An investigation of contaminant distribution in subsurface marine wood waste
at Mill-A South Terminal, Port of Everett, Washington

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Executive Summary

This project investigates the correlation between contaminants and the wood waste present in marine sediments off the shore of the Port of Everett in the former Weyerhaeuser Mill-A pulp mill site. The investigation includes the results of two field studies, which tested contaminant levels in 22 boreholes as well as several surface samples. The contaminants include heavy metals and wood waste byproducts. These results, along with 14 other bore logs, provide the framework for a three-dimensional site model, interpolating the full extent of the depositional units and organic and inorganic chemicals found at Mill-A.

The sediments of interest are divided into five depositional units defined by the percent wood content and type of wood: native material (<5% wood), intermediate (<30% wood), sawdust (<30% wood), woodchips (<30% wood), and poorly sorted sands with silt (SM-SP) (0% wood). The contaminants include arsenic, 2,4-dimethylphenol, and total organic carbon. Three-dimensional modeling software, RockWorks, interpolated the discrete borehole data of sediment and contaminants assuming horizontal continuity between sampling locations. The sediment distribution was calculated within concentration ranges for each contaminant of concern. The lowest detection limits, the screening levels, and the cleanup levels defined these ranges. Total organic carbon served as a proxy to estimate the quantity of wood waste in the sediment. As a known byproduct of wood decomposition, 2,4-dimethylphenol was expected to be more prevalent in the depositional units with more wood waste. Finally, arsenic was a proxy for other contaminants to determine if contaminants at Mill-A are dominant in sediments with high percentages of wood waste.

The volumetric distribution established that high levels of total organic carbon are present in the sediment with higher percentages of wood waste. This correlation was stronger in the decomposing sawdust-rich sediment than the woodchip-rich sediment. The 2,4-dimethylphenol concentrations above cleanup standards were dominant in the sawdust-rich, intermediate and native sediments. Concentrations of 2,4-dimethylphenol below cleanup levels characterized the native sediment. The distribution of arsenic showed no statistically significant correlation to wood content in sediment. These results do not support the hypothesis of contaminant-rich wood waste, as many of the high concentrations of contaminants were not in the wood-rich sediments. This suggests that the contaminants are more distributed among all depositional units at Mill-A rather than focused within sediments with a high percent of wood waste.

Understanding the distribution of potentially toxic compounds with wood waste is important for restoring the Puget Sound waterways to a more habitable environment. Future studies should include new data to validate these results and to limit the uncertainty of the extent of contaminants. Future studies may also find motive in looking for a correlation between contaminants and grain size based on previous studies linking these characteristics. These investigations will benefit the current cleanup effort as well as future cleanup efforts at similarly contaminated waterways.

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1.0 Introduction

Industrial pollution is an increasingly common concern for the health of marine habitats in the Puget Sound Region. The Puget Sound Initiative is a legislative effort to clean up toxic chemicals and restore Puget Sound for salmon, marine and human populations by 2020 (DOE, 2007). Past industrial activity was typically unregulated and has led to a buildup of contamination and waste in the Puget Sound waterways. This contaminated waste includes chemicals as well as woody debris products such as sawdust, wood chips, pulp and bark.

To better understand the presence of contaminants in the woody marine sediment, this project investigated the distribution of a set of contaminants in the marine depositional layers near a former mill. This site is located in the near-shore marine environment of the South Terminal, part of the Pacific Terminal in the Port of Everett, WA (Figure 1). The non-native depositional layers contain various quantities and types of wood and apparently were deposited from industrial operations on the adjacent terminal. The contaminants of interest in this investigation include arsenic, 2,4-dimethylphenol (2,4-DMP), and total organic carbon (TOC). Observed arsenic and 2,4-DMP levels reach up to 40 ppm and 800 ppb, respectively, at Mill-A. The Washington state cleanup criteria for contaminated soil, as defined in the Model Toxic Control Act, require cleanup for arsenic III (arsenite) in industrial sites above 20 ppm and arsenic V (arsenate) above 260 ppm (DOE, 2013B). The national cleanup criteria for 2,4-DMP in ambient water is 100 ppb (EPA, 2015).

The project area is the Weyerhaeuser Mill-A Former site, or Mill-A, which operated from the late 1800's to 1980. This mill produced up to 300 tons of pulp per day. The sulfite pulp process strips trees of bark and mills logs into woodchips for further processing. The resulting wood waste, which includes sawdust and bark, may have been burned or disposed of locally. Woody debris present in the bay may have been a result of this disposal, as well as from log rafting. Byproducts from pulp processing and wood burning can contaminate the discarded wood and waterways.

Thick deposits of wood waste may persist for decades due to slow degradation of the material (Ellis 1970; Conlan, 1977; Schultz and Berg, 1976; Harmon et al., 1986 as cited in Kendall and Michelsen, 1997; Breems and Goodman, 2009). Over time, the degradation of wood in the marine sediment can cause a buildup of additional contaminants such as methylated phenols (DOE, 2013A). Therefore, this site is at risk for poor ecological advancement without the intervention of an environmental cleanup. Thick woody deposits created a persistent barrier against vegetation growth on the marine floor. This rapid deposition of woody material smothered and displaced benthic organisms. Bacterial degradation of the woody debris also can create an anoxic environment, decreasing the biodiversity of the environment. These ecologic concerns were the driver for listing this site on the Washington State Department of Ecology's 1996 Sediment Management Standards Contaminated Sediment List (SMSCSL) (Geomatrix, 2007).

An Agreed Order[1] was signed in 2012 by the Port of Everett, the Weyerhaeuser Company, Washington State Department of Natural Resources, and Washington State Department of Ecology. The Puget Sound Initiative, the SMSCSL and the Agreed Order are driving the current Mill-A cleanup effort. One of the main objectives of this cleanup project is to restore the Puget Sound to a more habitable environment. Delisting criteria from the 1996 SMSCSL includes mitigation of identified chemicals of concern (COC) to below levels known to cause adverse effects to both benthic organisms and humans (DOE, 1996 and 2013C). The main contributing source of toxic chemicals at the Mill-A site is industrial activity over the past century, although non-point sources of contaminants and natural background levels of chemicals are also present. Several surface and subsurface sampling investigations performed at this site characterized the marine surface sediment and contaminants. Some of the contractors involved include the US Army Corps of Engineers, Geomatrix Consultants, Inc., and GeoEngineers, Inc.

Understanding the distribution of contaminants and wood waste is vital to planning for cleanup of this site. This includes information regarding the approximate extent and depth of contaminants. If a correlation exists between the quantity of wood and high levels of contaminants, then this distribution may be characteristic of similar industrial cleanup sites.

1.1 Scope of Work

This project uses data from Geomatrix (2007) and GeoEngineers (2015). Further sampling by GeoEngineers was completed at the end of 2015; however, due to the timing, the new data were not available for this project.

The goal of this project is to characterize the concentrations of selected chemicals in the marine sediment relative to wood content. One challenging feature of this site is the variation in thickness and extent of depositional units. Thus, a 3-D representation of the subsurface is a means to determine if a correlation exists between high concentrations of COCs and the wood waste. This requires an interpolation of sediment and chemical distribution between existing boreholes within the Mill-A cleanup site.

In this project, wood waste is a catch-all term, defined as any size of wood material including sawdust, woodchips, bark, twigs and logs. Some wood waste may be natural; however, most of the wood waste identified in these samples originates from former mill operations.

1.2 Study Site

1.2.1 Geographic setting

The project area is situated on the eastern shoreline in the north Puget Sound Lowland, which is an elongated basin between the Cascade and Olympic Mountains (Figure 1). Locally, the site is in the near-shore marine environment of Port Gardner Bay in Everett, Washington. It is bordered on the north by the Snohomish River delta and the south by a

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[1] Agreed Order: (legal term) the potentially liable person agrees to perform remedial actions at the site in accordance with the provisions of the agreed order and the department will not take additional enforcement action against the potentially liable person so long as the potentially liable person complies with the provisions of the order (WAC 173-340-530).

small stream named Pigeon Creek. Both of these freshwater sources may act as transport paths for sediment and chemicals sourced from upstream. The west trending headwaters of the Snohomish River are sourced by the convergence of the Skykomish and Snoqualmie Rivers that flow out of the foothills of the Cascade Range. These major rivers pass through glacial and interglacial deposits and bedrock. To the west of this site are deeper marine waters within the Puget Sound Lowland. To the east of this site is the upland cleanup area of the Pacific and South Terminals, which include shipping berths, storage facilities, and a railway just beyond the Port boundaries. The upland cleanup area is not discussed in this project. Areas peripheral to the terminals are dominantly residential and commercial. The industrial businesses are situated in the filled tidal flat areas of the bay.

1.2.2 Regional Geology

The Puget Sound was last carved by continental glaciation about 15,000 years ago during the Fraser Glaciation (Troost and Booth, 2008). Bluffs of glacially- and interglacially-derived material act as a topographic barrier between the terminals and the surrounding communities. Exposed bluffs contain a regionally characteristic sequence of glacial deposits, ranging from top to bottom: recessional outwash, glacial till, advance outwash, and lacustrine silts and clays (Troost and Booth, 2008). These deposits are spatially variable and may be missing from the sequence. The glacial deposits are interbedded with interglacial deposits of alluvium, colluvium, ash, peat, and landslide and lacustrine deposits (Troost and Booth, 2008). According to Minard (1985), the bluffs in this area are exposed with sections of transitional beds of Fraser glaciation to pre-Fraser sediment (Qtb) that contain lacustrine clays overlain by advance glacial outwash (Qva) (Figure 2). These sediments may be glacial and/or interglacial in origin.

Associated with its proximity to a major river mouth, a significant amount of alluvium is deposited in the harbor. This alluvium is dominantly coarse to fine sands and silts. The Port terminals are located on land that was once natural tidal flats. These flats have been altered through dredging and filling during development and industrialization of the region over the past century. The historical structures were built on wharfs, which continue to be used and upgraded for maritime industry. The current Pacific Terminal structure was built in 1998 and the South Terminal was converted after the demolition of the Weyerhaeuser mill in 1980 (The Port of Everett, 2015). The fill beneath this infrastructure consists of dredged material from the Snohomish River and other unknown origins (GeoEngineers, 2010; Port of Everett, 2008).

2.0 Background

The area of interest is a 900 by 1150-foot (~24 acres) zone of the harbor adjacent to the South Terminal in the Port of Everett, Washington (Figure 1).

2.1 Mill-A Cleanup Project

The current cleanup effort by the Port authority is integrating the current need for decontamination with future growth of the terminal (GeoEngineers, 2015). There are three phases to the Port's cleanup project. Phase 1 is the interim action including sediment sampling and dredging, which started in January 2010 and is projected to last until 2020

(Figure 3). Phase 2 is a continuation of the interim action, which includes further dredging of the remaining project area, adding fill to the location of a new bulkhead, and extension of the South and Pacific Terminals (Figure 3). Phase 3 includes maintenance dredging from alluvium buildup and integrated cleanup.

My project focuses on the methods used in Phase 1 to better understand the distribution of COCs in woody marine sediment. In Phase 1, dredging was the chosen method of cleanup because of the necessity to expand the port terminals to accommodate larger maritime cargo ships for the Pacific Terminal. The area will be dredged to an elevation of -42 feet below mean lower low water (MLLW), which represents the average height of the lowest tide.

Phase 1 methods included grab sampling, vibracore drilling, and sonic drilling to obtain surface and subsurface samples for sediment and chemical analyses. The samples recovered by these techniques ranged in thickness from 0.3 feet to 30 feet. These samples were taken offshore of the South Terminal at water level depths of 0.7 to 51 feet below MLLW.

2.2 Chemicals of Concern

The first step in understanding the contamination of a site is to determine the source of contamination. At Mill-A, since we assume the woody debris came from mill activities and log rafting, the sawdust and woodchips should be near the terminal boundary shoreline although bark may be more dispersed. If contaminants entered the sediments with the milled wood, it is expected that the COCs would be in highest concentrations near the shore.

For the sake of simplicity, COCs in this report refer to analytes measured within the sediment, including TOC, arsenic and 2,4-DMP. COCs are defined for this region on multiple criteria, which include: a suspected or demonstrated effect on human or ecologic health, high concentrations compared to natural conditions, persistence, and bioavailability (US Army Corps of Engineers, 2014). The following are descriptions for each COC in this investigation. A summary of COC levels is presented in Table 1.

Arsenic

Arsenic is a known carcinogen and the twentieth most abundant element in the earth's crust (NCBI, 2016A). Naturally occurring arsenic may be sourced from geothermal processes. Anthropogenic arsenic most commonly originated from pesticides used in the 1960's and earlier (NCBI, 2016A). Both of these sources could transport arsenic through weathering and groundwater and stream flow to the Puget Sound. The available data do not specify the form of arsenic measured at Mill-A, suggesting a measurement of total arsenic.

Natural background levels of arsenic are 7 to 12 ppm in Puget Sound sediments (King County, 2014). Previous studies determined that arsenic levels in Port Gardner Bay did not exceed the range of 2.9 and 12 ppm (DOE, 2014). The screening level of total arsenic in soil for open-water disposal is 57 ppm (US Army Corps of Engineers, 2014). This cleanup level is based on expected adverse effects from open-water disposal of dredged sediment containing arsenic at this level.

2,4-Dimethylphenol

Methylated phenols have both natural and industrial sources. Naturally, methyl phenols develop from the decomposition of wood, which come from the breakdown of lignins in water (DOE, 2013A and Geomatrix, 2007). Lignins are organic substances that bind cells in vascular plants and are present in wood and bark (ILI, 2016). Industrial sources of methyl phenols include waste effluents from pulp and paper mills (EcoChem and Pentec, 1993).

The screening level of 2,4-DMP for allowable open-water disposal is no more than 29 ppb (US Army Corps of Engineers, 2014). The ambient water criterion for cleanup is 100 ppb based on concern for potential drinking water contamination (EPA, 2015).

Total Organic Carbon

Total organic carbon (TOC) measures the organic content in sediment and water. The analytical process measures the organic content versus the mineral content to determine a weight-percent of organics, which can represent the maximum percentage of wood waste in the sediment (DOE, 2013A).

The screening levels of TOC are not well established, so for this report, the screening levels of total volatile solids (TVS) are assumed analogous to TOC. According to the Wood Waste Cleanup Guide by DOE (2013A), toxicity is more consistently observed in TVS values exceeding 15 percent, which is roughly equivalent to 50 percent wood volume. The Dredged Material Evaluation and Disposal Procedures Manual by the US Army Corps of Engineers (2014) identifies dredged material containing 25 percent or less organic fraction as suitable for open-water disposal, without exceedance of other COCs.

These COCs were chosen for their comparable characteristics to wood waste and significance to the region. TOC is used as a proxy for the maximum quantity of wood present in the sediment since there are additional sources of TOC. Methylated phenols have been identified previously as a primary COC for the Mill-A cleanup site (EcoChem and Pentec, 1993). 2,4-DMP was chosen over other methyl phenols because of its correlation to polycyclic aromatic hydrocarbons (PAH). PAHs are contaminants also typically found in industrial areas where burning or creosote manufacturing occurred (Geomatrix, 2007 and Ward et al, 2009). Arsenic was chosen as the third and final COC for this project because of its prevalence in Puget Sound. However, it is not known to correlate to wood waste or pulp mill effluence. If the expected correlations between TOC and wood and 2,4-DMP and wood are established with this investigation, then the distribution of arsenic can test the hypothesis for an overall increase of COCs in industrial wood waste at Mill-A.

Table 1: COC concentration levels.

COC	Unit	Detection Limit[1]	Natural Background Levels in Puget Sound	SMS Screening Level[2]	Highest Apparent Effects Threshold[2]	State/ National Cleanup
Arsenic	ppm	5	7-12[3]	57	700	20[4]*
2,4-DMP	ppb	20	31-84[5]	29	210	100[6]
TOC	wt %	0.02	0.5 – 3.5[7]	25	N/A	N/A

*The Sediment Management Standards (SMS) screening level represents the maximum concentration without apparent effects. The natural background limit for TOC is based on reported averages. *Required cleanup level for residential land and/or arsenite form of arsenic. Superscript citations: 1: Geomatrix, 2007, 2: Defined by acceptable maximum level for open-water disposal of dredged material (US Army Corps of Engineers, 2014), 3: King County, 2014; DOE, 2015B; NOAA et al., 1999, 4: King County, 2014; DOE, 2013B; DOE 2015B, 5: NOAA et al., 1999, 6: EPA, 2015, 7: DOE, 2015B.*

2.3 Fate and Transport of COCs in the Environment

The fate and transport of COCs is important to consider for this project since contaminants in the sediments may not be static or stable. As COCs enter the marine environment, they respond differently depending on their solubility in water. Examples of processes that control solubility include dissolution into the ambient water and sorption onto suspended sediment particles. Adsorbed particles may settle in as short a time as minutes to days depending on the size of the flocculants and the turbulence of the water. This initial transport of COCs in the marine environment affects the quantity and distance that COCs disperse from outfalls or point sources.

Tidal action and ship movement may disturb the path and natural settling processes of these COCs. Since this project area is located in a heavily used port, turbulence from ship transport and docking may affect contaminant settling. In general, the Puget Sound has a net outflow at the water surface and net inflow of water at depth (US Army Corps of Engineers et al., 1988). This pattern of inflow and outflow is caused by the salinity and density difference from tidal action and freshwater input to Puget Sound.

2.3.1 Arsenic

Heavy metals, such as arsenic, may be strongly adsorbed onto sediment or organic particulates in the water column. The tendency of heavy metals to flocculate decreases the settling time of these COCs (National Research Council et al., 1993).

The species of arsenic changes in oxygenated and anoxic environments with arsenate (As V) as the dominant species in oxic waters and arsenite (As III) in anoxic (Massacheleyn et al., 1991 as cited by Jaffe et al., 2002). This is an important distinction since arsenite is the more toxic form (NCBI, 2016). For cleanup standards, if the chemical analysis tests total arsenic or does not specify the form, it should be assumed to be arsenite. This, again, is an important distinction since arsenite has a cleanup standard level in soils of 20 ppm (DOE, 2013B) rather than 93 ppm for arsenate or 57 ppm for total arsenic (DOE, 2013C). The

form of arsenic also changes the tendency for the metal to adsorb to particles. Arsenic in the form of arsenate strongly sorbs to suspended sediment, but is only weakly adsorbed as arsenite (NCBI, 2016). Weakly or non-sorbed particles may diffuse through pore fluids in sediment more readily.

2.3.2 2,4-Dimethylphenol

Phenols may be toxic in aquatic environments above screening levels, but they are difficult to analyze due to sensitivities to seasonal temperature changes (DOE, 2013A). 2,4-DMP shows moderate mobility in saturated soils and water as a result of very low adsorption (NCBI, 2003). Biodegradation may occur in hours to days; however, under anaerobic conditions, biodegradation is insignificant and 2,4-DMP may be very persistent (NCBI, 2003).

2.3.3. Total Organic Carbon

The presence of organic material at Mill-A is assumed to be dominantly sourced from mill byproducts, such as the observed sawdust and woodchips (GeoEngineers, 2014 and Geomatrix, 2007). During drilling and sampling operations, an obvious odor of hydrogen sulfide was present in several core samples at Mill-A. Hydrogen sulfide results from the breakdown of organic matter in anoxic environments (NCBI, 2016B). The presence of hydrogen sulfide is key to understanding the fate of organic matter at Mill-A.

2.4 Previous Studies

In-water and upland characterizations of this site have been conducted since the 1980's (DOE, 2015A). This project focuses on the two most recent published reports.

2.4.1 Geomtarix, 2007

One of the two main datasets used for this model comes from a field study performed by Geomatrix consultants in May 2007. This study was prompted by the Puget Sound Initiative to better understand what mitigation needed to be completed in order to remove Mill-A from the 1996 SMSCSL (Geomatrix, 2007). The data from Geomatrix (2007) used in this project are labeled ST (Appendix A, Figures 3 & 4) and include a total of 23 cores and 22 grab samples taken at 33 locations (Figure 3). Of these sample locations, 22 cores are included in the framework of the 3-D site model. Some results from this report were soil descriptions, chemical analyses, and a discussion of potential sources of contamination.

These results defined soil units as recent, native, intermediate, rafting debris, sawdust, and woodchips based mainly on grain size, density, and presence and character of woody material. The chemical analyses include: polychlorinated biphenyl (PCBs), semi-volatile organic compounds (SVOCs), pesticides, metals, TOC, and dioxins/furans. The range of TOC in sediment samples containing woody debris is between 0.8 and 46.9 percent. The results also identified elevated levels of 2,4-dimethylphenol in various cores with a range of 20 to 800 ppb. Of the eleven samples analyzed for heavy metals, none exceeded the Sediment Management Standard screening level for arsenic of 57 ppm (US Army Corps of Engineers, 2014), but were present as high as 40 ppm.

2.4.2 GeoEngineers, 2015

GeoEngineers completed two field investigations since the 2007 report by Geomatrix. The first study collected core and sediment samples between January 12 and 16, 2015, which produced the results for samples labeled PT (Appendix A, Figures 3 & 4). The area of this first study was limited to the Interim Action Phase 1 dredging zone (Figure 3). This report included 14 sampling locations (Figure 3). The goals of this field investigation were to characterize the contamination level in the native sediment to define an acceptable dredging limit. The study determined that the contaminated sediment above the native material did not meet open-water disposal criteria, and potentially harmful levels of COCs would be exposed along the edges of the south/southeast sides of the dredge prism, but not within the native sediment (Figure 3). Although this report concluded that COCs were an issue along the Phase 1 dredge prism (Figure 3), the chemical analyses only identified acceptable concentrations in the native material. The TOC ranged between 0.9 and 7.7 weight-percent, 2,4-DMP was not detected above 24 ppb, and arsenic ranges were consistent with background levels of 4 to 9 ppm.

The second field investigation by GeoEngineers took place between October and November 2015. These samples were collected throughout the Mill-A project area to expand on the 2007 study by Geomatrix (Figure 3). The analytical results of this investigation were completed in February 2016, but a final report has yet to be published, and therefore the data are not included in this report.

For each field investigation, grab and core samples were collected for analyses. These samples were analyzed for: grain size, total metals, bulk ammonia, bulk sulfides, Total Volatile Solids (TVS), TOC, pH, dioxins/furans, PCBs, and phenols. These analyses, however, were not completed for all depth intervals or sample locations. Generally, the upper two feet of sediment were analyzed for bulk ammonia and bulk sulfides. The intervals of 0 to 2 feet, 2 to 4 feet, or 4 to 6 feet were tested for: grain size, TVS, TOC, total metals, SVOC, dioxin/furan, and PCBs. Phenols were tested from samples at a 2- to 4-foot depth. The other incremental depth samples were preserved for possible future testing.

2.5 Limitations of Data

The lack of interval data from the 2007 and 2015 field reports, as well as the inability to include the newest data, presents a significant limitation for this investigation. Of the 36 core locations included in the 3-D model, only three contain chemical analyses for more than one depth interval (Appendix A). In addition, many analyte values contain qualifiers. The data qualifiers signify estimated values (J) and undetected above non-detect limit (U) (Appendix A).

Another limitation is the inconsistency of analyses. Of the 36 sample locations included in this investigation, only 21 were analyzed for chemical analytes while the remaining 15 cores were only logged for sediment description. In addition, the Geomatrix 2007 field investigation did not measure all analytes for each sample, so there are only five reported values for arsenic of the 22 sample locations.

Another source of missing data concerns the analyte Total volatile Solids (TVS). According to the DOE (2013A) report on wood waste cleanup, TVS is a better predictor than TOC for

wood waste; however, TVS was not included as an analyte in the 2007 report. The discrepancy between TOC and TVS for wood waste measurements is attributed to the sampling methods, which allows for a more detailed insight into the spatial variability of wood waste through TVS values (DOE, 2013A).

3.0 Methods

GeoEngineers provided the reports and corresponding data from the Geomatrix 2007 and GeoEngineers 2015 investigations. A condensed version of these data is included in Appendix A. Below are descriptions of the methods for data handling, the RockWorks software analyses, and assumptions.

The first step to analyze data published by different firms was to compare descriptions and methods. The sediment descriptions varied between Geomatrix and GeoEngineers, so for simplification, I defined a set of depositional units based on the wood content (in percent) and wood type (sawdust or woodchips), which is more suitable for this investigation (Table 2). The suite of chemical analyses were also not consistent between the two reports, which is why the COCs were limited to the three discussed above.

Table 2: Sediment unit descriptions based on sediment samples from Geomatrix (2007) and GeoEngineers (2015).

Sediment Unit	Wood Content	Notes
SM-SP	0%	Generally poorly sorted sands with silt (SM-SP); contains no wood and is non-native. Considered recent sediment/alluvium deposited post-mill operations.
Woodchips	>30%	Generally unstained, includes woodchips, rafting debris and bark
Sawdust	>30%	Sawdust and other wood pieces. May be stained wood from treatment processes
Intermediate	<30%	Disturbed coarse sand to silty sand with various types of woody debris
Native	<5%	Grey, moderately dense, poorly graded sand to silty alluvium. May contain shells/fragments and trace amounts of wood or other organics (Geomatrix, 2007)

3.1 RockWorks Analysis

RockWorks software (version 16 level 4) was used to perform 3-D modeling operations. RockWorks is a commonly used program for subsurface data visualization (Figure A). The 3-D modeling capabilities require the input of borehole data including location (latitude and longitude), mudline elevation, total depth, and a g-value (Figure A). The g-value is similar to the value of a raster cell; it is an arbitrarily assigned integer that represents changes in space, such as lithology. In RockWorks, the "raster cells" are termed voxels, or 3-D pixels, which represent a single unit of volume based on the defined resolution.

The two main applications for RockWorks are *Utilities* and *Borehole Manager*. The Utilities application is a row and column data sheet that can process spatial data into maps, models and diagrams. The Borehole Manager application separates data into individual boreholes and can process the information into maps, 3-D models and diagrams.
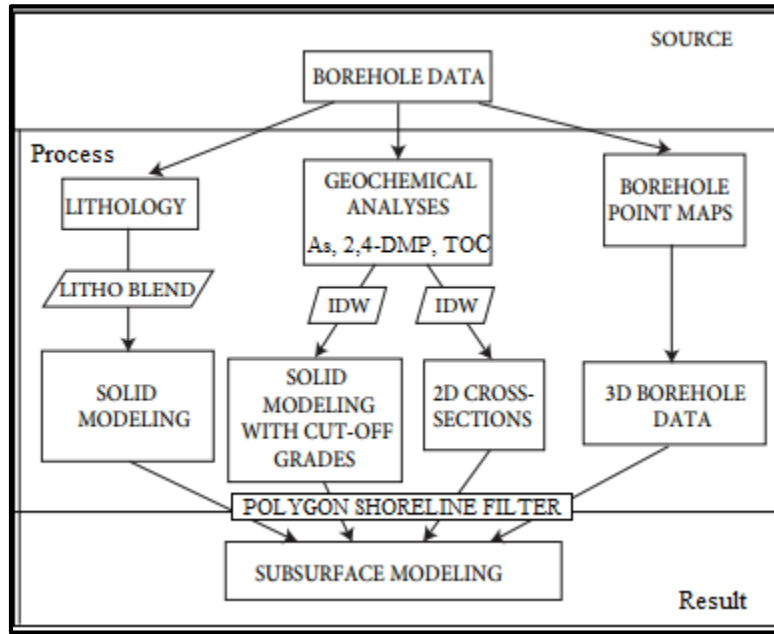

Figure A: Flow chart adapted from Akiska et al. (2013) summarizing the methods for model and diagram outputs using RockWorks software.

3.1.1 Data Input

Prior to data input, it was necessary to build a project folder, where all information could be saved, including defined project coordinates. The coordinates used are Universal Transverse Mercator (UTM) coordinate system with a WGS-84 (NAD-83) Zone 10 Datum. The voxel resolution is 25 by 25 feet horizontally with 1 foot vertically.

The compiled bore log data from both reports were imported into RockWorks Utilities (Appendix A). Once in RockWorks Utilities, the data can easily be transferred to the Borehole Manager. The borehole locations were converted to eastings and northings based on the UTM coordinate system and assigned a g-value for each depositional unit (Figure B). The sediments were defined in the *lithology* tool, which allows for repetition of units.

G-Value	Keyword	Pattern	Fill Percent	Density	Show in Legend
5,000.0	Native		100	1.0	☑
4,000.0	Intermediate		100	1.0	☑
3,000.0	Sawdust		100	1.0	☑
2,000.0	Wood Chips		100	1.0	☑
1,000.0	SM-SP		100	1.0	☑

Figure B: Example of data input for lithology types and g-values in RockWorks Borehole Manager. Each field is customizable based on the desired output.

RockWorks allows for multiple forms of geochemical or geophysical data input in the Borehole Manager application. These include interval downhole (I-data), time-dependent (T-data), and downhole point (P-data) data. The I-data is the most suitable option for these chemical values since it contains a range of depths for a given COC value rather than a single point or time-dependent data. After I defined geochemical data within RockWorks (Figure C), I input the I-data by hand for each borehole rather than importing a new datasheet. With more than a few dozen boreholes, this method is not recommended.

Visible	Order	Column Name	Min Value	Max Value	Units
☑	1	TOC	0	100	%
☑	2	Arsenic	0	100	ppm
☑	3	2,4-dimethylphenol	0	1000	ppb

Figure C: Example of COC input parameters for RockWorks Borehole Manager.

Once these sediment and chemical data were assigned for each borehole, RockWorks can output borehole location maps (Figure 4), and 3-D strip logs for sediment and COC data (Figure 5, Figure 6). Block, or solid, models of the subsurface require interpolation, which is discussed below.

3.1.2 Interpolation Options

RockWorks provides a step-by-step write-up for each option in the 3-D model tools. Some of these options include: *algorithm*, which chooses the modeling method of lithoblending or closest point; and *upper and lower surface filters*, which constrain the vertical model dimensions. The default algorithm of lithoblending was used for the initial lithology model (Figure A, Figure 7). Lithoblending is a closest-point algorithm within vertical constraints. This model was also bounded on the upper and lower surfaces, defined by the extent of the boreholes.

The same process was required to interpolate the spatial extent between boreholes of the COCs; however, the interpolation options differ for this tool. The algorithm options for modeling I-data are *closest point*, *distance to point*, *anisotropic inverse distance weighting* (IDW), *isotropic IDW*, and *directional*. The anisotropic IDW method was chosen for this model to best represent the variability in depositional units and ranges in COC values (Figure A). Additional options in the I-data modeling tool include, *tilting*, *warping*, *smoothing*, *high fidelity*, *upper/lower surface filters*, *distance filters*, and *polygon filters*. The

sediment was assumed to be horizontally deposited, so no tilting or warping options were selected. Other filters, including the high fidelity option, were selected in order to best constrain the interpolations to known data values (Figure 8, Figure 9, Figure 10).

The final modeling option applied to the Mill-A subsurface model was the *polygon filter,* which is a boundary constraint. Without this filter, the map and 3-D model tools interpolate the data within the entire project area despite the intersection of the shoreline. To force this boundary, a polygon of the project area was traced using Google Earth and added to the models via the *polygon clip* tool in RockWorks (Figure 4).

The algorithms were chosen based on the examination and removal of anomalies. For example, the first processing of the arsenic model showed an anomalous plume in the southeast corner of the model where no data points exist. Testing the outputs of each algorithm with other options showed that the anisotropic IDW modeling with high fidelity solved these anomaly issues.

To analyze the distribution of COCs within depositional units, the sedimentary model was combined with each COC model using the math operations tool, *model & model* in the Utilities application. Adding the sediment g-value to the COC concentration maintains the identifiable value for sediment and COC with a single value. Since the highest COC value was three digits and the g-values were four digits, adding the two values allowed the model to maintain the uniquely identifiable values of depositional units and COC levels. After processing, filters can adjust the visible output to allow for different visualizations. For example, a filter can be added to show a selected range of g-values and COC data, such as 5,005 to 5,020, which would only output the native sediment with values of COCs between 5 and 20 units. RockWorks reports the corresponding volume associated with that range of new g-values, which represents the distributions of each COC in each depositional unit.

Viewing the geographic position of high COC concentrations can be done by adjusting the opacity of the voxels or using cutouts to view inside of the model.

3.2 Sensitivity Analysis

It is customary to perform validation and sensitivity assessments on the outputs of a model; however, additional data is not yet available to do this. A proxy for the sensitivity analysis was a comparison of arsenic distributions with the inclusion of natural background levels. The sensitivity analysis tested for the change in distribution of arsenic given a change of input from null data to 7 ppm. This represents a more realistic distribution of arsenic given the known natural background levels for arsenic in Puget Sound. The consequences of this sensitivity analysis were also used as a proxy for uncertainty of all model outputs.

3.3 Assumptions

Several assumptions were made to create this subsurface representation of Mill-A. The subsurface model is based on the assumption that the depositional units are continuous between borehole locations and that the available data is representative of the Mill-A project area. Another assumption was to accept qualified data as accurate. For non-detect (U) qualifiers, the analyte is assumed not present above the reported level, but these values

were still included in the subsurface representation. The estimated (J) qualifiers were assumed accurate values. A summary of the COC values and qualifiers is in Appendix A.

4.0 Results

The surficial and profile views of the subsurface sedimentary model demonstrate the variability in sediment distribution (Figure 7, Figure 11). Vertically, all units are relatively shallow ranging from -1 to -7 feet below MLLW. The deeper sediments are native and intermediate materials (Table 3). Horizontally, the non-native sedimentary layers show no continuity from the shore outwards or along the strike of the shoreline (Figure 12). The native sediment generally underlies all other depositional units.

Table 3: Lowest and highest recorded elevations of each depositional unit based on 3-D representation depicted in Figure 7.

Unit	Highest Position (MLLW ft)	Lowest Position (MLLW ft)
Intermediate	-1	-58
Native	-7	-62
Sawdust	-7	-48
SM-SP	-3	-35
Woodchips	-5	-45

The subsurface representation of Mill-A has a sediment volume distribution of 44 percent native material, 24 percent intermediate, 24 percent sawdust, 7 percent woodchips and 0.4 percent SM-SP (Table 4, Figure 13). This accounts for a total volume of 4.3×10^5 cubic yards of sediment within the 24-acre project area.

Table 4: Percent volume of each depositional unit based on Figure 7.

Unit	Volume (cubic yards)	Percent of Total Volume
Native	1.90×10^5	44%
Intermediate	1.07×10^5	24%
Sawdust	1.06×10^5	24%
Woodchips	3.00×10^4	7.0%
SM-SP	1.70×10^3	0.4%

The extent of TOC with a high weight-percent (≥15%) is focused in the south, near-shore section of the project area (Figure 8). Merging this model with the woody sediment visually reveals that this high weight-percent of TOC (≥15%) is dispersed through the sawdust (Figure 14). The volumetric reports confirmed that the highest range of TOC (25% to 47%) is within the sawdust unit (Table 5, Figure 15). The high values of TOC are dominant in sawdust and woodchips, while low values of TOC are dominant in the native and intermediate material (Table 5). Viewing the distribution of TOC per depositional unit

indicates that the highest levels are present in sawdust, woodchips, and SM-SP material (Table 6, Figure 16).

Table 5: Summary of the percent distribution of COCs per depositional unit based on the ranges of values summarized in Table 2.

COC	Range	Unit	Native	Intermediate	Sawdust	Woodchips	SM-SP
TOC	0-0.5	%	*61%*	27%	11%	2%	0%
	0.5-15		*50%*	27%	16%	7%	0%
	15-25		22%	19%	*43%*	14%	2%
	25-47		**4%**	**4%**	**76%**	**15%**	**1%**
2,4-DMP	0-29	ppb	*59%*	26%	14%	1%	0%
	29-100		*41%*	18%	26%	15%	0%
	100-210		**25%**	**26%**	**36%**	**11%**	**1%**
	210-800		**30%**	**22%**	**37%**	**9%**	**1%**
Arsenic	0-5	ppm	*63%*	20%	15%	2%	0%
	5.0-20		*44%*	22%	24%	10%	1%
	20-40		***39%***	**33%**	**26%**	**3%**	**0%**

The lowest range represents the detection threshold. The highest value represents the highest analyzed value. Bolded values are at or above screening levels that require action. Percentages based off the 3-D illustration in Figure 7. Italicized/blue values represent the highest percent of sediment present within each COC range.

The extent of high concentrations (≥100 ppb) of 2,4-DMP is focused in the southern portion of the project area at medium depths (Figure 9). Both the visual representation of 2,4-DMP concentrations and the volumetric reports reveal that the highest concentrations of 2,4-DMP (100 to 800 ppb) fall within the sawdust, but are also dispersed throughout the native and intermediate soil (Table 5, Figure 17, Figure 18). The lowest concentrations are typically in the native material. The distribution of 2,4-DMP among depositional units indicated that cleanup levels are found in all depositional units with slightly higher percentages among the SM-SP and sawdust-rich sediments (Table 6, Figure 19).

Table 6: Distribution results of COC ranges per depositional unit.

COC	Range	Unit	Native	Intermediate	Sawdust	Woodchips	SM-SP
TOC	0-0.5	%	*14%*	11%	4%	2%	0%
	0.5-15		*75%*	72%	41%	53%	25%
	15-25		11%	16%	35%	34%	*68%*
	25-47		**1%**	**1%**	***20%***	**12%**	**7%**
2,4-DMP	0-29	ppb	*53%*	43%	22%	5%	0%
	29-100		26%	22%	29%	*51%*	6%
	100-210		**9%**	**18%**	**23%**	**23%**	***41%***
	210-800		**12%**	**17%**	**26%**	**21%**	***53%***
Arsenic	0-5	ppm	*11%*	7%	5%	2%	0%
	5.0-20		81%	79%	84%	95%	*100%*
	20-40		**8%**	***14%***	**11%**	**3%**	**0%**

The bolded values represent the levels of concern, or above screening for each COC. The italicized/blue values represent the highest percent for each COC range. Values were determined by volume of material per COC range divided by the total volume of sediment for each unit.

The extent of high concentrations (≥20 ppm) of arsenic is dominant in the offshore, deeper sediments of the project area (Figure 10). The merged representation of woody sediment and arsenic values imply that these elevated levels of arsenic, which are above cleanup levels, are located beneath the sawdust- and woodchip-rich sediments (Figure 20). The distribution of arsenic ranges demonstrated that arsenic levels above cleanup standards are dominant in all of the sediments (Table 5, Figure 21). Background levels and below-screening levels of arsenic are dominant in the native material. The distribution of arsenic for each depositional unit also confirmed that the ranges of arsenic above cleanup standards are dominant in all depositional units with slight increases in the native, intermediate and sawdust (Figure 22). The intermediate concentrations, which include the natural background levels of arsenic, are dominant throughout each depositional unit (Table 6).

The volumes of sediment containing COC concentrations above cleanup criteria are 135,000 cubic yards, 106,000 cubic yards, and 38,000 cubic yards for 2,4-DMP, TOC and arsenic, respectively (Table 7, Figure 23). By comparison, the total sediment represented in Figure 7 is about 430,000 cubic yards. The combined volume of sediment containing one or more COC above cleanup levels is 181,000 cubic yards; whereas, only about 6,700 cubic yards, or 3.7%, of contaminated sediment contain all three COCs above the cleanup levels.

Table 7: Volumes of sediment containing COCs above cleanup levels.

COC above Cleanup Level	Volume (cubic yards)
TOC (≥15%)	106,000
Arsenic (≥20 ppm)	38,000
2,4-DMP (≥100 ppb)	135,000
Combined	181,000
All 3 COCs present above cleanup levels	6,700

The combined volume accounts for overlap of the high concnetrations of the three COCs. The volumes are illustrated within the Mill-A project area in figure 23.

The sensitivity analysis, which established the distribution or arsenic with the addition of natural background levels (7 ppm) everywhere that there were no data, showed an inconsistent change in the distribution between the low, medium and high concentration ranges defined in Table 1 (Table 8). This addition of arsenic levels resulted in a +/-10%, +/-2%, and +/-53% for the low (0 to 5 ppm), mid (5 to 20 ppm), and high (≥20 ppm) concentrations, respectively (Figure 24, Figure 25). The changes of 3% or less were seen in the low-volume sedimentary units, woodchips and SM-SP (Table 8, Figure 24).

Table 8: Percent distribution of depositional unit per range of original arsenic values, arsenic with the addition of natural background values, and the change between these distributions.

Sediment	Range (ppm)	Original Arsenic	With Background	Change in Distribution
Native	0-5	*63%*	*53%*	-10%
	5-20	*44%*	*44%*	-
	20-40	**39%**	**14%**	-25%
Intermediate	0-5	20%	24%	+4%
	5-20	22%	23%	+1%
	20-40	**33%**	**86%**	+53%
Sawdust	0-5	15%	23%	+8%
	5-20	24%	25%	+1%
	20-40	**26%**	**0%**	-26%
Woodchips	0-5	2%	0%	-2%
	5-20	10%	8%	-2%
	20-40	**3%**	**0%**	-3%
SM-SP	0-5	0%	0%	-
	5-20	1%	0%	-1%
	20-40	**0%**	**0%**	-

Bolded values are above screening level. Italicized/blue values represent the highest percent per concentration range. Data depicted in figure 24.

The first model for the extent of arsenic implied a volume of sediment of approximately 37,500 cubic yards with concentrations at 20 ppm or higher. With the addition of natural background levels to boreholes with no data, this volume reduces to about 16,000 cubic yards, or 43% of the first model volume.

5.0 Discussion

The results of this investigation provide insight into both the correlation between COCs and wood waste and the geographic extent of COCs in the subsurface. This information is helpful in determining the amount of sediment to be removed to meet cleanup criteria at Mill-A.

The non-native sediment does not demonstrate any consistent depositional patterns. Each sedimentary unit varies in both horizontal extent and thickness. The native sediment should underlie all other sediment units, but this is often not the case with alternating layers of intermediate sediment and native sediment. This may be a result of decades of alternating native alluvium and non-native wood waste deposition at this site.

There does not appear to be a connection between the location and extent of high concentrations for each COC. High concentrations of TOC are mostly restricted to the shallow sediments in southeast quadrant of the project area, which is closest to the shoreline and infrastructure. The highest 2,4-DMP concentrations are in the southwest quadrant at mid depths. Also in the southwest quadrant is the high concentrations of arsenic, but within the deeper sediments. Since there is little spatial overlap of these toxic levels of COCs, the results do not support the findings from the Department of Ecology that toxicity is more consistent with TVS values higher than 15 percent (2013A).

The geographic focus of TOC in the upper portion of the sediment near the shoreline was consistent with the assumed source of sawdust. If sawdust were sourced from the terminal boundaries, then higher values of COC would be expected at these locations. An unexpected result was the high concentration of TOC in the SM-SP unit. This distribution was more apparent when comparing TOC ranges in a single sedimentary unit (Figure 16), which revealed that nearly 60 percent of the SM-SP material at this site contains mid ranges (15% to 25%) of TOC and about 10% higher ranges (25% to 47%) of TOC (Table 6). Contrary to this result, the SM-SP depositional unit was observed to contain no wood.

This unexpected distribution was an artifact of the interpolation method used to create the model. SM-SP comprises less than 1% of the overall sediment volume (Figure 13). This low-volume unit is not of concern as the results presented in Figure 16 for SM-SP and TOC distribution were well within the range of uncertainty for the model. The distributions of 2,4-DMP in SM-SP (Figure 19) demonstrated a similar unexpected result of high concentrations of 2,4-DMP despite the expectation that 2,4-DMP results from wood decomposition.

An overlap of less than 4% of sediment containing toxic concentrations of all three COCs is not statistically significant enough to suggest the extent of these COCs is related. High concentrations of arsenic in the deeper, native sediments is not consistent with the hypothesis that contaminants would have higher concentrations in wood-rich sediment

near the shoreline. This result is also contrary to the results of the Geomatrix (2007) report that native material contains COC levels below cleanup standards.

Although the distribution of COCs appears unrelated, their individual distribution within the sedimentary units reveal patterns. TOC, which serves as a proxy for the quantity of wood, had the highest concentration by volume in the sawdust-rich sediment (Figure 15). The presence of elevated TOC was more prominent in sawdust than the woodchips, despite both depositional units containing 30 percent or more wood. This difference can be attributed to the size of wood particles and how TOC is measured. Smaller wood pieces, such as sawdust, may decompose at a faster rate than woodchips. Alternatively, the pore water space may be larger in the sediments containing woodchips, which allows more mixing of the water. Mixing of water in the woodchips and not the sawdust would explain the higher amount of hydrogen sulfide observed in sawdust-rich sediments. According to the Department of Ecology (2013A), TOC may also assess anoxic environments, which would be greater in the sawdust-rich sediments where less mixing of ambient waters is occurring.

The distribution of 2,4-DMP also supports the notion that the sawdust is decomposing more quickly than the woodchips. Since 2,4-DMP occurs from the decomposition of wood waste, the higher concentrations should be located where the largest volumes of wood are decomposing. The distribution results indicate that the woodchip-rich sediment contains concentrations of 2,4-DMP below 100 ppb whereas the sawdust-rich sediment comprises the highest volume of sediment with 2,4-DMP above 100 ppb. The native sediments contain low ranges (<100 ppb) of 2,4-DMP (Figure 18). The distribution of 2,4-DMP in the intermediate soil is consistent through each concentration range.

All depositional units reported volumes of 11 to 30 percent containing median (29 to 210 ppb) and high (210 to 800 ppb) concentrations of 2,4-DMP, with the exception of SM-SP (Table 5). Besides wood decomposition rates differing between units, another explanation for the extent of 2,4-DMP at higher concentrations may be related to the pulp mill effluence, which released lignins into the ambient waters. If these 2,4-DMPs are related to the effluence, rather than the physical decomposition of wood waste, then we would not expect to see a correlation between the extent of high concentrations and wood-rich sediments. Besides effluent dispersal, another explanation of the dispersed nature of 2,4-DMP concentrations is potential leaching over time. Although, this theory cannot be confirmed without more information regarding mass balance and time of dispersal. In general, since 2,4-DMP does not strongly sorb to particles, a dispersed distribution within the site is a reasonable result.

Although the data for arsenic concentrations were the most limited of all three COCs in this report, the distribution of arsenic concentrations is scattered throughout the native sediment, intermediate, and sawdust-rich sediments (Figure 21). Separating the high concentration range of arsenic from 20 to 40 ppm to 20 to 30 ppm and 30 to 40 ppm reveal high concentrations of 30 to 40 ppm are more dominant in the native and intermediate sediments (Figure 26).

Since previous studies (DOE, 2014) found Port Gardner Bay to have natural background levels of total arsenic at about 7ppm, it can be assumed that the increased level of arsenic

at Mill-A is sourced from inorganic processes such effluent from the former pulp mill. Nevertheless, the high concentrations of arsenic are away from the shore, which is counterintuitive for the expected source of contaminants. An explanation for the high concentrations of arsenic in the deeper sediment is gaps in the data. Cores drilled in the shallower sediment are lacking analytical data for arsenic (Figure 20).

By adding natural background levels of arsenic to null boreholes, the distribution of high levels of arsenic drop except in the intermediate soil where the original sample was taken (Table 8, Figure 25). This drop in arsenic concentrations was expected since the IDW algorithm identifies nearest points as having a higher influence than more distant points, which creates a linear decrease between high to low concentrations. The midpoint between a high concentration of 40 ppm and low concentration of zero ppm is 20 ppm. If the low concentration were closer to 7 ppm, then the median value would be 23.5 ppm rather than 20 ppm, which implies a smaller gradient. The addition of background levels of arsenic accounts for a 17.5% decrease in the concentration gradient. The volume of sediment containing arsenic concentrations 20 ppm or higher with the addition of natural background levels results in a change of 21,500 cubic yards, or 57 percent decrease in volume.

The sensitivity analysis of arsenic with and without the presence of a natural background level suggests that the incidence and location of high concentrations of each COC have an uncertainty of up to 53 percent (Table 8, Figure 24). This level of uncertainty is roughly the same as the change in volume (57 percent) of soils requiring mitigation. Based on this information, for mitigation purposes, the volume of sediment to be removed around borehole ST-34 (Figure 4) is 21,500 cubic yards, but removing 53% to 57% more of the surrounding sediment would increase the chance of containing all sediments with arsenic above cleanup levels.

Seven parts per million of arsenic falls within the 5 to 20 ppm range of concentrations, but the addition of this background level did not change the distribution of arsenic in this range. However, it did alter the distribution of arsenic concentrations above 20 ppm. Since concentrations above 20 ppm are those of concern, there is a high uncertainty for what material would need to be removed to fulfill the cleanup criteria.

The sensitivity analysis also established that arsenic levels above the non-detect threshold (5 ppm) and below the cleanup level (20 ppm) have an uncertainty of plus or minus two percent. Since the main concern for COCs is the distribution of levels above the screening level, the more relevant uncertainty is the high concentrations ($\geq$20 ppm). Despite these uncertainties, these results would still be useful as a guideline for other contaminated sites. Since no correlation of arsenic to COCs and wood waste was established, it is likely that more than just the woody material would need to be removed or mitigated to restore this contaminated site. Since wood decomposition often creates anoxic environments with slow regeneration, this is reason enough to remove wood-rich sediment.

Although arsenic does not correlate to wood waste based on these results, a report by DOE (2014) determined that arsenic did correlate to TOC with an r-value of 0.635 using

Pearson's Linear Correlation method[2]. The data in this report may not be robust enough to confirm this correlation through the distribution results (Table 5, 6 and 7). The same DOE report also found a correlation of arsenic to percent fines with an r-value of 0.800. This relationship may give more insight to the observations that high concentrations of arsenic were present in the native and intermediate materials (Figure 26). If grain size were analyzed for the Mill-A data sets, future investigations may find a stronger correlation of arsenic at this site to percent fines rather than percent wood.

Based on the results of this report, a recommendation for moving forward with the Mill-A Cleanup Project would be to cap the dredged surface to limit COC exposure to the ambient water. According to the subsurface interpretation of sediment, if dredging during Phase 1 and Phase 2 are limited to -42 feet MLLW, then not all of the contaminated sediment will be removed. The sediment unit of main concern for ecologic advancement of the area is the sawdust, which would be 87 percent removed by dredging to -42 feet MLLW. Capping the dredged surface would prevent exposure of the remaining sawdust as well as the high levels of arsenic present below -42 feet MLLW.

Since the sparse data was a limitation for this project, the following is a discussion of available samples and suggestions for future sampling techniques. Most of the samples collected from Mill-A were not analyzed, and most cores were only analyzed at a single depth. An ideal sampling technique would be to drill to five feet into native material to confirm the extent of non-native sediment. This drilling depth was a standard depth used in sampling methods by GeoEngineers. The native material is identifiable by the change in density of the sediment. The cores should be logged, and samples should be taken at observable changes in depositional units rather than two-foot increments. The practice of taking samples at two-foot increments is unproductive if the samples are not analyzed and cannot be stored for any length of time without degradation. Limitations of time and money prevented many of these samples from being analyzed. A more realistic sampling approach is to analyze a single sample for each unit. For example, if a core has 10 feet of sawdust, 1 foot of woodchips, 3 feet of intermediate material, and 5 feet of native material, a total of four samples from this log should be analyzed for chemicals of concern, including one sample from each unit instead of one sample every two feet. For thicker layers, it would be important to plan a sampling scheme that allowed sampling at variable depths. An example of this would be to take a sample from the top 2 feet of sawdust in one core, the bottom 2 feet of sawdust in another core, and various centered samples in other cores. This ensures a more complete understanding of how COCs might transport through the layers of sediment.

6.0 Conclusions

The main objective of this investigation was to test if a correlation existed between wood content and high COC concentrations. This was accomplished through interpolating the volume of sediment and extent of COC concentrations from discrete borehole data. The

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[2] Method showing linear dependence between two variables with zero (0) as no correlation, one (1) as positive correlation and negative one (-1) as negative correlation (Laerd Statistics, 2013).

extent and locations of the high COC concentrations did not overlap significantly, nor did they obviously overlap with a sole depositional unit. The strongest correlation from this investigation was between high concentrations of TOC and sawdust-rich sediment. Although the high concentrations of arsenic and 2,4-DMP did not correlate with the wood-rich sediment, they did correlate with the non-native sediment, which includes the intermediate soil, sawdust, and woodchips. Low concentrations of each COC were dominant in the native sediment.

This distribution suggests that contaminants entered the marine sediment through anthropogenic processes, but may not necessarily correlate directly to the wood waste. Further understanding of the source of contaminants, mass balance of contaminants, and timing of contamination, along with the transport mechanisms for each COC, would help clarify their correlation to wood waste. Even without a conclusive connection between COCs and wood waste, this investigation is still able to estimate the location and volume of sediment containing actionable concentrations of COCs.

The sensitivity analysis represents the uncertainty of these results, which increases with higher concentrations. For the actionable concentrations of COCs, there is an uncertainty of extent greater than 50%. This uncertainty could be decreased with direct validation of the interpolated sediment between borehole data. Since the extent of high COC concentrations are directly related to the expense of mitigation, and because the distributions are uncertain by more than 50%, it would be worthwhile to obtain further data to refine this estimated extent.

6.1 Recommendations for Future Work

Validation requires a set of known values to compare to the model outputs. A new set of more robust data will be published later this year, which should be used for the validation to increase its accuracy. The difference between expected values and output values can further assess the uncertainty of the COC and sediment extents.

Incorporation of other COCs may also give more insight into the distribution of COCs at Mill-A. Since Mill-A is a former sulfite pulp mill, other COCs to consider are sulfides and ammonia, which are other byproducts of wood decomposition (DOE, 2013A).

7.0 Limitations

The software, RockWorks, is in itself a limitation to this project because of the capacity to modify and customize diagrams and models. Although there are numerous options for each tool, certain options were not available on all tools. Other output adjustments proved too difficult or impossible to do. An example of this is the borehole location map (Figure 4), which shows borehole labels off the map. In the *borehole location map* tool, there is no placement option for these labels; however, label placement is an option within other tools. Interpolations are also limited to the types offered by RockWorks.

Another limitation is in the sediment classifications, which are identified by wood content and type. The sediment identifiers (sawdust, woodchips) may be present in any unit identified to contain wood. Sawdust may be present in units identified as woodchips and

either sawdust or woodchips (treated or untreated wood) may be present in the intermediate layer skewing the results.

Despite visual inspection of anomalies, some obvious flaws in the model still exist. One example of this is seen in Figure 7 where there are holes in the deeper sediment. It is unlikely that there these holes are actually present in the marine sediment. A possible explanation for this irregularity is that the tops of these two cores were not recovered during the sampling process, which skewed the location of the mudline at these cores and created hole-like features in the subsurface representation of sediment.

Finally, SM-SP is not a significant unit (0.4% total volume) and may skew the distribution results. Interpretations of results may benefit from lumping SM-SP into the intermediate sediment. An example of the skewed data is in the TOC distribution, which suggested that there are high concentrations of TOC in SM-SP despite the lack of wood in that sedimentary unit (Figure 16).

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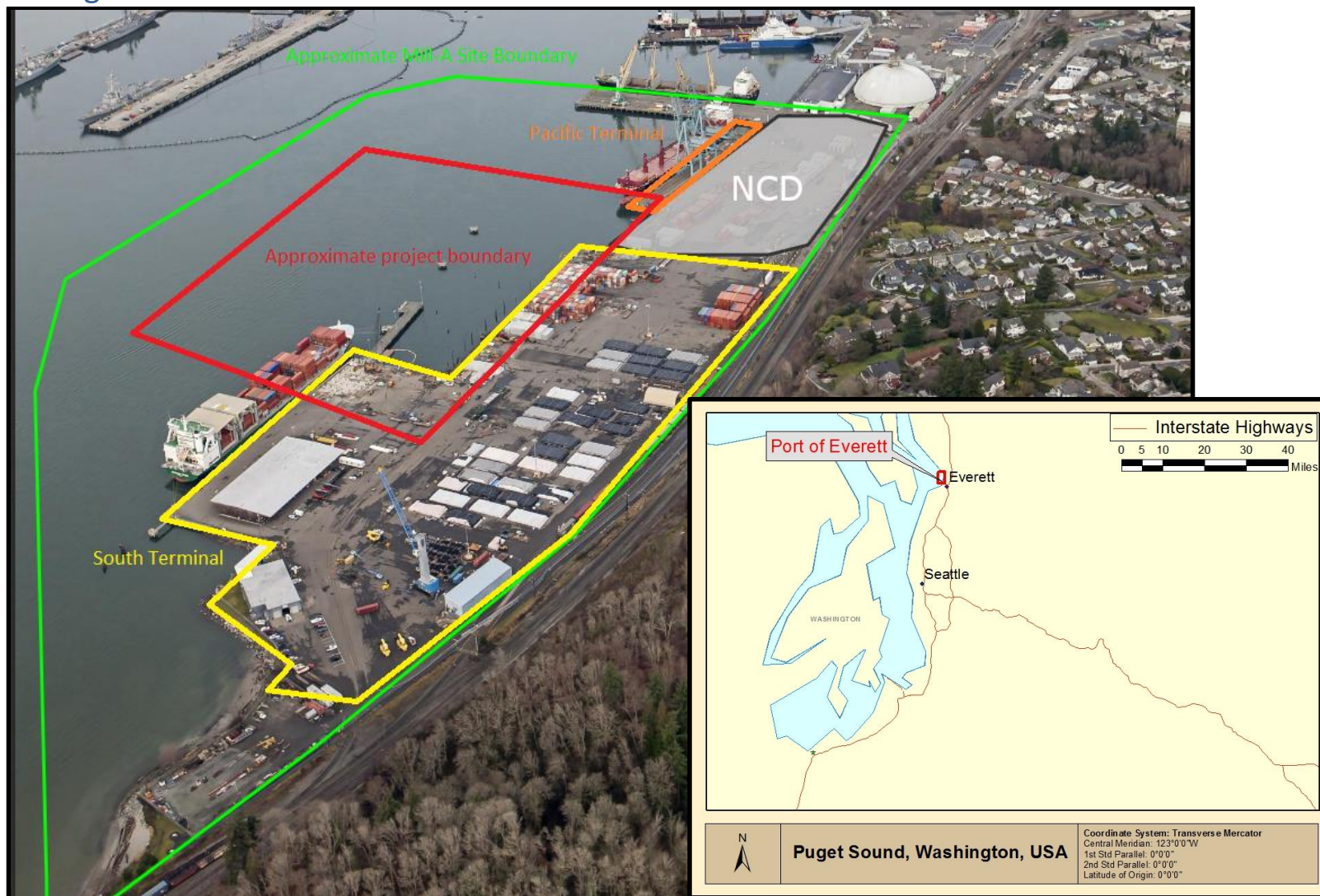
9.0 Figures

Figure 1: Site map for Mill-A project. Figure adapted from Mill-A Cleanup/Terminal Expansion Project Update by Erik Gerking (Port of Everett, 2015). Inset figure adapted from Northwest map in ArcGIS. NCD is the nearshore confined disposal facility.
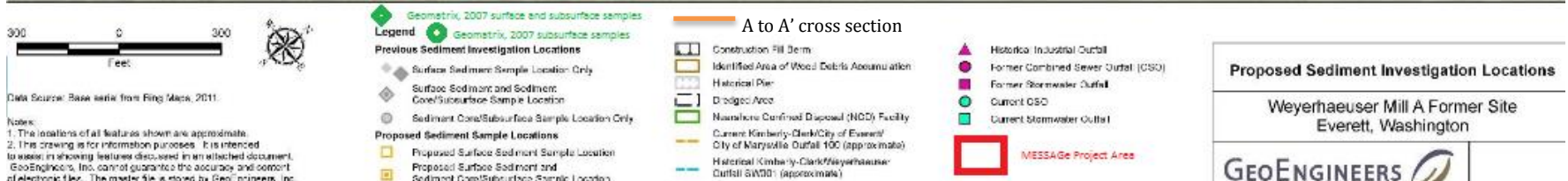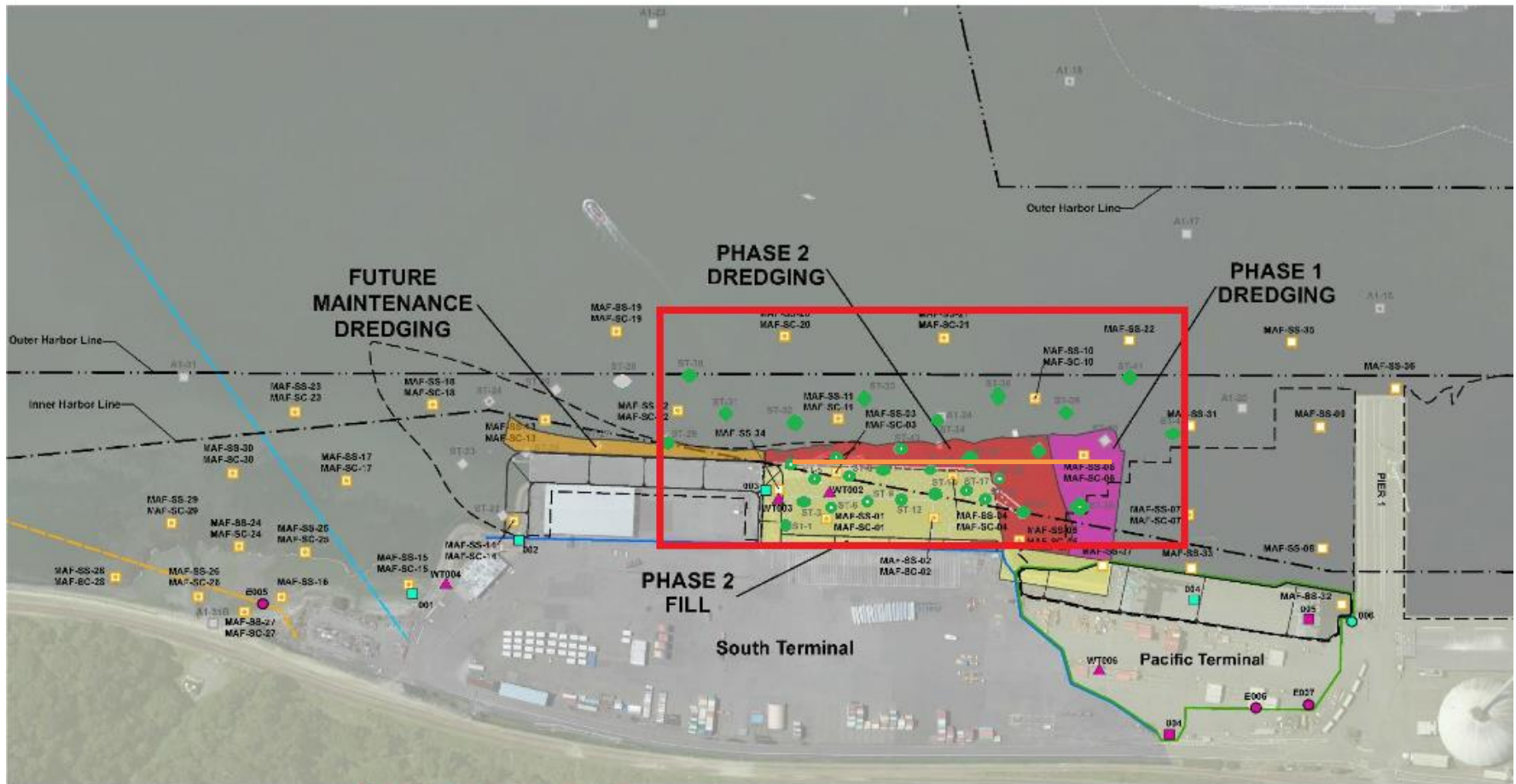
Figure 2: Geologic map of Everett, WA adapted from Minard (1985) with approximate Mill-A boundary outlined in red. Geologic legend in Appendix B.

Figure 3: Site map of project area showing borehole locations, Phase 1 dredging area, Phase 2 dredging/fill area. Project area outlined in red. Geomatrix (2007) sample locations in green. Unpublished data in yellow. Pink polygon represents area of GeoEngineers (2015) data taken in Phase 1 dredging zone (Figure 3). Figure adapted from GeoEngineers (2015). The corner coordinates of the project area are: North: 47.978002, -122.224623, East: 47.97480523, -122.224623, South: 47.97480523, -122.22844906, West: 47.978002, -122.22844906. These coordinates apply through all figures.
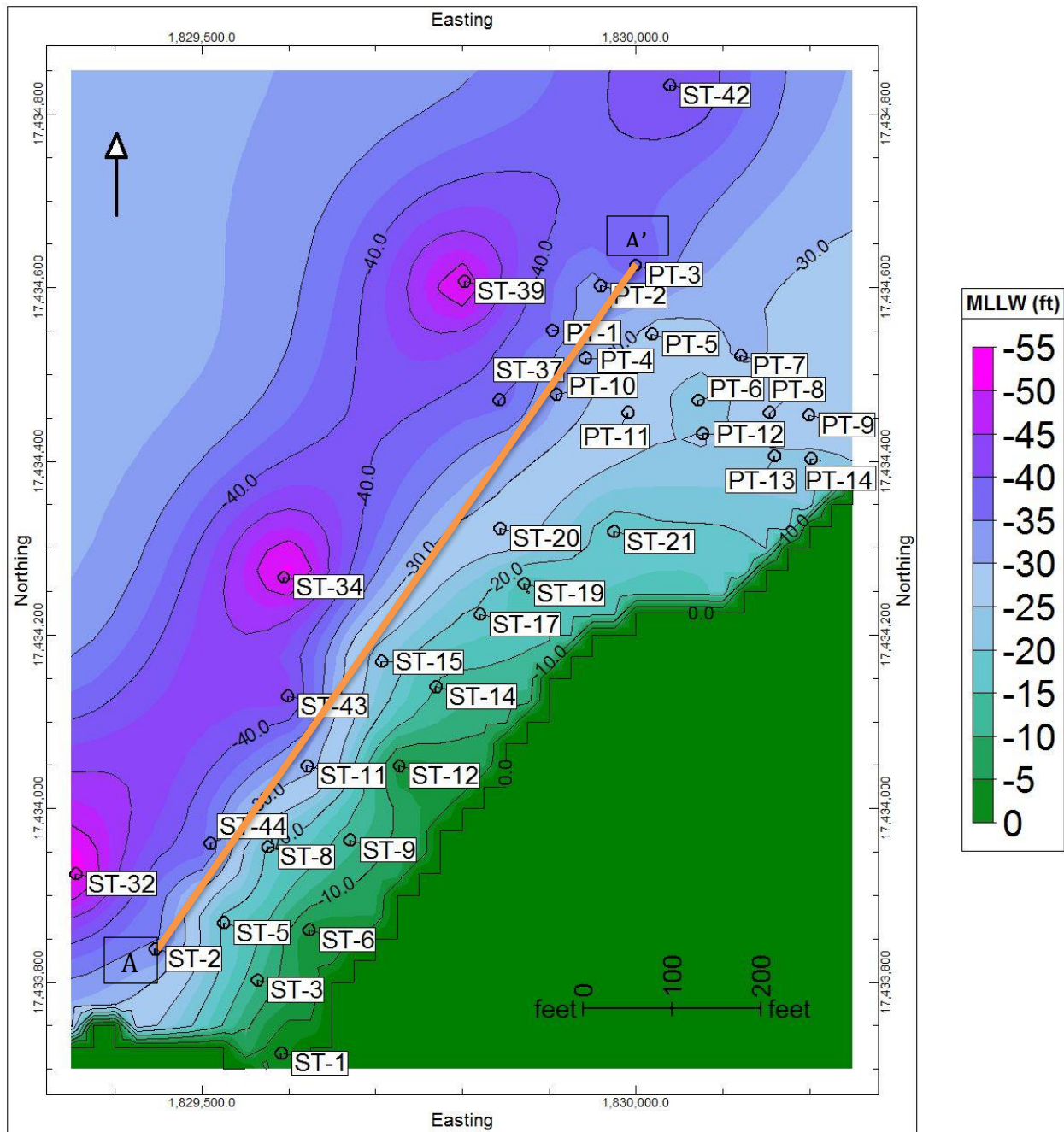
Figure 4: Borehole location map with corresponding elevations in feet below MLLW. Location and elevation values for each borehole are in Appendix A. Figure corrected for shoreline location with polygon clip (jagged contour). Cross section A-A' references Figure 11. Northing and Easting coordinates in UTM feet.
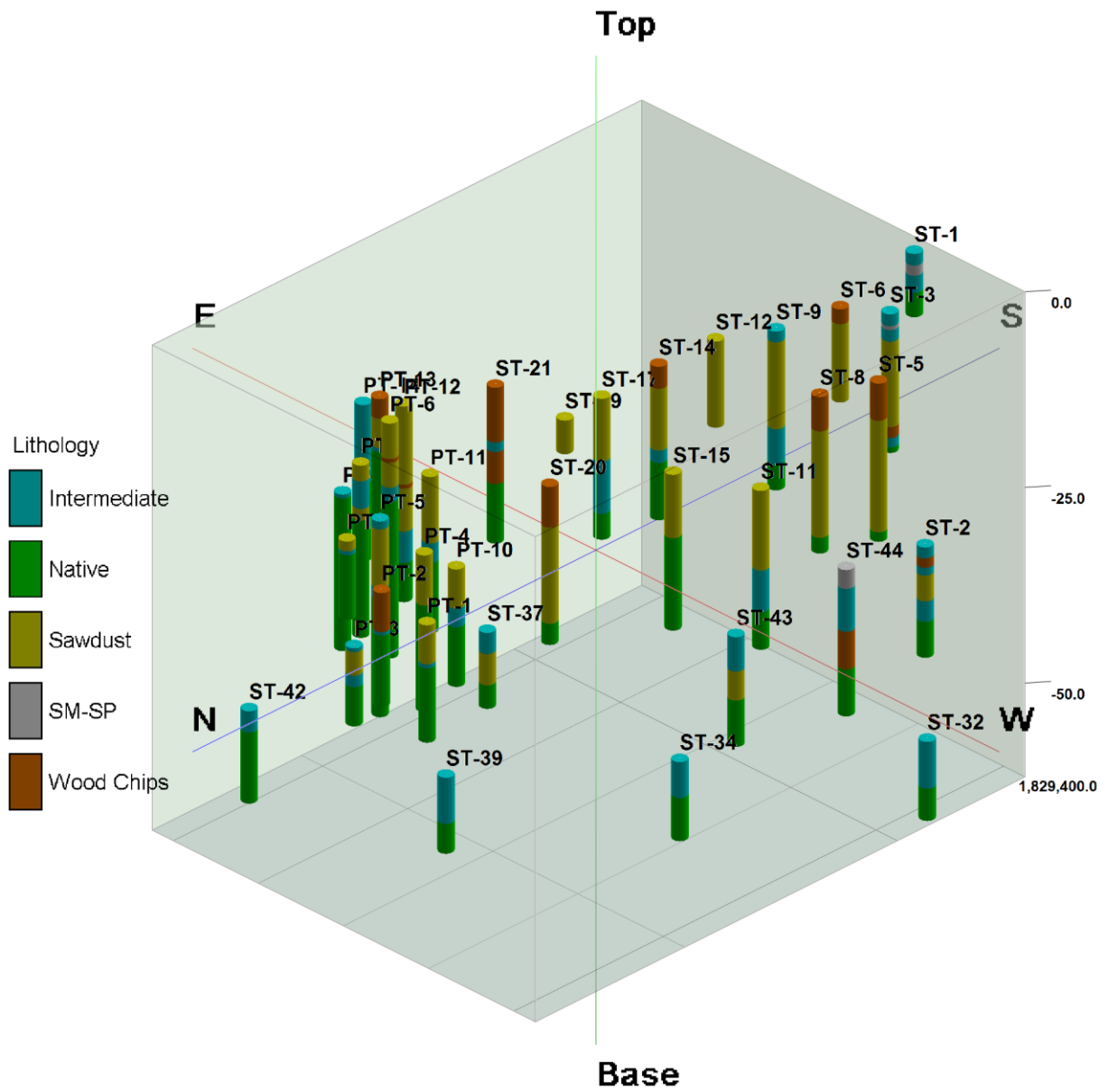
Figure 5: 3-D strip logs of depositional units (lithologies). 15x vertical exaggeration. Z-axis is feet below MLLW.
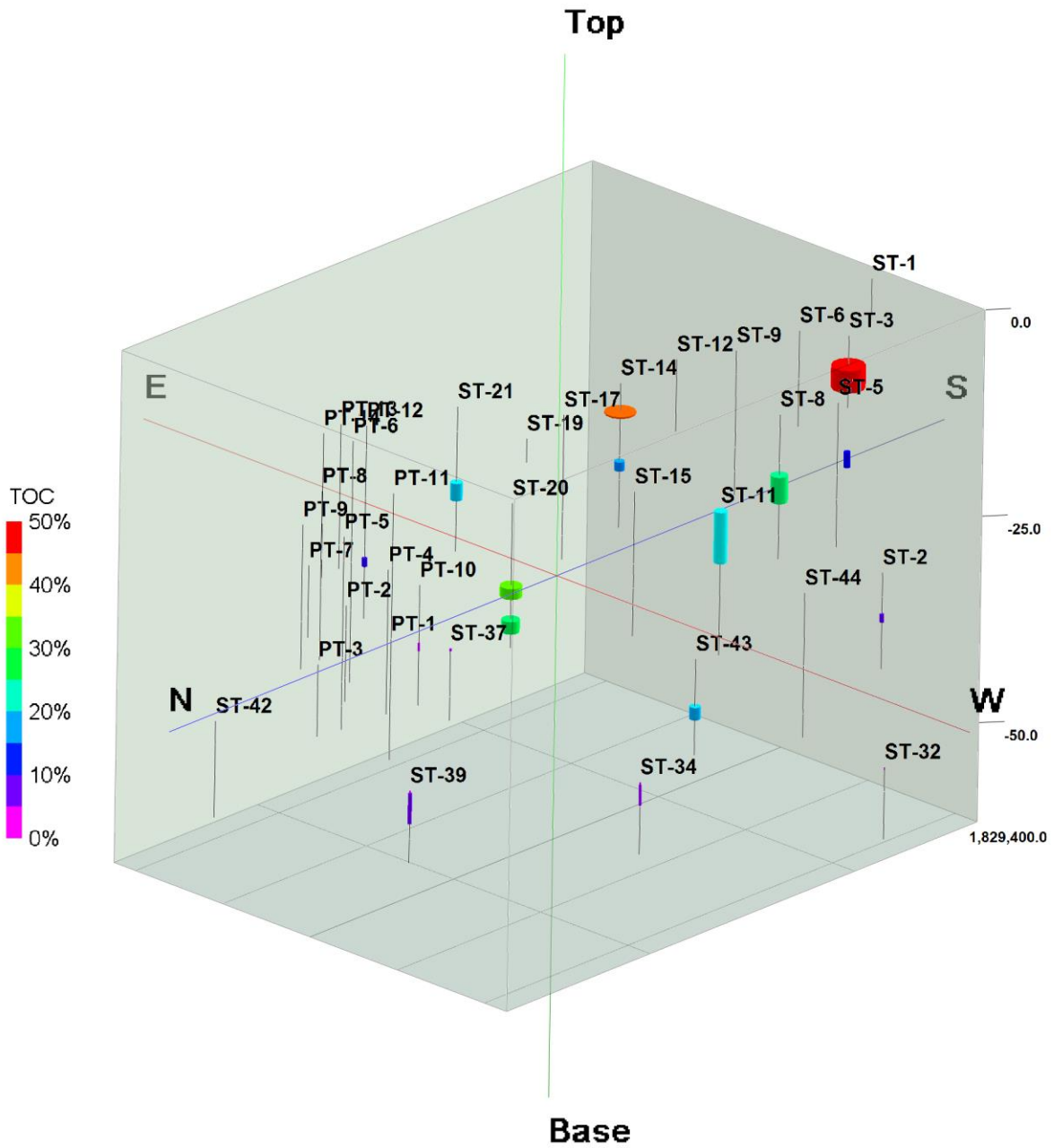
Figure 6: 3-D strip log of TOC values at each sample location. Line represents total depth and location of core sample. Cylinders represent location of sampled sediment and resulting TOC concentration. Vertical exaggeration 15x. Z-axis in feet below MLLW.
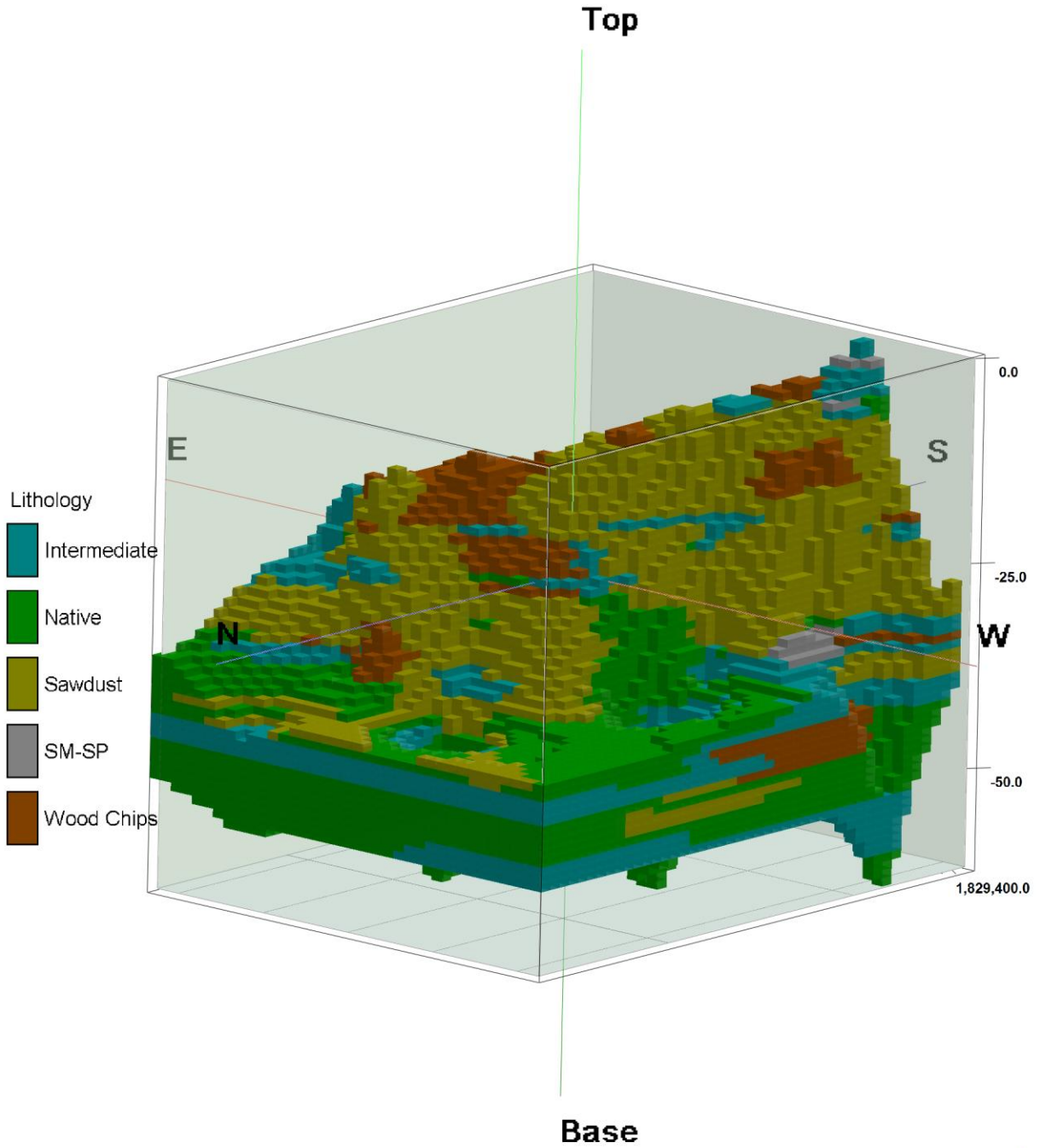
Figure 7: 3-D block (or solid) model depicting the continuous depositional units based on borehole data. Vertical exaggeration 15x. Visual orientation is looking towards the shoreline (SE). Z-axis units in feet below MLLW. 1,829,400 is the SW corner coordinate in UTM Feet. Corner coordinates match those in Figure 3.
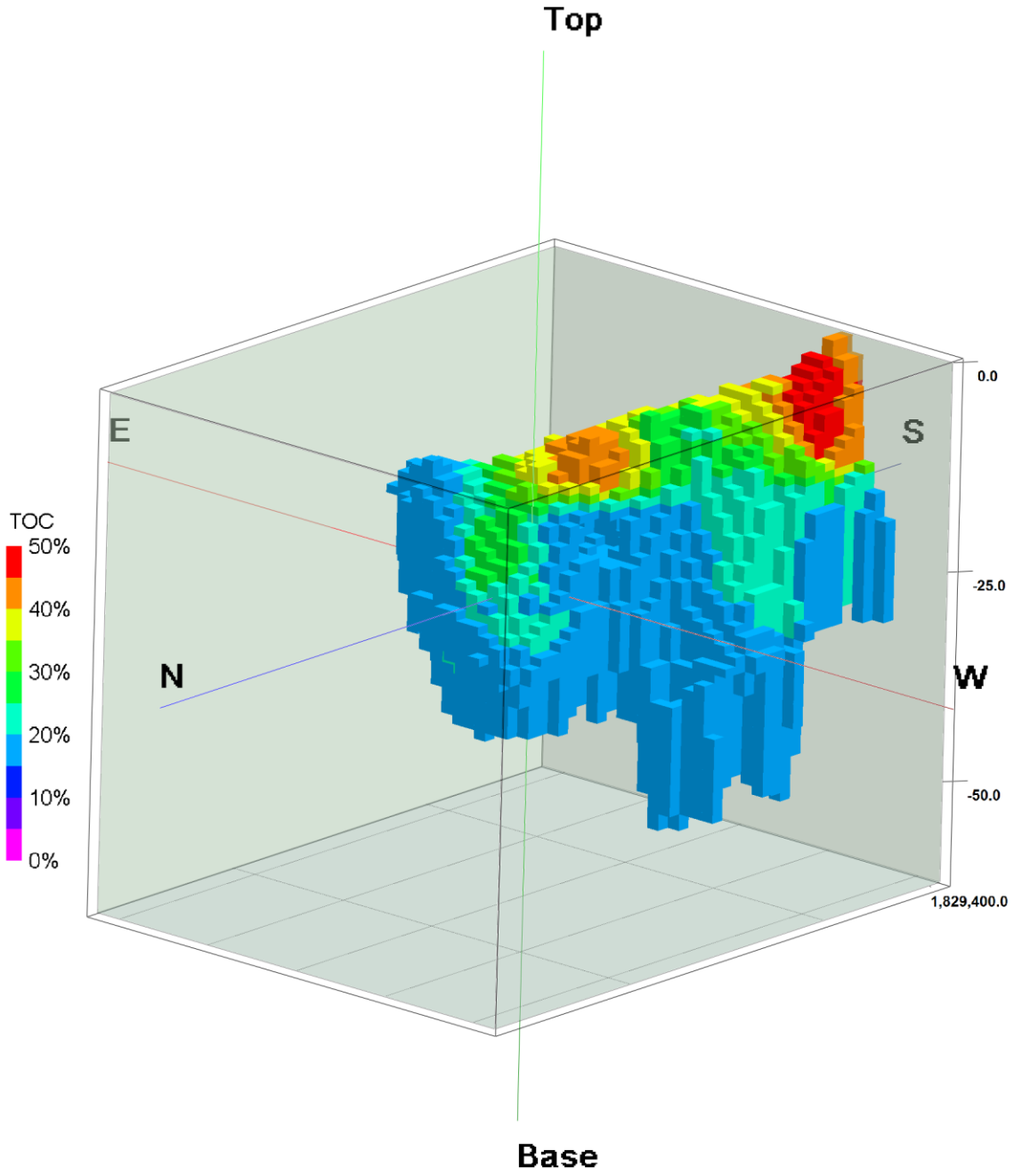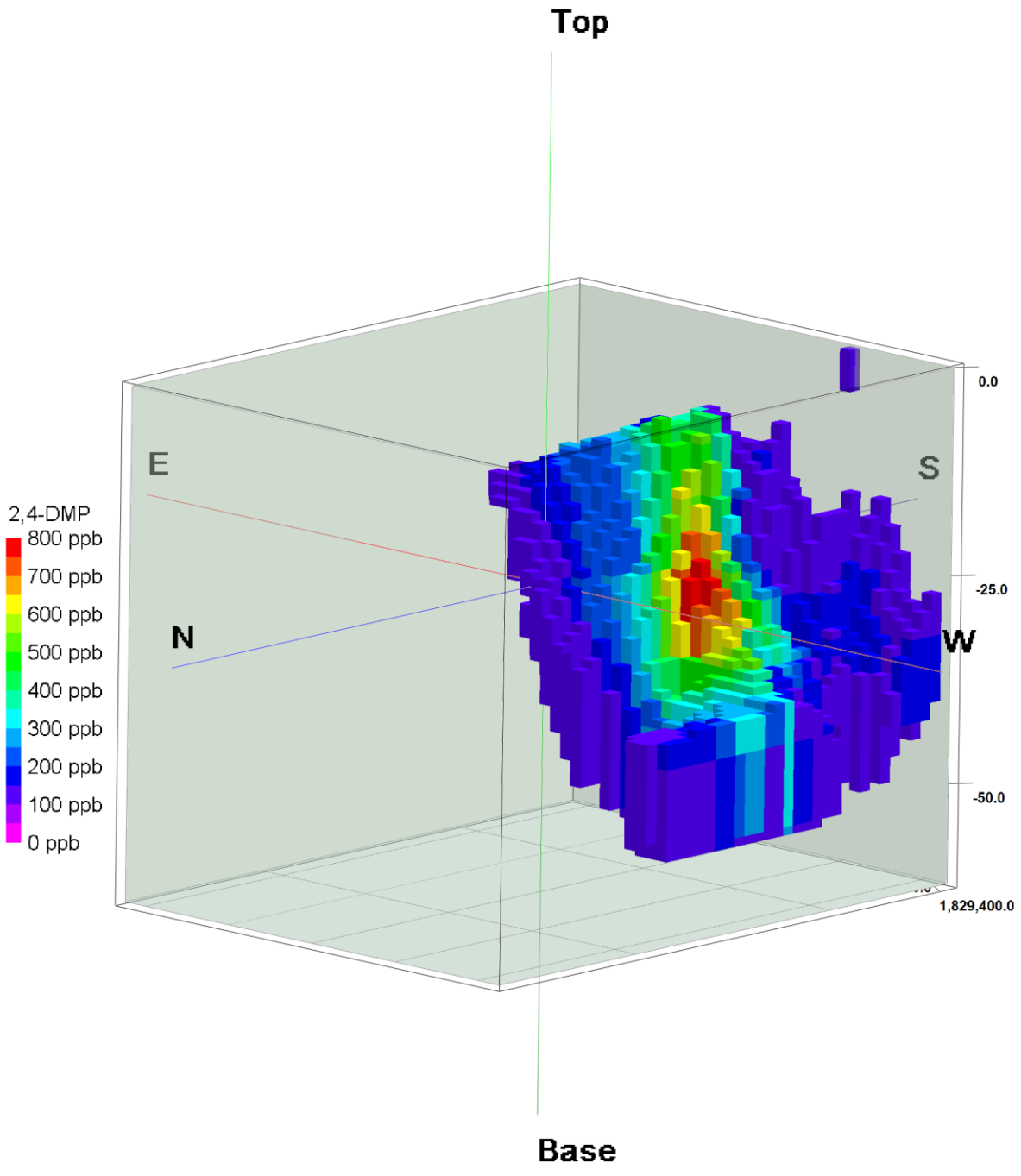
Figure 8: Extent of TOC with weight-percent of 15% or more. 15x vertical exaggeration. Visual orientation is looking inland towards the shoreline (SE). Z-axis units in feet below MLLW. 1,829,400 is the SW corner coordinate in UTM Feet. Corner coordinates match those in Figure 3.
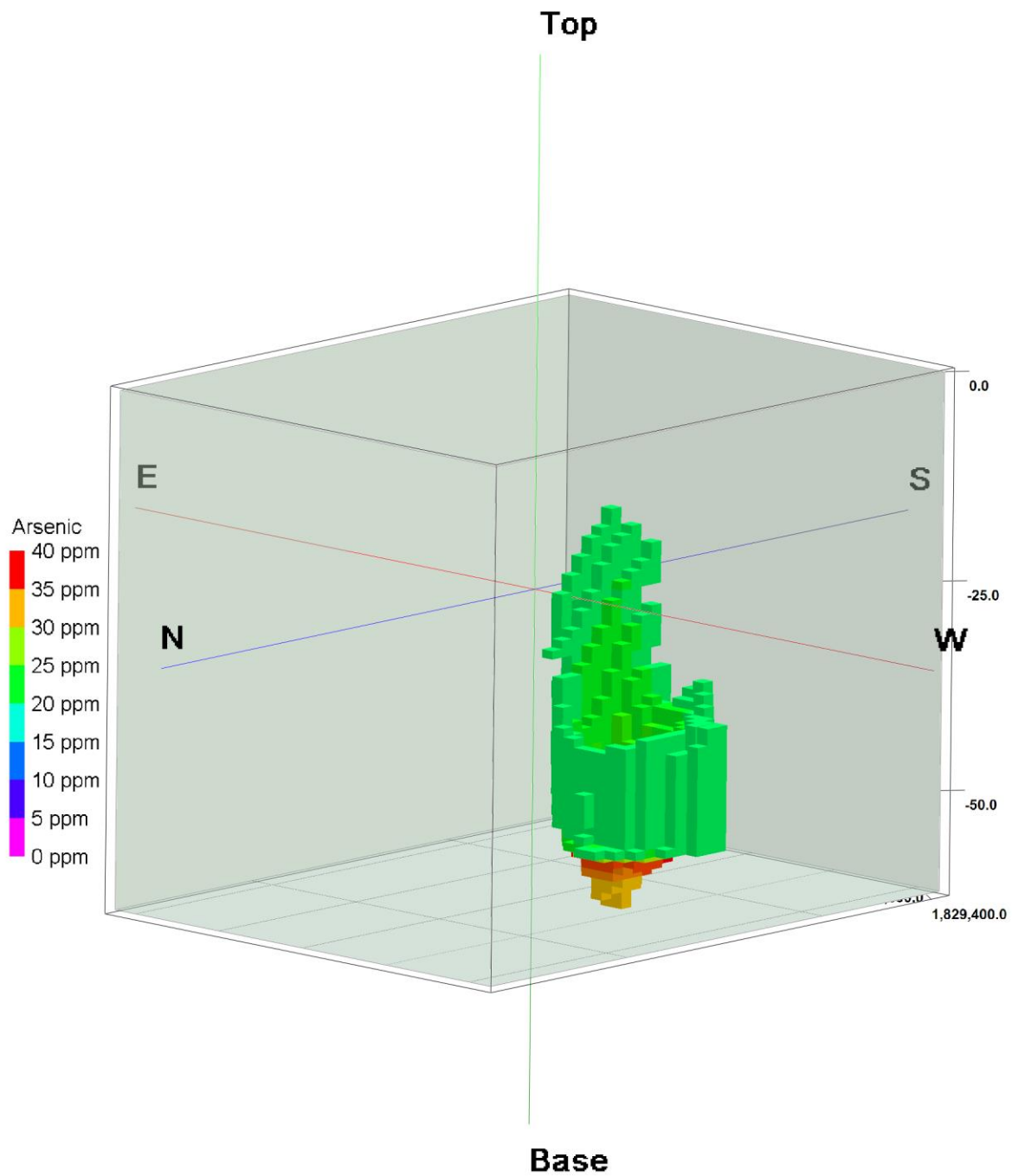
Figure 9: Extent of 2,4-dimethyphenol 100 ppb or more. 15x vertical exaggeration. Visual orientation is looking inland towards the shoreline (SE). Z-axis units in feet below MLLW. 1,829,400 is the SW corner coordinate in UTM Feet. Corner coordinates match those in Figure 3.

Figure 10: Extent of arsenic 20 ppm or more. 15x vertical exaggeration. Visual orientation is looking inland towards the shoreline (SE). Z-axis units in feet below MLLW. 1,829,400 is the SW corner coordinate in UTM Feet. Corner coordinates match those in Figure 3.
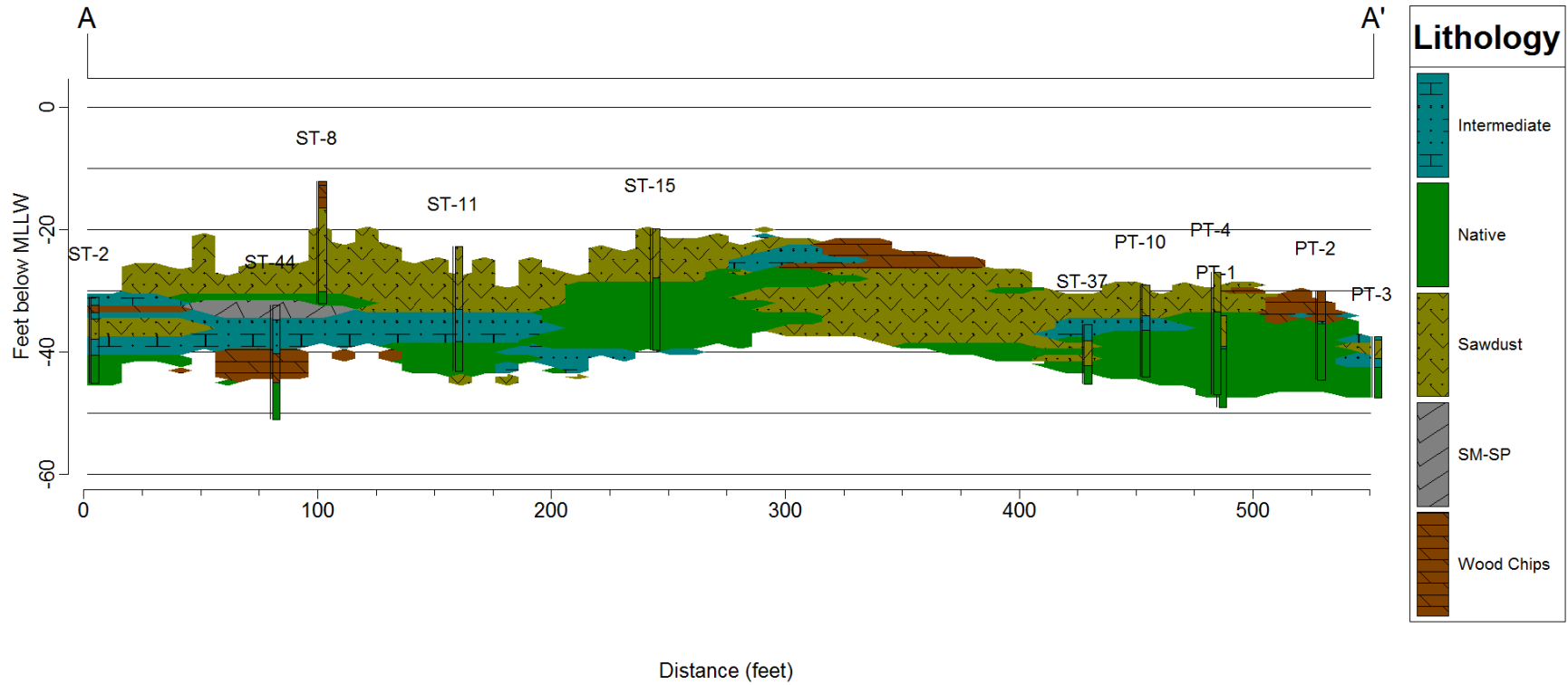
Figure 11: Profile view from cores ST-2 to PT-3 (A to A' Figure 4). 5x vertical exaggeration.
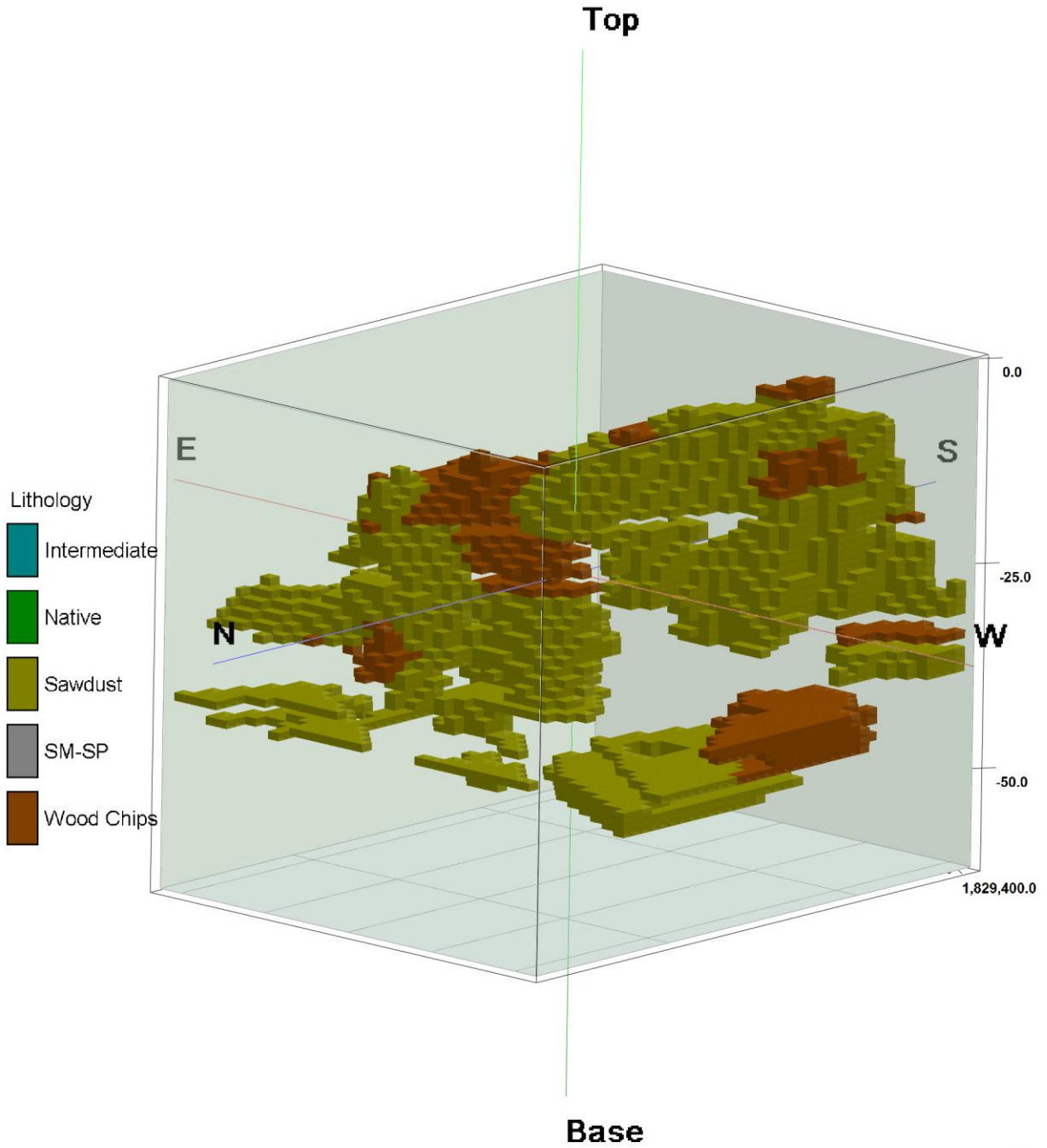
Figure 12: 3-D representation of sawdust- and woodchip-rich sediments. Vertical exaggeration of 15x. Z-axis in feet below MLLW.
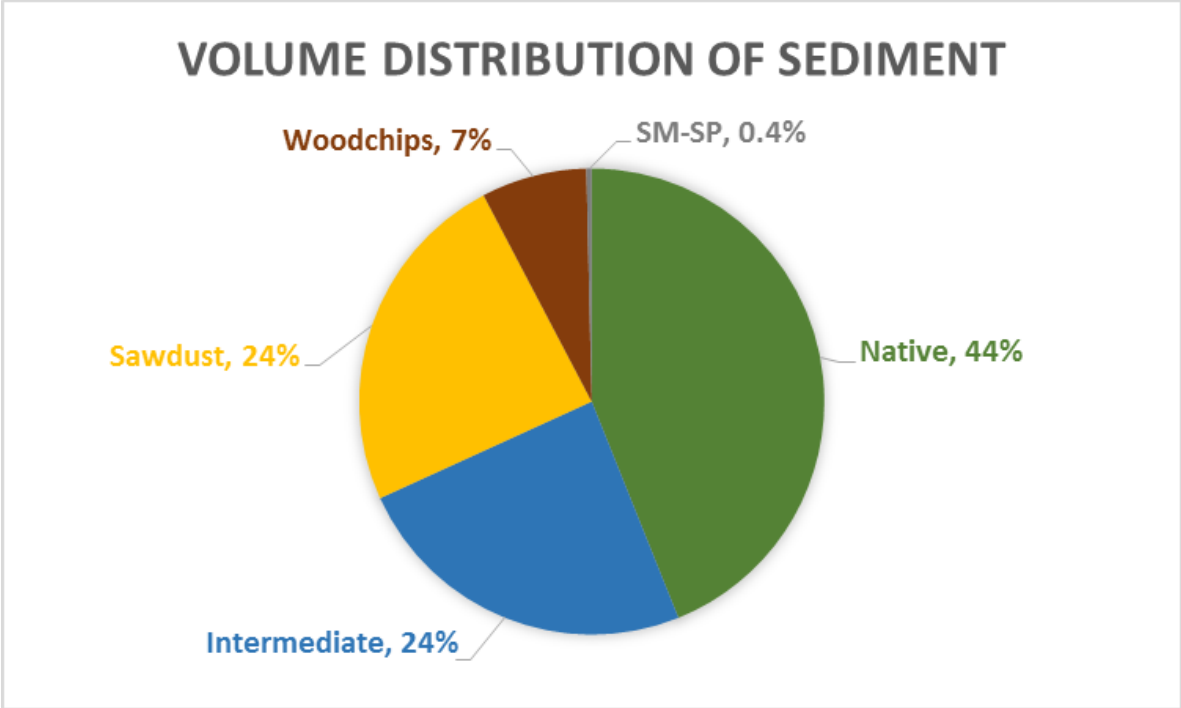
Figure 13: Volume distribution of sediment, or depositional units, based on 3-D model results.
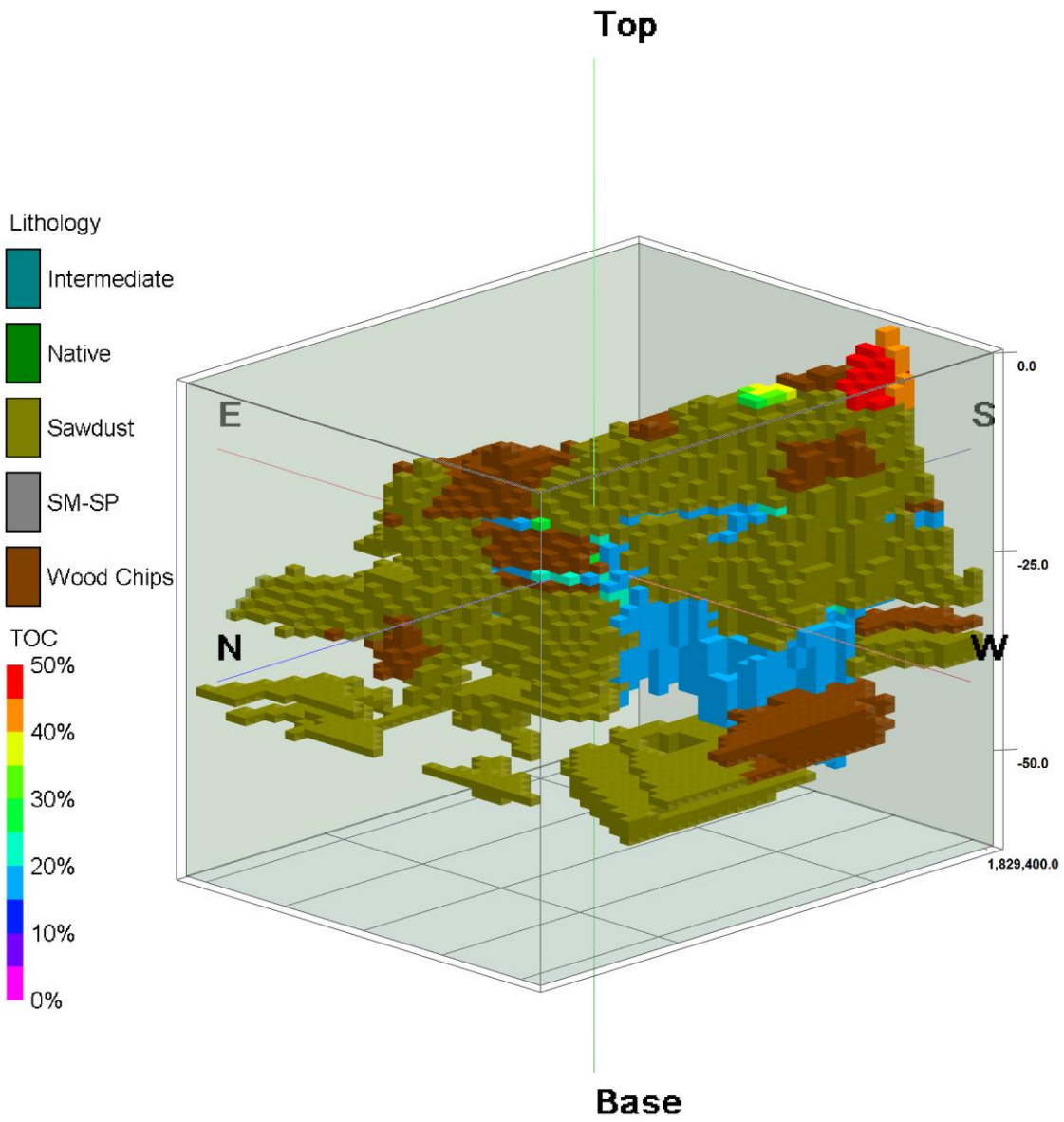
Figure 14: Depositional extent of sawdust and wood chip units inset TOC 15% or more (Figure 8). 15x vertical exaggeration. Depth in feet below MLLW.
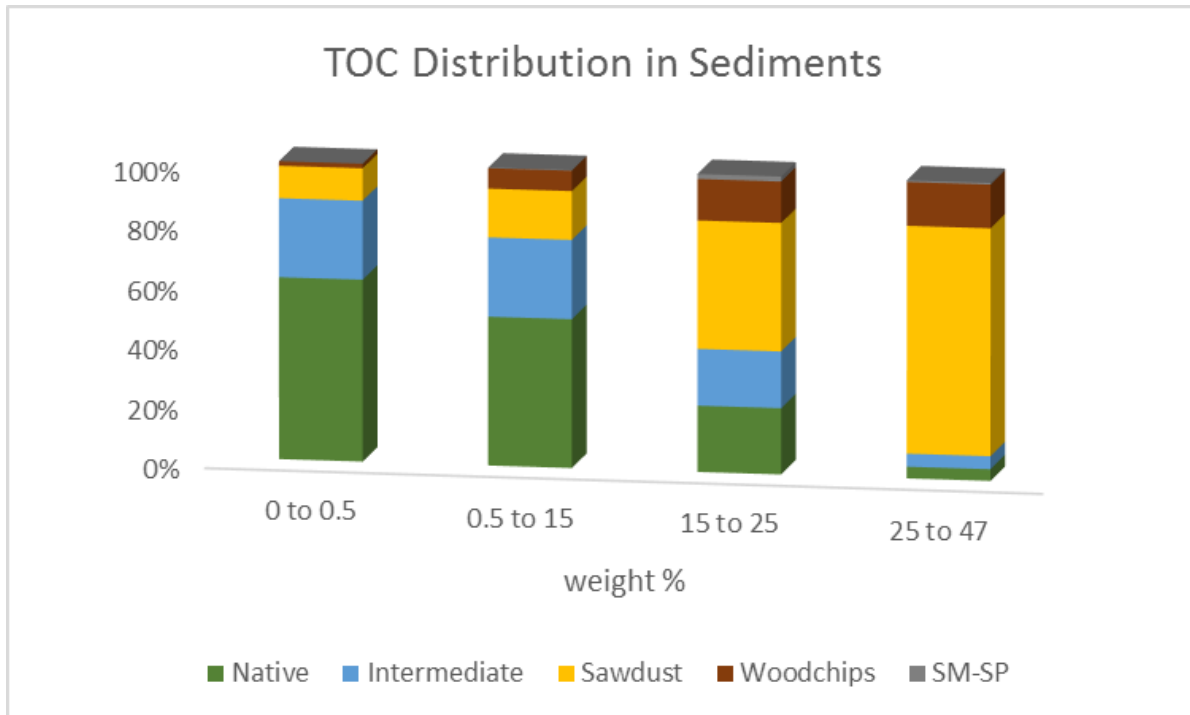
Figure 15: TOC distribution in sediment based on volumetric percentages in Table 5 and value ranges defined in Table 1.
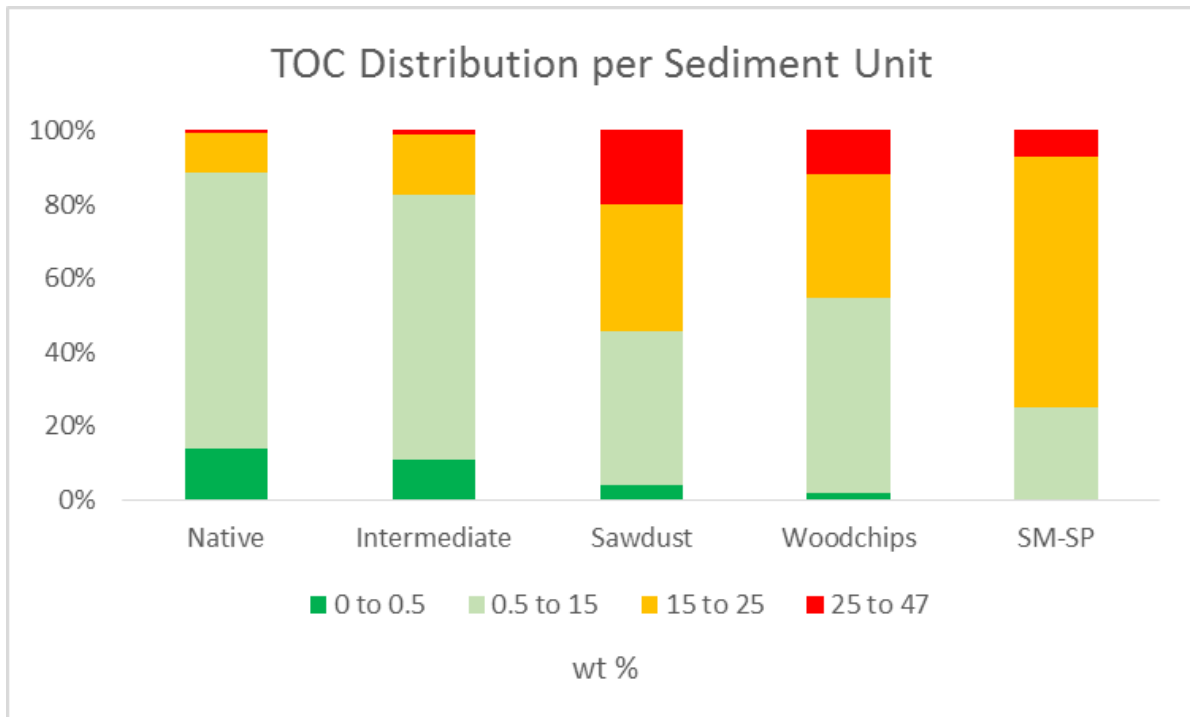

Figure 16: TOC distribution by sedimentary unit based on volumetric distributions in Tables 3 and 5.

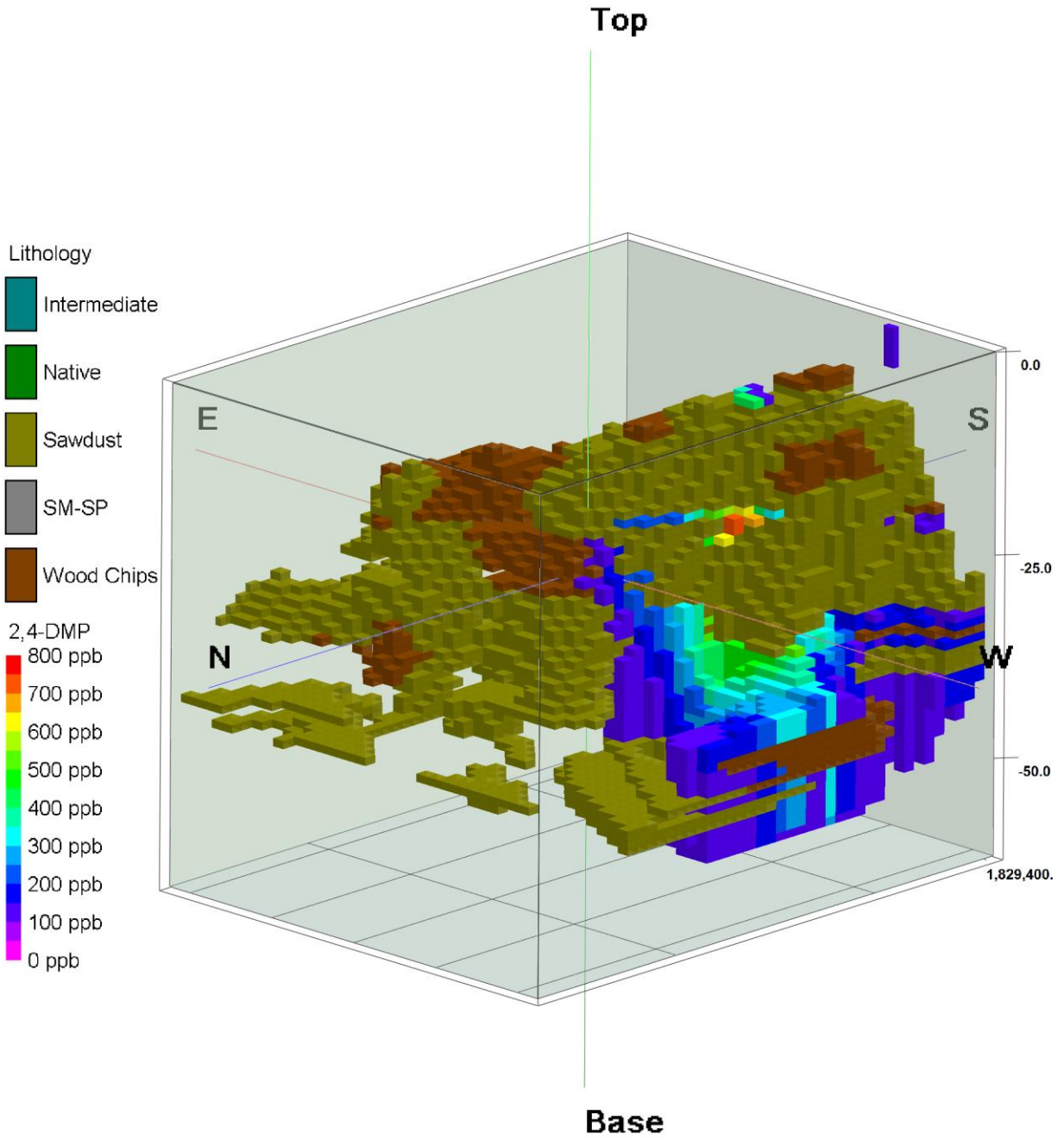*Figure 17: Depositional extent of sawdust and wood chip units inset 2,4-dimethylphenol 100ppb or more (Figure 9). 15x vertical exaggeration. Depth in feet below MLLW.*

Figure 18: 2,4-DMP distribution in sediment based on volumetric percentages in Table 5 and ranges defined in Table 1.

Figure 19: 2,4-DMP distribution by sedimentary unit based on volumetric distributions in Tables 3 and 5.
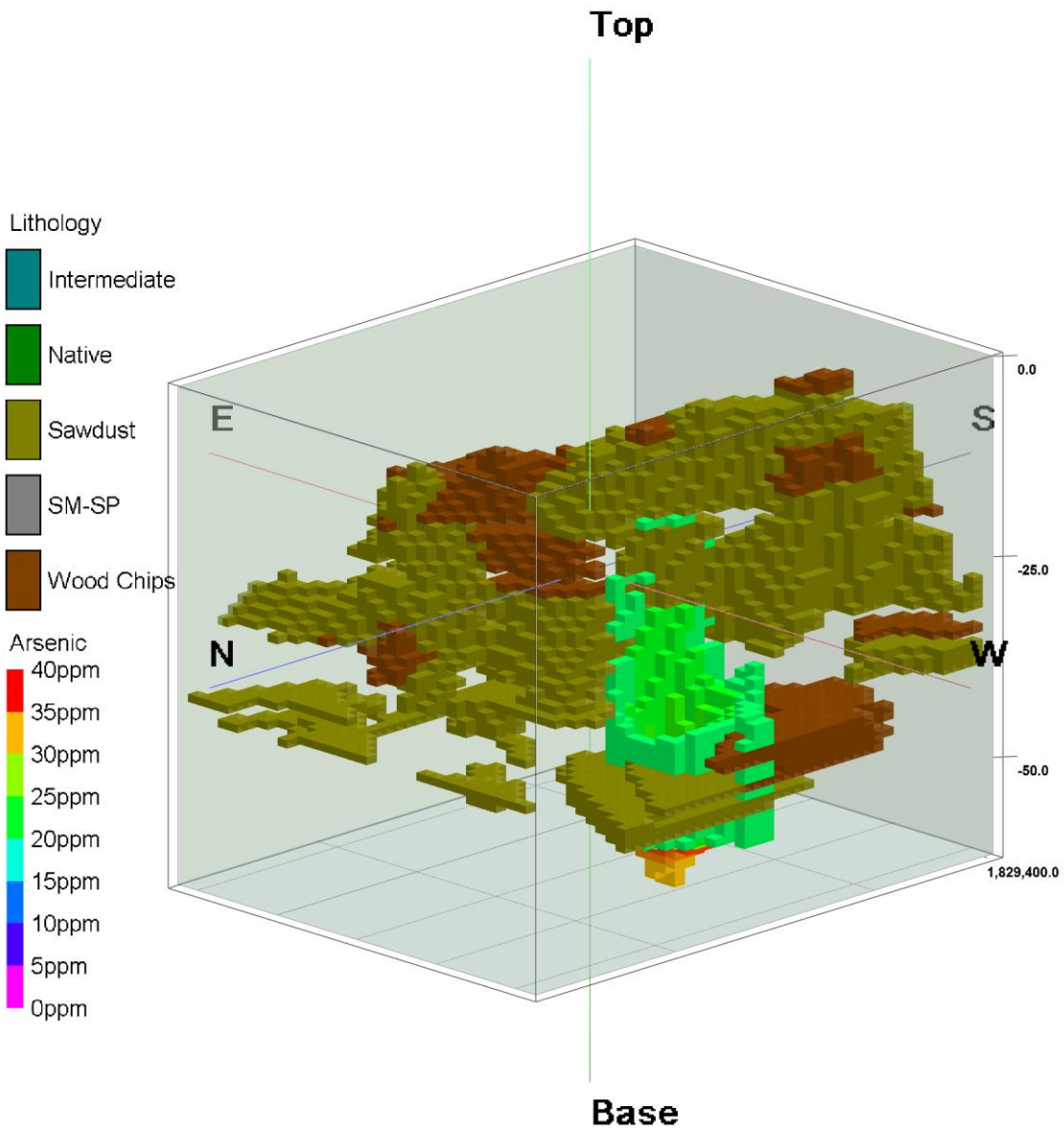
Figure 20: Depositional extent of sawdust and wood chip units with an inset extent of arsenic concentrations 20 ppm or more (Figure 10). 15x vertical exaggeration. Depth in feet below MLLW.
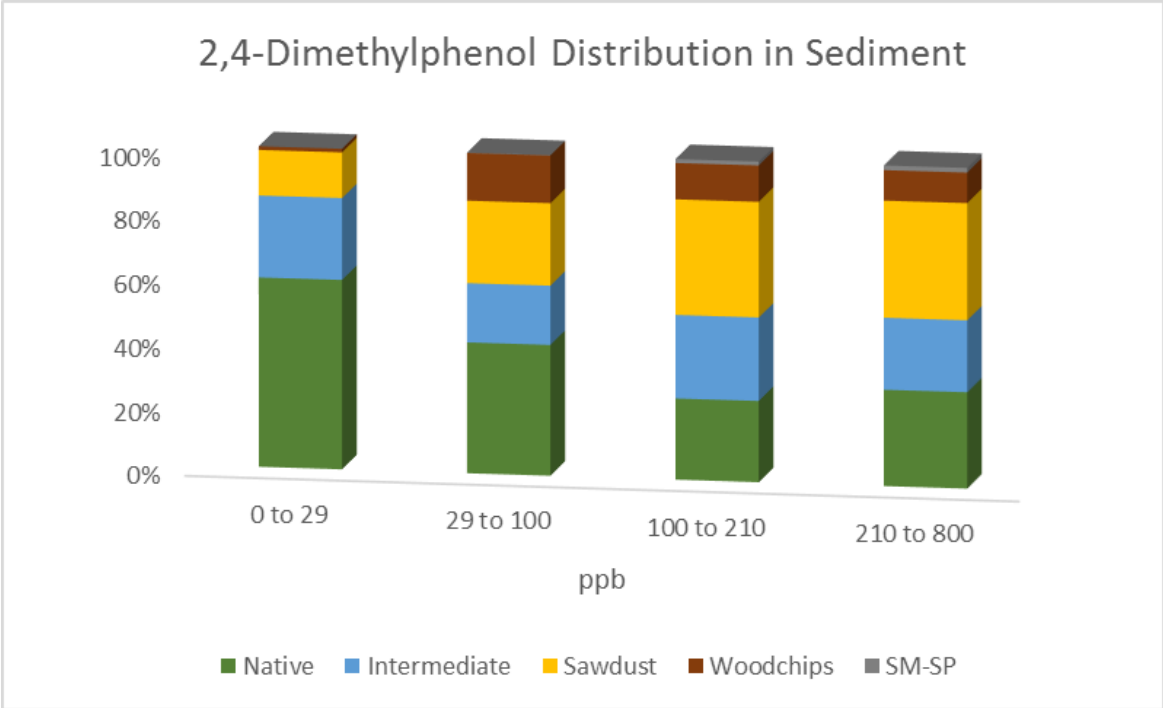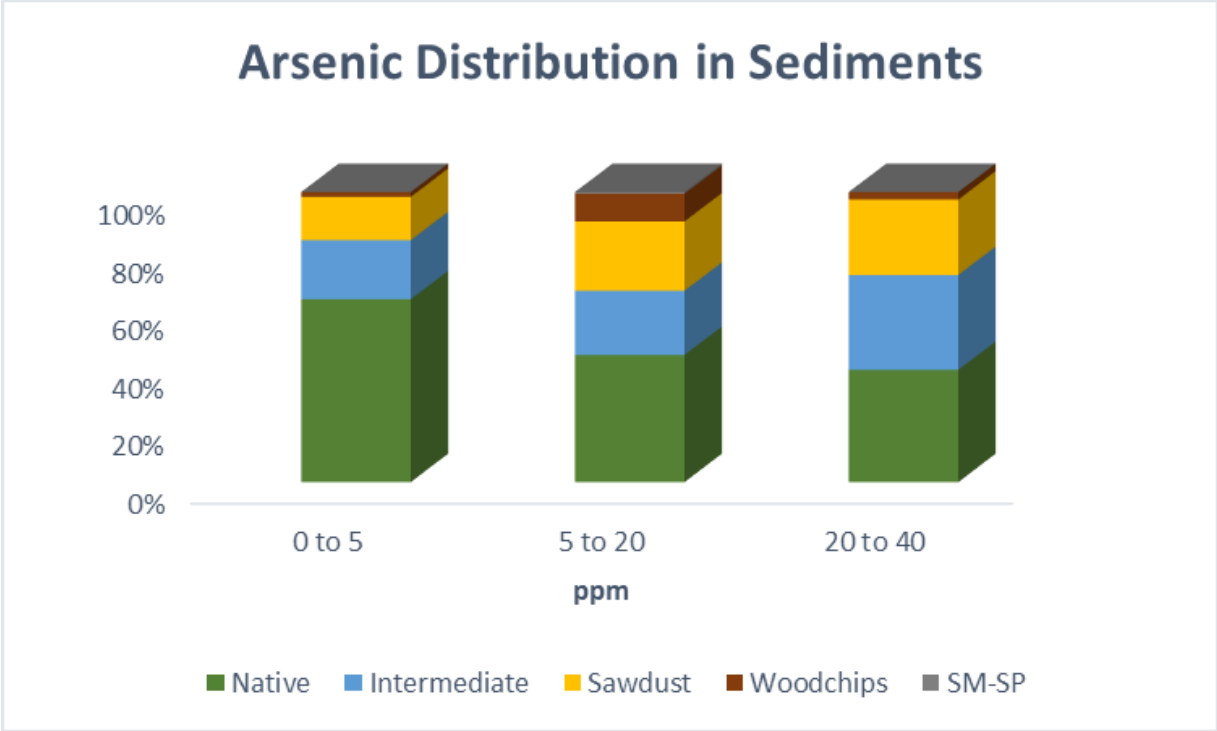
Figure 21: Arsenic distribution in sediment based on volumetric percentages in Table 5 and ranges defined in Table 1.
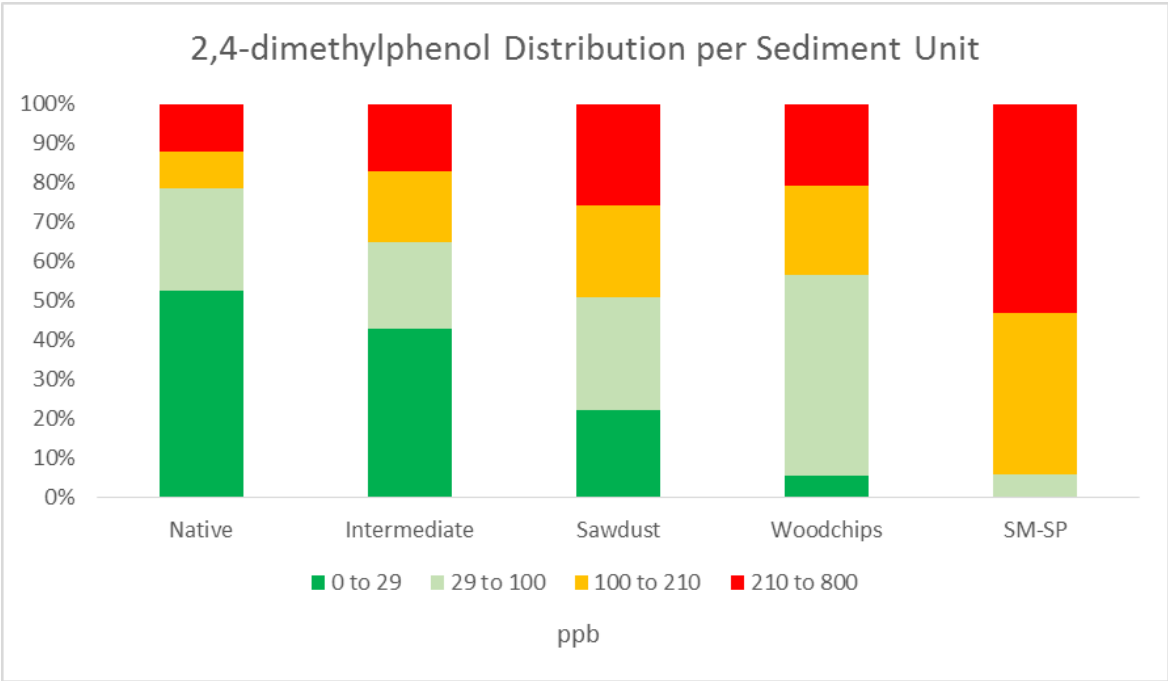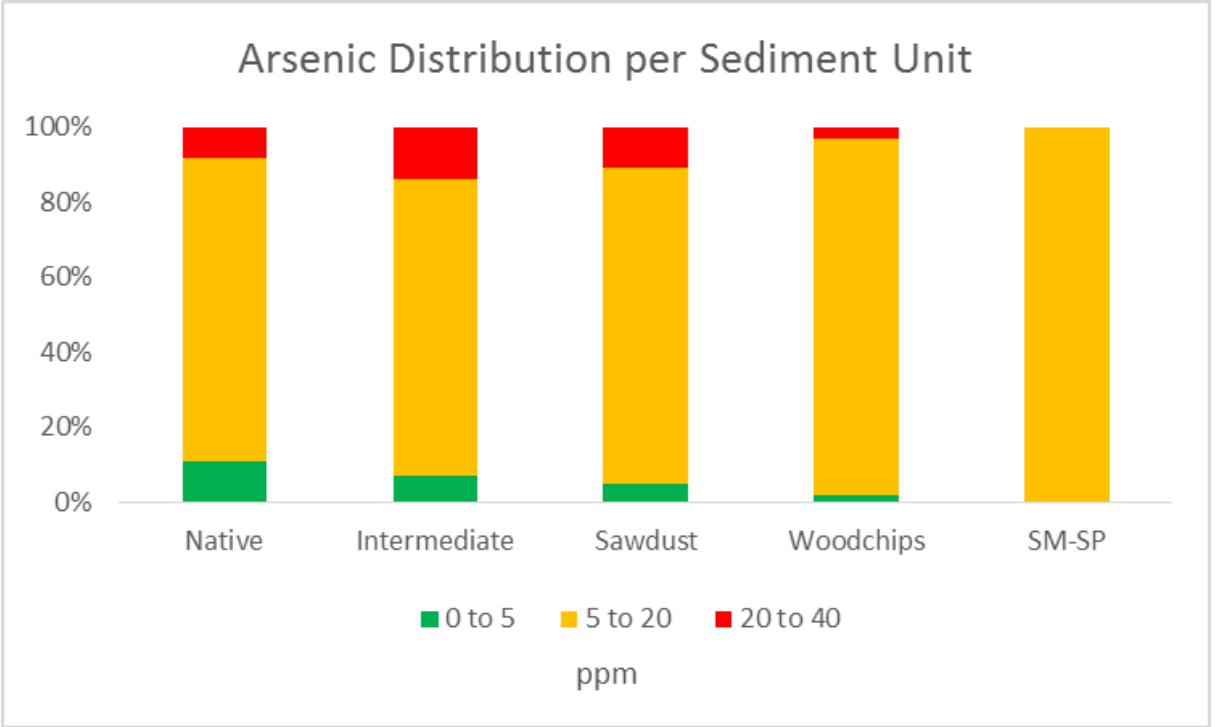

Figure 22: Arsenic distribution by sedimentary unit based on volumetric values in Tables 3 and 5.
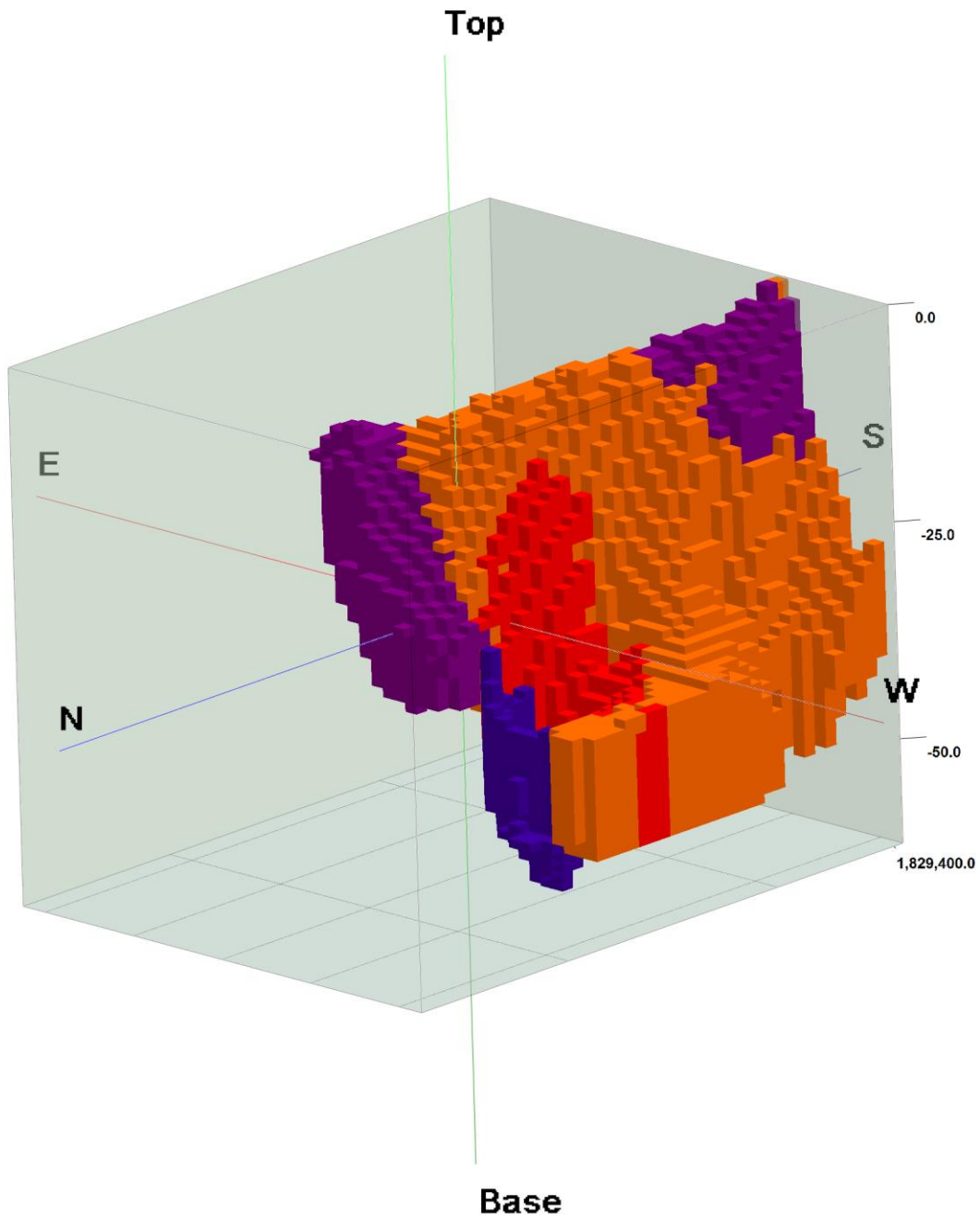
Figure 23: Extent of all three COCs above cleanup concentrations (arsenic ≥20 ppm, 2,4-DMP ≥100 ppb, TOC ≥15%). 15x vertical exaggeration. Z-axis in feet below MLLW. Purple = TOC, blue = arsenic, orange = 2,4-DMP and/or 2,4-DMP overlapping with TOC, red = 2,4-DMP overlapping with arsenic and/or all three COCs overlapping.
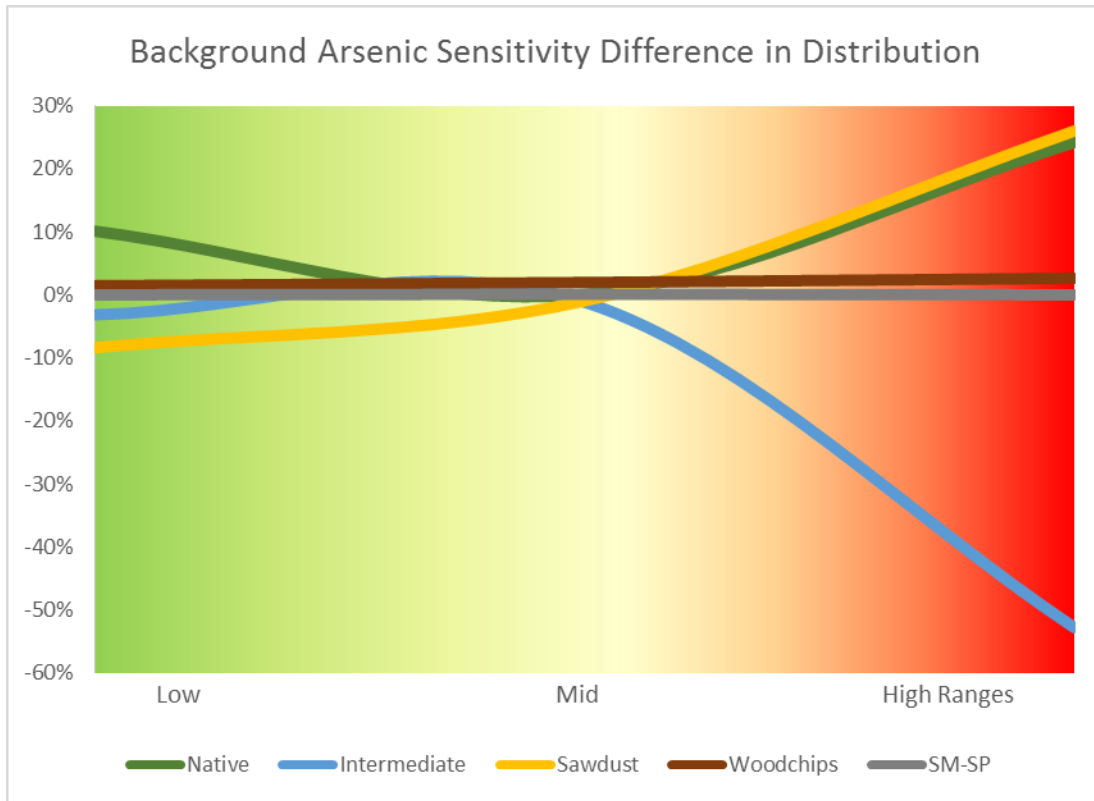
Figure 24: Difference in arsenic distribution with the addition of natural background levels of arsenic. Ranges of concentrations are low (0-5 ppm), mid (5-20 ppm), high (20+ ppm).
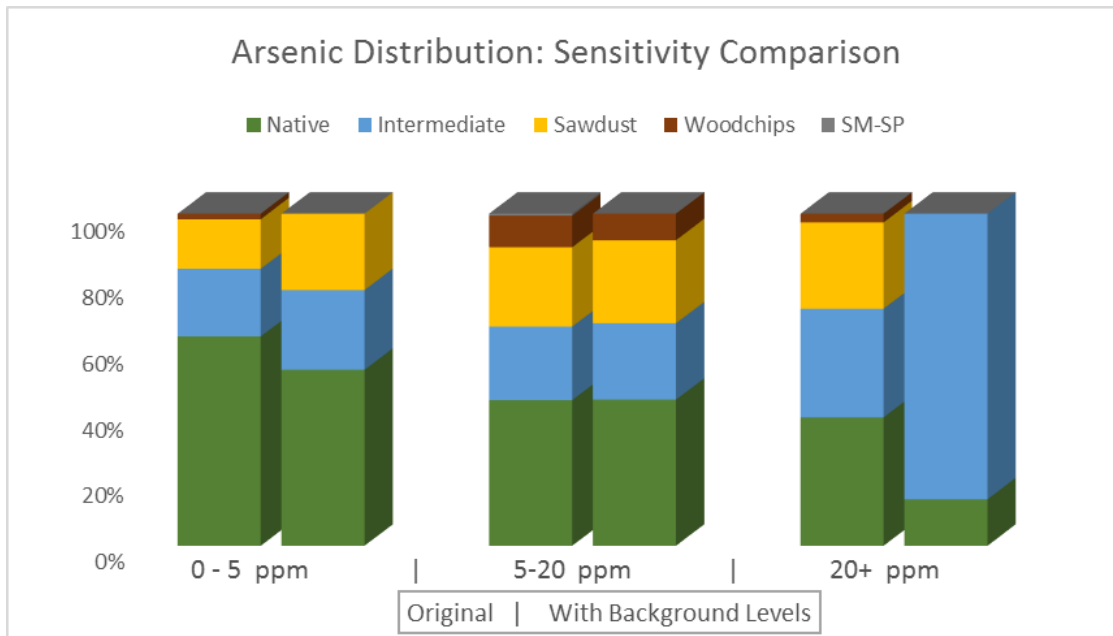
Figure 25: Arsenic distribution in depositional units compared to the original data (left) and the original data with added natural background levels to boreholes without arsenic analysis (right).
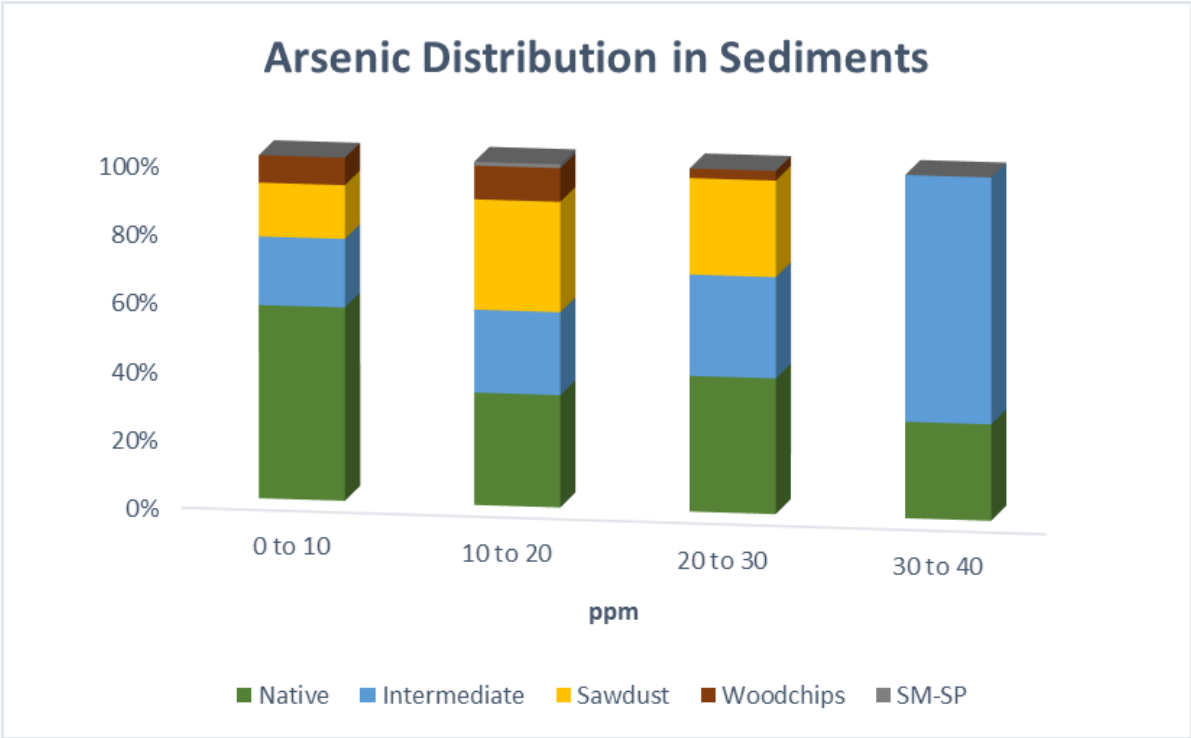
Figure 26: Distribution of arsenic in sediments with altered ranges of concentration compared to Figure 21.

Appendix A

Table A: Values in this table are summarized from the reports by Geomatrix (2007) and GeoEngineers (2015) for each bore log within the project area. Yellow highlighted borehole names represent boreholes that only contain sediment data. Green highlighted borehole names represent locations analyzed for COCs at two depths. Bolded COC levels represent a high threshold or levels above cleanup criteria. J = estimated value, U = undetected at that concentration.

|	Location Name	Source	Latitude	Longitude	MLLW mudline (ft)	Core Length (ft)	Sample Range (ft)	2,4-Dimethyphenol (ppb)	Arsenic (ppm)	TOC (%)	Unit
1	ST-1	Geomatrix	47.97488	-122.22741	-0.7	8.1	-	-	-		-
2	ST-2	Geomatrix	47.97522	-122.22710	-31	14.1	5-6	**170 J**	-	6.11	Sawdust
3	ST-3	Geomatrix	47.97511	-122.22752	-5.4	10.1	3.5-6.2	34	-	**46.9**	Sawdust
							14-15.9	42 J	-	9.21	Woodchips
4	ST-5	Geomatrix	47.97530	-122.22767	-11.4	20.2	0.9-2.5	-	-	-	Woodchips
5	ST-6	Geomatrix	47.97527	-122.22727	-4.8	11.9	-	-	-	-	-
6	ST-8	Geomatrix	47.97553	-122.22746	-12.1	20.0	7.3-10.5	**110**	-	**24.1**	Sawdust
7	ST-9	Geomatrix	47.97555	-122.22707	-6.1	20.3	10.1-12	-	-	-	Sawdust
8	ST-11	Geomatrix	47.97579	-122.22727	-22.8	20.3	0-6.2	**800**	-	**18.9**	Sawdust
9	ST-12	Geomatrix	47.975786	-122.22684	-6.6	11.0	-	-	-	-	-
10	ST-14	Geomatrix	47.97603	-122.22666	-8.5	19.6	3.4-3.6	**250**	-	**44**	Sawdust
							9.4-10.5	**240**	-	14.4	Sawdust
11	ST-15	Geomatrix	47.97612	-122.22692	-19.8	19.9	0.8-2.2	-	-	-	Sawdust
12	ST-17	Geomatrix	47.97626	-122.22645	-11.7	18.0	5.9-7.1	-	-	-	Sawdust
13	ST-19	Geomatrix	47.97636	-122.22624	-14.9	4.3	-	-	-	-	-
14	ST-20	Geomatrix	47.97653	-122.22635	-20.9	20.2	9.9-11.2	95	-	**30.8**	Sawdust
							14.0-15.5	87	-	**25.1**	Sawdust
15	ST-21	Geomatrix	47.97652	-122.22582	-11.9	19.9	9.1-11.2	48	-	17.1	Woodchips
16	ST-32	Geomatrix	47.97545	-122.22837	-51.0	10.1	0-0.3	20 U	10	1.74	Intermediate
17	ST-34	Geomatrix	47.97638	-122.22737	-50.8	10.1	0-0.3	20 U	10	2.05	Intermediate
							0-2.8	20 U	**40 J**	3.93	Intermediate
18	ST-37	Geomatrix	47.9769	-122.22635	-35.5	9.7	0-0.3	20 U	10 U	3.27	Woodchips?
19	ST-39	Geomatrix	47.97731	-122.22651	-49.2	9.7	0-0.3	20	9 U	1.69	Intermediate
							0-4	20 U	10	5.47	Intermediate
20	ST-42	Geomatrix	47.97793	-122.22553	-41	11.8	0-0.3	20 U	6 U	0.8	Intermediate
21	ST-43	Geomatrix	47.97601	-122.22736	-38.7	14.0	5.7-7.2	**410**	-	**15.9**	Sawdust
22	ST-44	Geomatrix	47.97555	-122.22773	-32.3	18.7	-	-	-	-	-
23	PT-1	GeoE2015	47.97720	-122.22610	-34	15	-	-	-	-	-
24	PT-2	GeoE2015	47.97730	-122.22587	-30	14.6	-	-	-	-	-
25	PT-3	GeoE2015	47.97736	-122.22570	-37.5	10	5.5-6.5	24 U	4.39 J	0.237	Native
26	PT-4	GeoE2015	47.97710	-122.22594	-27	20	-	-	-	-	-
27	PT-5	GeoE2015	47.97714	-122.22563	-24	25	18.75-19.75	24 U	4.64 J	0.193	Native

28	PT-6	GeoE2015	47.976931	-122.225418	-15	30	27.75-28.75	24 U	5.16 J	0.109	Native
29	PT-7	GeoE2015	47.977071	-122.225216	-30	10	-	-	-	-	-
30	PT-8	GeoE2015	47.97689	-122.225083	-23	22	19.75-20.75	24 U	6	0.114	Native
31	PT-9	GeoE2015	47.976881	-122.224898	-28	20	-	-	-	-	-
32	PT-10	GeoE2015	47.976955	-122.226085	-29	15	6.3-7.3	24 U	6.08 J	2.7	Inter-Nat
33	PT-11	GeoE2015	47.976895	-122.225749	-20	20	16-17	23 U	3.92 J	0.228	Inter
34	PT-12	GeoE2015	47.976826	-122.225398	-14	25	16-17	24 J	9	7.76	Native
35	PT-13	GeoE2015	47.976753	-122.225062	-16	20	13-14	25 U	7	0.214	Native
36	PT-14	GeoE2015	47.976743	-122.22489	-18	20	11-12	25 U	3.95 J	0.092	Native

Appendix B

DESCRIPTION OF MAP UNITS

Qyal   YOUNGER ALLUVIUM (HOLOCENE) = These deposits lie in and along present streams and are partly subject to seasonal flooding. The sediments consist mostly of unconsolidated, stratified, gray to brown clay, silt, and very fine sand to fine sand, with abundant organic material. Medium to coarse sand and gravel underlie much of the fine-grained flood plain sediments and are common in the small stream valley bottoms. Clasts are varied in composition and are similar to those in the recessional outwash. The younger alluvium was derived from some or all the adjacent older sediments and from sources some distance up the main river valleys beyond the boundaries of the quadrangle. The younger alluvium is from 1 m to possibly 20 m thick. It occurs as present and former stream channel and flood plain deposits, and mostly is poorly drained. Peat deposits and buried logs and stumps are common in the flood plain of the Snohomish River. Obvious areas of fill are west of the river near Lowell and along the shore of Port Gardner, also road and railroad embankments, and dikes or levees along Snohomish River and sloughs. No attempt was made to map peat deposits or fill within this unit. For the location of some such deposits, see Smith (1976)

Qp   PEAT (HOLOCENE) - This unit consists of deposits of fibrous brown peat, interbedded and intermixed with organic-rich mud and sand. The organic material includes plant stems and leaves, fibers, and comminuted organic debris, all deposited in water-filled depressions

Qls   LANDSLIDE DEPOSITS - (HOLOCENE) - These are deposits of intermixed debris from adjacent units transported downslope as landslides, slumps, and earth flows. Only a few small landslides are mapped in the Pigeon Creek valleys in the northwest part of the quadrangle. For additional possible landslides, refer to Smith (1976). The slides most often involve three map units: till, advance outwash, and the transitional beds. The clay in the transitional beds retards vertical internal drainage. Groundwater moves laterally atop the clay, sapping and undermining the overlying sand of the advance outwash all the way up to the till. Some water moving down vertical joints and along clay layers in the transitional beds locally creates low internal cohesion in that unit. Aided by these factors and the weight of the overlying beds, ground failure is common down into the transitional beds

Qoal   OLDER ALLUVIUM (HOLOCENE) - This unit includes deposits of mostly clean, stratified, gray to oxidized (to shades of brown) sand and gravel, with some sandy, pebbly, organic-rich silt. It includes colluvium along the bases of adjacent steep slopes. Clasts are varied in composition and are similar to those in the recessional outwash. The older alluvium is 1 to 5 m thick. It partly is a terrace landform several meters above the adjacent flood plain underlain by the younger alluvium. The older alluvium is partly covered by a series of young alluvial fans deposited by the numerous small streams flowing from the steep valley slope out onto the flood plain. The older alluvium is mostly well drained. It lies unconformably on the older underlying deposits

VASHON DRIFT (FRASER GLACIATION) - Consists of:

Qvr   RECESSIONAL OUTWASH - These are mostly deposits of clean, stratified, gray to oxidized sand and gravel; some beds are cemented by iron oxide. Clasts are varied in composition and are derived from some or all older adjacent units and ice transported debris. Rock types include basalt and metabasalt (greenstone), diabase, gabbro, volcanic breccia, andesite, rhyolite, pink granite, gray granite, granodiorite, quartz-hornblende gneiss, schist, quartzite, vein and crystalline quartz, limestone, sandstone, conglomerate, shale, argillite, and phyllite. Sand in these deposits includes particles and minerals from some or all these rock types. The recessional outwash generally is only a few meters thick. It was deposited by meltwater flowing from the receding Vashon glacier. It is well drained and lies unconformably on older underlying units

Qvt   TILL - These deposits mantle hills, ridges, and slopes. The till (referred to locally as the Vashon till) is a nonsorted mixture of mud, sand, pebbles, cobbles and boulders (diamicton); it resembles concrete mix. The till contains some lenses of stratified material, particularly in its lower part. It is compact to locally cemented lodgement till, commonly called hardpan. The till has a sheeting or fissility near and parallel to the surface and tends to spall and crumble where exposed. It is varied in clast composition and is similar to the recessional outwash. Outcrops of till are from 3 to 20 m thick in the quadrangle. The till was deposited directly by the ice as it advanced over bedrock and older Quaternary sediments. Its compactness partly results from the weight of the ice, which was hundreds of meters thick when it overrode the till. Drainage is good in the uppermost 1 to 2 m of loose, weathered material, but water ponds and moves laterally along the buried hardpan surface. The till lies unconformably on or against older underlying deposits

Qva   ADVANCE OUTWASH - These deposits underlie the till. They consist of clean, mostly gray, well stratified, unconsolidated sand with pebbles and some cobbles. It is locally silty and oxidized to shades of brown. Clasts are varied in composition and are similar to those in the recessional outwash. The advance outwash is as much as 70 m thick in outcrop in the quadrangle. It was deposited as bar and channel sediment in and along meltwater streams flowing from the advancing Vashon glacier, and as deltas in ponded areas. The advance outwash is one of the thickest and most extensive aquifers in the region. It lies conformably on the transitional beds. As mapped, the advance outwash contains the Esperance Sand Member of the Vashon Drift (Newcomb, 1952) (equivalent to Esperance sand as used by Smith, 1976) and the Upper Esperance coarse advance outwash (as designated by Smith, 1976)

Qtb   TRANSITIONAL BEDS (FRASER GLACIATION TO PRE-FRASER GLACIATION) = These deposits consist of clay, silt, and very fine to fine sand; some layers of peaty sand and gravel are in the lower part of compact but may be unstable because of high moisture content, plasticity, and local vertical jointing. The sediments were mostly deposited in still to slowly moving water, except for the coarse stream deposits in the lower part of the unit. The unit includes the Pilchuck Clay Member of the Vashon Drift (Newcomb, 1952), the Admiralty Clay, and part of the Whidbey Formation (Smith, 1976), particularly near the west edge of the quadrangle. The term "transitional beds" is an informal name originally used by the author in the Mukilteo quadrangle (Minard, 1982a)

Qog   OLYMPIA GRAVEL (PRE-FRASER GLACIATION) - This informally named unit consists of sandy pebble gravel with alternating beds and lenses of medium to coarse sand. It is partly oxidized to shades of brown and weakly to firmly cemented by iron oxide. The unit is 6 to 7 m thick in outcrop in the quadrangle. It was largely deposited by streams. It locally overlies and interfingers with the undivided till; elsewhere its base is covered. For details concerning the Olympia gravel and its stratigraphic relations, refer to Minard (1983)

Qtu   TILL, UNDIVIDED (PRE-FRASER GLACIATION) - This unit is a nonsorted mixture of clay, silt, sand, and gravel. It crops out in a small lens between the overlying transitional beds and Olympia gravel, and the underlying Whidbey Formation. It is about 2 m thick and occupies the stratigraphic position of the Possession Drift (Easterbrook and others, 1967). It may, in part, be marine glacial drift

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Figure B: geologic unit descriptions by Minard, 1985.