Administrative Code, 2008; New York State Department of Environmental Conservation and New York State Department of Health, 2006; Pennsylvania Department of Environmental Protection, 2001; Rhode Island Department of Environmental Management, 1996; Washington Administrative Code, 2007	Residential/ Unrestricted Use	7 to 40	Teaf et al., 2010

Appendix A: Overview of Mandatory Cleanup Levels (Continued)

LOCATION	AGENCY	EXPOSURE PATHWAY	RELEVANT ARSENIC LEVEL	SOURCE
Finland	Finland Ministry of the Environment, 2007	Residential/Unrestricted Use	5	Teaf et al., 2010
Canada	Canadian Council of Ministers of the Environment, 2007	Residential/Unrestricted Use	12	Teaf et al., 2010
UK	United Kingdom Environment Agency, 2009	Residential/Unrestricted Use	32	Teaf et al., 2010
Netherlands	Netherlands Environmental Assessment Agency, 2008	Residential/Unrestricted Use	76	Teaf et al., 2010
Australia	Australia National Environment Protection Council, 1999	Residential/Unrestricted Use	100	Teaf et al., 2010
Japan	Japan Ministry of the Environment, 2003	Residential/Unrestricted Use	150	Teaf et al., 2010
Canada	Ministry of Environment of Canada	Agricultural	25 mg/kg	Chen et al., 2001
		Industrial	50 mg/kg	
		Residential	25 mg/kg	
United Kingdom		Domestic Gardens	10 mg/kg	Chen et al., 2001
		Parks, Playing Fields, Open Spaces	40 mg/kg	

Appendix B: Overview of Arsenic Content by Rock Type

Appendix B: Dataset 1; From Tanaka (1988)

IGNEOUS ROCKS:

Lithologic Group	Examples of rock-types	Onishi and Sandell (1955)				Boyle and Jonasson (1973)			
		Number Samples Tested	Low (mg/ kg)	High (mg/ kg)	Average (mg/kg)	Number Samples Tested	Low (mg/ kg)	High (mg/ kg)	Average (mg/kg)
Ultrabasic Group	Dunite, Pyrox-enite	19	0.3	3	1	40	0.034	15.8	1.5
	Serpen-tinite	8	0.8	6.6	2.8	-	-	-	-
Mafic - Extrusives	Basalt	113	0.1	9	1.4	78	0.18	113	2.3
Mafic - Intrusives	Gabbro, Diabase	32	0.066	5.6	1.4	112	0.061	28	1.5
Inter-mediate - Extrusives	Andesite, Dacite	33	0.5	5.8	2.2	30	0.5	5.8	2.7
Inter-mediate - Instrusives	Diorite, Grano-diorite, Syenite	6	0.59	2.3	1.4	39	0.091	13.4	1.03
Felsic - Extrusives	Rhyolite	52	0.2	12.2	3.1	2	3.2	5.4	4.3
Felsic - Intrusives	Granite	148	0	8.5	1.9	116	0.18	15	1.29

Appendix B: Dataset 1; From Tanaka (1988) (Continued)

SEDIMENTARY ROCKS:

Lithologic Group	Examples of rock-types	Onishi and Sandell (1955)				Boyle and Jonasson (1973)			
		Number Samples Tested	Low (mg/kg)	High (mg/kg)	Average (mg/kg)	Number Samples Tested	Low (mg/kg)	High (mg/kg)	Average (mg/kg)
Recent Sediments	Stream, River, Lake Sediments	-	-	-	-	9691	1	13000	14.1
Recent Sediments	Ocean Sediments	30	0.4	60	13.7	75	0.4	455	33.7
Clastic Sedimentary Rocks	Shales, Black Shales, Pyritic Shales	-	-	-	-	75	3	500	17
Clastic Sedimentary Rocks	Shale, Argillite, Slate	304	0.3	59	12.3	113	0.3	500	14.5
Clastic Sedimentary Rocks	Sandstone, Arkose, Conglomerate	10[1]	0.6[1]	9.7[1]	2.3[1]	15	0.6	120	4.1
Clastic Sedimentary Rocks	Sandstone, Arkose, Conglomerate	98	-	-	15.5		-	-	-
Chemical Sedimentary Rocks	Limestone, Dolomite	37	0.1	23.5	3.5	40	0.1	20.1	2.6
Chemical Sedimentary Rocks	Iron Formations, Iron-rich Sediments	-	-	-	-	45	1	2900	-
Evaporites	Gypsum, Anhydrite, etc.	-	-	-	-	5	0.1	10	3.5
Evaporites	Phosphorite	95	0.4	188	17.4	41	3.4	100	14.6

1. Excludes 88 samples from the Chinle Formation. Additional average value includes these samples.

Appendix B: Dataset 1; From Tanaka (1988) (Continued)

METAMORPHIC ROCKS:

Lithologic Group	Examples of rock-types	Onishi and Sandell (1955)				Boyle and Jonasson (1973)			
		Number Samples Tested	Low (mg/kg)	High (mg/kg)	Average (mg/kg)	Number Samples Tested	Low (mg/kg)	High (mg/kg)	Average (mg/kg)
Sedimentary Origin	Quartzite	40	2.2	70	6.4	4	2.2	7.6	5.5
	Slate, Phyllite	32	0.5	70	16.5	75	0.5	143	18.1
Contact Metamorphism	Hornfels	1	0.7	0.7	0.7	2	0.7	11	5.9
	Skarn	6	5	20	11	-	-	-	-
Regional Metamorphism	Schist	13	0.4	15	3.9	9	0	18.5	1.1
	Gneiss	4	0.5	2.2	1.3	7	0.5	4.1	1.5
	Amphibolite, Greenstone	1	2.2	2.2	2.2	45	0.4	45	6.3

Appendix B: Dataset 2; From Mandal and Suzuki (2001)

Material	Arsenic Content (in mg/kg^{-1})
Igneous (6)	
Acidic	
Rhyolite (extrusive)	3.2-5.4
Granite (intrusive)	0.18-15
Intermediate	
Latite, andesite, trachyte (extrusive)	0.5-5.8
Diorite, granodiorite, syenite (intrusive)	0.09-13.4
Basic	
Basalt (extrusive)	0.18-113
Gabbro (intrusive)	0.06-28
Ultrabasic	
Peridotite, dunite, serpentinite	0.3-15..8
Metamorphic (7-9)	
Quartzite	2.2-7.6
Slate/phyllite	0.5-143
Schist/gneiss	0.0-18.5
Sedimentary (7-9)	
Marine	
Shale/claystone (nearshore)	4.0-25
Shale/claystone (offshore)	3.0-490
Carbonates	0.1-20.1
Phosphorites	0.4-188
Sandstone	0.6-9
Non-marine	
Shales	3.0-12
Claystone	3.0-10
Recent Sediments (marine)	
Muds (9)	3.2-60
Clays (9)	4.0-20
Carbonate (10)	<1.0
Stream/river (11)	5.0-4000 (mineralized area)
Lake (12)	2.0-300
Soils (13)	<0.1-97

Appendix C: Site Observations for Phase I (1995) Sites (Ashbaugh, 1995)

(Descriptions of soils taken at these sites are described in Appendix D: Description of Phase I Soil Samples (Ashbaugh, 1995))

Site	Easting (UTM NAD 83)	Northing (UTM NAD 83)	Elevation (m)	Vegetation	Drainage	Underlying Geologic Unit
C1	52209	5039042	191	Douglas Fir	Moderately – well drained	Qs
C2	503643	5046637	55	Douglas fir	Well drained	Qs
C3	487002	5056635	122	Douglas fir	Well drained	Tc
C4	483559	5059728	146	Douglas fir	Well drained	Tmst
C5	475233	5076304	441	Douglas fir	Well drained	Tco
C6	478660	5065818	340	Douglas fir	Well drained	Tco
C7	473195	5069554	267	Douglas fir	Well drained	Tco
C8	453382	5073882	116	Spruce	Well drained	Ttv
C9	447913	5082998	122	Douglas fir	Well drained	Tss
C10	447059	5083464	407	Huckleberry	Well drained	Ti
C11	429230	5090474	15	Douglas fir, Spruce	Well drained	Tms
C12	462768	5062718	733	Douglas fir	Well drained	Ttv
C13	466104	4937226	146	Douglas fir	Well drained	Tsr
C14	449814	49806902	182	Douglas fir	Well drained	Tt
C15	449880	4906339	255	Douglas fir	Well drained	Tt
M1	578682	5022223	366	Douglas fir, Cedar	Well drained	Qal
M2	581417	5018888	474	Douglas fir, Maple	Well drained	QTba
M3	585815	5019067	518	Douglas fir, Cedar	Well drained	Qal
M4	595656	5017183	1106	Douglas fir	Well drained	Qg
M5	601650	5017695	1459	Huckleberry, True fir	Well drained	Qa
M6	603308	5015023	1252	Douglas fir	Well drained	Qa
M7	602981	5005326	1191	Douglas fir	Well drained	QTba
M8	637441	4933297	620	Juniper, Sagebrush	Well drained	Ts
M9	639027	4933925	790	Sagebrush	Well drained	Ts
M10	647676	4940502	729	Grass	Well drained	Ts

Appendix C: Site Observations for Phase I(1995) Sites (Ashbaugh, 1995) (Continued)
(Descriptions of soils taken at these sites are described in Appendix D: Description of Phase I Soil Samples (Ashbaugh, 1995))

Site	Easting (UTM NAD 83)	Northing (UTM NAD 83)	Elevation (m)	Vegetation	Drainage	Underlying Geologic Unit
M11	639253	4960466	486	Ponderosa pine, Juniper Sagebrush	Well drained	Tsfj
M12	631098	4962527	790	Ponderosa pine, Juniper, Sagebrush	Well drained	Tob
M13	623961	4971108	802	Sagebrush, Grass	Well drained	Qgs
M14	627175	4980627	742	Ponderosa pine, Juniper, Grass	Moderately – well drained	Tca
M15	630735	4982276	790	Ponderosa pine, Juniper, Sagebrush, Grass	Well drained	Tsfj
M16	634767	4991684	681	Juniper, Sagebrush, Grass	Well drained	Tcg
M17	620659	4995427	960	Ponderosa pine, Douglas fir	Well drained	Qtba
M18	564920	4952727	486	Douglas fir, Vine maple	Well drained	Tu
M20	583707	4944123	729	Douglas fir, Huckleberry, Cedar	Well drained	QTba
M21	580192	4925274	1143	Douglas fir	Well drained	QTba
M22	583605	4920961	1119	Douglas fir	Well drained	Qyb
M23	590619	4918395	1489	Spruce, Douglas fir, Lodgepole pine	Well drained	QTba
M24	572420	4916602	1079	Ponderosa pine	Well drained	QTba

Appendix C: Site Observations for Phase I(1995) Sites (Ashbaugh, 1995) (Continued)
(Descriptions of soils taken at these sites are described in Appendix D: Description of Phase I Soil Samples (Ashbaugh, 1995))

Site	Easting (UTM NAD 83)	Northing (UTM NAD 83)	Elevation (m)	Vegetation	Drainage	Underlying Geologic Unit
P1	528311	5044245	79	Douglas fir	Well drained	Qgs
P2	554815	5018163	79	Douglas fir	Well drained	Qgs
P3	527879	5045407	58	Douglas fir	Well drained	Qgs
P4	528949	5042701	46	Douglas fir	Well drained	Qs
P5	526892	5043608	58	Douglas fir	Well drained	Qs
P6	513128	5049466	280	Douglas fir	Well drained	Qs
P7	520862	5042653	261	Douglas fir	Well drained	Qs
P8	554815	5018163	267	Grass	Well drained	QTba
P9	553925	5018732	261	Douglas fir	Moderately – well drained	QTba
P10	551620	5019797	207	Alder, Cottonwood	Well drained	QTba
P11	5488523	5018316	76	Douglas fir, Vine maple, Oregon grape	Well drained	Qal
P12	549544	5019348	117	Douglas fir, Oregon grape	Well drained	QTba
P13	541212	5027009	58	Douglas fir	Well drained	QTs
P14	518251	5054374	6	Cottonwood,	Well drained	Qal
P15	541144	5039793	76	Douglas fir	Well drained	Qgs
P16	523521	5039058	198	Maple, Douglas fir	Moderately – well drained	Qs
P17	533155	5020282	73	Alder, Maple	Moderately drained	QTs
P18	533053	5020069	116	Alder, Maple	Well drained	QTba
S2	491580	4976053	222	Oak	Well drained	Tcg
S5	492013	4975464	73	Maple, Douglas fir	Well drained	Tcg
S6	491838	4977670	213	Douglas fir, Maple	Well drained	Tcg
S7	496863	4976953	6	Maple, Alder, Cottonwood	Well drained	Qal
S8	497483	4975055	46	Oak, Grass	Well drained	Qs
S9	492343	4973847	43	Cottonwood, Grass	Well drained	Qal

Appendix C: Site Observations for Phase I(1995) Sites (Ashbaugh, 1995) (Continued)
(Descriptions of soils taken at these sites are described in Appendix D: Description of Phase I Soil Samples (Ashbaugh, 1995))

Site	Easting (UTM NAD 83)	Northing (UTM NAD 83)	Elevation (m)	Vegetation	Drainage	Underlying Geologic Unit
S10	498126	4969207	131	Douglas fir	Well drained	Tc
S11	499150	4963674	152	Oak, Grass	Well drained	Tc
S12	505693	4994240	55	Cottonwood; Poison oak	Moderately drained	Qs
W1	519284	5025030	36	Grass	Poorly drained	Qal
W2	518563	5022416	100	Douglas fir, Spruce	Well drained	Tc
W3	517701	5013384	55	Douglas fir	Well drained	Qs
W4	507600	5011319	53	Oak	Well drained	Qs
W5	457126	4993949	207	Douglas fir	Well drained	Ty
W6	451290	4994789	134	Douglas fir	Well drained	Tco
W7	509234	5016806	350	Grass	Well drained	Tc
W8	512110	5019153	213	Douglas fir	Well drained	Tc
W9	515080	5016470	49	Douglas fir	Well drained	Qs

Appendix D: Description of Phase I Soil Samples (Ashbaugh, 1995)

Descriptions for the site locations from which these soil samples were taken are found in Appendix C: Site Observations for Phase I (1995) Sites (Ashbaugh, 1995))

Site	Horizon	Depth (cm)	Color	Texture	Structure
C1	A	0-5	10YR 5/3	Loam	Weak massive, Subangular blocky
C1	Bt	5-45	10YR 6/4	Loam	Subanguar blocky
C2	A	0-13	10YR 6/2	Loam	Massive
C2	Bw	13-50	10YR 6/3	Loam	Massive
C3	A	0-20	10YR 4/3	Clay	Moderately massive, Subangular blocky
C3	Bs	20-250+	5YR 4/6	Clay	Strongly massive, Subangular blocky
C4	A	0-20	7.5YR 3/4	Silt Loam	Granular
C4	Bt	20-60	10YR 6/6	Silty Clay Loam	Moderately massive, Subangular blocky
C5	A	0-5	10YR 4/3	Sandy Loam	Granular
C5	Bw	13-50	10YR 6/4	Sandy Clay Loam	Weakly massive, Subangular blocky
C6	A	0-5	10YR 5/3	Silty Loam	Granular
C6	Bt	10-45	10YR 6/4	Clay Loam	Moderately massive, Subangular blocky
C7	A	0-5	10YR 4/3	Sandy Loam	Weakly massive, Subangular blocky
C7	Bt	5-50	10YR 5/3	Sandy Clay Loam	Moderately massive, Subangular blocky
C8	A	0-25	10YR 3/3	Gravelly Sandy Loam	Weakly massive, Subangular blocky
C8	Bt	25-50	10YR 4/3	Gravelly Sandy Loam	Moderately massive, Subangular blocky
C9	A	0-50	10YR 3/3	Gravelly Sandy Loam	Weakly massive, Subangular blocky
C9	Bw	50-80	10YR 4/3	Gravelly Sandy Loam	Moderately massive, Subangular blocky
C10	A	0-12	10YR 2/2	Silty Loam	Subangular blocky
C10	Bt	12-45	10YR 4/4	Clay Loam	Subangular blocky
C11	A	0-10	10YR 2/2	Loamy Sand	Granular, Massive
C11	Bw	10-55	10YR 4/4	Sandy Loam	Weakly-moderately massive, Subangular blocky

Appendix D: Description of Phase I Soil Samples (Ashbaugh, 1995) (Continued)

Descriptions for the site locations from which these soil samples were taken are found in Appendix C: Site Observations for Phase I (1995) Sites (Ashbaugh, 1995))

Site	Horizon	Depth (cm)	Color	Texture	Structure
C12	A	0-5	10YR 2/2	Sandy Loam	Weakly massive, Subangular blocky
C12	Bw	5-35	10YR 2/2	Sandy Loam	Weaky massive, Subangular blocky
C13	A	0-25	10YR 4/3	Sandy Loam	Granular, Massive
C13	Bw	25-50	10YR 4/5	Clay Loam	Moderately massive, Subangular blocky
C14	A	0-20	10YR 6/6	Silty Loam	Granular, Massive
C14	Bw	20-60	10YR 4/3	Silty Clay Loam	Moderately massive, Subangular blocky
C15	A	0-30	10YR 6/3	Sandy Loam	Granular,Massive
C15	Bw	30-80	10YR 6/4	Sandy Loam	Moderately massive, Subangular blocky
C16	A	0-25	7.5YR 6/4	Silty Clay Loam	Granular, Massive
C16	Bt	25-100	7.5YR 6/5	Silty Clay Loam	Moderately massive, Subangular blocky
M1	A		7.5YR 6/2	Sandy Loam	Granular, Single grain
M1	Bw	45	10YR 5/4	Loamy Sand	Granular, Single grain
M2	A	0-8	2.5YR 5/2	Loamy Sand	Granular, Single grain
M2	Bw	15-37	10YR 4/3	Sandy Loam	Granular, Single grain
M3	A	0-5	5YR 3/1	Loamy Sand	Granular, Single grain
M3	Bw	5-25	7.5YR 6/2	Sandy Loam	Massive
M4	A	0-8	7.5YR 3/4	Loamy Sand	Granular, Single grain
M4	Bt	8-60	10YR 6/4	Loamy Sand	Massive
M5	A	0-15	10YR 5/2	Loamy Sand	Granular, Single grain
M5	Bw	15-45	10YR 6/3	Sandy Loam	Granular, Single grain
M6	A	0-20	10YR 4/1	Loamy Sand	Granular, Single grain
M6	Bw	20-50	10YR 6/4	Loamy Sand	Granular, Single grain
M7	A	0-5	10YR 3/1	Loamy Sand	Granular, Single grain
M7	Bt	5-30	10YR 6/4	Sandy Loam	Granular, Single grain
M8	A	0-15	10YR 4/2	Loamy Sand	Granular, Single grain
M8	Bt	15-30	10YR 4/2	Loamy Sand	Granular, Single grain

Appendix D: Description of Phase I Soil Samples (Ashbaugh, 1995) (Continued)
Descriptions for the site locations from which these soil samples were taken are found in Appendix C: Site Observations for Phase I (1995) Sites (Ashbaugh, 1995))

Site	Horizon	Depth (cm)	Color	Texture	Structure
M9	A	0-10	10YR 4/3	Sandy Clay Loam	Granular, Single grain
M9	Bt	10-30	10YR 4/2	Sandy Clay Loam	Weakly massive, Subangular blocky
M10	A	0-10	10YR 4/3	Loamy Sand	Granular, Single grain
M10	Bw	10-30	10YR 5/2	Sandy Loam	Massive
M11	A	0-17	10YR 6/3	Silty Clay Loam	Weakly massive, Subangular blocky
M11	Bt	17-30	10YR 7/2	Silty Clay Loam	Weakly massive, Subangular blocky
M12	A	0-17	10YR 5/4	Sandy Clay Loam	Granular, Single grain
M12	Bt	17-35	10YR 4/4	Clay Loam	Granular, Single grain
M13	A	0-15	10YR 6/3	Sandy Clay Loam	Granular, Single grain
M13	Bt	15-35	10YR 6/2	Sandy Clay Loam	Moderately massive, Subangular blocky
M14	A	0-5	5YR 4/2	Clay	Granular, Single grain
M14	Bt	5-30	5YR 3/3	Clay	Strongly massive, Subangular blocky
M15	A	0-15	10YR 6/2	Silty Clay Loam	Weakly massive, Subangular blocky
M15	Bt	15-35	10YR 6/2	Silty Clay Loam	Moderately massive, Subangular blocky
M16	A	0-17	10YR 5/4	Sandy Clay Loam	Weakly massive, Subangular blocky
M16	Bt	17-35	10YR 4/4	Sandy Clay Loam	Moderately massive, Subangular blocky
M17	A	0-10	10YR 5/3	Sandy Loam	Granular, Single grain
M17	Bt	10-35	7.5YR 4/3	Sandy Loam	Granular, Single grain
M18	A	0-5	7.5YR 4/2	Loamy Sand	Granular, Single grain
M18	Bw	10-35	7.5YR 5/2	Loamy Sand	Granular, Single grain

Appendix D: Description of Phase I Soil Samples (Ashbaugh, 1995) (Continued)
Descriptions for the site locations from which these soil samples were taken are found in Appendix C: Site Observations for Phase I (1995) Sites (Ashbaugh, 1995))

Site	Horizon	Depth (cm)	Color	Texture	Structure
M19	A	0-3	7.5YR 4/3	Loamy Sand	Granular, Single grain
M19	Bt	5-35	7.5YR 5/2	Sandy Loam	Weakly massive, Subangular blocky
M20	A	0-5	10YR 3/3	Loamy Sand	Granular, Single grain
M20	Bt	5-40	10YR 5/6	Loamy Sand	Granular, Single grain
M21	A	0-5	7.5YR 5/3	Loamy Sand	Granular, Single grain
M21	Bt	5-40	10YR 5/6	Loamy Sand	Granular, Single grain
M22	A	0-8	10YR 4/3	Loamy Sand	Granular, Single grain
M22	Bt	8-50	10YR 6/6	Loamy Sand	Granular, Single grain
M23	A	0-3	10YR 3/3	Loamy Sand	Granular, Single grain
M23	Bw	3-40	10YR 4/3	Loamy Sand	Granular, Single grain
M24	A	0-5	10YR 3/3	Loamy Sand	Granular, Single grain
M24	Bt	20-50	10YR 4/3	Loamy Sand	Granular, Single grain
P1	Bw	15-45	10YR 6/2	Silty Loam	Weakly massive, Subangular blocky
P2	Cox (B)	25-37	5YR 3/2	Gravelly Sandy Loam	Massive
P3	B	10-15	10YR 6/6	Gravelly Sandy Loam	Moderately massive, Subangular blocky
P4	B	25-37	10YR 5/4	Silty Loam	Weakly massive, Subangular blocky
P5	B	30-45	10YR 6/4	Silty Loam	Moderately massive, Subangular blocky
P6	A	0-25	10YR 3/3	Silty Loam	Granular, Massive
P6	Bw	25-45	10YR 5/3	Silty Loam	Weakly massive, Subangular blocky
P7	A	0-20	10YR 3/3	Silty Loam	Granular
P7	Bw	20-50	10YR 503	Silty Loam	Weakly massive, Subangular blocky
P8	A	0-20	5YR 3/3	Silty Clay Loam	Granular, Massive
P8	Bw	20-45	7.5YR 4/6	Clay Loam	Moderately massive, Subangular blocky

Appendix D: Description of Phase I Soil Samples (Ashbaugh, 1995) (Continued)
Descriptions for the site locations from which these soil samples were taken are found in Appendix C: Site Observations for Phase I (1995) Sites (Ashbaugh, 1995))

Site	Horizon	Depth (cm)	Color	Texture	Structure
P9	A	0-20	5YR 3/3	Silty Clay Loam	Granular, Massive
P9	Bt	20-50	7.5YR 5/8	Clay Loam	Moderately massive, Subangular blocky
P10	A	0-30	10YR 5/3	Silty Clay Loam	Granular, Single grain
P10	Bt	30-75	10YR 6/4	Gravelly Silty Clay Loam	Skeletal
P11	A	0-8	10YR 4/3	Sandy Loam	Granular, Single grain
P11	C (B)	8-30	10YR 6/3	Sand	Granular, Single grain
P12	A	0-10	10YR 3/3	Silty Sandy Loam	Massive
P12	Bw	10-35	10YR 4/3	Silty Sandy Loam	Massive
P13	A	0-12	7.5YR 3/3	Silty Sandy Loam	Granular, Single grain
P13	Bw	12-35	10YR 6/3	Gravelly Silty Sandy Loam	Skeletal
P14	A	0-15	10YR 3/3	Loamy Sand	Granular, Single grain
P14	C (B)	15-40	2.5YR 6/3	Samd	Granular, Single grain
P15	A	0-20	10YR 2/2	Loamy Sand	Granular, Single grain
P15	Bt	20-45	10YR 6/6	Gravelly, Silty Sandy Loam	Skeletal
P16	A	0-20	10YR 5/2	Silty Loam	Granular, Single grain
P16	Bt	20-50	10YR 6/4	Silty Loam	Moderately massive, Subangular blocky
P17	A	0-30	10YR 6/2	Silty Loam	Granular
P17	Bw	30-75	10YR 7/2	Silty Loam	Weakly massive, Subangular blocky
P18	A	0-20	7.5YR 3/3	Clay Loam	Granular, Massive
P18	Bt	20-100	7.5YR 5/6	Clay Loam	Granular, Massive
S2	A	0-20	7.5YR 4/3	Loam	Granular, Massive
S2	Bw	20-35	7.5YR 4/4	Gravelly, Loam	Skeletal

Appendix D: Description of Phase I Soil Samples (Ashbaugh, 1995) (Continued)
Descriptions for the site locations from which these soil samples were taken are found in Appendix C: Site Observations for Phase I (1995) Sites (Ashbaugh, 1995))

Site	Horizon	Depth (cm)	Color	Texture	Structure
S5	A	0-30	10YR 4/3	Clay Loam	Granular, Massive
S5	Bw	30-65	10YR 5/3	Clay Loam	Weakly massive, Subangular blocky
S6	A	0-30	7.5YR 4/4	Clay Loam	Weakly massive, Subangular blocky
S6	Bt	30-45	7.5YR 4/6	Clay Loam	Weakly massive, Subangular blocky
S7	A	0-15	10YR 5/2	Loamy Sand	Granular, massive
S7	C (B)	15-25	10YR 5/2	Sand	Granular, Single grain
S8	A	0-8	10YR 5/3	Sandy Loam	Granular, Massive
S8	Bw	8-35	10YR 6/3	Gravelly Sandy Loam	Skeletal
S9	A	0-20	10YR 5/3	Sandy Loam	Granular, Massive
S9	C (B)	20-30	10YR 5/2	Sand	Granular, Massive
S10	A	0-15	7.5YR 4/4	Clay Loam	Weakly massive, Subangular blocky
S10	Bt	15-600	7.5YR 5/4 Clay	Clay	Strongly massive, Subangular blocky
S11	A	0-15	5YR 4/3	Clay Loam	Granular, Massive
S11	Bt	12-600	5YR 5/6	Clay	Strongly massive, Subangular blocky
S12	A	0-5	10YR 6/2	Silty Loam	Granular, Massive
S12	Bw	5-35	10YR 6/3	Silty Loam	Granular, Massive
W1	A	0-25	10YR 4/2	Silty Loam	Granular, Massive
W1	Bg	25-35	10YR 5/2	Silty Clay	Moderately massive, Subangular blocky
W2	A	0-22	10YR 5/2	Loam	Weakly massive, Subangular blocky
W2	B	22-45	10YR 5/4	Silty Clay	Moderately massive, Subangular blocky
W3	A	0-25	10YR 5/3	Silty Loam	Granular, Massive
W3	Bw	25-60	10YR 5/4	Silty Clay Loam	Weakly massive, Subangular blocky

Appendix D: Description of Phase I Soil Samples (Ashbaugh, 1995) (Continued)
Descriptions for the site locations from which these soil samples were taken are found in Appendix C: Site Observations for Phase I (1995) Sites (Ashbaugh, 1995))

Site	Horizon	Depth (cm)	Color	Texture	Structure
W4	A	0-30	10YR 5/2	Loam	Granular
W4	Bw	30-45	10YR 5/2	Silty clay Loam	Weakly massive, Subangular blocky
W5	A	0-40	10YR 4/3	Loam	Granular
W5	Bt	40-55	10YR 4/6	Clay	Moderately massive, Subangular blocky
W6	A	0-22	10YR 6/4	Silty Clay	Granular, Massive
W6	BC	22-30	10YR 6/3	Clay	Moderately massive, Subangular blocky
W7	A	0-60	7.5YR 4/4	Silty Clay Loam	Granular, massive
W7	Bt	60-120	7.5YR 5/6	Clay	Strongly massive, Subangular blocky
W8	A	0-45	7.5YR 5/4	Silty Clay Loam	Granular, Massive
W8	Bt	45-150	7.5YR 5/4	Clay	Strongly massive, Subangular blocky
W9	A	0-20	10YR 5/3	Silty Loam	Granular, Massive
W9	Bw	20-50	10YR 6/3	Silty clay Loam	Granular, Massive

Appendix E: Site Observations for Phase II (2010) Sites

(Descriptions of soils taken at these sites are described in Appendix F: Description of Phase II Soil Samples (2010). Photos of sites are included in Appendix G: Site and Soil Pit Images from Sites Sampled During Phase II Sampling (2010))

Site	Easting (UTM NAD 83)	Northing (UTM NAD 83)	Vegetation	Elevation (by GPS)	Drainage Note	Underlying Geologic Unit
TR1	532794	5020289	Maple, Alder	509	well drained	QTb
TR2	538370	5032348	Douglas Fir, Hazelnut, Ferns	569	well drained	QTb
TR3	478253	5055388	Douglas Fir, Cedar, Maple	205	well drained	Ti
TR4	476365	5055716	Douglas Fir, Maple,	560	well drained	Ti
TR5	432411	5019746	Alder, Douglas Fir	253	well drained	Tsd
TR6	429312	5018963	Western Hemlock,	226	Good	Tsd
TR7	425260	4990592	Western Hemlock,	785.3	well drained	Tpb
TR8	424371	4992681	Western Hemlock; Douglas Fir	137.8	well drained	Tpb
TR9	518803	4914773	Douglas Fir, berries	207	well drained	Tub
TR10	518782	4914988	Douglas Fir, Maple	276	well drained	Tub
TR11	555775	4916836	Douglas Fir,	1415	well drained	Tus
TR12	560076	4915917	Douglas Fir		well drained	Tus
TR13	575374	4896162	Douglas Fir,		well drained	Tfc
TR14	575103	4898916	Douglas Fir	1929	well drained	Tfc

Appendix E: Site Observations for Phase II (2010) Sites (Continued)

(Descriptions of soils taken at these sites are described in Appendix F: Description of Phase II Soil Samples (2010). Photos of sites are included in Appendix G: Site and Soil Pit Images from Sites Sampled During Phase II Sampling (2010)

Site	Easting (UTM NAD 83)	Northing (UTM NAD 83)	Vegetation	Elevation (by GPS)	Drainage Note	Underlying Geologic Unit
TR15	582877	4921228	Douglas Fir,	3700	well drained	Qg
TR16	580184	4925531	Douglas Fir	3817	well drained	Qg
TR17	579650	4930556	Hemlock, Douglas Fir	3158	well drained	Tbaa
TR18	580593	4937061	Douglas Fir, Western Hemlock, Rhododendron, Huckleberry	2678	well drained	Tbaa

Appendix F: Description of Phase II Soil Samples (2010)

Descriptions for the site locations from which these soil samples were taken are found in Appendix F: Description of Phase II Soil Samples (2010). Photos of these soil pits are included in Appendix G: Site and Soil Pit Images from Sites Sampled During Phase II Sampling (2010))

Site	Horizon	Depth (cm)	Color	Texture	Clay %	Structure
TR1	A	3	7.5YR 4.6	Heavy Sandy Clay Loam	30	Subangular Blocky
TR1	Bt	22	5YR 4/6	Sandy Clay Loam	50	Subangular Blocky
TR2	A	3	5YR 3/2	Silt Loam	15	Subangular Blocky
TR2	Bw	12.5	7.5YR 5/3	Silt Loam	25	Weak Subangular Blocky
TR3	A	8	10YR 4/3	Sandy Loam	10	Weak Subangular Blocky
TR3	Bw	35	10YR 4/6	Sandy Loam	15	Weak Subangular Blocky
TR4	A	10	10YR 4/3	Sandy Loam	8	Weak Subangular Blocky
TR4	Bw	45	10YR 3/4	Sandy Loam	12	Weak Subangular Blocky
TR5	A	5	10YR 4/4	Fine Sandy Loam	10	Weak Subangular Blocky
TR5	Bw	35	10YR 6/8	Fine Sandy Loam	18	Weak Subangular Blocky
TR6	A	6	10YR 2/2	Sandy Loam	5	Weak Subangular Blocky
TR6	Bw	40	10YR 4/4	Sandy Loam	15	Weak Subangular Blocky
TR7	A	10	5YR 3/2	Sandy Loam	5	Weak Subangular Blocky
TR7	Bw	32.5	2.5YR 3/3	Sandy Loam	12	Weak Subangular Blocky

Appendix F: Description of Phase II Soil Samples (2010) (Continued)

Descriptions for the site locations from which these soil samples were taken are found in Appendix F: Description of Phase II Soil Samples (2010). Photos of these soil pits are included in Appendix G: Site and Soil Pit Images from Sites Sampled During Phase II Sampling (2010))

Site	Horizon	Depth (cm)	Color	Texture	Clay %	Structure
TR8	A	15	10YR 2/2	Sandy Loam	5	Weak Subangular Blocky
TR8	Bw	30	10YR 3/3	Sandy Loam	15	Weak Subangular Blocky
TR9	A	2	10YR 5/4	Sandy Loam	10	Moderate Subangular Blocky
TR9	Bt	5	7.5YR 5/3	Sandy Clay Loam	30	Well Developed Subangular Blocky
TR10	A	2	7.5YR 4/2	Sandy Loam	10	Moderate Subangular Blocky
TR10	Bt	40	7.5YR 4/2	Sandy Clay Loam	30	Well Dev SBK
TR11	A	15	10YR 4/2	Sandy Loam	5	Weak Subangular Blocky
TR11	Bw	55	10YR 5/4	Sandy Loam	12	Weak Subangular Blocky
TR12	A	12	10YR 4/3	Sandy Loam	5	Weak Subangular Blocky
TR12	Bw	45	10YR 5/3	Sandy Loam	12	Weak Subangular Blocky
TR13	A	8	10YR 3/3	Sandy Loam	5	Weak Subangular Blocky
TR13	Bw	32.5	10YR 4/4	Sandy Loam	12	Weak Subangular Blocky

Appendix F: Description of Phase II Soil Samples (2010) (Continued)

Descriptions for the site locations from which these soil samples were taken are found in Appendix F: Description of Phase II Soil Samples (2010). Photos of these soil pits are included in Appendix G: Site and Soil Pit Images from Sites Sampled During Phase II Sampling (2010))

Site	Horizon	Depth (cm)	Color	Texture	Clay %	Structure
TR14	A	8	10YR 3/3	Sandy Loam	5	Weak Subangular Blocky
TR14	Bw	45	10YR 6/4	Sandy Loam	12	Weak Subangular Blocky
TR15	A	10	10YR 2/2	Sandy Loam	2	Weak Subangular Blocky
TR15	Bw	45	10YR 4/6	Sandy Loam	12	Weak Subangular Blocky
TR16	A	10	7.5YR 3/3	Sandy Loam	5	Weak Subangular Blocky
TR16	Bw	47.5	10YR 4/6	Sandy Loam	12	Weak Subangular Blocky
TR17	A	8	7.5YR 3/2	Sandy Loam	5	Weak Subangular Blocky
TR17	Bw	40	10YR 6/4	Sandy Loam	12	Weak Subangular Blocky
TR18	A	5	2.5YR 3/2	Sandy Loam	5	Weak Subangular Blocky
TR18	Bw	40	10YR 5/4	Sandy Loam	12	Weak Subangular Blocky

Appendix G: Site and Soil Pit Images from Sites Sampled During Phase II Sampling (2010)

This appendix contains two photographs for each site sampled during Phase II Sampling in 2010 (Appendix E: Site Observations for Phase II (2010) Sites; Appendix F: Description of Phase II Soil Samples (2010)).

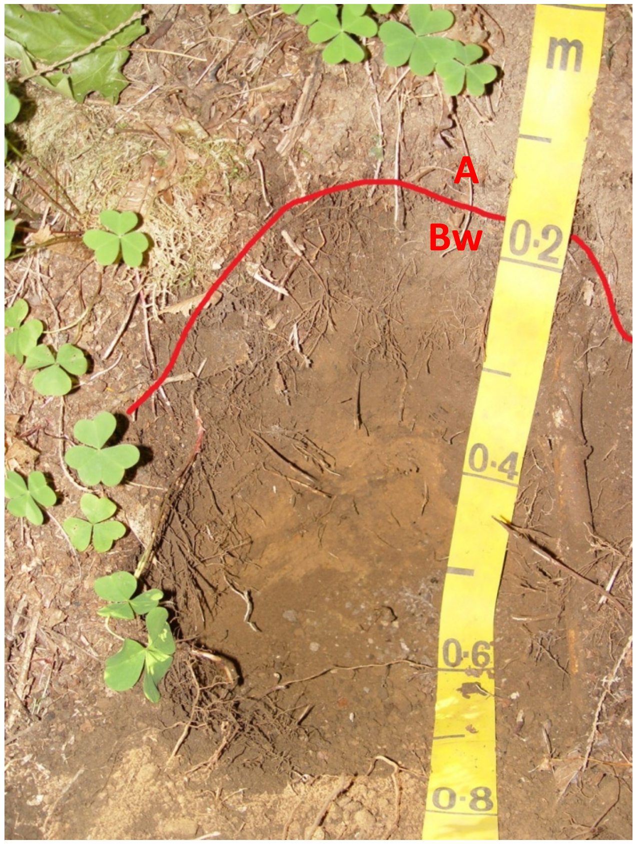
The upper photograph for each site shows the soil pit from which the samples were collected. The red line drawn on each of the upper photographs separates the A horizon and B horizon. Horizons are labeled on each photograph. The B horizon soils are further classified as Bw (younger) or Bt (older and more well developed) horizons (Birkeland, 1999). The samples taken at each pit are further described in Appendix F: Description of Phase II Soil Samples (2010).

The lower photograph for each site illustrates the surrounding conditions at the site, particularly vegetation. Site descriptions are further described in Appendix E: Site Observations for Phase II (2010) Sites.

SITE TR-1:

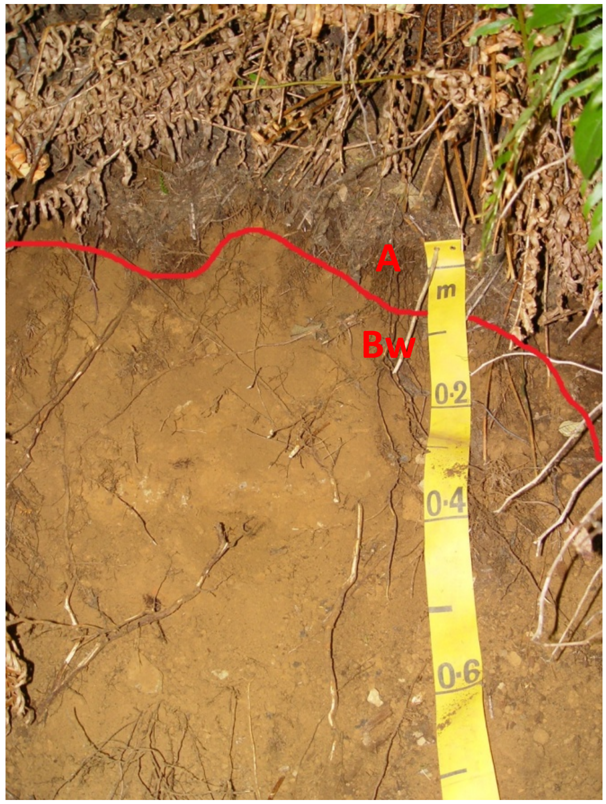
SITE TR-2:

SITE TR-3:



SITE TR-4:

SITE TR-5:

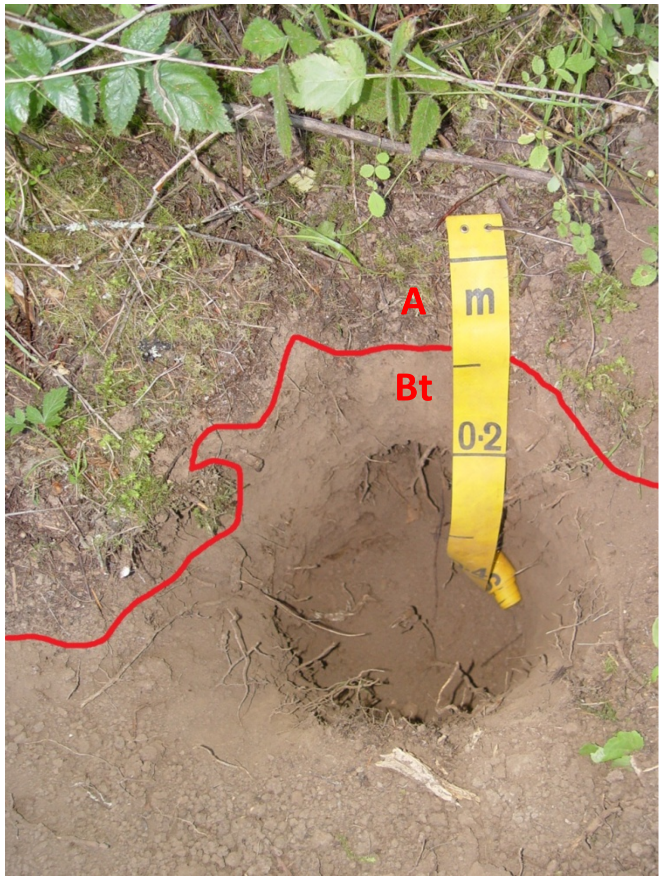


SITE TR-6:

SITE TR-7:

SITE TR-8:

SITE TR-9:



SITE TR-10:

SITE TR-11:

SITE TR-12:

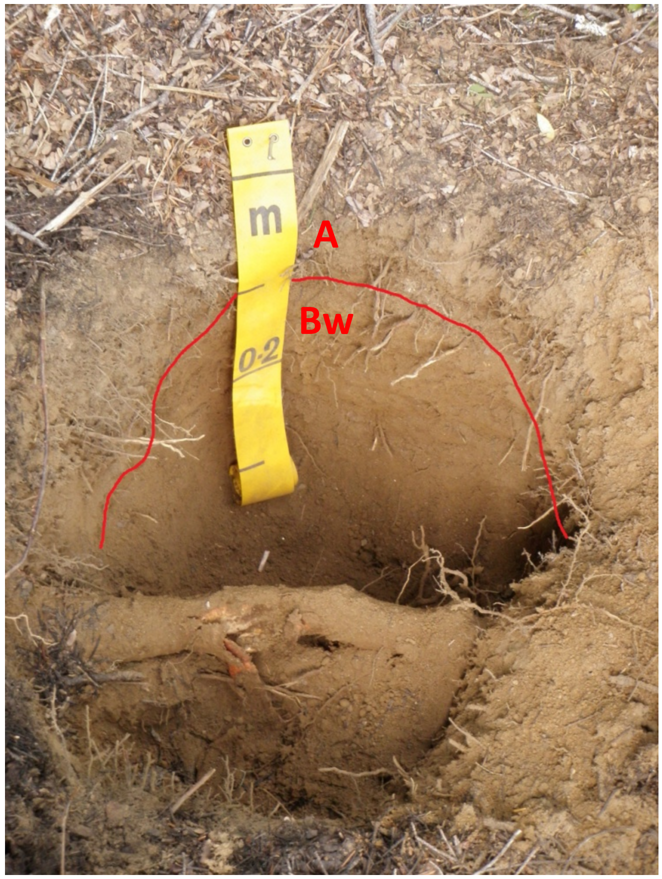
SITE TR-13:

SITE TR-14:

SITE TR-15:

SITE TR-16:

SITE TR-17:



SITE TR-18:


m
A
0.2
Bw
0.4

Appendix H: Example page from APEX Laboratory's Quality Control Sample Results Report

Apex Labs

12232 S.W. Garden Place
Tigard, OR 97223
503-718-2323 Phone
503-718-0333 Fax

GeoEngineers -Seattle	Project: **Oregon Metals Evalutaion**	
600 Stewart St. Suite 1700	Project Number: 2787-050-000	**Reported:**
Seattle, WA 98101	Project Manager: Neil Morton	05/01/10 10:42

QUALITY CONTROL (QC) SAMPLE RESULTS

DRAFT: Total Metals by EPA 6020 (ICPMS)

Analyte	Result	MDL	Reporting Limit	Units	Dil.	Spike Amount	Source Result	%REC	%REC Limits	RPD	RPD Limit	Notes
Batch 1004105 - EPA 3051A							Soil					
Blank (1004105-BLK1)						Prepared: 04/08/10 09:29	Analyzed: 04/08/10 16:16					
EPA 6020												
Antimony	ND	---	1.00	mg/kg wet	10	---	---	---	---	---	---	
Arsenic	ND	---	2.00	"	"	---	---	---	---	---	---	
Beryllium	ND	---	1.00	"	"	---	---	---	---	---	---	
Cadmium	ND	---	1.00	"	"	---	---	---	---	---	---	
Lead	ND	---	1.00	"	"	---	---	---	---	---	---	
Selenium	ND	---	2.00	"	"	---	---	---	---	---	---	
Silver	ND	---	1.00	"	"	---	---	---	---	---	---	
Thallium	ND	---	1.00	"	"	---	---	---	---	---	---	
LCS (1004105-BS1)						Prepared: 04/08/10 09:29	Analyzed: 04/08/10 15:58					
EPA 6020												
Antimony	25.8	---	1.00	mg/kg wet	10	25.0	---	103	80-120%	---	---	
Arsenic	48.9	---	2.00	"	"	50.0	---	98	"	---	---	
Beryllium	24.7	---	1.00	"	"	25.0	---	99	"	---	---	
Cadmium	50.1	---	1.00	"	"	50.0	---	100	"	---	---	
Lead	46.6	---	1.00	"	"	"	---	93	"	---	---	
Selenium	23.9	---	2.00	"	"	25.0	---	96	"	---	---	
Silver	24.6	---	1.00	"	"	"	---	99	"	---	---	
Thallium	23.8	---	1.00	"	"	"	---	95	"	---	---	
Duplicate (1004105-DUP1)						Prepared: 04/08/10 09:29	Analyzed: 04/08/10 16:54					
QC Source Sample: P07B1a (A10D053-05)												
EPA 6020												
Antimony	ND	---	1.11	mg/kg dry	10	---	ND	---	---	---	40%	
Arsenic	**2.69**	---	2.22	"	"	---	2.81	---	---	5	40%	
Beryllium	ND	---	1.11	"	"	---	ND	---	---	---	40%	
Cadmium	ND	---	1.11	"	"	---	ND	---	---	---	40%	Q-05
Lead	**16.2**	---	1.11	"	"	---	15.9	---	---	2	40%	
Selenium	ND	---	2.22	"	"	---	ND	---	---	---	40%	
Silver	ND	---	1.11	"	"	---	ND	---	---	---	40%	
Thallium	ND	---	1.11	"	"	---	ND	---	---	---	40%	
Matrix Spike (1004105-MS1)						Prepared: 04/08/10 09:29	Analyzed: 04/08/10 16:57					
QC Source Sample: P07B1a (A10D053-05)												

DRAFT REPORT

The results provided in this report are PRELIMINARY and are subject to change based on subsequent analysis, QC validation or final data review. Please use these results with the understanding that they may have not been finalized by the laboratory

DRAFT REPORT, DATA SUBJECT TO CHANGE

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Appendix I: Descriptions of Lithology by Lithologic Group

This appendix contains an explanation of rock units found within the study area of this project. descriptions of all underlying bedrock geology from above which soil was sampled for this project. Descriptions are provided primarily verbatim from Walker and MacLeod's (1991) Geologic Map of Oregon. The units are not listed in order of youngest to oldest, but are provided grouped by the lithologic groups discussed in Chapter 4.4: GROUPINGS FOR STATISTIC ANALYSIS.

Appendix I.1: Quaternary/ Tertiary Sediments and Sedimentary Rocks

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 unconsolidated sediment marginal to playas, soils containing abundant organic material, and thin peat beds.

Qs – Lacustrine and fluvial sedimentary rocks (Pleistocene)

Unconsolidated to semiconsolidated lacustrine clay, silt, sand, and gravel; in places includes mudflow, fluvial, and eolian deposits and discontinuous layers of peat. In places contains mollusks or vertebrate fossils indicating Pleistocene age; mostly deposits of late Pleistocene age, but locally includes some deposits of early Holocene age. Includes Touchet Beds of Flint (1938) and deposits of valley terraces of Newcomb (1965). **Author's Note:** This unit includes Missoula Flood sediments.

Qg – Glacial deposits (Pleistocene)

Unsorted boulder gravel, sand, and rock flour in ground, terminal, and lateral moraines.

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. Includes alluvial gravel and mudflow deposits of Walters Hill and Springwater Formations (Trimble, 1963). In places, grades laterally through palagonite tuff and breccia into basalt flows.

Ts – Tuffaceous sedimentary rocks and tuff (Pliocene and Miocene)

Semiconsolidated to well-consolidated mostly fluviatile tuffaceous sandstone, siltstone, mudstone, concretionary claystone, conglomerate pumicite, air-fall and water-deposited vitric ash, palagonitic tuff and tuff breccia. Palagonitic tuff and breccia grade laterally into altered and unaltered basalt flows of unit Tob. Also includes thin, welded and nonwelded ash-flow tuffs. Includes the Dalles Formation of Newcomb (1966, 1969); the Madras (or Deschutes) Formation, and the Sandy River Mudstone and the Troutdale Formation of Trimble (1963) and the lower Pliocene Helvetia Formation of Schlicker and Deacon (1967).

Qgs – Glaciofluvial, lacustrine, and pediment sedimentary deposits (Pleistocene)

Unconsolidated, poorly sorted silt, sand, and gravel. Mostly in northern Morrow and Umatilla Counties where unit represents deposits of swollen late Pleistocene Columbia River (Hogenson, 1964)

Appendix I.2: Marine Sediments and Sedimentary Rocks

Tco – Cowlitz Formation (upper and middle Eocene)

Micaceous, arkosic to basaltic marine sandstone, siltstone, and mudstone. Foraminiferal assemblages are referred to the upper Narizian Stage of Mallory (1959) in Newton and Van Atta (1976).

Tms – Marine sedimentary rocks (middle and lower Miocene)

Fine- to medium -grained marine siltstone and sandstone that commonly contains tuff beds. Includes the Astoria Formation, which is mostly micaceous and carbonaceous sandstone, and the middle Miocene Gnat Creek Formation of Niem and Niem (1985), which overlies Frenchmen Springs Member of the Wanapum Basalt of east of Astoria. The Astoria Formation locally contains calcareous concretions and sulfide nodules; foraminifera in formation are assigned to the Saucesian and Relizian Stange (Kleinpell, 1938; Rau, 1981) and molluscan fossils to the Newportian Stage of Addicott (1976, 1981). Also includes Nye Mudstone, which is massive to poorly bedded siltstone and mudstone; foraminiferal assemblages assigned to the Saucesian Stage (Kleinpell, 1938; Rau, 1981) and molluscan fauna to Pillarian (?) Stage (Armentrout, 1981).

Tmst – Marine sedimentary and tuffaceous rocks (middle Miocene to upper Eocene)

Tuffaceous and arkosic sandstone, locally fossiliferous, tuffaceous siltstone, tuff, glauconitic sandstone, minor conglomerate layers and lenses, and a few thin coal beds. Includes Scappoose Formation (Trimble, 1963; Wells et al., 1983), mudstone of Oswald West (Niem and Van Atta ,1973; Wells et al., 1983), Pittsburg Bluff Formation (Wells et al., 1983), and Smuggler Cove and Northrup Creek formations (informal names) of Niem and Niem (1985).

Tsd – Sedimentary rocks (Oligocene and upper Eocene)

Marine shale siltstone, sandstone, and conglomerate, in places partly composed of tuffaceous and basaltic debris; interbeds of arkosic, glauconitic and quartzose sandstone. Foraminifera are referable to the Refugian and Zemorrian stages (see marine sedimentary rocks – units Toes and Toem – of Wells et al., 1983). Includes Bastendorff Formation of Baldwin (1974).

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. Includes the Nestucca Formation, which contains a foraminiferal assemblage assigned to the upper Narizian and lowermost Refugian Stages (Snavely et al., 1969; McKeel, 1980); the Spencer Formation, which contains Narizian Stage foraminifera; the Keasy Formation, which contains upper Narizian and lower Refugian Stage foraminifera (McDougall, 1975, 1980); the Coaledo and Bateman formations of Baldwin (1974); upper Eocene sandstone of Bela (1981); and the Sager Creek Formation (informal name) of Niem and Niem (1985).

Tt – Tyee Formation (middle Eocene)

Very thick sequence of rhymically 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. Foraminiferal fauna are referred to the Ulatisian Stage (Snavely et al., 1964). Groove and flute casts indicate deposition by north-flowing turbidity currents (Snavely et al., 1964), but probable provenance of unit is southwest Idaho (Heller et al., 1985).

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. Foraminiferal assemblages in siltstone referred to the Ulatisian and lower Narizian Stages (Snavely et al., 1969; McKeel, 1980) Includes the Elkton Formation of Baldwin (1974; also see Beaulieu and Hughes, 1975), which consists of thin-bedded siltstone and minor sandstone interbeds.

Appendix I.3: Mafic Intrusions

Ti – Mafic intrusions (Oligocene)

Sheets, sills, and dikes of massive granophyric ferrogabbro; some bodies strongly differentiated and include pegmatic gabbro, ferrogranophyre, and granofyre (MacLeod, 1981). Plagioclase and amphibole from unit have yielded K-Ar ages of about 30 Ma (Snavely et al., 1976a).

Appendix I.4: Coast Range Basalts

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 alkalic 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 (Snavely et al., 1968). Foraminiferal assemblages referred to the Ulatisian and Penutian Stages (Snavely et al., 1969); K-Ar ages range from 50.7+/-3.1 to 58.1+/-1.5 Ma (Duncan, 1982); includes the lower part of the Roseburg Formation of Baldwin (1974), which has yielded K-Ar ages as old as 62 Ma.

Ttv – Tillamook Volcanics (upper and middle Eocene)

Subaerial basaltic flows and breccia and submarine basaltic breccia, pillow lavas, lapilli and augite-rich tuff with interbeds of basaltic sandstone, siltstone, and conglomerate. Includes some basaltic andesite and, near the top of the sequence, some dacite. Potassium-argon ages on middle and lower parts of sequence range from about 43 to 4 Ma (Magill et al., 1981): one potassium-argon age from dacite near top of sequence is about 40 Ma (Wells et al., 1983).

Appendix I.5: Columbia River Basalts

Tc – Columbia River Basalt Group and related flows (Miocene) (Cascade Range)

Subaerial basalt and minor andesite lava flows and flow breccia; locally may include invasive basalt flows. Flows locally grade laterally into subaqueous pillow-palagonite complexes and bedded palagonitic tuff and breccia. In places includes tuffaceous sedimentary interbeds. Joints commonly coated with nontronite and other clayey alteration products. Locally deeply weathered to lateritic soil. Occurs principally in the Cascade Range. Unit includes correlative Stayton Lavas of Thayer (1936, 1939). See also description of unit for eastern Oregon. Swanson et al. (1979) and Swanson et al. (1981) locally separated rocks into: (Wanapum Basalt and Grande Ronde Basalt)

Tcg – Grande Ronde Basalt (middle and lower Miocene)

Flows of dark-gray to black, aphyric tholeiitic basalt, including both high- and low-Mg chemical types (Swanson et al., 1979). Potassium-argon ages mostly in the range of 15 to 17 Ma (Lux, 1982; Fiebelkorn et al., 1983).

Tob – Olivine basalt (Pliocene and Miocene)

Thin, commonly open-textured (diktytaxitic), subophitic to intergranular olivine basalt flows, intercalated with and grades laterally through palagonite breccias and tuff into tuffaceous sedimentary rocks (unit Ts). Potassium-argon ages ranging from about 4 to 7 Ma indicate unit is mostly of early Pliocene and late Miocene age. Includes Shumuray Ranch Basalt and Antelope Flat Basalt of Kittleman et al. (1965), Grassy Mountain Basalt of Corcoran et al. (1962), Drinkwater Basalt of Bowen et al. (1963), basalt formerly assigned to Danforth Formation by Piper et al. (1939) (Walker, 1979), Hayes Butte Basalt of Hampton (1964), Pliocene and upper Miocene basalt flows capping and interstratified with the Madras (or Deschutes) Formation, and basalt flows interstratified in the Dalles Formation of Newcomb (1966; 1969).

Tpb – Porphyritic Basalt (Upper Eocene)

Subaerial lava flows and breccia of porphyritic basalt, minor basaltic andesite, and rare dacite. Includes basalt of Cascade Head (Wells et al., 1983), Yachats basalt (Snavely et al., 1976b), and Goble Volcanic Series (Warren et al., 1945). Also includes camptonitic extrusive rocks (tuff breccia, lapilli tuff, and minor pillow flows) interbedded in Nestucca Formation.

Tub – Basaltic lava flows

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

Appendix I.6: Quaternary Basalts

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).

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 hypersthenes. Flows and breccia form shields, lava cones, and valley fill; in places greatly dissected and modified by glacial and fluvial erosion. Includes Boring Lava of Trimble (1963) and Hampton (1972) and Battle Ax Basalts of Thayer (1936). Potassium-argon ages from this unit range from about 1.2 to 3.9 Ma; in places difficult to distinguish from youngest flows of unit Trb.

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 (14C); isotopic ages on flows range from about 1,000 to 6,000 yr B.P. (14C). Author's Note: Young cinder cones.

Appendix I.7: Andesites

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.

Appendix I.8: Rhododendron/Sardine Formations

Tbaa – Basaltic and andesitic rocks (upper to 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 aerially 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. Potassium argon ages range from about 10 Ma to about 17 Ma. Much of this unit was previously assigned to the Sardine Formation (Peck et al. 1964), although the type locality of the Sardine

Formation ("Sardine Series" as mapped by Thayer, 1939) may be older. Includes Elk Lake Formation (White, 1980a, 1980b), part of the Rhododendron Formation (Trimble, 1963; Wise, 1969) and andesite of Nohorn Creek of Hammond et al. (1982).

Tfc – Flows and clastic rocks, undifferentiated (Miocene)

Chiefly basaltic andesite and andesite lava flows and flow breccia containing plagioclase and pyroxene (hypersthenes 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. The oldest radiometrically dated rocks assigned to this unit are about 17 Ma (Sutter, 1978); in part lapped by flows questionably assigned to unit Tba, radiometrically dated at about 10 Ma, and unconformably overlain by flows of unit Trb. Includes some of rocks formerly mapped as Sardine Formation and some mapped as Rhododendron Formation.

Appendix I.9: Volcanic Sediments

Tca – Clastic rocks and andesite flows (lower Oligocene?, Eocene, and Paleocene?)

Mostly andesitic lava flows, domes, breccia, and small intrusive masses and lesser basaltic to rhyolitic rocks; interlayered saprolite, bedded volcaniclastic and epiclastic mudstone, claystone, siltstone, sandstone, conglomerate, and mudflow (lahar) deposits. Mostly consists of Clarno Formation of central Oregon. Fossil plants and vertebrates in these rocks are Eocene in age. Andesite and basalt lava flows are typically slightly altered; most glass is devitrified and altered to clay minerals, zeolites, and secondary feldspar. Reliable K-Ar ages of rocks from unit range from about 54 Ma to about 37 Ma (Evernden and James, 1964; Fiebelkorn et al., 1983). Although these rocks are lithologically similar to, but generally less altered than, rocks of the Clarno Formation, they are coeval with the John Day Formation. Most of these enigmatic rocks of Oligocene and early Miocene age are included in unit Tas.

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, airfall, 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.

Tsfj – John Day Formation of east-central Oregon (lower Miocene, Oligocene, and uppermost Eocene?)

Vent-filling ash-flow tuff is intruded by dacite and rhyolite plugs and dikes and ringed by a belt of rhyolite domes and flows. The caldera margin is coincident with prominent gravity and aeromagnetic anomalies. The volcanic field contains 18 map units that range in composition from basalt to rhyolite.

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. Originally included in Little Butte Volcanic Series (Peck et al., 1964); includes Mehama Volcanics and Breitenbush Tuffs or Series of Thayer (1933, 1936, 1939), Breitenbush Formation of Hammond et al. (1982), Mehama Formation of Eubanks (1960), and Molalla Formation of Miller and Orr (1984). In Columbia River Gorge, includes Miocene and older rocks previously assigned to the Skamania Volcanic Series (Trimble, 1963), or to the Eagle Creek Formation (Waters, 1973). Lower parts of unit exhibit low-grade metamorphism with primary constituents altered to clay minerals, calcite, zeolites (stilbite, laumontite, heulandites), and secondary silica minerals. In contact aureoles adjacent to stocks and larger dikes of granitic and dioritic composition or in areas of andesitic dike swarms, both wallrocks and intrusions are pervasively propylitized; locally, rocks also have been subjected to potassic alteration. Epiclastic part of assemblage locally contains fossil plants assigned to the Angoonian Stage (Wolfe, 1981) or of Oligocene age. A regionally extensive biotite-quartz rhyodacite ash-flow tuff, the ash-flow tuff of Bond Creek of Smith et al. (1982), is exposed in southern part Western Cascade Range near and at base of unit. A K-Ar age of 4.9 Ma was determined on biotite from the tuff (Smith, 1980). Ash-flow tuffs, higher in the section and in the same area, have been radiometrically dated at 22 to 32 Ma by potassium-argon methods (J.G. Smith, unpub. Data; Evernden and James, 1964; Fiebelkorn et al., 1983). In the central part of the Western Cascade Range, the unit has yielded a number of K-Ar ages in the range of about 2 to 19 Ma (Verplanck, 1985, p. 53-54). A fission-rack age of 23.8+/-1.4 Ma was obtained on a red, crystal-rich ash-flow tuff (J.A. Vance, oral commun., 1983) collected at an elevation of about 3,000 ft or U.S. Highway 20 west-southwest of Echo Mountain. Most ages from basalt and basaltic andesite lava flows are in the range of about 35 to 18 Ma. Locally intruded by small rocks of granitoid rocks and by dikes, sills, plugs and invasive flows of basaltic andesite and basalt; in many places, the intrusions are indistinguishable from poorly exposed interbedded lava flows; K-Ar ages on several of the mafic intrusions or invasive flows are about 27 to 31 Ma.

Appendix J: Soil Arsenic Data from Northwest Oregon

Site Number	Easting (UTM NAD 83)	Northing (UTM NAD 83)	Underlying Unit	A Horizon As (ppm)	B Horizon As (ppm)	Lithologic Group
C1	522049	5039042	Qs	3.44	3.32	Quaternary/ Tertiary Sediments / Sedimentary Rocks
C2	503643	5046637	Qs	3.26	5.24	Quaternary/ Tertiary Sediments / Sedimentary Rocks
C3	487002	5056635	Tc	0	8.4	Columbia River Basalts
C4	483559	5059728	Tmst	3.8	20.4	Marine Sediments/ Sedimentary Rocks
C5	475233	5076304	Tco	3.72	3.65	Marine Sediments/ Sedimentary Rocks
C6	478660	5065818	Tco	3.82	4.08	Marine Sediments/ Sedimentary Rocks
C7	473195	5069554	Tco	3.49	7.12	Marine Sediments/ Sedimentary Rocks
C8	453382	5073882	Ttv	0	0	Coast Range Basalts
C9	447193	5082998	Tss	6.08	14.7	Marine Sediments/ Sedimentary Rocks
C10	447059	5083464	Ti	8.26	8.83	Mafic Intrusions
C11	429230	5090474	Tms	6.45	8.66	Marine Sediments/ Sedimentary Rocks
C12	462768	5062718	Ttv	0	0	Coast Range Basalts
C13	466104	4937226	Tsr	2.62	2.68	Coast Range Basalts
C14	449814	4906902	Tt	5.82	10.5	Marine Sediments/ Sedimentary Rocks
C15	449880	4906339	Tt	5.06	7.13	Marine Sediments/ Sedimentary Rocks

See Chapter 4.4: GROUPINGS FOR STATISTIC ANALYSIS for descriptions of lithologic groups. See Appendix I: Descriptions of Lithology by Lithologic Group for descriptions of geologic units.

Appendix J: Soil Arsenic Data from Northwest Oregon (Continued)

Site Number	Easting (UTM NAD 83)	Northing (UTM NAD 83)	Underlying Unit	A Horizon As (ppm)	B Horizon As (ppm)	Lithologic Group
M1	578682	5022223	Qal	0	0	Quaternary/ Tertiary Sediments / Sedimentary Rocks
M2	581417	5018888	QTba	3.99	3.52	Quaternary Basalts
M3	585815	5019067	Qal	0	0	Quaternary/ Tertiary Sediments / Sedimentary Rocks
M4	595656	5017183	Qg	0	0	Quaternary/ Tertiary Sediments / Sedimentary Rocks
M5	601650	5017695	Qa	0	0	Andesites
M6	603308	5015023	Qa	0	0	Andesites
M7	602981	5005326	QTba	0	0	Quaternary Basalts
M8	637441	4933297	Ts	0	0	Quaternary/ Tertiary Sediments / Sedimentary Rocks
M9	639027	4933925	Ts	0	0	Quaternary/ Tertiary Sediments / Sedimentary Rocks
M10	647676	4940502	Ts	0	0	Quaternary/ Tertiary Sediments / Sedimentary Rocks
M11	639253	4960466	Tsfj	0	2.48	Volcanic Sediments
M12	631098	4962527	Tob	0	2.14	Columbia River Basalts

See Chapter 4.4: GROUPINGS FOR STATISTIC ANALYSIS for descriptions of lithologic groups. See Appendix I: Descriptions of Lithology by Lithologic Group for descriptions of geologic units.

Appendix J: Soil Arsenic Data from Northwest Oregon (Continued)

Site Number	Easting (UTM NAD 83)	Northing (UTM NAD 83)	Underlying Unit	A Horizon As (ppm)	B Horizon As (ppm)	Lithologic Group
M13	623961	4971108	Qgs	0	2.14	Quaternary/ Tertiary Sediments / Sedimentary Rocks
M14	627175	4980627	Tca	0	0	Volcanic Sediments
M15	630735	4982276	Tsfj	0	0	Volcanic Sediments
M16	634767	4991684	Tcg	0	2.43	Columbia River Basalts
M17	620659	4995427	QTba	0	0	Quaternary Basalts
M18	564920	4952727	Tu	0	0	Volcanic Sediments
M20	583707	4944123	QTba	0	0	Quaternary Basalts
M21	580192	4925274	QTba	0	0	Quaternary Basalts
M22	583605	4920961	Qyb	0	0	Quaternary Basalts
M23	590619	4918395	QTba	0	0	Quaternary Basalts
M24	572420	4916602	QTba	0	0	Quaternary Basalts
P1	528311	5044245	Qgs	9.2	3.92	Quaternary/ Tertiary Sediments / Sedimentary Rocks
P2	554815	5018163	Qgs	9.23	6.55	Quaternary/ Tertiary Sediments / Sedimentary Rocks
P3	527879	5045407	Qgs	12.9	3.53	Quaternary/ Tertiary Sediments / Sedimentary Rocks

See Chapter 4.4: GROUPINGS FOR STATISTIC ANALYSIS for descriptions of lithologic groups.
See Appendix I: Descriptions of Lithology by Lithologic Group for descriptions of geologic units.

Appendix J: Soil Arsenic Data from Northwest Oregon (Continued)

Site Number	Easting (UTM NAD 83)	Northing (UTM NAD 83)	Underlying Unit	A Horizon As (ppm)	B Horizon As (ppm)	Lithologic Group
P4	528949	5042701	Qs	13.9	5.09	Quaternary/ Tertiary Sediments / Sedimentary Rocks
P5	526892	5043608	Qs	4.51	6.47	Quaternary/ Tertiary Sediments / Sedimentary Rocks
P6	513128	5049466	Qs	3.35	3.09	Quaternary/ Tertiary Sediments / Sedimentary Rocks
P7	520862	5042653	Qs	3.11	2.81	Quaternary/ Tertiary Sediments / Sedimentary Rocks
P8	554815	5018163	QTba	3.6	4.92	Quaternary Basalts
P9	553925	5018732	QTba	2.89	2.5	Quaternary Basalts
P10	551620	5019797	QTba	3.38	3.6	Quaternary Basalts
P11	548523	5018316	Qal	3.1	3.24	Quaternary/ Tertiary Sediments / Sedimentary Rocks
P12	549544	5019348	QTba	2.95	3.22	Quaternary Basalts
P13	541212	5027009	QTs	3.78	3.53	Quaternary/ Tertiary Sediments / Sedimentary Rocks

See Chapter 4.4: GROUPINGS FOR STATISTIC ANALYSIS for descriptions of lithologic groups. See Appendix I: Descriptions of Lithology by Lithologic Group for descriptions of geologic units.

Appendix J: Soil Arsenic Data from Northwest Oregon (Continued)

Site Number	Easting (UTM NAD 83)	Northing (UTM NAD 83)	Underlying Unit	A Horizon As (ppm)	B Horizon As (ppm)	Lithologic Group
P14	518251	5054374	Qal	2.63	2.51	Quaternary/ Tertiary Sediments / Sedimentary Rocks
P15	541144	5039793	Qgs	3.35	3.21	Quaternary/ Tertiary Sediments / Sedimentary Rocks
P16	523521	5039058	Qs	3.24	4.8	Quaternary/ Tertiary Sediments / Sedimentary Rocks
P17	533155	5020282	QTs	0	3.7	Quaternary/ Tertiary Sediments / Sedimentary Rocks
P18	533053	5020069	QTba	3.21	3.67	Quaternary Basalts
S2	491580	4976053	Tcg	2.38	0	Columbia River Basalts
S5	492013	4975264	Tcg	2.49	0	Columbia River Basalts
S6	491838	4977670	Tcg	5.25	4.99	Columbia River Basalts
S7	496863	4976953	Qal	3.05	2.79	Quaternary/ Tertiary Sediments / Sedimentary Rocks
S8	497483	4975055	Qs	0	3.69	Quaternary/ Tertiary Sediments / Sedimentary Rocks

See Chapter 4.4: GROUPINGS FOR STATISTIC ANALYSIS for descriptions of lithologic groups.
See Appendix I: Descriptions of Lithology by Lithologic Group for descriptions of geologic units.

Appendix J: Soil Arsenic Data from Northwest Oregon (Continued)

Site Number	Easting (UTM NAD 83)	Northing (UTM NAD 83)	Underlying Unit	A Horizon As (ppm)	B Horizon As (ppm)	Lithologic Group
S9	492343	4973847	Qal	5.01	3.95	Quaternary/ Tertiary Sediments / Sedimentary Rocks
S10	498126	4969207	Tc	5.04	4.28	Columbia River Basalts
S11	499150	4963674	Tc	5.41	5.19	Columbia River Basalts
S12	505693	4994240	Qs	6.4	6.3	Quaternary/ Tertiary Sediments / Sedimentary Rocks
TR01	532794	5020289	QTb	3.29	3.63	Quaternary Basalts
TR02	538370	5032348	QTb	1.8	1.26	Quaternary Basalts
TR03	478253	5055388	Ti	2.87	1.94	Mafic Intrusions
TR04	476365	5055716	Ti	2.4	2.78	Mafic Intrusions
TR05	432411	5019746	Tsd	10.4	12.6	Marine Sediments/ Sedimentary Rocks
TR06	429312	5018963	Tsd	4.82	11.0	Marine Sediments/ Sedimentary Rocks
TR07	425260	4990592	Tpb	5.99	6.39	Columbia River Basalts
TR08	424371	4992681	Tpb	3.28	5.02	Columbia River Basalts
TR09	518803	4914773	Tub	5.48	5.31	Columbia River Basalts
TR10	518782	4914988	Tub	7.2	6.52	Columbia River Basalts
TR11	555775	4916836	Tus	10.5	11.3	Volcanic Sediments
TR12	560076	4915917	Tus	4.22	4.94	Volcanic Sediments
TR13	575374	4896162	Tfc	1.29	1.57	Rhododendron/ Sardine Fm.

See Chapter 4.4: GROUPINGS FOR STATISTIC ANALYSIS for descriptions of lithologic groups. See Appendix I: Descriptions of Lithology by Lithologic Group for descriptions of geologic units.

Appendix J: Soil Arsenic Data from Northwest Oregon (Continued)

Site Number	Easting (UTM NAD 83)	Northing (UTM NAD 83)	Underlying Unit	A Horizon As (ppm)	B Horizon As (ppm)	Lithologic Group
TR14	575103	4898916	Tfc	2.1	1.92	Rhododendron/ Sardine Fm.
TR15	582877	4921228	Qg	0.263	0.404	Quaternary/ Tertiary Sediments / Sedimentary Rocks
TR16	580184	4925531	Qg	0	0.991	Quaternary/ Tertiary Sediments / Sedimentary Rocks
TR17	579650	4930556	Tbaa	1.47	1.33	Rhododendron/ Sardine Fm.
TR18	580593	4937061	Tbaa	1.03	1.02	Rhododendron/ Sardine Fm.
W1	519284	5025030	Qal	7.48	8.27	Quaternary/ Tertiary Sediments / Sedimentary Rocks
W2	518563	5022416	Tc	4.32	3.4	Columbia River Basalts
W3	517701	5013384	Qs	3.46	3.99	Quaternary/ Tertiary Sediments / Sedimentary Rocks
W4	507600	5011319	Qs	4.64	5.29	Quaternary/ Tertiary Sediments / Sedimentary Rocks
W5	457126	4993949	Ty	8.12	12.3	Marine Sediments/ Sedimentary Rocks

See Chapter 4.4: GROUPINGS FOR STATISTIC ANALYSIS for descriptions of lithologic groups.
See Appendix I: Descriptions of Lithology by Lithologic Group for descriptions of geologic units.

Appendix J: Soil Arsenic Data from Northwest Oregon (Continued)

Site Number	Easting (UTM NAD 83)	Northing (UTM NAD 83)	Underlying Unit	A Horizon As (ppm)	B Horizon As (ppm)	Lithologic Group
W6	451290	4994789	Tco	11.5	11	Quaternary/ Tertiary Sediments / Sedimentary Rocks
W7	509234	5016806	Tc	4.54	5.29	Columbia River Basalts
W8	512110	5019153	Tc	4.83	4.86	Columbia River Basalts
W9	515080	5016470	Qs	5.65	5.02	Quaternary/ Tertiary Sediments / Sedimentary Rocks

See Chapter 4.4: GROUPINGS FOR STATISTIC ANALYSIS for descriptions of lithologic groups.
See Appendix I: Descriptions of Lithology by Lithologic Group for descriptions of geologic units.

Appendix K: High and Low Values for Samples by Mapping Unit

Mapping Unit	Number of Samples	A Horizon Low As Value (ppm)	A Horizo n High As Value (ppm)	A Horizon Number of Zeros	B Horizon Low As Value (ppm)	B Horizon High As Value (ppm)	B Horizon Number of Zeros
Qa	2	0	0	2	0	0	2
Qal	7	0	7.48	2	0	8.27	2
Qg	3	0	0.26	2	0	0.99	1
Qgs	5	0	12.90	1	2.14	6.55	0
Qs	12	0	13.90	1	2.81	6.47	0
QTb	2	1.80	3.29	0	1.26	3.63	0
Qtba	12	0	3.99	6	0	4.92	6
QTs	2	0	3.78	1	3.53	3.70	0
Qyb	1	0	0	1	0	0	1
Tbaa	2	1.03	1.47	0	1.02	1.33	0
Tc	6	0	5.41	1	3.40	8.40	0
Tca	1	0	0	1	0	0	1
Tcg	4	0	5.25	1	0	4.99	2
Tco	4	3.49	11.50	0	3.65	11.00	0
Tfc	2	1.29	2.10	0	1.57	1.92	0

1. It is not known if these are high and low values for individual sampling sites.
2. Refer to section 5.4: A VS B HORIZON ANALYSIS for more detail.
3. Refer to Appendix I: Descriptions of Lithology by Lithologic Group for descriptions of geologic units.

Appendix K: High and Low values for Samples by Mapping Unit

Mapping Unit	Number of Samples	A Horizon Low As Value (ppm)	A Horizon High As Value (ppm)	A Horizon Number of Zeros	B Horizon Low As Value (ppm)	B Horizon High As Value (ppm)	B Horizon Number of Zeros
Ti	3	2.40	8.26	0	1.94	8.83	0
Tms	1	6.45	6.45	0	8.66	8.66	0
Tmst	1	3.80	3.80	0	20.40	20.40	0
Tob	1	0	0	1	2.14	2.14	0
Tpb	2	3.28	5.99	0	5.02	6.39	0
Ts	3	0	0	3	0	0	3
Tsd	2	4.82	10.40	0	10.96	12.60	0
Tsfj	2	0	0	2	0	2.48	1
Tsr	2	2.62	2.74	0	0	2.68	1
Tss	1	6.08	6.08	0	14.70	14.70	0
Tt	2	5.06	5.82	0	7.13	10.50	0
Ttv	2	0	0	2	0	0	2
Tu	1	0	0	1	0	0	1
Tub	2	5.48	7.20	0	5.31	6.52	0
Tus	2	4.22	10.50	0	4.94	11.30	0
Ty	1	8.12	8.12	0	12.30	12.30	0

1. It is not known if these are high and low values for individual sampling sites.
2. Refer to section 5.4: A VS B HORIZON ANALYSIS for more detail.
3. Refer to Appendix I: Descriptions of Lithology by Lithologic Group for descriptions of geologic units.

Appendix L: Outline Illustrating Outcomes of Stated Goals

1. Obtained soil samples from above as many major geologic formations in my study area as possible.
    a. Figure 9: Location of sites sampled during Phase II (2010) fieldwork along with geologic unit associations. Unit labels and descriptions after Walker and MacLeod, 1991.
    b. Appendix C: Site Observations for Phase I (1995) Sites (Ashbaugh, 1995)
    c. Appendix D: Description of Phase I Soil Samples (Ashbaugh, 1995)
    d. Figure 10: Geographic extent of lithologic groups and all site locations (Walker and MacLeod, 1991; Ashbaugh, 1995).
    e. Appendix E: Site Observations for Phase II (2010) Sites
    f. Appendix F: Description of Phase II Soil Samples (2010)
    g. Appendix G: Site and Soil Pit Images from Sites Sampled During Phase II Sampling (2010)
2. Determined the arsenic content of the sampled soils and
3. Produced a database of soil arsenic values
    a. Appendix J: Soil Arsenic Data from Northwest Oregon
4. Analyzed the data for significant trends.
    a. Statistically evaluate data to determine connections between the measured level of arsenic in soils above similar rock types
        i. Table 8: A Horizon data ANOVA
        ii. Figure 11: Stem-box plot showing mean, upper and lower quartile, data range, and outliers for the A horizon values of the five tested groups.
        iii. Figure 13: Multiple comparison of A horizon arsenic concentrations finds that group MS is distinct from group QB in this horizon.
        iv. Table 9: B Horizon data ANOVA
        v. Figure 12: Stem-box plot showing mean, upper and lower quartile, data range, and outliers for the B horizon values of the five tested groups.
        vi. Figure 14: Multiple comparison of B horizon arsenic concentrations finds that group MS is distinct from all other tested groups in this horizon.
        vii. Table 10: A Horizon Data Kruskal-Wallis Analysis
        viii. Figure 15: Multiple comparison test of A horizon data based on the Kruskal-Wallis analysis. This test shows the arsenic levels of group MS are statistically different from those of groups QB and QTS in the A horizon. The X axis values represent the mean and standard deviation of the group's ranks.
        ix. Table 11: B Horizon Kruskal-Wallis Analysis

x. Figure 16: Multiple comparison test of B horizon data based on the Kruskal-Wallis analysis. This test shows the arsenic levels of group MS are statistically different from those of groups QB, QTS and VS in the B horizon. The X-axis values represent the mean and standard deviation of the group's ranks.
xi. Figure 27: Bar graph connecting lithologic groups (X-axis) to the groups resulting from the three group cluster analysis (color symbology). Color symbology reflects clusters noted in Figure 21 and Figure 22.
xii. Figure 28: Bar graph connecting lithologic groups (X-axis) to the groups resulting from the four group cluster analysis (color symbology). Color symbology reflects clusters noted in Figure 23 and Figure 24.
xiii. Figure 29: Bar graph connecting lithologic groups (X-axis) to the groups resulting from the five group cluster analysis (color symbology). Color symbology reflects clusters noted in Figure 25 and Figure 26.

b. Statistically evaluate the data to determine connections between the measured arsenic level of soils in the A and B horizon.
    i. Table 13: A vs B Horizon data ANOVA
    ii. Figure 18: Stem-box plot showing mean, upper and lower quartile, data range, and outliers for A and B horizon data by lithologic group. X-Horizon labels indicate lithologic group and horizon.
    iii. Figure 19: The standard ANOVA multiple comparison test indicates that group MS in the A horizon is distinct from group QB in the A and B horizon. Group MS in the B horizon is distinct from all other tested groups.
    iv. Table 14: A vs B Horizon Kruskal-Wallis Analysis
    v. Figure 20: The Kruskal-Wallis multiple comparison test indicates group MS in the A horizon is distinct from group QB in both the A and B horizon. Group MS in the B horizon is distinct from groups QB, QTS and VS in the A and B horizons.

5. Mapped the arsenic values using GIS in a scientifically appropriate manner based on the conducted statistical analysis.
    a. Table 12: Basic arsenic statistics of groups mapped based on analysis
    b. Figure 17: Map showing the distribution of Marine Sedimentary and Sedimentary Rocks group units and the other tested lithologic groups throughout the northwest Oregon study area. This map illustrates areas where soil arsenic content is statistically distinct (Walker and MacLeod, 1991).