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AN ABSTRACT OF THE THESIS OF

Louis Arighi for the degree of Master of Science in Geology presented on April 9, 2004.
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Low-permeability geologic units may offer significant chemical and hydraulic protection of adjacent aquifers, and are important for managing groundwater quality, especially in areas with significant non-point source contamination. Nitrate in the Willamette Valley is attenuated across the Willamette Silt, a semi-confining unit overlying a regionally important aquifer. To quantify the main mechanism responsible for nitrate attenuation, soil cores were taken at 19 locations, and profiles of nitrate concentrations were constructed for each site. In 7 locations a sharp, major geochemical transition – a "redoxcline" – is present near the base of the Willamette Silt; this redoxcline is characterized by a color change from red-brown to blue-gray, an increase in iron(II) concentration, a rise in pH, and the appearance of carbonate minerals. At all sites where a significant surface input of nitrate was detected, the nitrate signal was attenuated before reaching the base of the silt. Denitrifier Enzyme Activity assays from one site show no denitrification potential in the profile, suggesting that a non-biological mechanism is responsible. We suggest that iron(II) is reducing the nitrate abiotically to nitrite, and that the blue-gray reducing zone of Willamette Silt is indicative of the presence of sufficient iron(II) for the reaction to go forward. To increase the usefulness of this study to regional water management agencies, a thickness isopach map of the reduced zone was created both for the northern and southern Willamette Valley to help determine areas where nitrate is most likely to be attenuated.

QUANTIFICATION OF THE NITRATE ATTENUATION CAPACITY OF LOW-PERMEABILITY MISSOULA FLOOD DEPOSITS IN THE WILLAMETTE VALLEY OF OREGON

By
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APPROVED:

Major Professor, representing Geology

Chair of the Department of Geosciences

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Louis M. Arighi, Author

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INTRODUCTION

Physical barriers to groundwater contamination are generally easier to characterize than geochemical barriers, but geochemical and biological barriers can be as important, and sometimes more important, than their more often studied counterparts. In the Willamette Valley of Oregon (Figure 1), nitrate (NO_3^-) is a contaminant of particular concern. Nitrate from fertilizers and other anthropogenic sources can cause health problems if it reaches drinking water. Studies have shown a link between nitrate in drinking water and methemoglobinemia (low blood oxygen levels) in infants, spontaneous abortions, and non-Hodgkin's lymphoma at concentrations of as little as 4 mg/L (Nolan 2001).

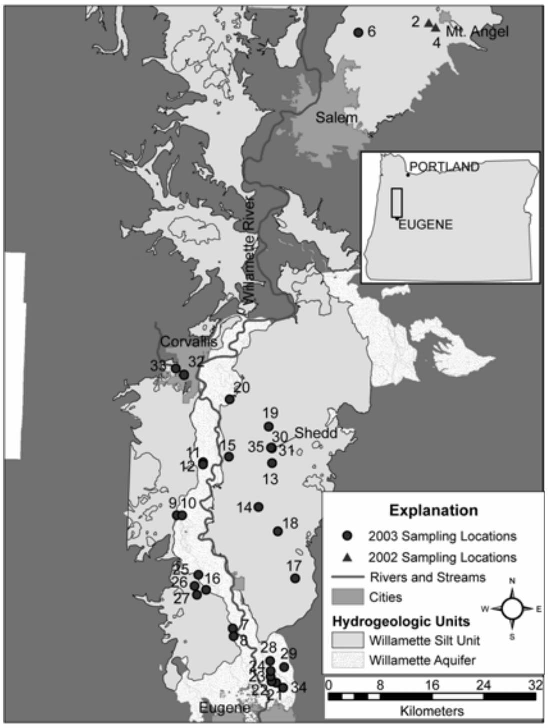

Figure 1. Location of sites sampled in this study. Inset shows study area in relation to the state of Oregon. Hydrogeologic data from Gannet and Caldwell (1998) (courtesy of Marshall Gannet) and O'Connor et al (2001).

Nitrate is a concern in many places because it is a highly mobile chemical that is easily transported by groundwater. The Willamette Valley is vulnerable since it is the most productive agricultural region in Oregon as well as home to almost 70% of Oregon's population (Orzol et al. 2000). As the population of the Willamette Valley grows, surface water supplies are becoming strained, and more water districts are looking to groundwater for their municipal needs. The Willamette Aquifer, the most heavily used aquifer in the valley, is used for domestic water supply in many rural areas in the Willamette Valley, and much of it lies underneath large point- and non-point-source nitrogen inputs.

The Willamette Silt, a low permeability unit deposited during the Missoula Floods 15 to 12.7 ka, overlies the Willamette Aquifer (Figure 1), a regionally important aquifer supplying approximately 25% of the domestic water supply (Broad and Collins 1996). The Silt acts as a hydraulic and chemical buffer, protecting groundwater from point and non-point contamination (Iverson 2002). To identify where the Silt offers nitrate protection, the mechanism for nitrate attenuation must be understood. Therefore, we did a case study in the Willamette Valley to look in detail at the geochemical and biological buffering capabilities of the Willamette Silt. Quantifying the chemical protection offered by the Willamette Silt and mapping the valley can be important management tools for both communities and government agencies, allowing for identification of the most sensitive areas, and providing more information to agricultural and groundwater users. Our study has implications for similar hydrostratigraphic units elsewhere – for example, clayey tills in Denmark (Ernstsen et al. 1998), glacially deposited silts in southern Ontario (Robertson et al. 1996), glacial till in southern Alberta (Hendry et al. 1986), and glacial outwash in west-central Minnesota (Puckett and Cowdery 2002).

BACKGROUND

During the Late Pleistocene, between 15 and 12.7 ka, the Willamette Valley was repeatedly inundated by jökulhlaups that originated near Missoula, Montana, when Glacial Lake Missoula broke through its ice-dam (Glenn 1965; Allison 1978). The Missoula Floods backed up into the Willamette Valley forming Lake Allison, and re-deposited fine-grained glacial deposits from Eastern Washington. These fine-grained deposits make up the Willamette Silt (WS), which is the surface unit across much of the central and southern Willamette Valley (Figure 1). Because the Missoula Floods entered the valley from the north, the WS thins from approximately 30m in the north to less than 10m south of Salem, pinching out entirely south of Harrisburg (O'Connor et al. 2001). The WS generally has a low hydraulic conductivity, from 0.01 ft/day ($8x10^{-7}$ m/s) to 8 ft/day ($7x10^{-4}$ m/s), with a median of 0.1 ft/day ($8x10^{-6}$ m/s) (Woodward et al. 1998; Iverson 2002), and acts as an upper semi-confining unit for the Willamette Aquifer. Hydraulic conductivities generally decrease north to south.

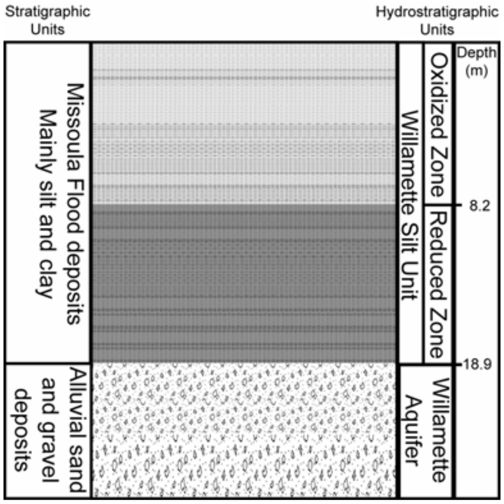

Figure 2.
Cross-section of site 2. The base of the lower-most unit extends beyond the bottom of the figure.

In many places around the Willamette Valley, the Willamette Silt is composed of two zones, an upper oxidized zone, and a lower reduced zone (Figure 2). The boundary between the oxidized portion of sediment and the reduced portion below (Robertson et al.'s "redoxcline," 1996, p. 267), is closely correlated with the boundary between red-brown and blue-gray colors, and is a very abrupt boundary across which nitrate usually does not penetrate. In the northern valley, previous studies by Iverson (2002), and by the Oregon Department of Geology and Mineral Industries have shown that the color change (and presumably the redoxcline) exists in much of the Willamette Silt north of Salem. Although it is not known how the redoxcline was formed, some investigators have speculated that the redoxcline in northern tills is the result of a lowered water table during the drier climate of the Altithermal 9500 to 6500 years ago (Hendry et al. 1984). Research in the Willamette Valley suggests that the redoxcline is related to the location of the water table during more modern times. Iverson's data (2002) shows the water table fluctuating around the redox boundary at site 2, and work by DOGAMI (Madin 2004, pers. comm.) in the Mt. Angel area shows a strong correlation between the redox boundary at the local topography, also suggesting relation to modern water tables. Sampling at site 2 during three different years (2000, 2002, and 2003) showed no discernable movement of the redoxcline suggesting that it does not respond to short term changes in the location of the water table.

Previous studies have found nitrate concentrations dropping off abruptly in silty confining layers (Robertson et al. 1996; Rodvang and Simpkins 2001; Ernstsen et al. 1998) and attributed a significant amount of the nitrate loss in reduced (also called "unweathered") confining layers to bacterial denitrification. Robertson et al. (1996) suggested autotrophic denitrification as the main mechanism because of a correlation between the loss of nitrate and an increase in oxidized sulfur. Ernstsen et al. (1998) found bacterial denitrification was of secondary importance in an organic-carbon-poor confining layer, but of much more importance in an organic-carbon-rich confining layer.

In the organic-carbon-poor environment, Ernstsen et al. (1998) suggested that reduction of nitrate by structural iron was responsible for the lowered nitrate concentrations. Rodvang and Simpkins (2001) detail studies that have shown denitrification with a variety of substrates as the electron donor, all of which are bacterially mediated. Most of the studies that found evidence of bacterial denitrification found it in the upper 4 m of the soil, although one study in Alberta found chemistry suggesting denitrification at depths of 12-23 m. None of the studies that tested for the presence of denitrifying bacteria tested samples below 4 m of depth, leaving open the question of how deep one can expect find bacterial denitrification.

In the Mount Angel area, near the Pudding River, Iverson (2002) studied the hydraulic connection between surface water and groundwater, and estimated that the average travel time of the water from the surface to the aquifer was approximately 23 years. The study site had been under fertilization for approximately 60 years, and if nitrate were being transported conservatively (i.e. without denitrification), it should have reached the aquifer. A variety of crops have been grown at the site, and since 1997 in-ground nursery plants have been the main crop (Iverson 2002). The site is irrigated regularly from the end of March through the end of July from an on-site irrigation well (Iverson 2002). Chemical analyses of two sediment cores showed that nitrate concentrations drop to background levels at approximately 8 m below land surface, almost 10 m above the Silt/Aquifer contact. A previous study (Hinkle 1997) found a correlation between low nitrate concentrations and thick clay deposits above sample locations. However, since a significant fraction of the water sampled pre-dated 1953, it was likely to have low nitrate concentrations anyway. Iverson’s study (2002) shows that, at least at one field site, low nitrate concentrations could not be attributed simply to transport time, and possibly were controlled by denitrification.

Nitrate Transport

Nitrate (NO_3^-) is a relatively stable ion under surface conditions, and can be easily absorbed by plants through their roots and used by microbes for cellular growth (the latter only after reduction to ammonium) (Sylvia et al. 1999). Because it is readily taken up by plants, nitrate is a common component of synthetic fertilizers as well as a major part of natural soil amendments (such as manure). As a highly soluble chemical, nitrate can be transported away from the area in which it is applied relatively quickly, so it is often applied in much higher amounts than plants can use to compensate for losses. This can result in elevated levels of nitrate in surface runoff and groundwater infiltration. Surface water contamination in the Willamette Valley has been discussed elsewhere (Rinella and Janet 1998), and our study is concerned with groundwater only.

Almost all aquifers have nitrate-reducing microbial communities, made up primarily of heterotrophic (using organic carbon as a cellular carbon source), facultative anaerobes (can use O_2 or alternate electron acceptors) (Korom 1992). Autotrophic (using inorganic carbon as a cellular carbon source) denitrifiers have also been found, but are less common. Nitrate is the most thermodynamically favorable terminal electron acceptor under anaerobic conditions so it is used more commonly than other potential electron acceptors (e.g. MnO_2, FeOOH, or SO_4^{2-}). The bacteria reduce the nitrate through a series of steps that usually culminate in the production of N_2, although in some environments the final enzyme is inhibited and the end product is N_2O (Sylvia et al. 1999). Oxygen concentrations are often low in the saturated zone, and diffusive processes moving oxygen from the unsaturated zone into the saturated zone operate on relatively long time scales, leaving the saturated zone anaerobic the majority of the time. Heterotrophic denitrifiers are by far the most common type of denitrifying bacteria, although autotrophic denitrification has been observed (Sylvia et al 1999).

METHODS

To determine how denitrification is occurring and its connection to the redoxcline, sediment samples were taken at 33 sites in the Willamette Valley (Figure 1). Sites were selected both on (19) and off (14) the known locations of Willamette Silt, and were selected in areas with either previously documented elevated nitrate levels, from previous studies, or suspected surface nitrate input, such as agricultural field and residential lawns and gardens.

Soil sampling

Four continuous soil cores were taken with a push-probe sampler by Geo-Tech Exploration Inc. One core was taken at a nursery near Mt. Angel, Oregon, where detailed geologic and hydrologic data are available (Iverson 2002), one at another agricultural field located 1.3 km southeast of the nursery, and two others in the northern valley. The other 29 sites were sampled with the Oregon Department of Environmental Quality's (DEQ) push-probe sampler. All samples were tested for nitrate concentrations and pH at regular intervals and selected cores were tested for organic matter. In addition the Fe(II) and Fe(III) concentrations at sites 2 and 4 were measured to construct a profile of iron with depth. Nitrate + nitrite, pH, and organic matter assays were performed (see Appendix F for procedures). Samples to be tested for Fe(II) and Fe(III) were placed in a solution of 0.5M HCl in the field to prevent change in oxidation state. The samples were then stored under dark conditions to prevent photo reduction, and processed using a modified Roth-Olson method (modified from Stucki and Anderson 1981). The concentrations of reduced and oxidized iron were calculated colorimetrically using orthophenatroline, which reacts with Fe(II) to make a red-orange color. The intensity, and thus the concentration can then be measured with a spectrophotometer. Once the concentration of Fe(II) is known, another sample is taken, treated with a reducing agent, and then analyzed with the same technique to give a value for total iron (reduced + oxidized). To calculate the concentration of Fe(III), the concentration of Fe(II) is subtracted from the total iron concentration. The Fe(III)/Fe(II) ratio indicates whether the soil is experiencing reducing or oxidizing conditions.

Samples at site 2 were also tested for the presence of denitrifying bacteria using a Denitrifier Enzyme Activity (DEA) assay. The enzyme activity is used as a proxy for the ability of the soil (microorganisms) to use nitrate under favorable conditions. Using samples taken at 76 cm and 15 cm intervals, a profile of denitrification potential was constructed between 0.81 m depth and 10.5 m depth. Denitrifying bacteria transform nitrate (NO_3) into nitrogen gas (N_2) through a four-step process. The final step, from nitrous oxide (N_2O) to N_2 is mediated by the enzyme nitrous oxide reductase. This enzyme is strongly inhibited by the presence of acetylene ($CH_3{=}CH_3$). In a DEA assay, a soil sample is amended with nitrate and soluble organic carbon (glucose) and incubated at room temperature (~24°C) in the presence of acetylene gas (Luo et al. 1996). The acetylene gas prevents the bacteria from converting N_2O to N_2 gas, and so all nitrate used by bacteria is converted to N_2O. Samples of the gas in the head space of the bottle are taken at regular time intervals, and analyzed with a gas chromatograph for N_2O content. The evolution of N_2O over time indicates the presence of a bacterial population capable of denitrification. A sample known to have heterotrophic denitrifying bacteria, was used to confirm that the methodology was correct and that all equipment was in proper working order.

Spatial Mapping of Redoxcline, Willamette Silt, and extrapolation of isopachs

The depth and thickness of silt was recorded at all sampling sites, and compared to published data (Gannet and Caldwell 1998; O'Connor et al. 2001). Combining data from our study and DOGAMI (Maddin 2004, unpublished data), a GIS database of wells was created to produce an isopach of the reduced zone. In the southern valley where wells with known GPS coordinates were more scarce, public well logs were used to check the contours for. Well logs were only available for some sections in the area and some wells could not be located any more precisely than to the section. The larger number of well logs found to the west of Shedd allowed for a greater accuracy than to the east of Shedd, where there are fewer wells.

RESULTS

North valley sites

Two sites in the northern Willamette Valley were studied intensively. The Willamette Silt at site 2 is 18.9 m thick (Iverson 2002), with a blue-gray layer from 8.2 m bls to the base of the silt, while at site 4, 1.3 km SE, the Willamette Silt is 14.9 m thick, with a blue-gray layer extending from 7.9 m bls to the base of the silt. Site 4 is approximately 4m higher than site 1, so the difference in thickness is entirely consistent with Missoula Flood-style deposition. The uniformity in depth from the surface to the blue-gray layer is impressive, especially compared to the south valley sites. At the time of drilling, saturated conditions occurred at approximately 4.5 m depth at both sites 2 and 4.

X-ray diffraction (XRD) showed increased levels of carbonates in the blue-gray zone at site 2 (Appendix B). A sample of blue-gray silt from 3.5 cm below the color change contained calcite and dolomite. A sample of red-brown silt taken ~3.5 cm above the color change in the same core did not have any detectable calcite or dolomite. Another blue-gray sample from site 2 effervesced vigorously in cold, dilute HCl, indicating the presence of calcite. The samples were taken less than 15 cm apart, indicating that the abrupt color change is most likely tied to the mineralogical boundary. This is consistent with work by DOGAMI (Maddin 2004) that showed the red-brown and blue-gray silt had distinctly contrasting shear-wave velocities. The infilling of pore space by carbonate precipitation could increase the density of the blue-gray silt causing a density contrast between the red-brown and blue-gray zones, and thus a shear-wave

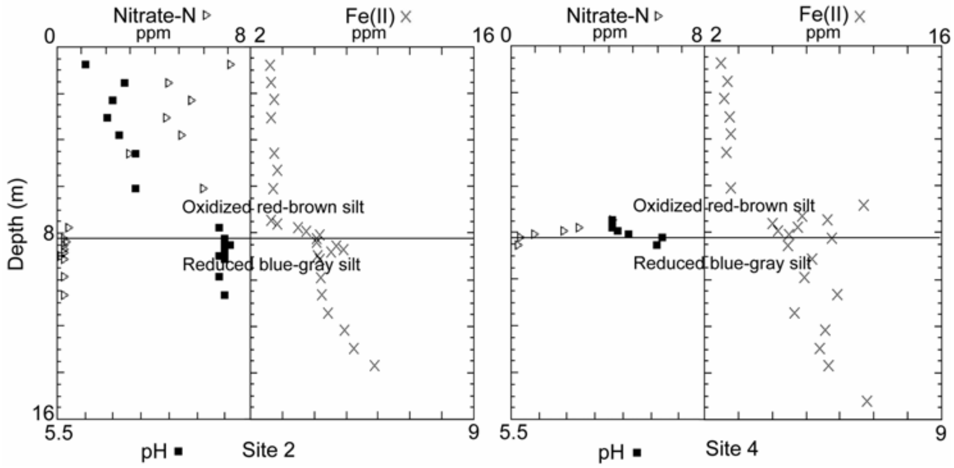

Figure 3. Chemical data for sites near Mt. Angel. Fe data collected in 2002, other data collected in 2003.

velocity contrast.

The Willamette Silt at site 2 has been extensively examined by Iverson (2002), who measured an average vertical hydraulic conductivity of $2x10^{-7}$ m/s, and an average porosity of 0.40. Sites 2 and 4 have nitrate profiles that suggest a barrier to nitrate transport at approximately 7.9 m below land surface (bls) (Figure 3). Nitrate levels (measured nitrate values are nitrate + nitrite except where otherwise noted), which are elevated at the surface, drop below background (2-3 ppm) levels below 7.9 m. At both sites, nitrate disappears at least 0.3 m above the color change.

Fe(II)/Fe(III) sampling done in the summer of 2002 shows a change from an Fe(III)-dominated environment to an Fe(II)-dominated environment, indicating a change from oxidizing conditions above to reducing conditions below. The transition from Fe(III)-dominated to Fe(II)-dominated is abrupt, and occurs 15 cm above the color change in core 2, and 1.2 m above the color change in core 4. Total iron concentrations at both site 2 and site 4 are constant with depth even as the dominant species changes, indicating a change in the oxidation conditions of the silt.

The pH at site 2 gradually increases from 6.0 near the surface to 6.9 at 6.1 m bls, and then jumps to 8.4 in less than 1.8 m. The jump is coincident with the increase in Fe(II), and 46 cm above the appearance of carbonate. Since reduction of Fe(III) to Fe(II) consumes H+, the dramatic pH increase supports the hypothesis that the increase in Fe(II) is from reduction of Fe(III) in the soil, and not an influx of Fe(II) from some other source.

DEA results from site 2 show no potential for heterotrophic denitrification at any point in the profile. After 2 hours of incubation, gas samples still did not have N_2O

concentrations above the detection limit (~250 ppb). A sample from the base of the reduced zone at site 35 in Shedd also did not show any N_2O evolution. Since any heterotrophic bacteria in the sample should have been producing N_2O, the lack of N_2O strongly indicates the absence of heterotrophic denitrifiers. No autotrophic denitrifying bacteria were active in the samples either, as they would also produce N_2O, but it is possible that they were present and could not utilize the nitrate because of a lack of substrate. While bacterial denitrification may be occurring at the surface of these sites, these results imply that it is not a significant process at depth.

Organic matter at the sites was also analyzed for, as a proxy for organic carbon. The organic matter percentage was found by the Loss On Ignition (LOI) method. Carbon is commonly considered to be approximately 50% of soil organic matter (Sparks 2003) so estimates of organic carbon were made by dividing the percentage organic matter by two. The values at sites 2 and 4 ranged between 1.0 and 2.1%, with most values at site 4 falling below 1.3%. These values conform to other estimates in the Willamette Silt (Iverson 2003, pers. comm.). Organic matter values showed no discernable trend at any sites.

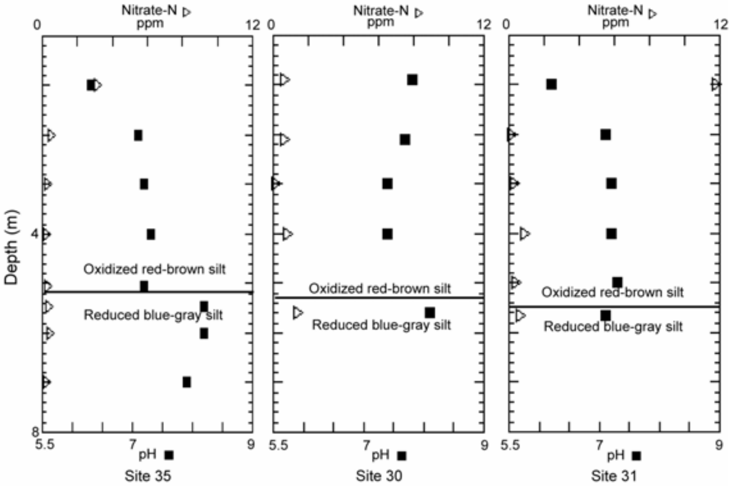

Figure 4. Nitrate and pH data for the three sample sites in Shedd, OR. Site 35 was on a residential lawn, site 30 in a grass field, and site 31 in the right-of-way of a narrow residential street across from a bulk fertilizer facility.

South valley sites

Twenty-nine boreholes were drilled in the southern Willamette valley, between Corvallis and Eugene. Willamette Silt was identified at 16 of the sites (Appendix A), five of which had a blue-gray zone near the bottom of the unit. Nitrate and pH measurements were taken from every site, along with organic matter at 11 of the sites. The five sites where a blue-gray zone was found were all in central Linn county (sites 13, 19, 30, 31, and 35), near the town of Shedd (Figure 1). A sample from the blue-gray zone at each of the five sites was tested for calcite with HCl, with only the sample from site 13 effervescing significantly. All of the south valley nitrate profiles were strikingly similar to each other: a slightly elevated concentration near the surface, dropping to background by 2 meters below the surface (Figure 4). This pattern was true at sites that had silt and sites that did not. The pH profiles were not as consistent, falling into two main categories: a gradual increase with depth, or a sharp increase at some point further down. Some sites show a gradual increase and then a sharp increase, and one site shows a sharp drop in pH. Site 13 shows a sharp pH decrease and a sharp nitrate increase at 7.0 m below the surface (Figure 5). Water sampled from below the base of the unit contained 6.2 ppm nitrate-N (Appendix D), a higher concentration than all but the deepest sample. The absence of significant nitrate in the profile above 7.0 m suggests that the nitrate must be coming

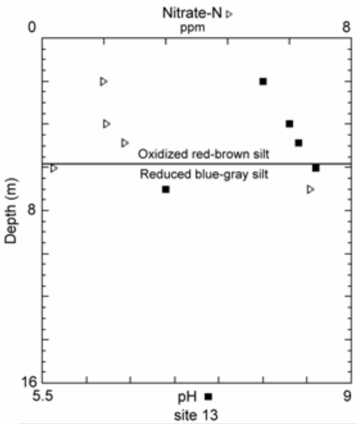

Figure 5. Nitrate and pH profiles for site 13. Note increase in nitrate and decrease of pH at deepest sample.

from somewhere other than the surface, but there is not likely to be an upward gradient from the higher permeability layer below.

Extent of reduced Willamette Silt

A fine-grained unit identified as the Willamette Silt was found at 19 of 33 total field sites (Appendix A). Thickness variations followed established spatial patterns (Gannet and Caldwell 1998, O'Connor et al. 2001): sites north of the Salem hills and south of the Tualatin basin (northern valley) included thicker silt units than those south of the Salem hills (south valley). Sites near the Willamette river and south of Harrisburg generally did not contain significant amounts of silt. The thicknesses of Willamette Silt found in this study closely matched the isopach map of Gannet and Caldwell (1998) but are more extensive than the Missoula Flood Deposits of O'Connor et al. (2001) in the Junction City area.

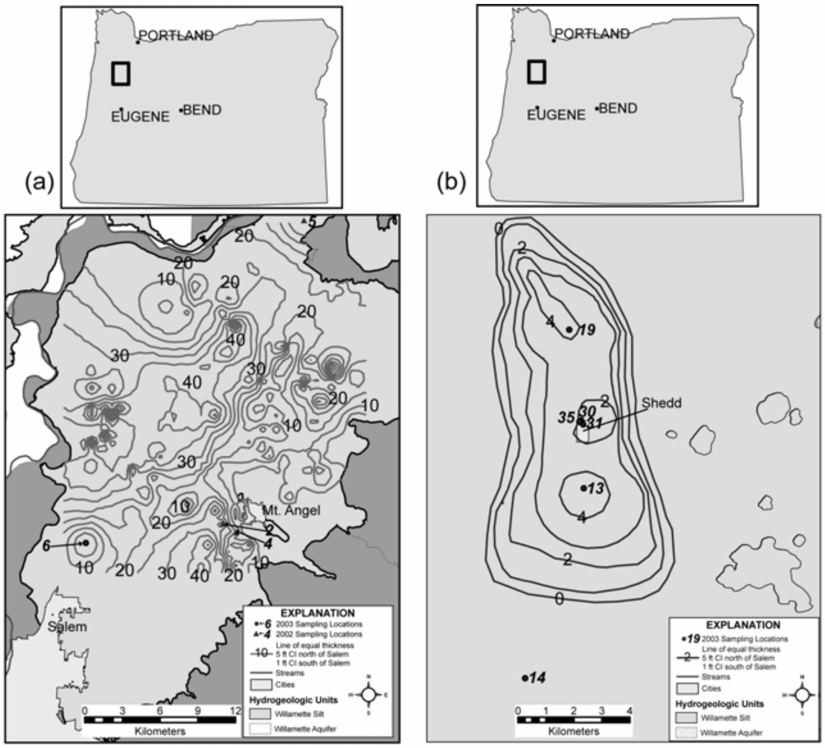

Figure 6. Isopach maps of the reduced zone of the Willamette Silt, showing the thickness northeast of Salem (a) and near Shedd (b).

The Willamette Silt was predominantly red-brown in color at all sample locations. At five locations around Shedd the lower part of the unit was a blue-gray color, similar to the reduced zone found at sites 2 and 4. Well logs for other wells in the area suggest that the blue-gray silt layer does not extend much more than 1.6 km in any direction from the sample sites. Figure 6 shows a map with isopachs depicting the thickness of the blue-gray layer in both the north (6a) and south (6b) valley.

The blue-gray layer identified in the north valley was found in 5 cores in the south valley: all three Shedd cores (cores 30, 31, and 35), core 19, approximately 3 km north of Shedd, and core 13, approximately 1 km south of Shedd. The location of the blue-gray layer appears to be most closely tied to depth below the surface, whereas the occurrence of the blue-gray layer appears to be most closely tied to the thickness of the silt. The locations with the thickest reduced zone generally are the areas with the thickest Willamette Silt, but several areas with thick section of Silt have relatively thin reduced zones, indicating that the thickness and presence of the reduced zone are controlled by more than just depth. The blue-gray silt appears at all south valley sites where the silt is thicker than 5.2 m (17 ft) with the exception of site 15. The silt at site 15 is 7.0 m (23 ft) thick, but is red-brown down to the base of the unit. Nearby well logs confirm the lack of a blue-gray layer in the Willamette Silt around site 15.

Isopach maps of the reduced zone are more valuable than their simple areal extent counterparts because they give a qualitative indication of the degree of protection offered. The buffering capacity of the reduced zone should increase with increasing thickness, since there is more ferrous iron available to reduce nitrate, so an area above a thick reduced zone will be better protected than an area above a thin reduced zone.

DISCUSSION

Correlation of nitrate profiles and redoxcline

At both sites 2 and 4, the nitrate + nitrite concentrations dropped below background levels approximately 0.5 m above the blue-gray zone. In the profile for site 4, a rapid continuous decrease is seen in the half-meter above the blue-gray zone. At both sites the denitrification appears spatially tied to the redoxcline. Since DEA assays show no denitrification potential at depth, chemical reduction of the nitrate by ferrous iron is thought to be the main mechanism of nitrate attenuation. However, at the Shedd sites, the nitrate penetration fronts did not penetrate more than 1 m below the ground, far above the reduced zone. At these shallow depths bacterial denitrification may be the main mechanism of nitrate reduction. Site 31, located in a parking strip across from a bulk fertilizer facility, had a concentration of 11.8 ppm NO_3^--N at 1.0 m below the surface that was reduced to .20 ppm within the next meter. The loss of nitrate + nitrite at this site is more closely correlated with the moisture conditions than the redoxcline. The sample was dry to a depth of approximately 1.7 m, at which point it became very moist. Denitrification at this site may be linked to the upper edge of the anaerobic zone. If the upper 1.7 m is dry, it is likely much more aerated than the water saturated soil below and oxygen inhibits denitrification.

Hypothesis of chemical reactions involved

In both the north and south valley sites where a blue-gray Willamette Silt layer is present, we see repeated patterns of nitrate decrease and pH increase. We suggest that as groundwater moves down through Willamette Silt, aerobic respiration of bacteria deoxygenates the water and increases the amount of dissolved CO_2. Under anaerobic conditions, nitrate acts as a terminal electron acceptor (TEA), either through bacterial denitrification (near the surface) or through chemical reduction by ferrous iron. The nitrite produced through reduction of nitrate is also leaving the system, likely via formation of nitrophenols through reaction with dissolved organic matter (DOM). Once the nitrate supply has been exhausted, iron(III) minerals are next to be reduced. Iron(III), in the form of ferrihydrite or goethite, can be reduced either through a biologically-mediated reaction, or abiotically.

Hydrolysis of organic carbohydrates under anaerobic conditions produces bicarbonate ion (HCO_3^-), acid (H^+), and electrons. This process is commonly biologically mediated, with bacteria using carbohydrates as electron donors, and the most thermodynamically favorable molecule available as the TEA: O_2, NO_3^-, or Fe^{3+}. Acidity in the soil will weather silicate minerals, freeing major cations such as Ca^{2+}, $Fe^{2+/3+}$, and Mg^{2+}. These ions play important roles in the other pertinent reactions. Nitrate can be reduced abiotically by Fe^{3+}-containing minerals (goethite, ferrihydrite, etc.), Fe^{3+} and H^+ are consumed by Fe reduction, and Ca^{2+}, Mg^{2+}, and HCO_3^- are consumed by carbonate precipitation. The overall stoichiometry of carbohydrate hydrolysis is:

$$(1/24)C_6H_{12}O_6 + (1/2)H_2O \rightarrow (5/4)H^+ + (1/4)HCO_3^- + e^- \quad (1)$$

Organic carbon is the primary electron donor in the subsurface, often in the form of Dissolved Organic Carbon (DOC). Oxidation of organic carbon is primarily a biologically mediated process carried about by a variety of bacteria.

Nitrate can be reduced abiotically by ferrous iron through the reaction:

$$2Fe^{2+} + NO_3^- + 3H_2O \rightarrow 2FeOOH_{(s)} + NO_2^- + H^+ \quad (2)$$

This has been found to be the major mechanism of nitrate reduction in other soils (Davidson et al. 2003) and we hypothesize that it is the main mechanism in the Willamette Silt. The “Ferrous Wheel Hypothesis” of Davidson et al. (2003) describes a systems where nitrate is reduced by the oxidation of Fe(II) to Fe(III) and then Fe(III) is reduced back to Fe(II) by reduced carbon (such as that found in carbohydrates). We hypothesize that a similar feedback loop is responsible for the loss of nitrate observed in our study.

Nitrite is highly reactive at low pH with constituents of DOM, forming organic compounds within a few hours, dominantly nitrophenols (Davidson et al. 2003). The pH values in the Willamette Silt are generally higher than that of the Davidson et al. (2003) experiments, perhaps lowering the rate of reaction in the Willamette Silt. The exact mechanism(s) for this reaction are not known, but Davidson et al. (2003) note that phenolic compounds commonly present in DOM can promote nitration (nitrite addition) and nitrosation (nitric oxide addition) of aromatic structures.

Iron reduction is hypothesized to play the major role in pH increase and the appearance of the blue-gray zone. The large increase in pH is coincident with the increase in Fe(II) concentration. Fe(III) in the subsurface The half-reaction describing the reduction of goethite or ferrihydrite is:

$$FeOOH_{(s)} + 3H^+ + e^- \rightarrow Fe^{2+} + 2H_2O \quad (3)$$

The consumption of H^+ in ferrihydrite reduction is likely the main cause of the pH increase observed in this study. The jump in pH is coincident with the increase in Fe(II) concentration at sites 2 and 3, where we have Fe(II) profiles. When the pH increases, the groundwater becomes relatively oversaturated with respect to calcite and dolomite, causing carbonate precipitation:

$$2Ca^{2+} + Mg^{2+} + 3HCO_3^- \rightarrow CaCO_{3\,(s)} + CaMg(CO_3)_{2\,(s)} + 3H^+ \quad (4)$$

An overall reaction can be written for these reactions to make the inputs and outputs clear

$$(1/2)C_6H_{12}O_6 + 10FeOOH + NO_3^- + 2Ca^{2+} + Mg^{2+} + 14H^+ \rightarrow$$

$$10Fe^{2+} + NO_2^- + CaCO_{3\,(s)} + CaMg(CO_3)_{2\,(s)} + 15H_2O \quad (5)$$

Although iron acts as both an oxidant and a reductant in the profile, organic carbon is the ultimate source of electrons in the overall reaction. The source of the organic carbon was not determined in this study, but the lack of a discernable trend in the organic matter concentration profiles suggests that preserved organic carbon from flood deposits can be ruled out.

The disappearance of nitrite at depth requires more study. Although the production of nitrophenolic compounds seems likely, not enough data is available to say definitively either way. Analyses for dissolved organic matter and dissolved organic nitrogen (DON) are needed to understand the form and fate of nitrogen applied at the surface. Unlike nitrate and nitrite, DON does not pose significant health issues, nor does the EPA set a maximum contaminant level (MCL) for it. Transformation of an EPA-controlled substance to one with not set MCL or known toxicity makes the redoxcline extremely useful.

Nitrate reduction by reduced iron should result in a molar equivalent decrease of reduced iron. Given a molecular weight for nitrogen of 14.01 g/mol and a molecular weight of iron as 55.55 g/mol, the concentration of reduced iron should be reduced by approximately four times the loss of NO_3-N (nitrate as nitrogen). This was not seen at either site 2 or 4. At site 2 nitrate values drop by 5.5 ppm, but the iron(II) values drop by only 0.101 ppm, or only about 2% of the nitrate decrease. At site 4 nitrate concentrations drop by 1.4 ppm and iron(II) concentrations decrease by 3.21 ppm, or about 2.3 times as much as the nitrate. One possible explanation for this discrepancy is that the samples analyzed were not taken at a fine enough scale (~15 cm apart) to observe the full iron(II) increase before being augmented by reduction of iron(III) minerals.

Because the location of the redoxcline seems to be controlled by the location of the reduced iron, any change in the depth at which iron is being reduced would lead to a change in the depth of the redoxcline. An increase in nitrate concentrations at depth could oxidize enough iron to shift the redoxcline down, or a decrease in the amount of electron-donor available to reduce ferric iron back to ferrous iron after nitrate reduction. Further study is needed to confirm that these abiotic reduction of nitrate by ferrous iron is the dominant process in the Willamette Silt. DOC levels should decrease at the same depth that Fe^{2+} increases dramatically, and dissolved organic nitrogen (DON) should increase.

CONCLUSIONS

The Willamette Silt provides a geochemical barrier to nitrate transport in some areas of the Willamette Valley. Nitrate reduction by ferrous iron is hypothesized to be the main mechanism by which nitrate is transformed, although bacterial denitrification may play a role near the surface (less than 2 meters deep). More work is needed to asses the importance of autotrophic denitrification, but our study suggests that it is minor if present at all. The presence of a reduced iron zone can be visually identified by the presence of a blue-gray zone at the base of the unit and has been found in much of the Willamette Silt north of Salem, and a small area between Salem and Eugene. Areas overlying the reduced zone will have less nitrate from the surface reach the aquifer below, although it is not known whether there is an upper limit to the flux of nitrate that can be transformed by this barrier. Further studies are needed to understand the limitations of this geochemical barrier, such as a maximum concentration that it can affect, or whether the barrier may eventually disappear due to a lack of ferrous iron.

The red-brown to blue-gray color change in the Willamette Silt is a visible sign of a geochemical change that is a barrier to nitrate transport. Soil iron becomes strongly reduced within 30 cm above the redoxcline. This change to a reduced environment is coincident with the appearance of carbonate minerals that are presumed to be precipitating out of solution, a pH increase, and the consistent attenuation of nitrate.

This barrier is extremely useful for those trying to manage land use and drinking water quality because it converts nitrate, a chemical of concern, to DON, a relatively benign form of nitrogen. Knowing the location of the redoxcline will be another tool available to those protecting groundwater quality.

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APPENDICES

APPENDIX A

Sampling site locations

Site No.	Site Name	MW ID	LAT	LONG	UTME	UTMN	INTERSECTION
2	Eder Nursery		45.0608	-122.8275	513.5816	4989.5069	Hook Rd and 114th
4	Beyer Farm		45.0547	-122.8139	514.6549	4988.8304	Hook Rd and Mt Angel Hwy
5	NWREC		45.2800	-122.7539	519.3032	5013.8690	Miley Rd, east of I-5
6	Brooks CSD		45.0440	-122.9653	502.7368	4987.6208	End of Richland Rd, S. of Brooklake
7	Skiller		44.2075	-123.1739	486.1069	4894.7164	River Rd & El Rio
8	Edwards		44.1964	-123.1715	486.2974	4893.4881	River Rd, S of Brown's Landing
9	Crocker		44.3628	-123.2893	476.9463	4911.9957	Hubbard Rd, E of 99W
10	Lindseth		44.3629	-123.2791	477.7631	4912.0052	Hubbard Rd, E of 99W
11	Crawford		44.4381	-123.2419	480.7517	4920.3449	Hurlburt, S of Smith Lp Rd
12	Seed Research of Oregon	MW-4	44.4349	-123.2419	480.7462	4919.9931	Hurlburt, S of Smith Lp Rd
13	Pugh Dairy N.		44.4400	-123.1078	491.4211	4920.5316	Pugh Dairy Dr, E of 99E
14	Curtis II		44.3781	-123.1314	489.5335	4913.6655	Crook Dr, E of Powerline Rd
15	Curtis		44.4470	-123.1920	484.7222	4921.3248	Abraham Dr, E of Blueberry Rd
16	Gifford		44.2601	-123.2279	481.8043	4900.5737	99W, N of Lingo Ln
17	Field 16		44.2800	-123.0559	495.5393	4902.7590	Diamond Hill Dr and Belts Dr
18	Field 19		44.3450	-123.0924	492.6356	4909.9825	Twin Buttes W Dr, .8 mi E of 99E
19	Field 27		44.4908	-123.1166	490.7288	4926.1741	Bell Plain Dr, 0.3 mi W of 99E
20	George Davis South	MW-3	44.5271	-123.1943	484.5643	4930.2191	Harvest Dr, E of Peoria Rd
21	Bowser		44.1335	-123.0864	493.0892	4886.4862	
22	Anderson		44.1350	-123.0953	492.3805	4886.6597	Coburg Btm Lp & Freedom Rd
23	Halverson		44.1421	-123.0975	492.1993	4887.4467	Coburg Btm Lp between Green Island and Freedom
24	DesReis	MW-6	44.1496	-123.0976	492.1936	4888.2797	Coburg Btm Lp & Green Island
25	Parmenter	MW-5	44.2807	-123.2438	480.5427	4902.8666	99w, Washburn Wayside Rest
26	Nielsen		44.2649	-123.2503	480.0231	4901.1157	Hulbert Lake Rd, N of Ferguson

27	Dumdi		44.2527	-123.2453	480.4182	4899.7539	Ferguson, E of Hulbert Lake Rd
28	Hazlett		44.1637	-123.0993	492.0577	4889.8441	Coburg Rd & Powerline Rd
29	Swango		44.1557	-123.0718	494.2602	4888.9563	Coburg Rd N, S of Indian Dr
30	L3 Farms		44.4618	-123.1099	491.2548	4922.9522	Boston Mill Rd & Hwy 99E
31	ROW-WE01		44.4606	-123.1090	491.3279	4922.8255	1st St & A St
32	Upper reach	MW-1	44.5667	-123.3012	476.0811	4934.6479	Campus Way and Irish Bend covered Bridge
33	Lower reach	MW-2	44.5588	-123.2847	477.3931	4933.7657	30th St at Bridge, across from stadium
34	Funke Rd	MW-7	44.1268	-123.0725	494.2004	4885.7418	Funke Rd & Coburg Btm Lp Rd
35	Jackson		44.4614	-123.1107	491.1911	4922.9089	Fayetteville & Hwy 99E

NAME	**CITY**	**COUNTY**	**Comments**	**Elevation (m)**
Eder, Chuck	Mt. Angel	Marion	Drilled 6/18/02, and 6/20/03	50
Beyer, John	Mt. Angel	Marion	Drilled 6/18/02	56
NWREC	Aurora	Clackamas	Drilled 6/18/02	46
Mark Terrill	Brooks	Marion	Drilled 6/20/03	56
Skiller	Junction City	Lane	Wickwire is a private road so sample location is on North side of Wickwire, just west of River road ROW	102
Edwards	Junction City	Lane	Sample location is on South side of private road, adjacent to West Side of River Road	102
Crocker	Monroe	Benton	Sample Location is on North side of Hubbard Rd, just east of the Long Tom Bridge	82
Lindseth	Monroe	Benton	Sample Location is North of residence, on the north side of Hubbard Rd where the road curves from N/S to E/W.	85
Crawford	Corvallis	Benton	Sample Location is at residence's NW corner, on East side of Rd.	75
Seed Research Of Oregon	Corvallis	Benton	Sample Location is adjacent to fence post, west side of gravel entrance to property	71
George Pugh	Shedd	Linn		81
George Pugh	Shedd	Linn		92
George Pugh	Shedd	Linn		82
Gifford	Junction City	Lane	Sample location is at resident's mail box, west side of Hwy 99	94
Dennis Glaser	Tangent	Linn		101
Dennis Glaser	Tangent	Linn		92
Dennis Glaser	Tangent	Linn		90

George Pugh	Shedd	Linn		73
Bowser	Coburg	Lane	Near survey marker	122
Anderson	Coburg	Lane		115
Halverson	Coburg	Lane	Sample location is on S side of Rd. just before rd turns to the North.	113
DesReis	Coburg	Lane	Sample site is located NE of residence on NE side of intersection of Coburg bottom Loop Rd. and Coburg Rd.	120
Parmenter	Junction City	Lane	Sample location is south of residence at the Washburn Wayside Rest Stop in median between Hwy 99 and parking area	100
Nielsen	Junction City	Lane	Sample location is adjacent to south side of resident's Driveway, west side of Hulbert Lake Road	92
Dumdi	Junction City	Lane	Sample location is on South side of Ferguson, adjacent to east side of west Driveway	93
Hazlett	Coburg	Lane	N side of intersection of Coburg Rd. and Poleline Rd.	113
Swango	Coburg	Lane	Next to MH Community 91750 Coburg Rd. north	118
Monte Lewis	Shedd	Linn		82
Darren Lane	Shedd	Linn		89
Linda Sarnoff	Corvallis	Benton		77
Linda Sarnoff	Corvallis	Benton		78
	Coburg	Lane		124
Mr. Jackson	Shedd	Linn		91

Willamette Silt?	**Thickness of Silt (m)**	**Thickness of blue-gray layer (m)**	**TRS**
yes	18.90	10.36585366	6S, 1W, Sec 8
yes	15.24	7.164634146	6S, 1W, Sec 16
no	3.05		
yes	7.32		6S, 2W, Sec 17 SW1/4
no	0.30		
no	0.30		
no	0.30		
no	0.61		
no	3.66		
yes	2.90	0.300	
yes	7.32	1.524	13S, 3W, Sec 18
yes	5.11		
yes	7.01		
no	0.91		
yes	3.66		
yes	3.05		

yes	7.11	1.268	12S, 4W, Sec 36
yes	4.57		12S, 4W, Sec 17
no	0.91		
no	1.96		
no	2.44		
no	1.22		
yes	2.44		
yes	4.57		
yes	1.83		
no	1.98		
no	2.03		
yes	5.64	0.279	13S, 3W, Sec 7
yes	5.67	0.152	13S, 3W, Sec 7
yes	4.27		
yes	1.83		
no	0.00		
yes	6.55	1.289	13S, 4W, Sec 12

APPENDIX B

Well logs for sampling sites

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Skiller	Louis Arighi	DEQ	Push Probe	1.5	07/14/03	07/14/03
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum	County	
7	12	44.2075	123.1739	101.0	NAD83	Lane	
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
N/A		N/A					
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	7-1	27 inches missing		Medium brown, dry, silt loam			
4-8	7-2	32.5 inches missing		Medium brown, pebbly, sandy loam (85% sand)			
8-12	7-3	12 inches missing, sleeve stuck in rod		Medium brown, moist, 5% F3M, pebbly (40% pebbles) sand (90-95% sand)			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Edwards	Louis Arighi	DEQ	Push Probe	1.5	7/14/2003	7/14/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
8	19	44.1964	123.1715		NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
		15.5		4:10pm	7/14/2003	19	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	8-1	45 inches missing		Light brown, dry, silt loam			
0-8	8-2	No recovery		No recovery			
8-11	8-3	17 inches missing		Light brown, moist, 2% F3M, pebbly, sandy loam (			
11-15	8-4	36.5 inches missing		Dark brown, 2% F3M, pebbly, sandy clay loam			
15-19	8-5	36 inches missing		Dark brown, wet, 2% F3M, pebbly, sandy clay loam			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Crocker	Louis Arighi	DEQ	Push Probe	1.5	7/15/2003	7/15/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
9	18	44.3628	123.2893		NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
		14		11:27 AM	7/15/2003	18	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	9-1	13.5 inches missing		Top 2 inches: pebbly, light gray silt loam. Rest of core: dark brown, dry, pebbly (10% pebbles) loam			
4-8	9-2	31 inches missing		Medium brown, dry, 3-5% F3M, pebbly, silty sand. Masses increase with depth			
8-12	9-3	22 inches missing		Red-brown, 3% F3M, 3% F2M, pebbly (40% pebbles), sandy loam			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Lindseth	Louis Arighi	DEQ	Push Probe	1.5	7/15/2003	7/15/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
10	20	44.3629	123.279	88m	NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
				2:45 PM	7/15/2003	25	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	10-1	24 inches missing		Dark brown, micaceous, pebbly, silty clay. Becomes moist at 13 inches from bottom			
4-8	none	No recovery		No recovery			
8-12	10-2	44.5 inches missing		Red-brown, moist, micaceous, silty clay loam			
12-16	10-3	41 inches missing		Light brown, wet, sand			
16-20	10-4	30 inches missing		Red-brown, wet, pebbly (5-10% pebbly), silty sand			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Crawford	Louis Arighi	DEQ	Push Probe	1.5	7/16/2003	7/16/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
11	28	44.4381	123.2418		NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
		13.2		11:20 AM	7/16/2003	20	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	11-1	14.5 inches missing		Light brown, dry, silty clay loam			
4-8	11-2	Intact core		Dark brown, moist, silty clay			
8-12	11-3	7 inches missing		Dark brown, moist, silty clay to 10 feet, then dark brown, moist, silty clay loam			
12-16	11-4	23.5 inches missing		Dark brown, wet, loam (40% sand, 15% clay)			
16-20	11-5	39 inches missing		Dark brown, wet, silt loam (20% clay, 25% sand)			
20-24	11-6	3.5 inches missing		Red-brown, wet, pebbly (5-10%), sand			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Seed Research	Louis Arighi	DEQ	Push Probe	1.5	7/16/2003	7/16/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
12	28	44.4350	123.2419	71	NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
		12.6		4:05 PM	7/16/2003	25	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	12-1	16.5 inches missing		7.5 inches of road bed. Dark brown, moist, silty clay loam, moisture increases 4.5 inches from bottom			
4-8	12-2	11 inches missing		Dark brown, moist, micaceous, silty clay			
8-12	12-3	5 inches missing		Dark brown, moist, micaceous, clay (60% clay, 3% sand)			
12-16	12-4	9.5 inches missing		Dark brown, moist, micaceous clay, transitioning 18 inches from bottom to dark brown loam (20% clay, 35% sand)			
16-20	12-5	3 inches missing		Dark brown, moist, loam (20% clay, 45% sand), transitioning ~3 inches from bottom to dark brown silt loam (30% sand, 15% clay)			
20-24	12-6	3 inches missing		Blue-gray silt loam (20% clay, 25% sand), transitioning ~3 inches from bottom to yellow-brown, pebbly, sandy loam (10% clay, 75% sand)			
24-28		Core stuck, sample taken from cutting shoe		Blue-gray pebbly loam			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Pugh Dairy N	Louis Arighi	DEQ	Push Probe	1.5	7/17/2003	7/17/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
13	28	44.4400	123.1078		NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
		7.9		11:40 AM	7/17/2003	24	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	13-1	31 inches missing		Yellow-brown, moist, micaceous, silt loam			
4-8	13-2	7.5 inches missing		Yellow-brown, moist, micaceous, silt loam (20% clay, 1% sand), transitioning at ~3 inches from the bottom to medium brown, moist, micaceous, 2% F3M, silty clay loam (30% clay, 1% sand)			
8-12	13-3	2 inches missing		Medium brown, moist, micaceous, 2% F3M, silty clay loam, transitioning at ~3 inches from the bottom to yellow-brown, moist, micaceous, 2% F3M, silty clay loam			
12-16	13-4	1.5 inches missing		Yellow-brown, moist, micaceous, 2% MNM, silty clay loam. 2% F3M near bottom, 0% MNM			
16-20	13-5	29.5 inches missing		Top 7.25 inches: yellow-brown, very wet, 2% MNM, pebbly (35%), silt loam. Rest of sample: blue-gray, dry, silty clay loam			
20-24	13-6	21.5 inches missing		Blue-gray, moist, 10% F3M, clay (60% clay, 3% sand)			
24-28	13-7, 13-8	Sampling problems, partial cores retrieved in two attempts		Upper portion: 60/40 mix of yellow-brown, pebbly, silty clay loam with blue-gray clay. Lower portion: blue-gray, pebbly (85%), clay loam (25% sand, 35% clay)			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Curtis II	Louis Arighi	DEQ	Push Probe	1.5	7/17/2003	7/17/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
14	17	44.3781	123.1314	92	NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	14-1	34 inches missing		Yellow-brown, moist, micaceous, silty clay loam (30% clay, 3% sand)			
4-8	14-2	16 inches missing		Yellow-brown, moist, micaceous, silty clay loam (30% clay, 3% sand)			
8-12	14-3	Intact core		Yellow-brown, moist, micaceous, silty clay loam (30% clay, 3% sand)			
12-16	14-4	22.5 inches missing		Medium brown, micaceous, 10% RMFs (F3M, MNM, FMM), silty clay			
16-17		Drill stuck on gravels		Red-brown, 10% RMFs, pebbly (35%), loam			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Curtis	Louis Arighi	DEQ	Push Probe	1.5	7/17/2003	7/17/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
15	24	44.4470	123.1920		NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	15-1	27.3 inches missing		Yellow-brown, moist, micaceous, silt loam (1% sand, 25% clay)			
4-8	15-2	6.3 inches missing		Yellow-brown, moist, micaceous, silt loam (1% sand, 25% clay)			
8-12	15-3	Intact core		Yellow-brown, very moist, micaceous, silty clay loam (1% sand, 30% clay), transitioning at ~3 inches from bottom to medium brown, very moist, micaceous, 10% F3M, silty clay loam			
12-16	15-4	Intact core		Yellow-brown, moist, micaceous, silty clay (45% clay), transitioning at ~3 inches from bottom to medium brown, moist, micaceous, 10% F3M, silty clay			
16-20	15-5	9 inches missing		Medium brown, moist, micaceous, 10% F3M, 1% FMN, silty clay, transitioning at ~3 inches from bottom to dark brown, moist, 2% FSN, silty clay (55% clay)			
20-24	15-6	12 inches missing		Dark brown, moist, silty clay. Gravel at 24 feet			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Gifford	Louis Arighi	DEQ	Push Probe	1.5	7/21/2003	7/21/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
16	20	44.2601	123.2280		NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	16-1	31.2 inches missing		Brown, dry, micaceous, loam			
4-8	16-2	35.3 inches missing		Dark brown, moist, sand			
8-12	16-3	39 inches missing		Dark brown, moist, sand, transitioning at ~3 inches to dark brown, moist, pebbly (75%), sand			
12-16	16-4	20.4 inches missing		Dark brown, moist, pebbly (75%), sand (3% silt, 3% clay), becomes wet at 15 ft depth			
16-20	16-5	21.6 inches missing		Dark brown, wet, pebbly (80%), sand			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Glaser 16	Louis Arighi	DEQ	Push Probe	1.5	7/21/2003	7/21/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
17	18.5	44.2800	123.0559	101	NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
		6		5:00 PM	7/21/2003	14	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	17-1	16.5 inches missing		Light gray, dry, clay (55% clay, 5% sand), transitioning at ~3 inches from bottom to yellow-brown, dry, clay (65% clay, 3% sand)			
4-8	17-2	16.25 inches missing		Yellow-brown, moist, 5% F3M, 5% MNM, clay (65% clay, 1% sand)			
8-12	17-3	16.5 inches missing		Light brown, dry, clay (70% clay, 1% sand), gradual transition starting at 6 inches from bottom to dark brown, moist, 10% F3M, silt loam (55% sand, 10% clay)			
12-16	17-4	15.5 inches missing		Dark brown, moist, pebbly (30%), sand (86% sand, 7% clay), transitions at ~6% to dark brown, wet, sand (93% sand, 4% clay)			
16-18.5	17-5	16.5 inches missing		Dark , wet, silt loam (70% sand, 5% clay), transitioning at bottom to dark brown, wet, sand (85% sand, 10% clay)			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Glaser 19	Louis Arighi	DEQ	Push Probe	1.5	7/22/2003	7/22/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
18	24	44.3450	123.0924	92	NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
		8.25		11:20 AM	7/22/2003	23	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	18-1	43 inches missing		Blue-gray, dry, powdery, 1% F3M, root wads, silt loam			
4-8	18-2	27.5 inches missing		Blue-gray, dry, powdery, 1% F3M, root wads, silt loam, transitioning at ~3 inches to yellow-brown, dry, micaceous, 2% F3M, silty clay loam			
8-10.5	18-3	6 inches missing		Yellow-brown, dry, micaceous, 2% F3M, silty clay loam, transitioning ~2 inches from bottom to yellow-brown, dry, very pebbly (40%), silty clay loam (35% clay, 5% sand)			
10.5-12	18-4	9 inches missing		Dark brown, 30% sand-size FMN, extremely pebbly (85%), loam (40% sand, 25% clay)			
12-16	18-5	Intact core, hard drilling		Dark red-brown, dry, 8% F3M, very pebbly (80%), loam (30% sand, 20% clay)			
16-20	18-6	16.5 inches missing		Dark red-brown, dry, 8% F3M, very pebbly (80%), loam (30% sand, 20% clay), transitioning at ~7 inches from bottom to dark brown, wet, very pebbly (75%), silt loam (70% sand, 15% clay)			
20-24	18-7	Intact core		Red-brown, wet, loam (40% sand, 15% clay), transitioning to pebbles (92%) with red-brown, wet, loam			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Glaser 27	Louis Arighi	DEQ	Push Probe	1.5	7/22/2003	7/22/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
19	24	44.4908	123.1166	90	NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	19-1	43 inches missing		Dark brown, dry, few roots, silty clay loam			
4-8	19-2	11 inches missing		Dark brown, dry, micaceous, silty clay loam, transitioning at ~3 inches from bottom to yellow-brown, moist, micaceous, 5% F3M, silty clay loam (30% clay, 1% sand)			
8-12	19-3	Intact core		Yellow-brown, moist micaceous, 5% F3M, silty clay loam (30% clay, 1% sand), increasing to 10% F3M in the bottom 2 inches			
12-16	19-4	Intact core		Yellow-brown, moist micaceous, 10% F3M, silty clay loam (35% clay, 1% sand), increasing to 15% F3M in the bottom 2 inches			
16-20	19-5	19 inches missing		Yellow-brown, very moist, micaceous, 15% F3M, silty clay loam, transition at ~10 inches from bottom to blue-gray, moist, micaceous, silty clay (50% clay, 2% sand)			
20-24	19-6	23 inches missing		Blue-gray, moist, micaceous, 2% F3M, silty clay, transitioning at ~8 inches from bottom to blue-gray, extremely pebbly (80%) silt loam (15% clay, 55% sand)			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	G. Davis. S	Louis Arighi	DEQ	Push Probe	1.5	7/22/2003	7/22/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
20	20	44.5271	123.1943	73	NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
		6.2		4:15 PM	7/22/2003	20	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	20-1	33.5 inches missing		Dark brown, dry, silty clay loam (30% clay, 1% sand)			
4-8	20-2	21 inches missing		Dark brown, dry, silty clay loam (30% clay, 1% sand), transitioning at ~3 inches from bottom to medium brown, moist, silty clay loam (35% clay, 5% sand)			
8-12	20-3	Intact core		Medium brown, moist, 5% F3M, silty clay loam (35% clay, 5% sand)			
12-16	20-4	Intact core		Dark brown, very moist, 15% F3M, silty clay loam (30% clay, 15% sand), transitioning at ~2 inches from bottom to medium brown, very moist, loam (10% clay, 50% sand)			
16-20	20-5	8 inches missing		Yellow-brown, wet, loam (40% sand, 15% clay), transitioning at ~3 inches from bottom to dark brown, wet, extremely pebbly (70%), loam (50% sand, 15% clay)			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Bowser	Louis Arighi	DEQ	Push Probe	1.5	7/23/2003	7/23/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
21	24	44.1335	123.0864	122	NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	21-1	27 inches missing		Light gray, dry, silt loam (15% sand, 15% clay), transitioning at ~2 inches from bottom to medium brown, dry, very pebbly (60%), sand (5% silt, 95% sand)			
4-8	21-2	17.5 inches missing		Medium brown, dry, very pebbly (60%), sand, transitioning at ~3 inches from bottom to medium brown, dry, extremely pebbly (80%), sand (5% clay, 5% silt)			
8-12	21-3	11 inches missing		Medium brown, dry, extremely pebbly (80%), sand (5% clay, 5% silt)			
12-16	21-4	13.5 inches missing		Dark brown, moist, extremely pebbly (85%), sand (5% silt, 5% clay)			
16-20	21-5	18 inches missing		Dark brown, moist, extremely pebbly (85%), sand (5% silt, 5% clay), transitioning at ~3 inches from bottom to red-brown, wet, extremely pebbly sand			
20-24	21-6	21.5 inches missing		Dark brown, wet, loamy sand, transitioning at ~3 inches from bottom to dark brown, moist, extremely pebbly (65%) sand (5% silt, 5% clay)			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Anderson	Louis Arighi	DEQ	Push Probe	1.5	7/23/2003	7/23/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
22	12	44.1350	123.0953		NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	22-1	40 inches missing		Red-brown, dry, silty loam (25% clay, 5% sand)			
4-8	22-2	21.5 inches missing		Red-brown, dry, silty loam (25% clay, 5% sand), transitioning at ~17 inches from bottom to red-brown, 45% F3M, Loam (50% sand, 10% clay), transitioning at ~2 inches from bottom to medium brown, moist, extremely pebbly (75%), sand (5% silt, 5% clay)			
8-12	22-3	From cutting shoe		Brown, dry, loose, extremely pebbly (75%), loam (35% sand, 20% clay)			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Halverson	Louis Arighi	DEQ	Push Probe	1.5	7/23/2003	7/23/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
23	20	44.1421	123.0975		NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	23-1	33.5 inches missing		Dark brown, dry, 5% FMN (~2mm diameter), silty loam (25% clay, 10% sand)			
4-8	23-2	45 inches missing		Red-brown, dry, few pebbles, loam (35% sand, 20% clay)			
8-12	23-3	40.5 inches missing		Dark brown, dry, few pebbles, sandy loam (70% sand, 15% clay)			
12-16	23-4	26.5 inches missing		Dark brown, dry, extremely pebbly (70%), sandy loam			
16-20	23-5	36 inches missing		Dark brown, wet, extremely pebbly (85%), sand (5% clay, 90% sand)			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Des Reis 47	Louis Arighi	DEQ	Push Probe	1.5	7/23/2003	7/23/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
24	24	44.1496	123.0976		NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
		12		2:15 PM	7/23/2003	24	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	24-1	41 inches missing		Medium brown, dry, hard, silty clay loam (35% clay, 5% sand)			
4-8	24-2	37 inches missing		Medium brown, dry, loose, extremely pebbly (65%), sand (2% silt, 98% sand)			
8-12	24-3	11.5 inches missing		Pebbles with 5% sand (5% silt, 95% sand), 20% F3M			
12-16	24-4	12.5 inches missing		Pebbles with 8% red silty clay loam (5% sand, 30% clay), transition ~2 inches from top to pebbles with 8% gray, wet, sand (5% clay, 5% sand)			
16-20	24-5	11 inches missing		Red-brown, wet, extremely pebbly (75%), silt loam (10% sand, 25% clay), transitioning at ~2 inches from bottom to red-brown, wet, extremely pebbly (75%), silt loam (10% clay, 30% sand)			
20-24	24-6	21.5 inches missing		Red-brown, wet, extremely pebbly (75%), silt loam (10% clay, 30% sand), transitioning at ~3 inches from bottom to pebbles with red-brown, wet, loam (40% sand, 15% clay)			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Washburn Wayside	Louis Arighi	DEQ	Push Probe	1.5	7/24/2003	7/24/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
25	24	44.2807	123.2438		NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
		10.25		9:10 AM	7/24/2003	24	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	25-1	13.5 inches missing		Red-brown, dry, hard, silty clay loam (30% clay, 5% sand)			
4-8	25-2	11 inches missing		Red-brown, dry, hard, 2% F3M, silty clay loam (30% clay, 5% sand), transitioning at ~3 inches from bottom to red-brown, moist, loam (45% sand, 20% clay)			
8-12	25-3	32.5 inches missing		Medium brown, wet, loamy sand (85% sand, 10% clay)			
12-16	25-4	9 inches missing		Medium brown, wet, loamy sand (85% sand, 10% clay), transitioning at ~2 inches from bottom to pebbles with 10% brown, wet, sand (5% clay, 5% silt)			
16-20	25-5	10 inches missing		Top ten inches are red, wet, loamy sand, transitioning to pebbles with 10% brown, wet, sand			
20-24	25-6	4 inches missing		Medium brown, wet, sand (5% clay, 5% silt), transitioning at ~3 inches from bottom to brown, wet, extremely pebbly (85%) sand			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Nielsen	Louis Arighi	DEQ	Push Probe	1.5	7/24/2003	7/24/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
26	16	44.2649	123.2503		NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
		6.4		11:15 AM	7/24/2003	16	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	26-1	23.5 inches missing		Red-brown, moist, clay (1% sand, 60% clay)			
4-8	26-2	2 inches missing		Red-brown, dry, 15% F3M, clay, FMN appear 16 inches from bottom, transitioning at ~3 inches from bottom to red-brown, moist loam (25% sand, 20% clay)			
8-12	26-3	7.5 inches missing		Brown, moist, silty clay (40% clay, 8% sand), transitioning at ~1 inch from bottom to dark brown, moist, silty loam (20% sand, 15% clay)			
12-16	26-4	1 inch missing		Brown, wet, silty loam (8% sand, 20% clay), transitioning at ~2 inches from bottom to pebbles with 10% yellow-brown, wet, sand (90% sand, 5% clay)			
16-20	26-5	27.5 inches missing		Medium gray, wet, sand (4% clay, 1% silt)			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Dumdi	Louis Arighi	DEQ	Push Probe	1.5	7/24/2003	7/24/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
27	18	44.2527	123.2453		NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
		6		1:20 PM	7/24/2003	18	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	27-1	30 inches missing		Red-brown, moist, silty clay (50% clay, 3% sand)			
4-8	27-2	1 inch missing		Red-brown, moist, silty clay (50% clay, 3% sand), transition at ~23 inches from bottom to light brown, moist, loam (45% sand, 15% clay)			
8-12	27-3	Intact core		Red-brown, moist, clay (40% clay, 25% sand), transitioning at ~3 inches from bottom to brown, 40% F3M, silty loam (15% clay, 5% sand)			
12-16	27-4	Intact core		Light brown, 25% F3M, silty loam (45% clay, 4% sand), transitioning ~2 inches from bottom to medium brown, 10% F3M, silty loam (15% clay, 3% sand)			
16-20	27-5	From shoe		Brown, very pebbly (40%), loamy sand (85% sand, 10% clay)			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Hazlett	Louis Arighi	DEQ	Push Probe	1.5	7/24/2003	7/24/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
28	20	44.16637	123.0993		NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	28-1	37.5 inches missing		Dark brown, dry, hard, silty loam (20% clay, 3% sand)			
4-8	28-2	11 inches missing		Dark brown, dry, 3% FSN, silty loam (25% clay, 3% sand), transitioning at ~18 inches from bottom to dark brown, wet, pebbly (30%), sand (8% clay, 2% silt)			
8-12	28-3	11.5 inches missing		Dark brown, wet, pebbly (30%), sand (8% clay, 2% silt), transitioning to dark brown, wet, pebbly (30%), sand (100%)			
12-16	28-4	11 inches missing		Yellow-brown, wet, extremely pebbly (65%), loamy sand (10% clay, 5% sand), increasing to 85% pebbly at bottom			
16-20	28-5	2 inches missing		Dark brown, wet, few pebbles, sand (100%), increasing to 85% pebbly at bottom			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Swango	Louis Arighi	DEQ	Push Probe	1.5	7/24/2003	7/24/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
29	20	44.1557	123.0718		NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
		8.75		4:45 PM	7/24/2003	20	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	29-1	38 inches missing		Medium brown, dry, roots, silty clay (15% clay, 85% silt)			
4-8	29-2	20 inches missing		Medium brown, dry, roots, silty clay (15% clay, 85% silt), transitioning at ~16 inches from bottom to pebbles with 5% dry sand			
8-12	29-3	38.5 inches missing		Pebbles with 8% dark brown, wet, sand			
12-16	29-4	18.5 inches missing		Pebbles with 8% dark brown, wet, sand (95% sand, 5% clay)			
16-20	29.5	10 inches missing		Small pebbles (80%), sand (5% clay, 3% silt), transitioning to large (38 mm max. diameter) pebbles with 5% sand (5% clay, 3% silt)			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	L3 Farms	Louis Arighi	DEQ	Push Probe	1.5	9/15/2003	9/15/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
30	18.5	44.46176	123.1099	82	NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-3	30-1	24 inches missing		Yellow brown, slightly moist, silty clay (45% clay, 3% sand)			
3-7	30-2	18 inches missing		Yellow brown, slightly moist, silty clay (45% clay, 3% sand), transitioning at ~2 inches from bottom to yellow-brown, moist, micaceous, 5% F3M, silty clay (45% clay, 55% silt)			
7-10.5	30-3	Intact core		Yellow-brown, moist, micaceous, 5% F3M, silty clay (45% clay, 55% silt), transitioning at ~2 inches from bottom to yellow-brown, moist, micaceous, 10% F3M, silty clay (52% clay, 1% sand)			
10.5-14.5	30-4	Intact core		Yellow-brown, moist, micaceous, 10% F3M, silty clay (52% clay, 1% sand), transitioning at ~3 inches from bottom to yellow-brown, slightly oist, micaceous, 25% F3M, clay (60% clay, 2% sand)			
14.5-18.5	30-5	16 inches missing		Yellow-brown, slightly moist, micaceous, 25% F3M, clay (60% clay, 2% sand), transitioning at ~11 inches from bottom to blue-gray, slightly moist, 1% F3M, clay (60% clay, 1% sand), gravel at base of core			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Shedd ROW	Louis Arighi	DEQ	Push Probe	1.5	9/15/2003	9/15/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
31	18.6	44.46062	123.1090	89	NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-3.7	31-1	34 inches missing		Light-brown, dry, few mica flakes, silty clay (50% clay, 3% sand)			
3.7-7.2	31-2	21 inches missing		Light-brown, dry, few mica flakes, silty clay (50% clay, 3% sand), transitioning at ~3 inches from bottom to yellow-brown, very moist, micaceous, silty clay loam (38% clay, 3% sand)			
7.2-11	31-3	Intact core		Yellow-brown, very moist, micaceous, silty clay loam (38% clay, 3% sand), transitioning at ~3 inches from bottom to silty clay (42% clay, 3% sand) with 3% F3M			
11-14.8	31-4	Intact core		Yellow-brown, very moist, 1% F3M, micaceous, silty clay (42% clay, 3% sand)			
14.8-18.6	31-5	15 inches missing		Yellow-brown, very moist, 1% F3M, micaceous, silty clay (42% clay, 3% sand) transitioning at ~6 inches from bottom to blue-gray, slightly moist, clay (65% clay, 1% sand)			

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	OSU U.R.	Louis Arighi	DEQ	Push Probe	1.5	9/16/2003	9/16/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
32	17.4	44.5667	123.2847	77	NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
		10.5		10:42 AM	9/16/2003	17.4	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-3.5	32-1	36 inches missing		Light brown, pebbly, silt loam (10% clay, 70% silt)			
3.5-7.5	32-2	17 inches missing		Light brown, pebbly, silt loam (10% clay, 70% silt), transitioning at ~3 inches from bottom to brown, moist, 15% F3M, clay (57% clay, 5% sand)			
7.5-11.2	32-3	1 inch missing		Brown, moist, 15% F3M, clay (57% clay, 5% sand), transitioning at ~2 inches from bottom to pale gray-green, moist, 15% F3M, silty clay loam (10% sand, 40% clay)			
11.2-14.2	32-4	14.5 inches missing		Pale gray-green, moist, 15% F3M, silty clay loam (10% sand, 40% clay), increasing to 30% pebbly at bottom			
14.2-17.4	N/A	Done with "Maverick"		No sample			
Note:							
Site 32 may be on a "fill" dump from previous road construction. The top 10 feet or so may not be in place.							

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	OSU L.R.	Louis Arighi	DEQ	Push Probe	1.5	9/16/2003	9/16/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
33	18.6	44.5588	123.2849	78	NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
		13		2:01 PM	9/16/2003	18.6	

Depth (ft)	Sample No.	Remarks	Lithologic description
0-3.6	33-1	25 inches missing	Light brown, dry, silty clay (50% clay, 5% sand)
3.6-7.6	33-2	23 inches missing	Light brown, dry, silty clay (50% clay, 5% sand), transitioning at ~ 3 inches from bottom to light brown, dry, silty clay loam (15% sand, 40% clay). Bright orange streaks from 13.75 inches above bottom to 5.5 inches above bottom
7.6-11.2	33-3	13 inches missing	Light brown, dry, few pebbles, silty clay loam (15% sand, 40% clay), transitioning to dark brown, dry, clay (65%, clay, 3% sand). Bright orange material from 19.5 inches above bottom to 13.5 inches above bottom
11.2-14.8	33-4	2 inches missing	Dark brown, dry, clay (65%, clay, 3% sand), transitioning at ~9 inches from bottom to dark brown, moist, 5% F3M, clay loam (40% clay, 20% sand)
14.8-18.6	33-5	From shoe	80% pebbles with blue-gray and red-brown, moist, clay (50% clay, 15% sand)
Note:			

Site 33 may be on a "fill" dump from previous road construction. The top 10 feet or so may not be in place.

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Funke Rd	Louis Arighi	DEQ	Push Probe	1.5	9/18/2003	9/18/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
34	23.5	44.1268	123.0725	124	NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	

Depth (ft)	Sample No.	Remarks	Lithologic description
0-3.6	34-1	31 inches missing	Medium brown, dry, sand (3% clay, 5% silt)
3.6-7.1	34-2	17.5 inches recovered	Medium brown, dry, sand (3% clay, 5% silt), becomes pebbly (35%) at 14 inches from bottom
7.1-10.8	34-3	14.5 inches missing	Medium brown, dry, very pebbly (45%), sand (3% clay, 5% silt), increasing to extremely pebbly (80%) at bottom
10.8-14.5	34-4	20 inches missing	Light brown, dry, very pebbly (65%), loam (50% sand, 15% clay), increasing to 75% pebbly at bottom
14.5-18.2	34-5	20 inches missing	Light brown, dry, 5% F3M, very pebbly (65%), loam (50% sand, 15% clay), increasing to 85% pebbly, slightly moist, at bottom
18.2-21.5	34-6	23 inches missing	Light brown, moist, 5% F3M, very pebbly (85%), loam (50% sand, 15% clay), becoming very moist at 3 inches from bottom
21.5-23.5	34-7	10 inches missing	Light brown, moist, 5% F3M, very pebbly (85%), loam (50% sand, 15% clay)

Project Name	Site name	Geologist	Drilling contractor	Drilling method	Hole Diameter (in)	Date begun	Date completed
SWVGA	Jackson	Louis Arighi	DEQ	Push Probe	1.5	10/16/2003	10/16/2003
Boring no.	Total depth (ft)	Lat (dec. deg N)	Long (dec. deg S)	Ground elevation (m)	Datum		
35	23	44.4614	123.1107	120	NAD83		
Water level data:		Depth to water (ft)		Time	Date	Boring depth (ft)	
Depth (ft)	Sample No.	Remarks		Lithologic description			
0-4	35-1	34 inches missing		Light brown, dry, silt loam (3% sand, 15% clay)			
4-8	35-2	7.5 inches missing		Light brown, dry, 2% F3M, silt loam (3% sand, 15% clay), transitioning at ~3 inches from bottom to red-brown, moist, 8% F3M, micaceous, silty clay loam (30% clay, 3% sand)			
8-12	35-3	Intact core		Red-brown, moist, 8% F3M, micaceous, silty clay loam (30% clay, 3% sand), very moist at bottom			
12-15	35-4	Intact core		Red-brown, very moist, 8% F3M, micaceous, pebbly (30%), silty clay loam (30% clay, 3% sand)			
15-18	35-5	Intact core		Red-brown, very moist, hard, 8% F3M, micaceous, pebbly (5%), silty clay loam (30% clay, 3% sand), transitioning at 9 inches from bottom to blue-gray, slightly moist, silty clay loam (30% clay, 3% sand)			
18-21	35-6	Intact core		Blue-gray, slightly moist, silty clay loam (30% clay, 3% sand), becoming moist at bottom with 2% FSN			
21-23	35-7	1 inch missing		Blue-gray, slightly moist, silty clay loam (30% clay, 3% sand), transitioning at 19.5 inches from bottom to red-brown, very moist, pebbly (30%), sand (3% clay, 3% silt)			

APPENDIX C

Soil chemical data and XRD analysis

Figure B1: Site 2 chemical data, 2003

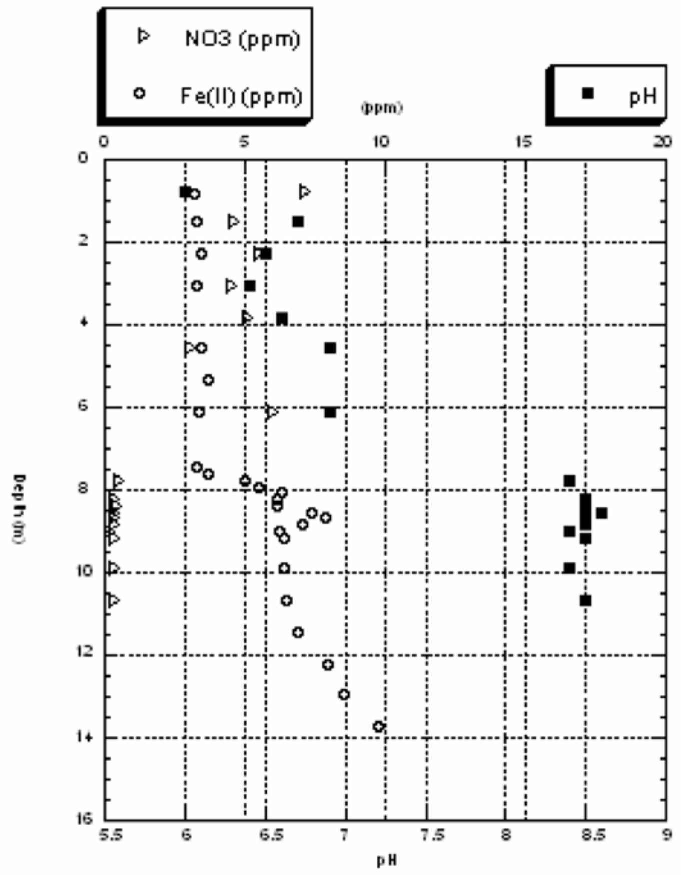


Figure B2: Site 2 Organic Matter

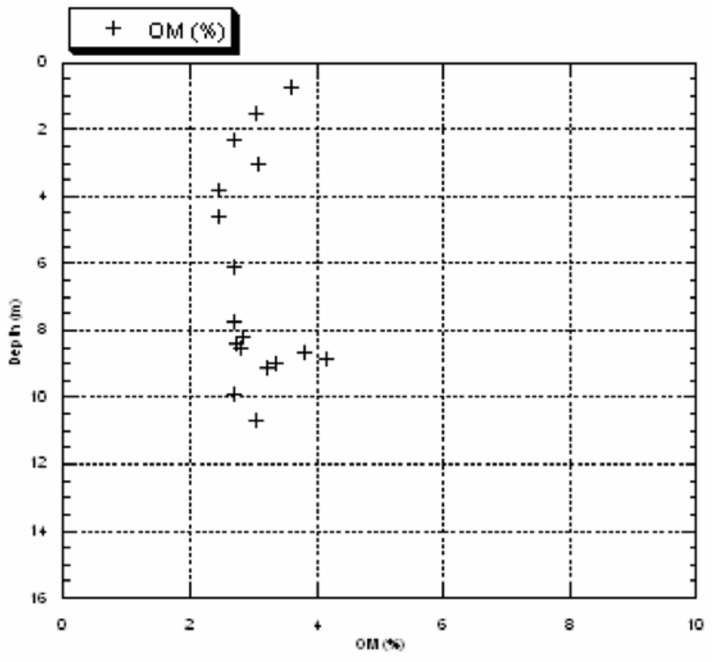


Figure B3: Site 4 chemical data

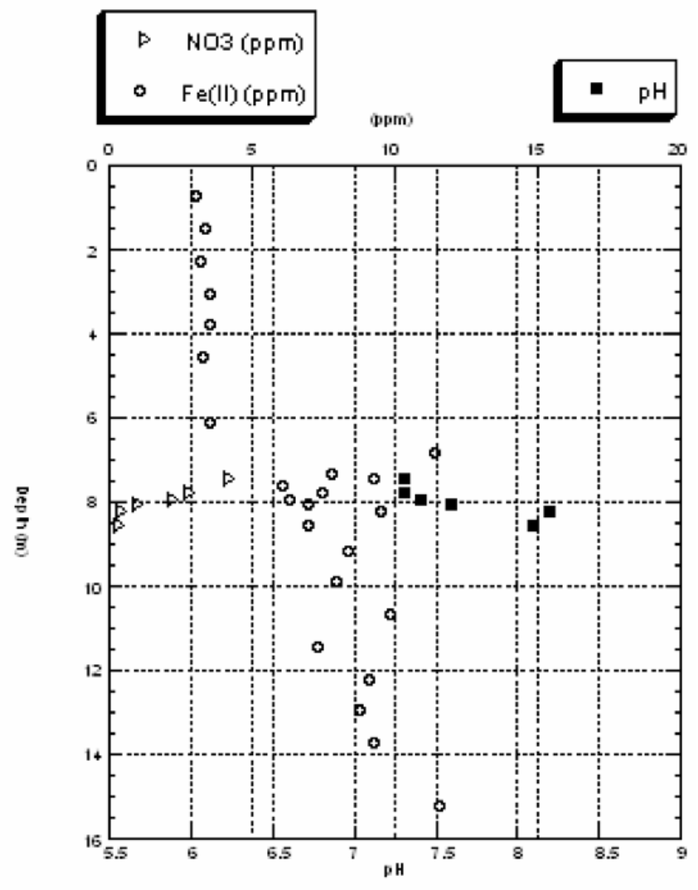


Figure B4: Site 4 organic matter

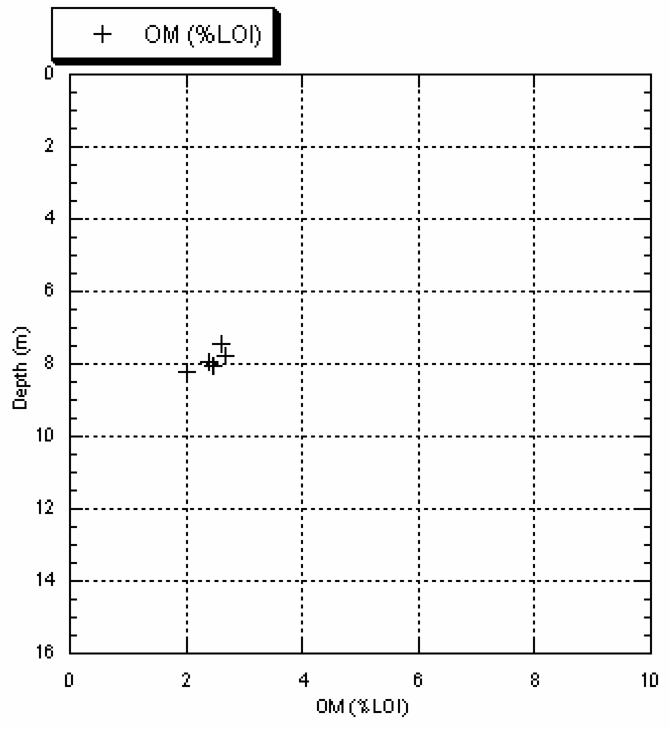


Figure B5: Site 6 chemical data

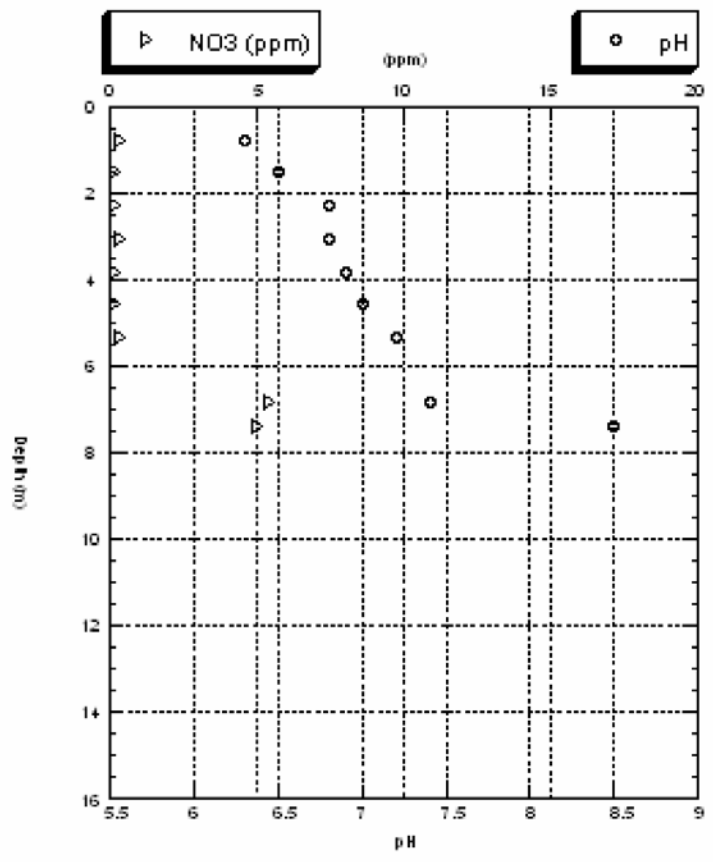


Figure B6: Site 6 organic matter

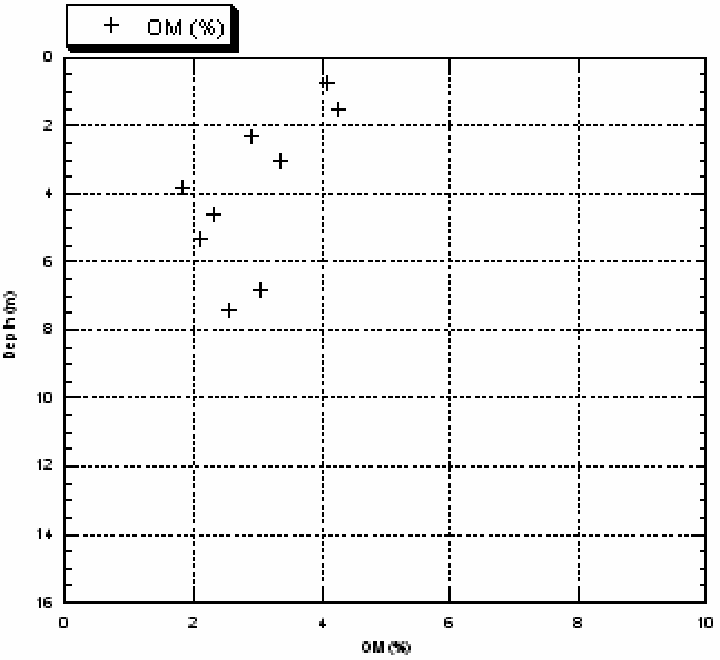


Figure B7: Site 7 chemical data

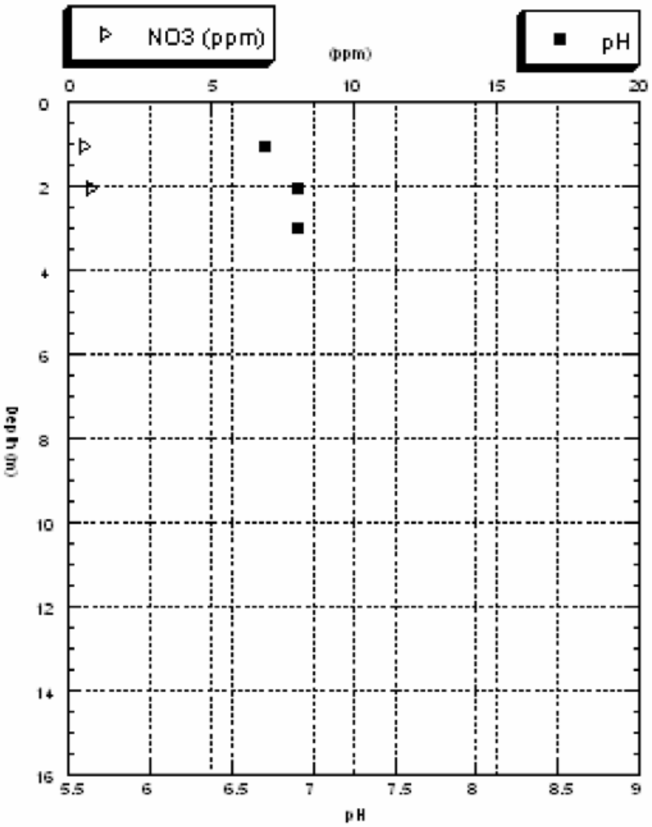


Figure B8: Site 8 chemical data

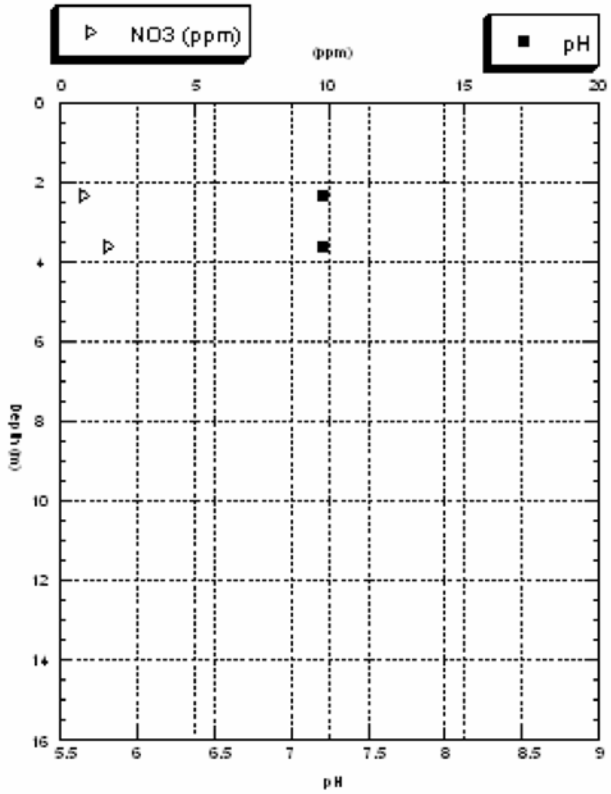


Figure B9: Site 11 chemical data

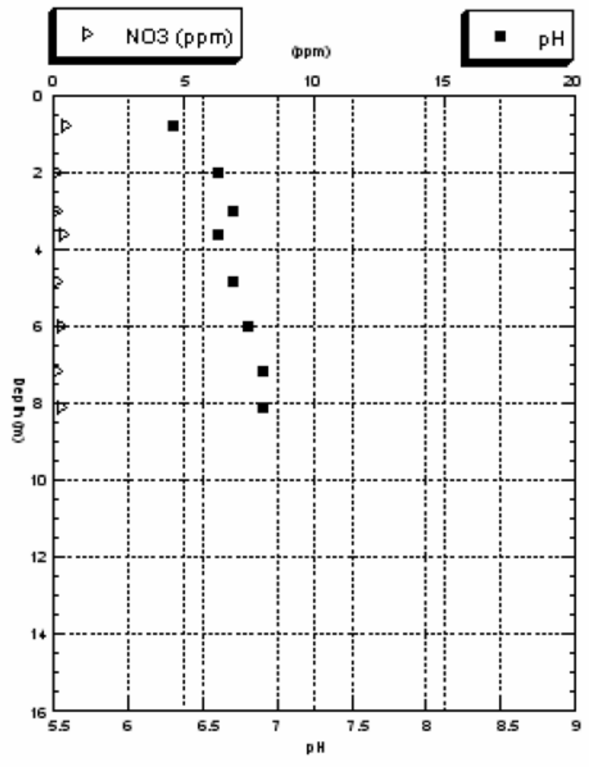


Figure B10: Site 12 chemical data

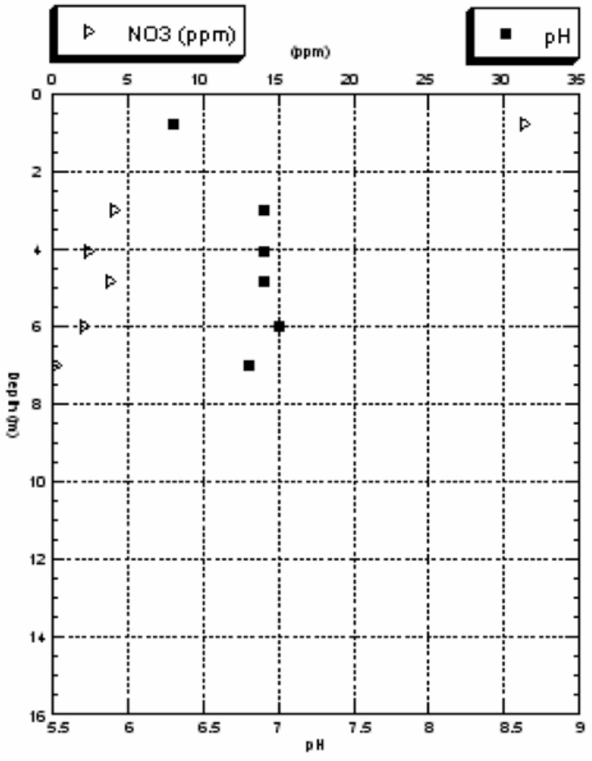


Figure B11: Site 13 chemical data

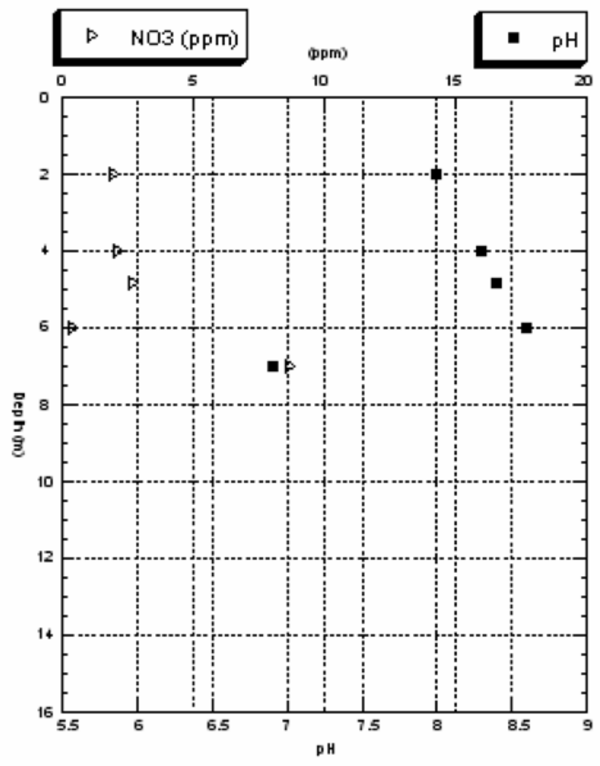


Figure B12: Site 13 organic matter

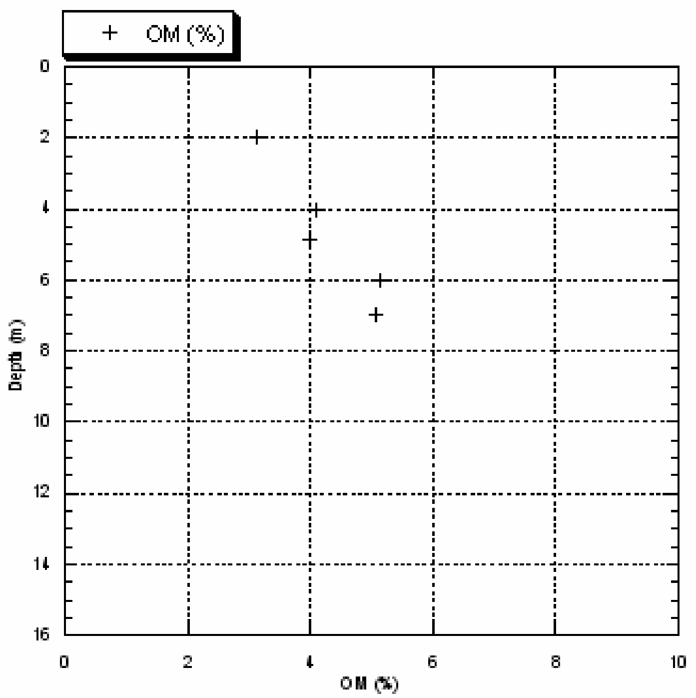


Figure B13: Site 16 chemical data

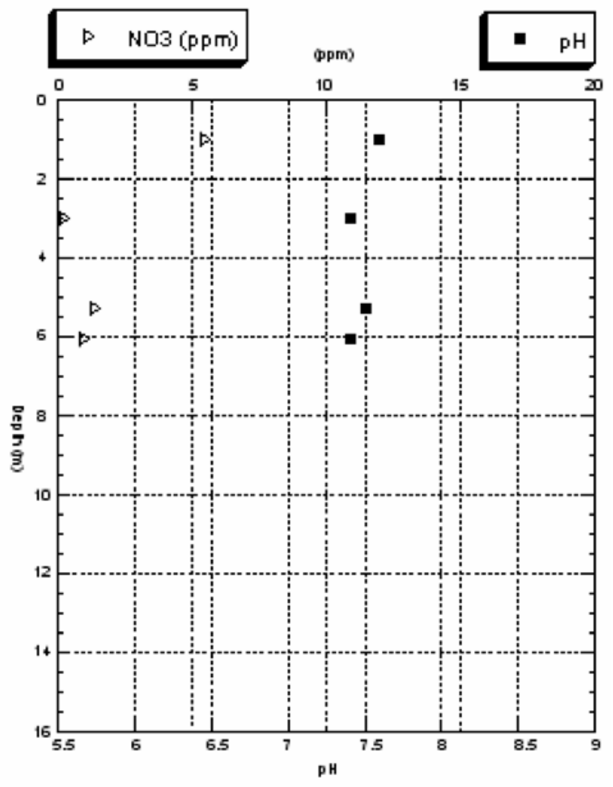


Figure B14: Site 17 chemical data

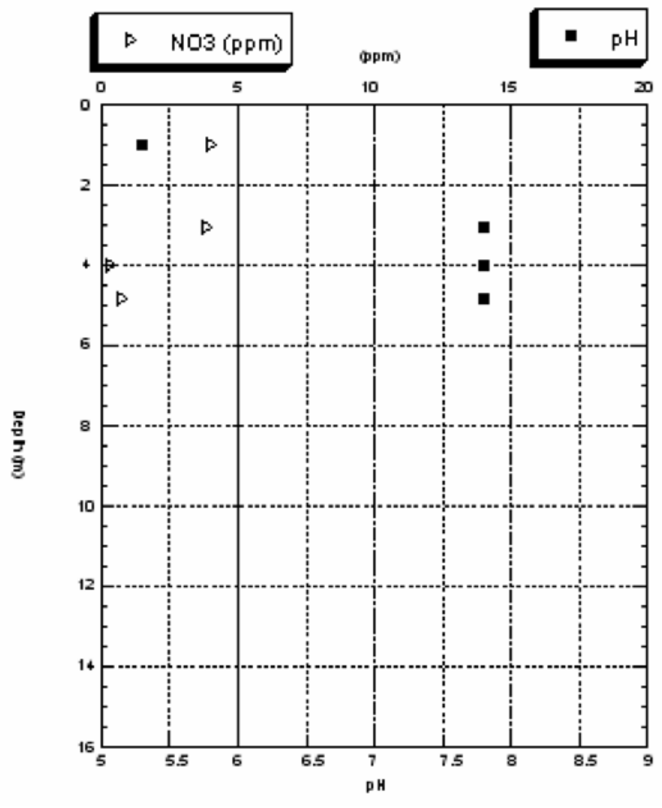


Figure B15: Site 18 chemical data

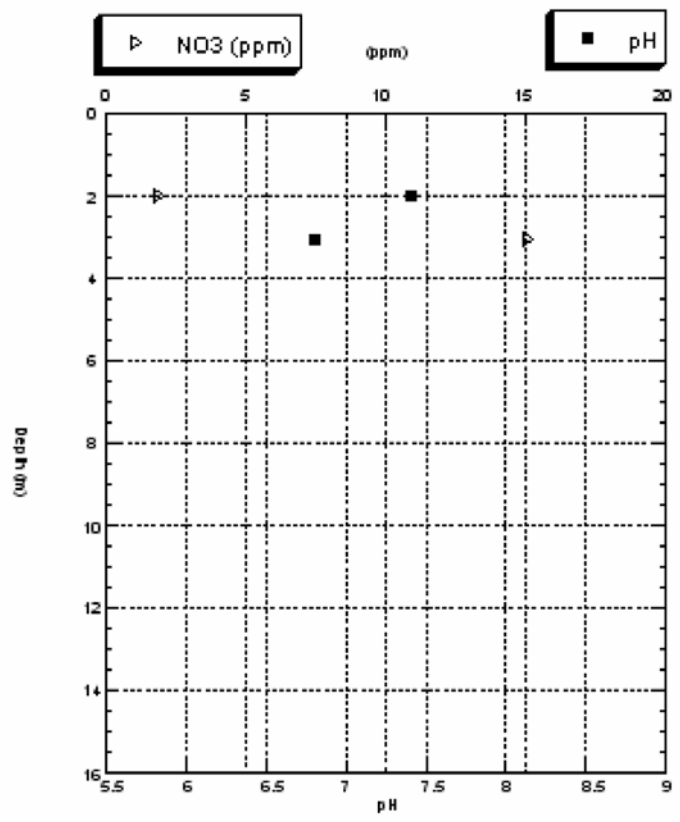


Figure B16: Site 19 chemical data

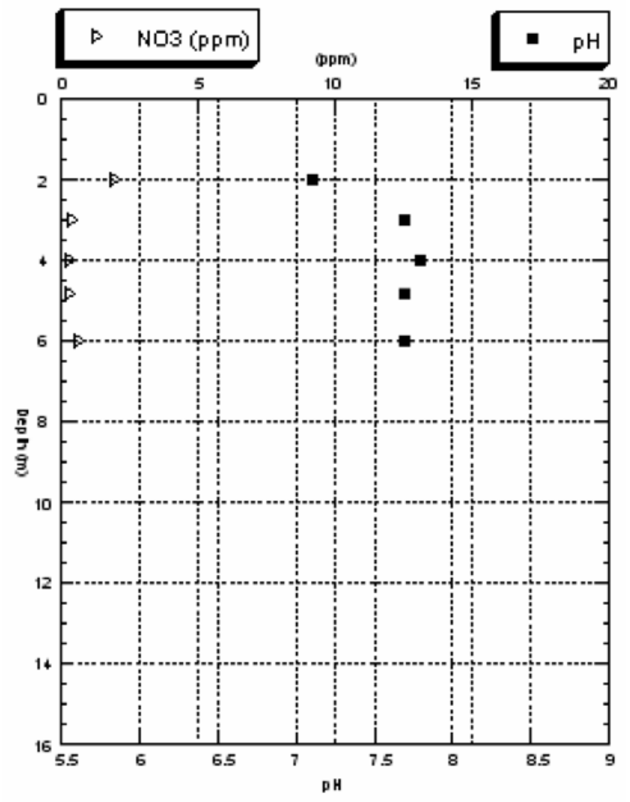


Figure B17: Site 19 organic matter

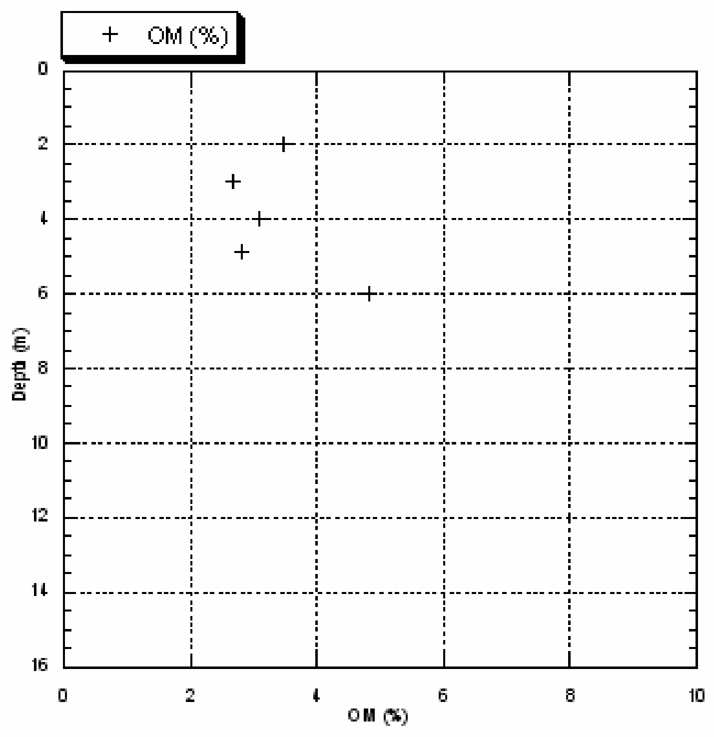


Figure B18: Site 20 chemical data

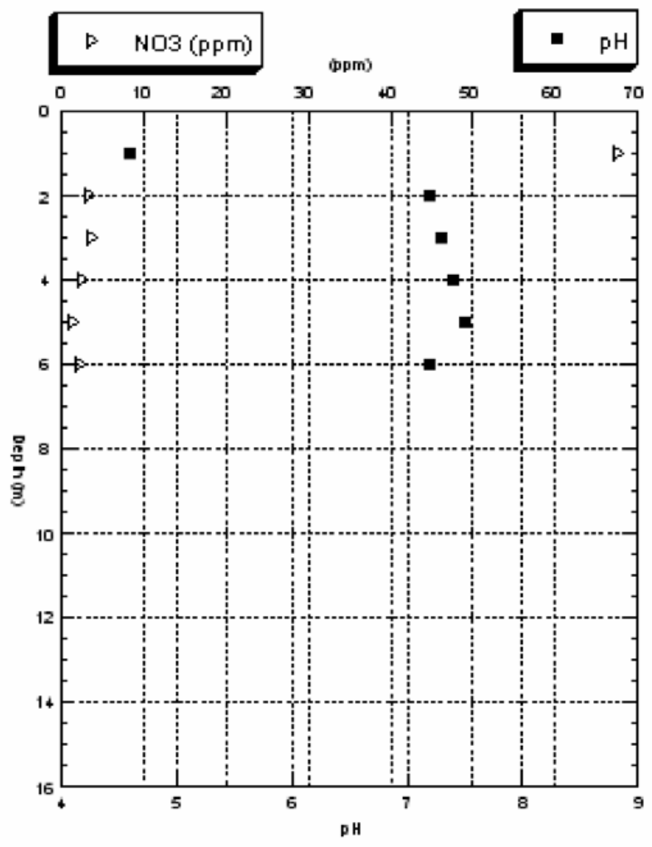


Figure B19: Site 20 organic matter

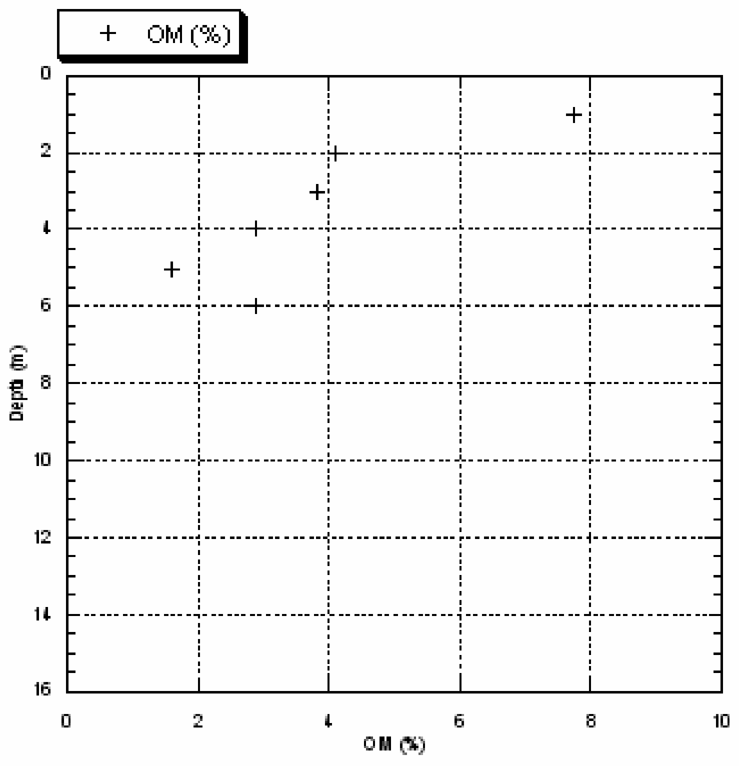


Figure B20: Site 25 chemical data

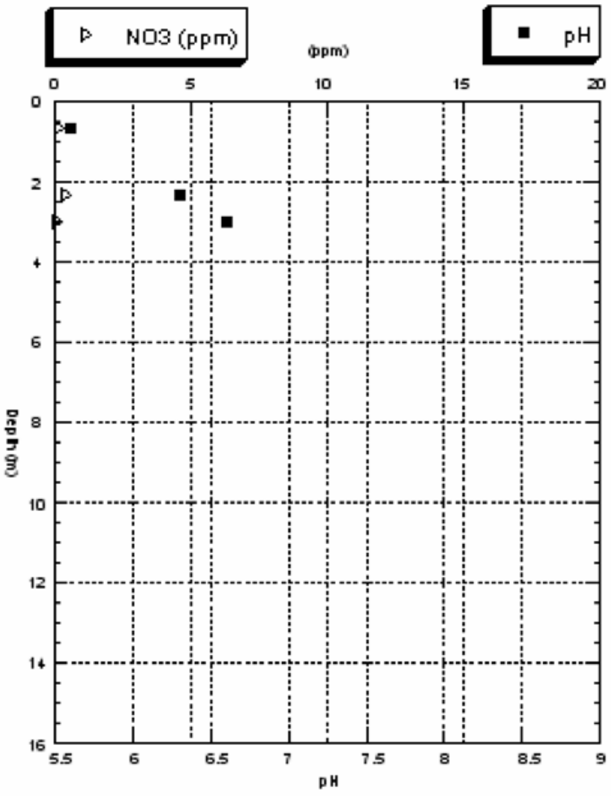


Figure B21: Site 26 chemical data

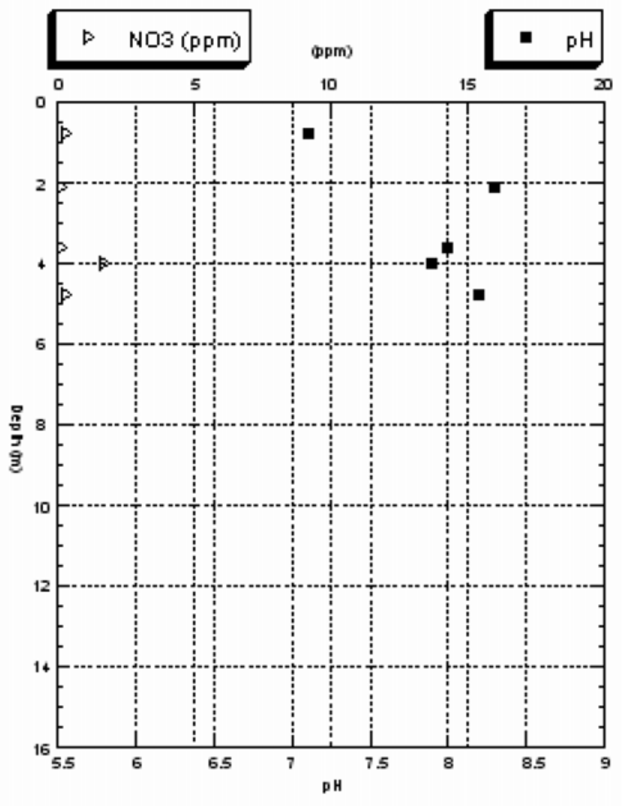


Figure B22: Site 27 chemical data

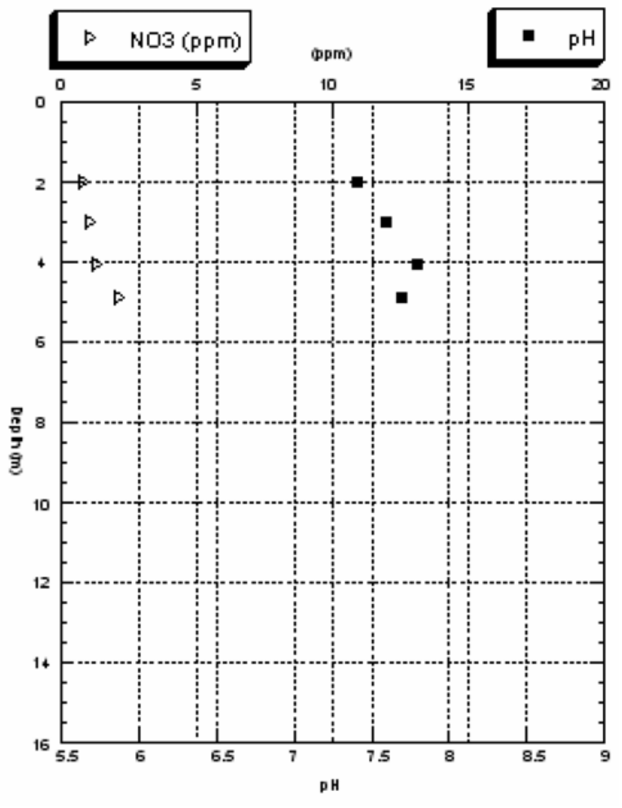


Figure B23: Site 28 chemical data

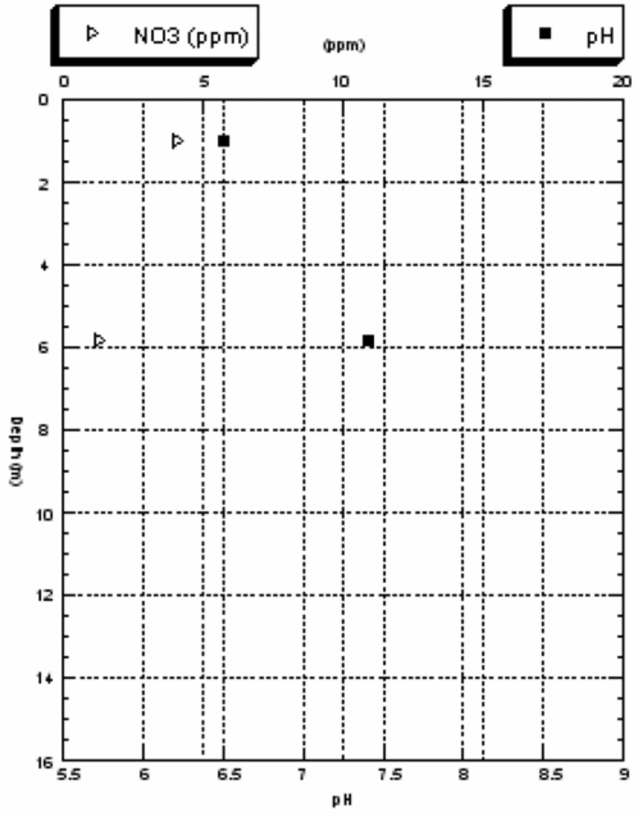


Figure B24: Site 30 chemical data

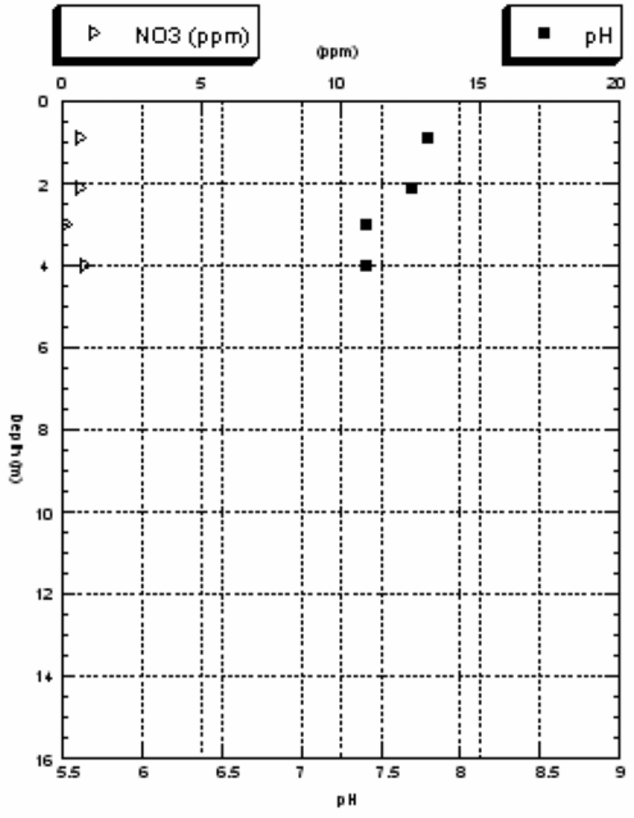


Figure B25: Site 30 organic carbon

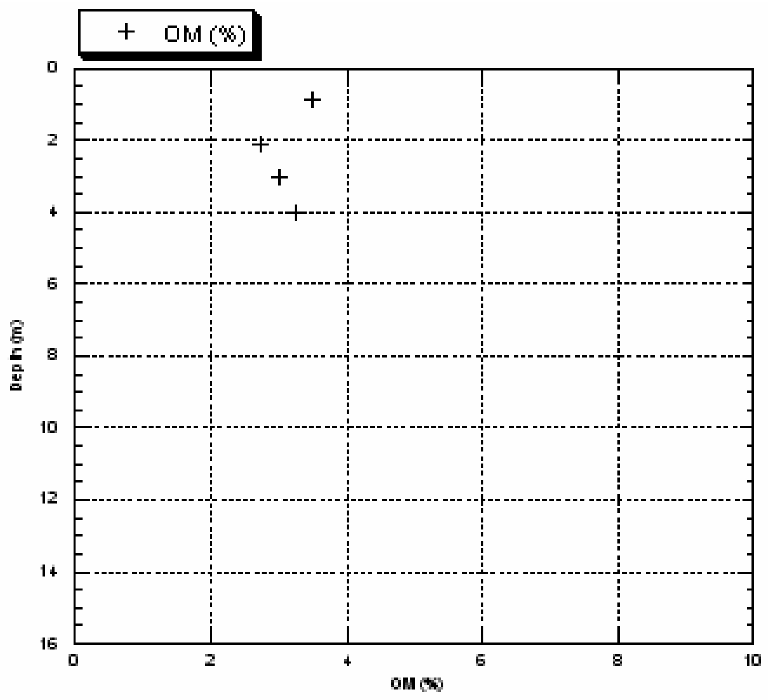


Figure B26: Site 31 chemical data

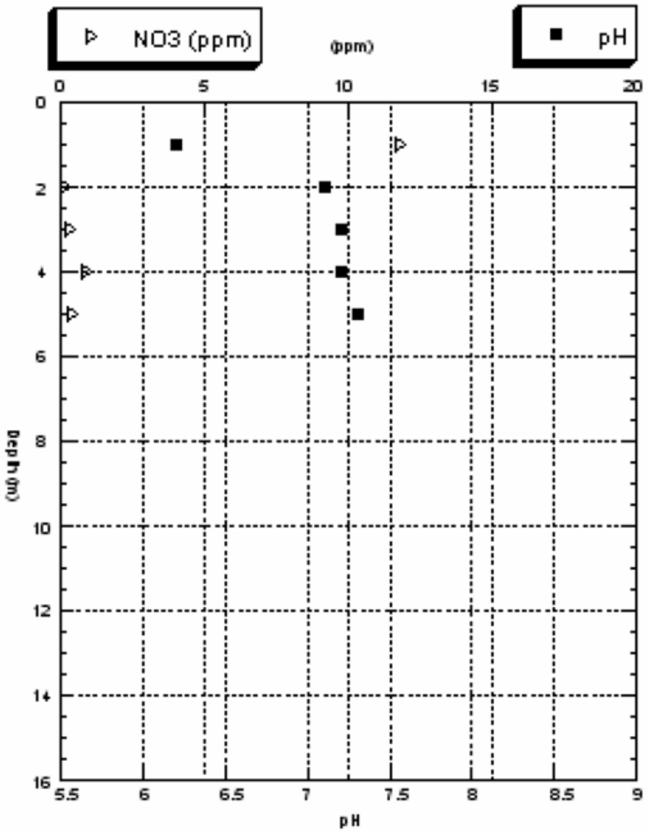


Figure B27: Site 31 organic carbon

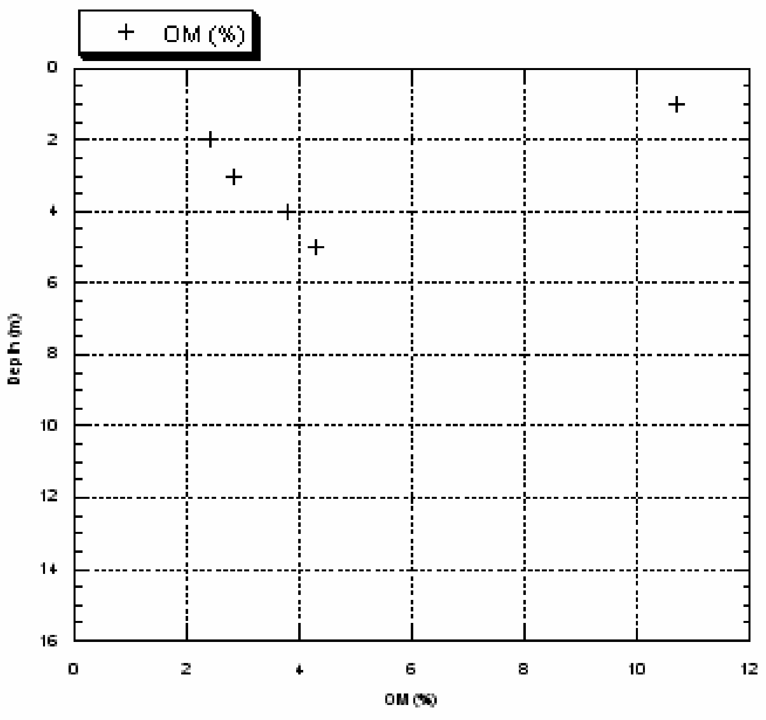


Figure B28: Site 32 chemical data

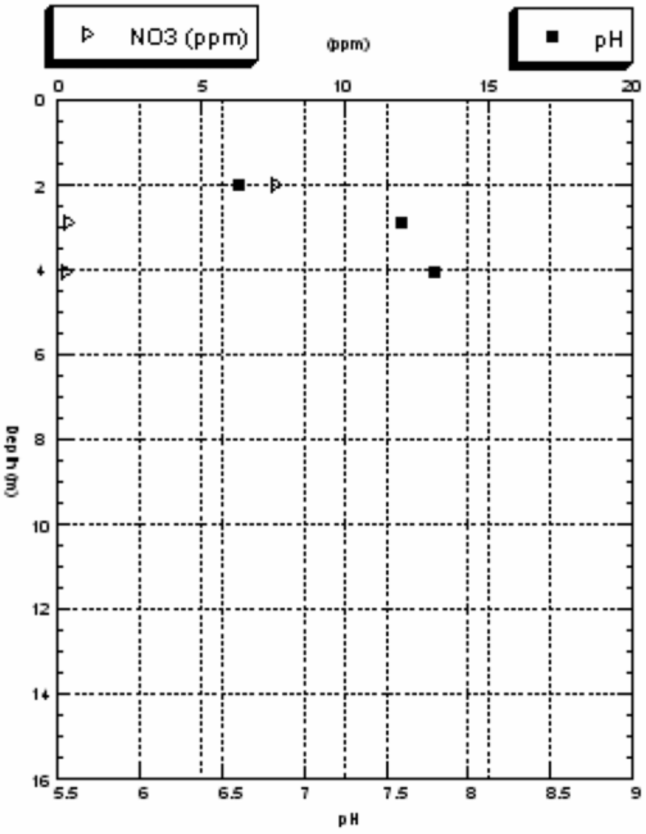


Figure B29: Site 32 organic carbon

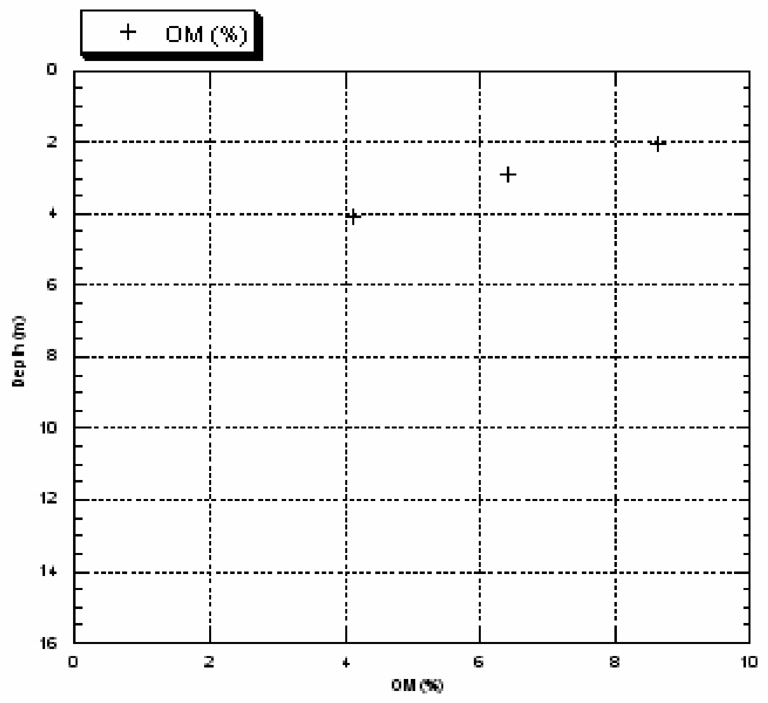


Figure B30: Site 33 chemical data

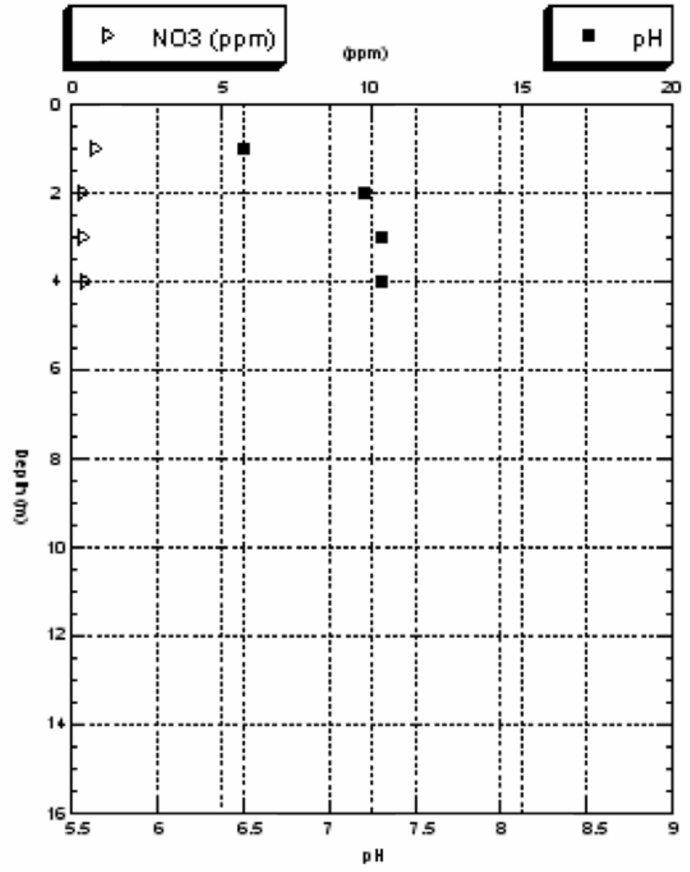


Figure B31: Site 33 organic carbon

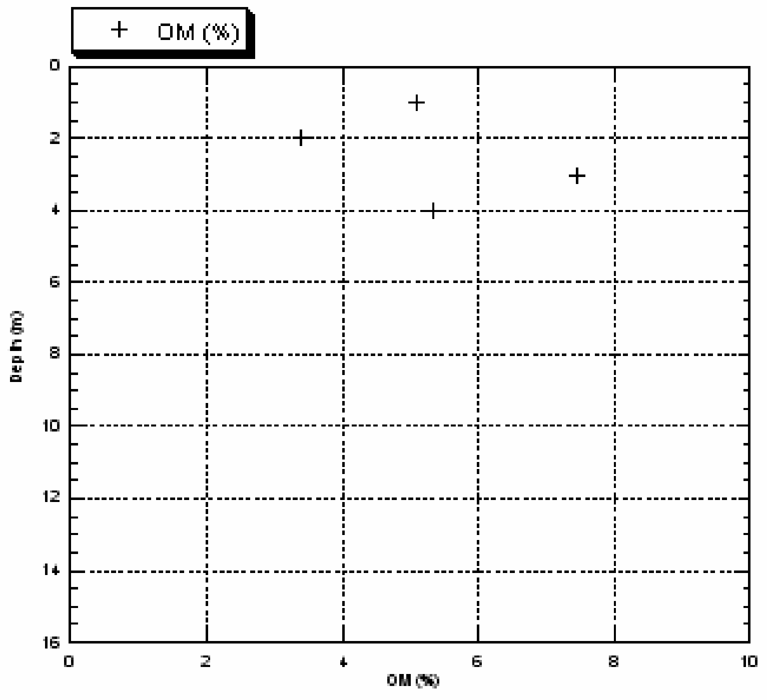


Figure B32: Site 34 chemical data

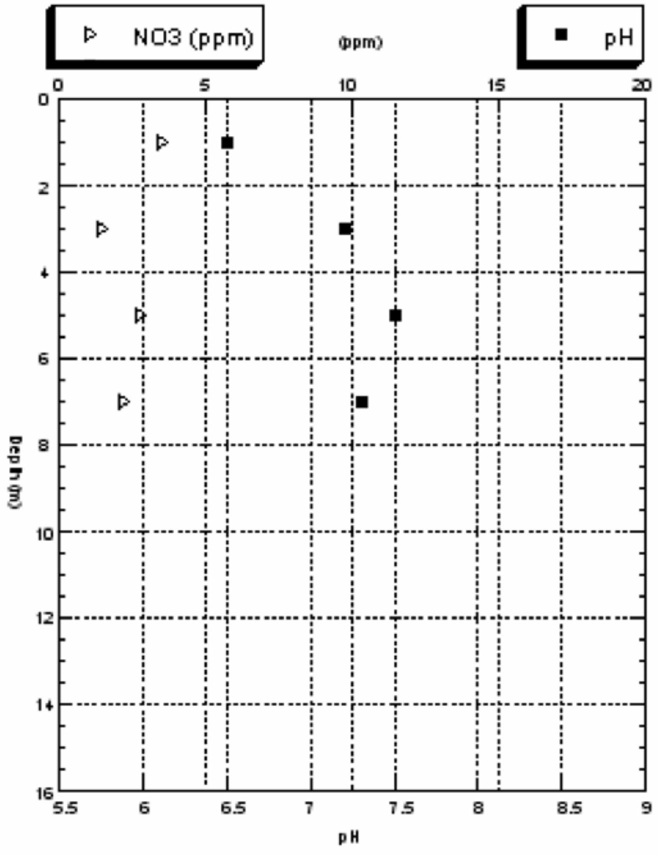


Figure B33: Site 34 organic carbon

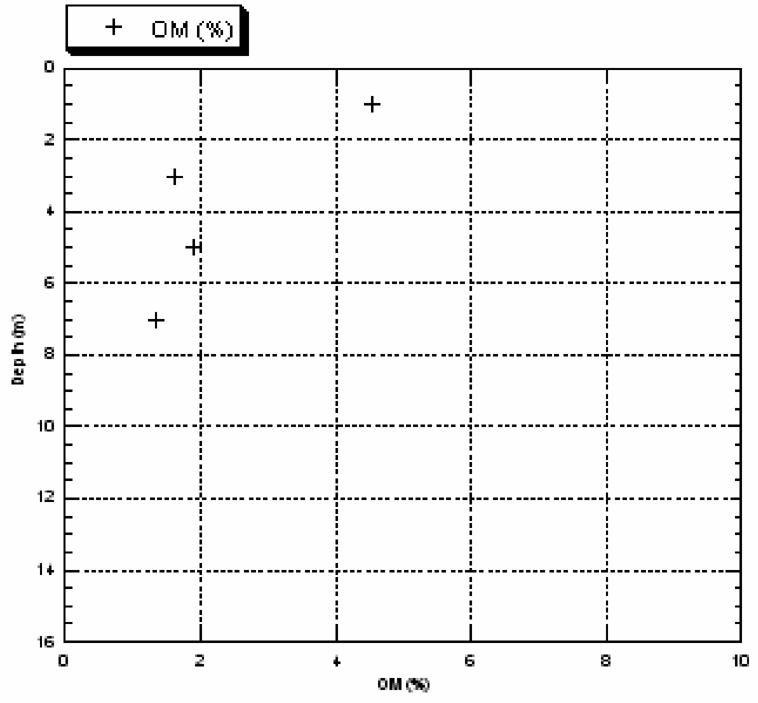


Figure B34: Site 35 chemical data

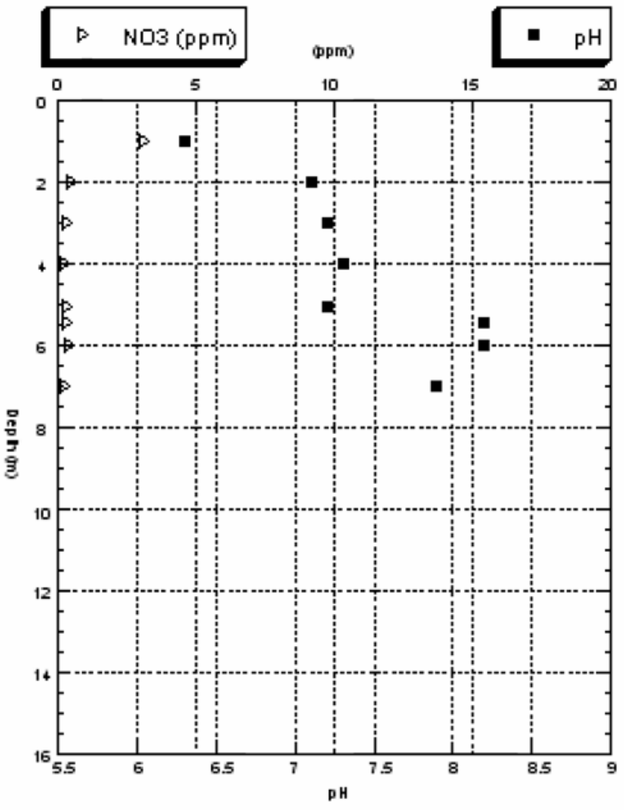


Figure B35: Site 35 organic carbon

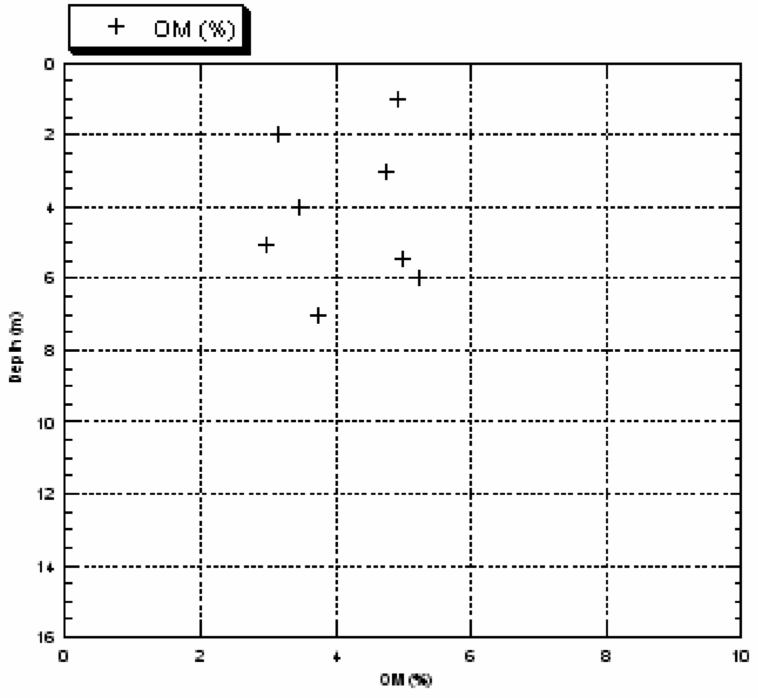


Figure B36: X-ray Diffraction graph of oxidized silt at site 2

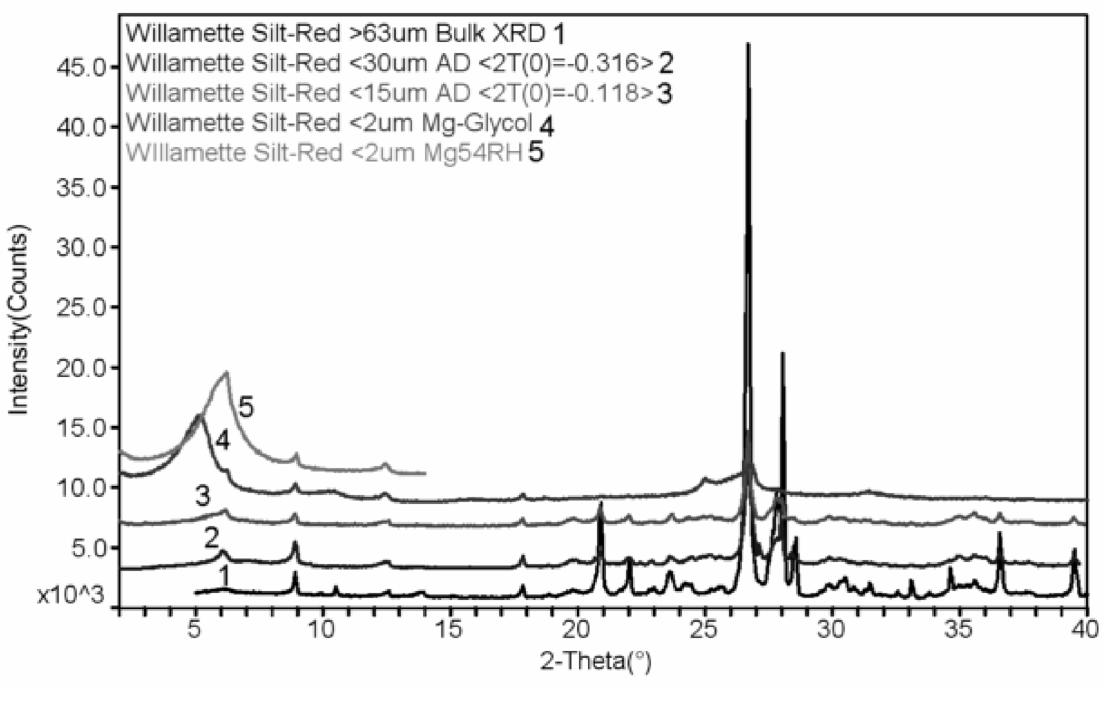
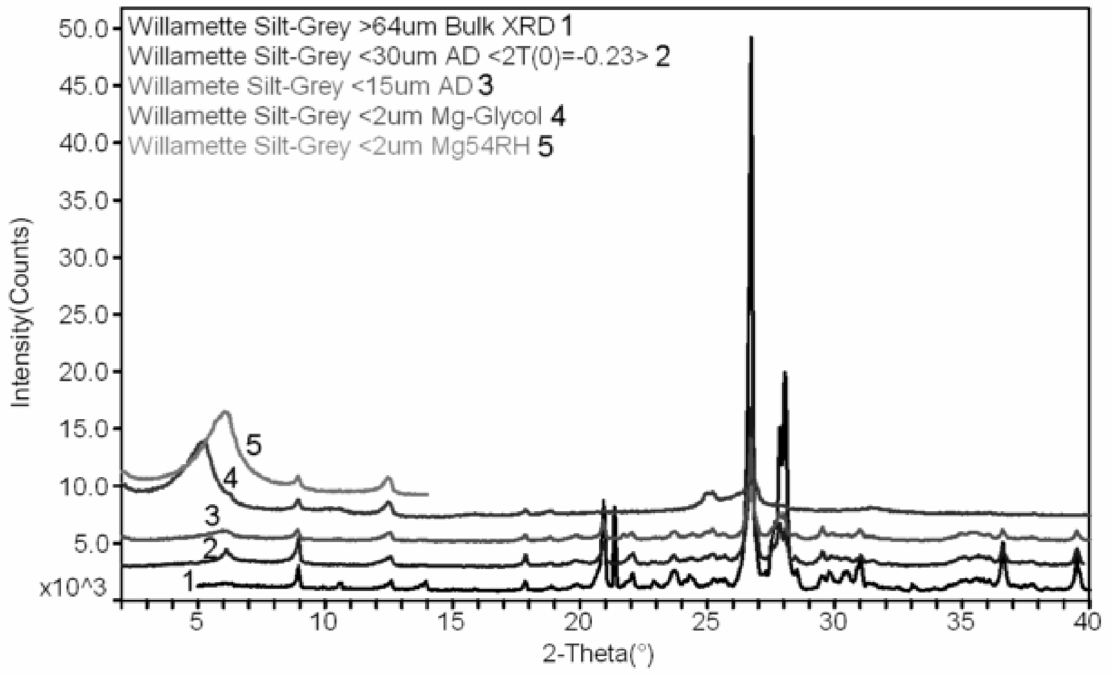


Figure B36: X-ray Diffraction graph of reduced silt at site 2



APPENDIX D

Groundwater analyses from selected sites

(analyses by Chris Vick, OSU)

Site no.	Nitrate mg/L	Nitrite mg/L
13	1.9454	0.0253
17	1.388	0
18	18.143	n/a
20	3.3417	0.0842
25	16.1086	0.3164

APPENDIX E
DEA and iron testing procedures

DEA testing

Soil cores were frozen in the field, and then stored in a freezer at OSU for 6 months. Samples were then taken from the frozen core at 2.5 foot and 0.5 foot intervals. Samples were then brought to room temperature, weighed to approximately ten grams, and mixed with 20mL of prepared solution in a 125 mL Erlenmeyer flask. The solution contained 40 millimolar (mM) K_2HPO_4 and 20 mM KH_2PO_4 (as buffers), 10 mM $C_6H_{12}O_6$ (glucose), and 5 mM KNO_3. The flask was then stoppered and the head space replaced with argon. 15 cc's of gas were then removed via syringe from the flask, and replaced with 15 cc's of C_2H_2 (acetylene). The flask was then put on a shaking table and shaken at room temperature (approximately 23°C), and samples of the head space were taken at 20 minute intervals over the course of approximately 2 hours. Gas samples were run immediately on a Varian 3700 gas chromatograph with either a Spectra-Physics SP4290 integrator or a Hewlett-Packard HP3392A integrator. Samples of 20 ppm N_2O gas were run on both columns of the Varian 3700 to calibrate the retention time for N_2O.

Iron testing

Samples were taken in the field at 2.5 foot and 0.5 foot intervals and placed in a 0.5 M HCl solution. Samples were kept at room temperature out of the light to prevent photoreduction until they could be assayed. The samples were diluted to 0.1% of their original strength, then 0.5 mL of sample, 3 mL water, 0.5 mL acetate (as a buffer), and 0.5 mL orthophenanthroline were mixed together. These samples were run on a Hewlett-Packard spectrophotometer. A second set of samples was then diluted to the same strength, then 200 g/L hydroxlamine was added to reduce all Fe^{2+} to Fe^{3+} and the samples were run on the same spectrophotometer.

APPENDIX F

Central Analytical Laboratories instruments and procedures

1. The Perkin Elmer Optima 3000DV is an inductively-coupled plasma optical emission spectrometer with a diode array detector. The dual view is capable of viewing the plasma axially for improved detection limits, or radially to provide lower matrix effects and fewer spectral interferences. Routine analysis includes P, K, Ca, Mg, Mn, Fe, Cu, B and Zn and this instrument is capable of running any ICP analyte. Contact the lab for further information.

2. The Leco CNS-2000 Macro Analyzer simultaneously determines carbon, nitrogen and sulfur in solid samples. No digestion or extraction is required. Up to 2g of ground sample can be used for maximum accuracy in heterogeneous samples.

3. The Alpkem Flow Solution with digital and monochromater detectors provides automated analysis of Total Kjeldahl N, NH4, NO3, Total P, or ortho-P in soil, plant and water samples. The Random Access Sampler allows simultaneous analysis of 2 analytes and automatic dilution of off-scale samples. This instrument is used primarily for low level detection in water samples.

4. The Alpkem RFA 300 provides automated analysis of Total Kjeldahl N, NH4, NO3, Total P, or ortho-P in soil, plant and water samples. This instrument is used primarily for higher concentration levels in soil and plant samples.

5. Waters Capillary Ion Analysis System performs separations by applying an electrical field to the sample in a capillary filled with an electrolyte.