5-14-1997

Geochemistry, Stratigraphy and Provenance of the Portland Hills Silt in the Tualatin Mountains, Portland, Oregon

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THESIS APPROVAL

The abstract and thesis of John L. Lawes III for the Master of Science in Geology were presented May 14, 1997 and accepted by the thesis committee and the department.

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An abstract of the thesis of John L. Lawes III for the Master of Science in Geology presented May 14, 1997.

Title: Geochemistry, Stratigraphy and Provenance of the Portland Hills Silt in the Tualatin Mountains, Portland, Oregon

Soil morphology and geochemistry of loess were investigated at nine sites in the Tualatin Mountains west of Portland and at additional sites in The Dalles, eastern Washington and Puget Sound. A total of forty samples were examined using Instrumental Neutron Activation Analysis (INAA).

Stratigraphic relationships and soil development suggest that the PHS ages of Lentz (1977) be revised. The age of the Portland Hills Silt (PHS) ranges from 12,000 to at least 960,000 years before present.

The geochemistry of the PHS supports the Lentz (1977) hypothesis of the PHS as a loess of continental origin. Thorium/scandium ratios in the PHS are in the continental range of 0.8 to 1.2 Th/Sc. This contrasts with the 0.2 to 0.5 Th/Sc ratio more typical of arc volcanics such as Boring Lava.

Soil properties and INAA data suggest that the 53rd Street PHS contains four episodes of loess deposition with

immature soil horizon development. Paleosol clay enrichment is typically less than 25% by weight and shows considerable randomness between paleosol and loess. Harden indices for paleosols ranged from 0.09 to 1.01, similar to the Holocene and late Pleistocene soils of Harden (1982). Large cation mobilization, particularly sodium, appears to be a good indicator of soil formation. Lack of similar eluviation of potassium and rubidium indicate that the 53^{rd} Street paleosols are relatively immature.

The geochemical similarity between the PHS and deeper silty sediments on the West Hills previously described as Helvetia Formation by Schlicker and Deacon (1967) or "Sandy River Mudstone-equivalent" by L.R. Squier (1993) suggests that these sediments are an ancient PHS.

The 12,000 to 15,000-year-old surface soils (Birkeland, 1984) observed at Elm Street and 53rd Street suggest the likelihood that the uppermost one- to five-meter-thick loess may also incorporate sediment from Missoula Flood silts.

GEOCHEMISTRY, STRATIGRAPHY AND PROVENANCE OF THE PORTLAND HILLS SILT IN THE TUALATIN MOUNTAINS, PORTLAND, OREGON

by

JOHN L. LAWES III

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

MASTER OF SCIENCE
in
GEOLOGY

Portland State University
1997

ACKNOWLEDGEMENTS

My grateful thanks to my primary advisors, Dr. Marvin Beeson and Dr. Scott Burns of Portland State University, for their constant assistance and encouragement; to Michelle Barnes, whose admirable work was essential, and to Rodney Lentz, whose work was the basis for this investigation. To all those who rendered aid, comfort and information: Mr. Gary Peterson of L.R. Squier & Associates; Dr. Matthew Mabey of DOGAMI; Curran Mohney of ODOT, and; Ken Walsh of Parsons Brinckerhoff. To The Oregon Department of Geology and Mineral Industries, whose grant to PSU (90-262-7232, May, 1992) helped defray the cost of this thesis.

To John Cunningham, P.E., from whom I learned that the truth is in the soil. To Russell Martin, who taught me to use the AutoCAD system on which the bulk of the graphics of this report were prepared. Most of all, to my wife, Cynthia, who was in all things and in all ways, the foundation of all that I have ever done, and all I have ever built.

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INTRODUCTION

Among the Quaternary deposits of the Lower Columbia Basin region, the Portland Hills Silt (PHS) has been a subject of dispute from the earliest investigators such as Diller (1896). The origin and mode of deposition of this massive silty upland deposit were debated. Some geologists proposed a fluvial regime for PHS deposition while others favored an eolian method of deposition. This dispute has been largely settled by the publications of R.T. Lentz (1977, 1981). His petrologic investigation and summary of sedimentary evidence suggested a continental loess origin and an eolian mechanism of deposition. This model has been widely accepted as a working hypothesis for the origin and deposition of the Portland Hills Silt.

Since Lentz's thesis work was completed, further geologic and geotechnical investigations have been performed in the Portland West Hills, notably along the West Side Light Rail Tunnel (WLRT) corridor. The borehole sampling program of L.R. Squier and Associates, as documented in their *West Side Light Rail Geotechnical Report* (Squier, 1993), has provided a quantity of valuable new subsurface information. In addition to the information collected and published in the light rail geotechnical report, a borehole was drilled through the PHS to the underlying Columbia River basalt (CRB) by the Oregon Department of Geology and Mineral Industries (DOGAMI) on Northwest 53rd Street in Forest Park, approximately two miles north of the WLRT borings.

This spate of geotechnical exploration during the early 1990s has provided a resource that was unavailable to Lentz during his work in the 1970s: several complete core sections through the Portland Hills Silt. The WLRT investigation borings produced additional knowledge of Portland's West Hills Cenozoic stratigraphy. Arguably, the most important product of this study has been complete east-west geologic cross-sections through the post-Miocene portion of the West Hills. The geotechnical borings for the WLRT penetrated the Pleistocene Portland Hills Silt and a young (0.26 Ma) Boring Lava flow (Conrey and others, 1996) to the silty and silty sand sediments underlying or interbedded with the older, lower Boring Lava flows and atop the upper flows of the Columbia River basalt. This detailed stratigraphy is a major improvement on the geology of the Portland area since the time of Lentz (1977).

At the same time, geochemical analysis by Instrumental Neutron Activation Analysis (INAA) have added new and potentially valuable data for addressing the question of provenance and internal variation of the Portland Hills Silt.

The intent of this study is to use the information acquired through INAA to geochemically characterize the Portland Hills Silt, as well as provide a general range of the chemical variation within the unit. Another objective is to learn more about the cause and extent of variation within the PHS geochemistry, particularly the effect of weathering and soil processes. This data set will also be used as a basis for comparison with the geochemistry of potential source area silt sediments, as well as with older sediments from the West Hills, with the goal of providing an independent corroboration for the conclusions of Lentz (1977, 1981). Of particular interest is comparison of the geochemistry of known Portland Hills Silt materials to the yellow to red, silty to sandy silt sediments encountered in the WLRT borings below the 0.26 Ma Boring Lava flow and above the top of the CRB. This material has been identified by Squier (1993) as a Sandy River Mudstone equivalent of the Miocene-Pliocene sediment originally observed in east Multnomah County. Considered a fine-grained facies of the lower Troutdale Formation by Hodge (1933) and Treasher (1942), the Sandy River Mudstone was identified by Trimble (1963) as a discrete formation of early Pliocene age (Schlicker and Finlayson, 1979).

The uppermost 25.9 meters (85 feet) of the 1992 DOGAMI continuous-core boring TB-810 drilled at N.W. 53rd Street in

Forest Park is probably the most complete in-situ record of Portland Hills Silt acquired to date. One of the objectives of this work is to examine and evaluate the significance of this unique core.

To accomplish these objectives, neutron activation geochemical analysis was performed on samples taken from a range of Pacific Northwest locations (Figure 1).

Samples were taken from the full thickness of Portland Hills Silt cored in the DOGAMI 53rd Street drillhole as well as from boreholes spaced across the West Hills (Figure 2). This database also included samples taken from two potential glaciofluvial sediment or loess source areas: the Puget Sound glacial lobe outwash fan along the Chehalis River in northwestern Washington (Figure 3) and the upper Columbia River regions of northeastern Oregon and southeastern Washington (Figures 4 and 5). This group of samples forms the body of evidence used in this study.

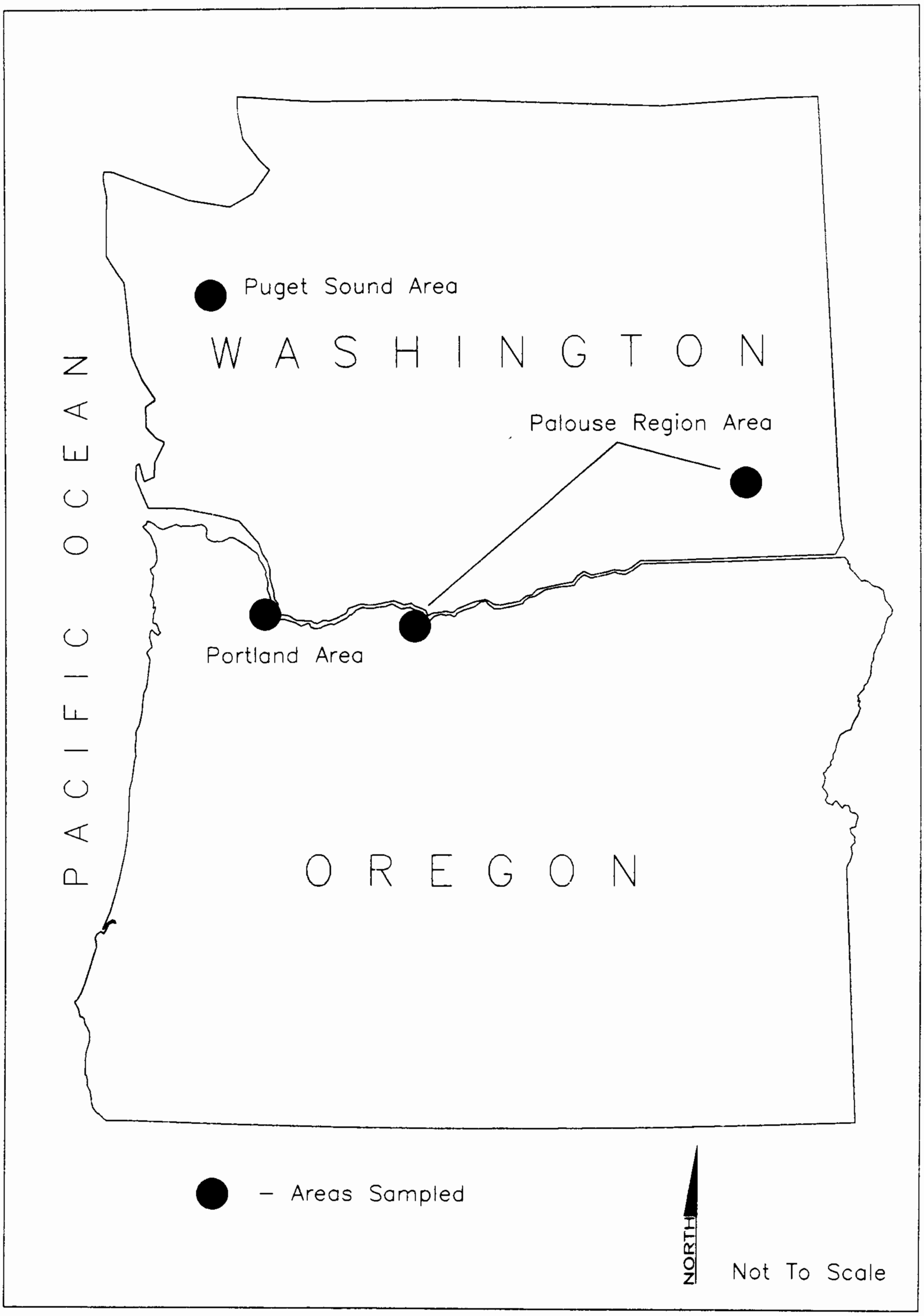

Figure 1: Study Area

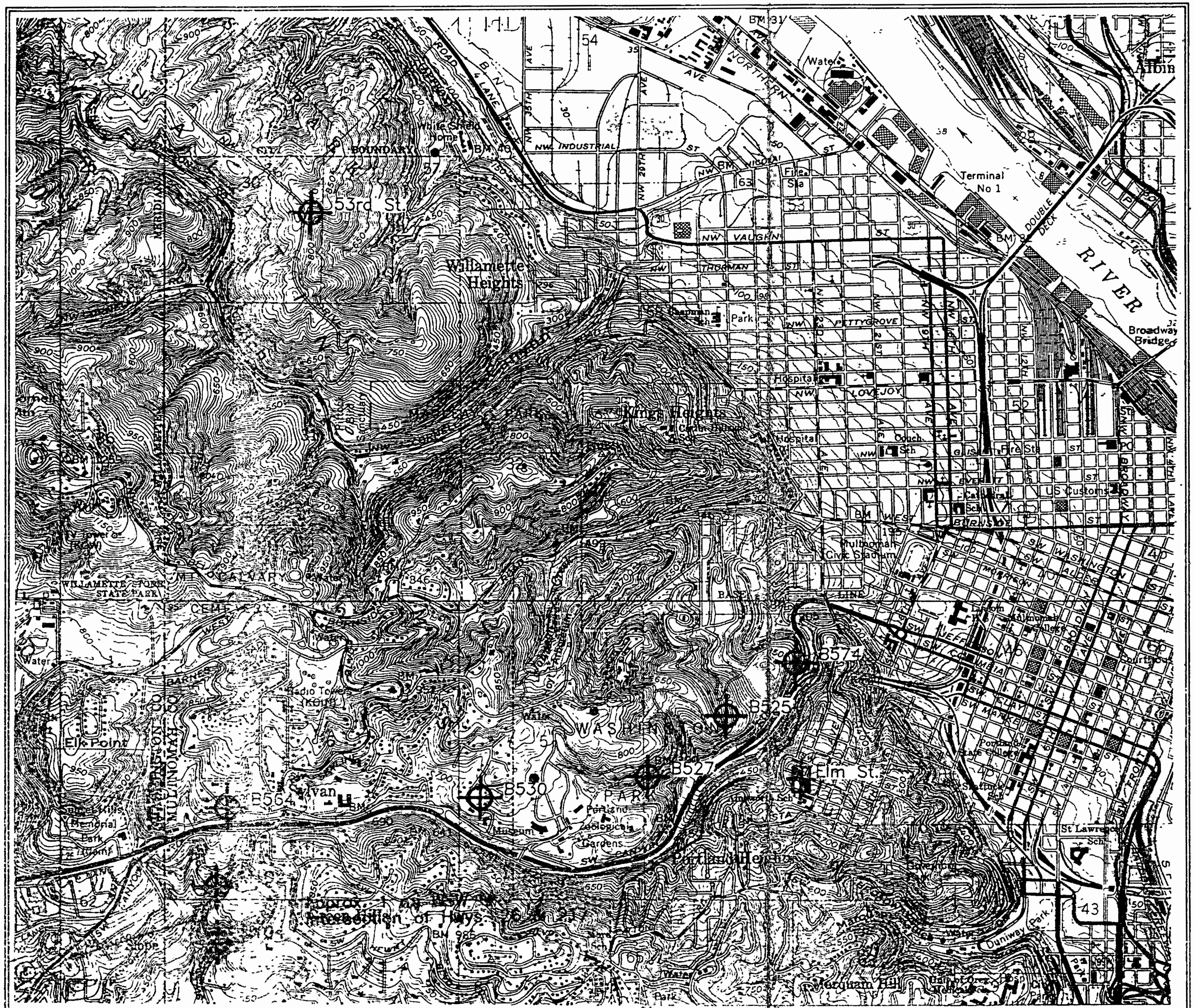

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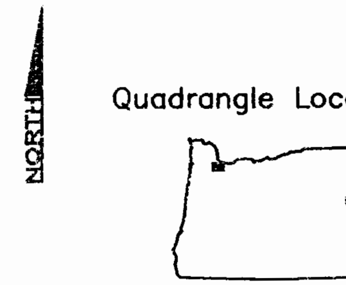
Figure 2
Sample Locations
Portland Area
Oregon



Portland/Beaverton USGS 7.5' Quads

45°22' N 122°45' W

0m 2000m 4000m

SCALE: 1" = 610 meters

SCALE: 1" = 2000'

Explanation

B574 Approx. Location of DOGAMI/WLRT Soil Boring

Elm St. Approx. Location of Shallow Soil Excavation or Test Pit

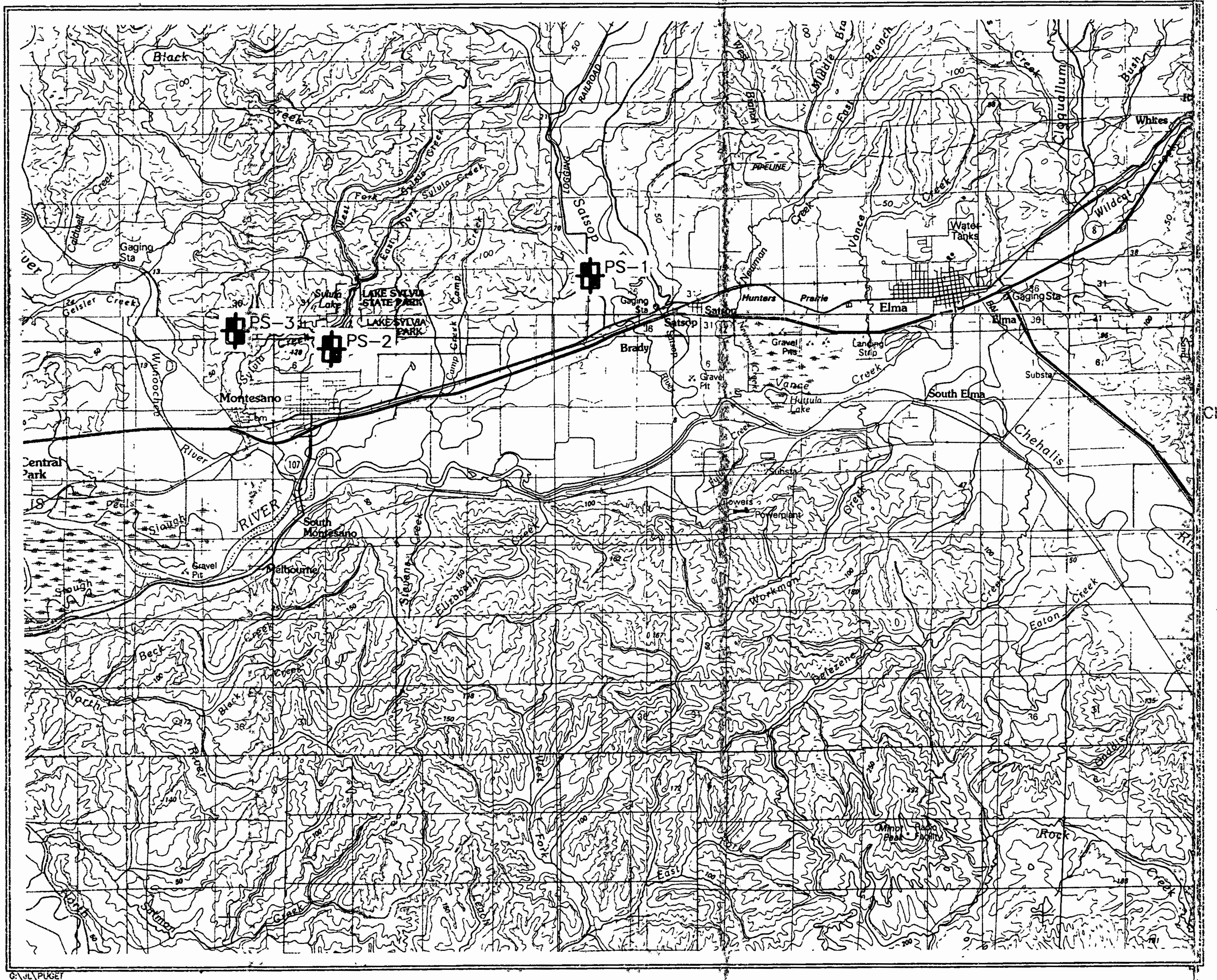


Figure 3
Sample Locations Puget Sound Area Washington

NORTH

Quadrangle Location

Chehalis R./Shelton USGS 30'x60' Quads
46°30' N 123°30' W

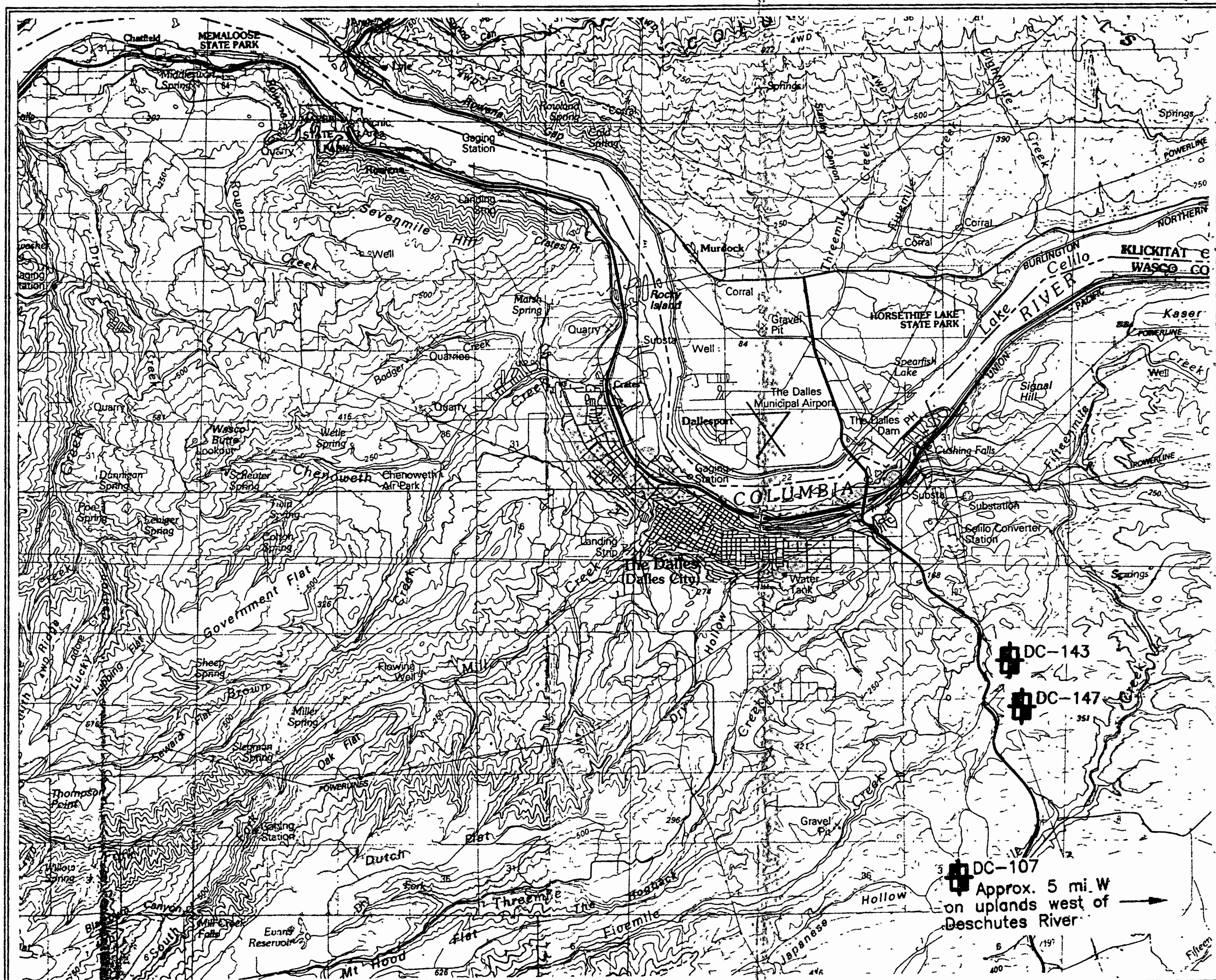
0km 5km

SCALE: 1cm = 1 kilometer

Explanation

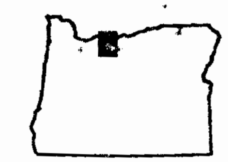
PS-2 Approx. Location of Shallow Soil Excavation or Test Pit

Figure 4
Sample Locations
The Dalles Vicinity
Oregon



NORTH

Quadrangle Location



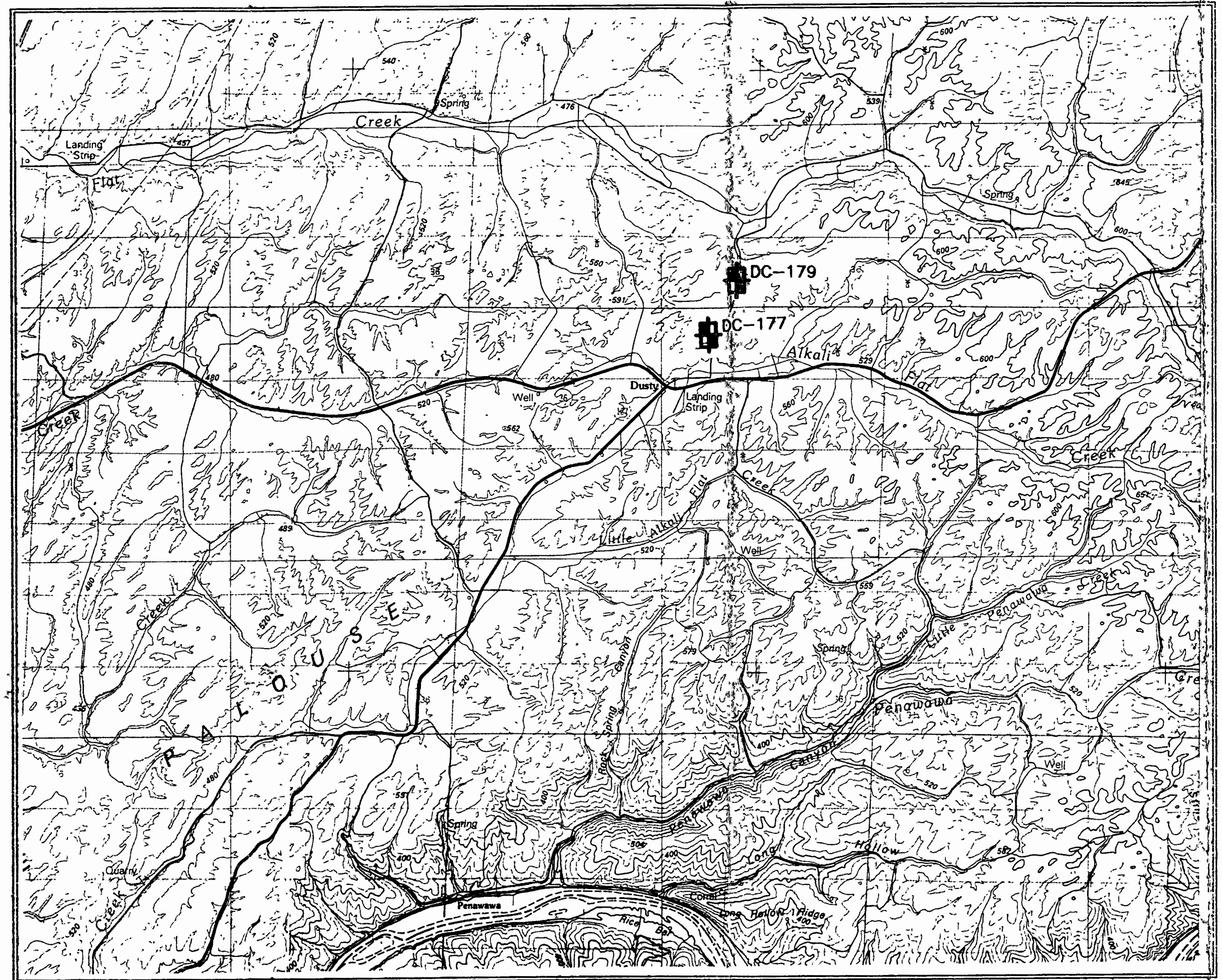
Hood River USGS 30'x60' Quads
45°40' N 121°15' W

0km 5km

SCALE: 1cm = 1 kilometer

Explanation

DC-143 Approx. Location of Shallow Soil Excavation or Test Pit



G:\JL\WHITMAN

Figure 5
Sample Locations
Whitman County
Washington

NORTH

Quadrangle Location

Pullman USGS 30'x60' Quad
46°45' N 117°30' W

0km 5km

SCALE: 1cm = 1 kilometer

Explanation

DC-177 — Approx. Location of Shallow Soil Excavation or Test Pit

THE STUDY AREA

The area of investigation (Figure 1) includes approximately 2600 hectares (10 square miles) of the Portland West Hills (Tualatin Mountains), located within eight kilometers (five miles) of downtown Portland, Oregon (Figure 2). The Portland study area is compared with two geographically separate potential loess-source areas: the Puget Lowland drainages of western Washington (Figure 3), eastern Oregon (Figure 4) and eastern Washington (Figure 5). The Portland study area is approximately bounded on the northeast by the east slope of the Portland West Hills above the 60-meter (200-foot) contour, on the south and west by the map boundaries of the U.S. Geological Survey Portland 7½-minute quadrangle (Figure 2). Samples from the Chehalis River Valley of Washington (Figure 3) and the Columbia River Basin of eastern Oregon (Figure 4) and eastern Washington (Figure 5) were also collected to provide information on potential sediment source areas.

Geology of the Portland Study Area

The Portland West Hills, described as the "upland in the southwest corner of the Portland quadrangle" by Beeson and others (1991), is best described in that same publication:

> Our present interpretation is that the Tualatin Mountains are part of a larger northwest-trending dextral wrench fault zone (Beeson and others 1989; Beeson and Tolan, 1990). The Tualatin Mountains mark the southwest side of this zone that includes the Portland Basin, which we have interpreted to be a fault-bounded pull-apart basin (Beeson and others, 1985, 1989; Beeson and Tolan, 1990). The basic form of the Tualatin Mountains in the Portland Quadrangle is that of an asymmetrical anticline that has been extensively modified by faulting.

The West Hills are a portion of the larger Portland Basin region, a part of the forearc province of the Cascadia subduction zone region (Geomatrix, 1995). Regional tectonics are dominated by the Juan de Fuca-North America subduction zone located approximately 200 km west of the Portland metropolitan area. Oblique subduction of the Juan de Fuca plate has produced an east-west compressional tectonic regime in the overriding North American plate, creating the major structural features of the vicinity, including the Portland structural basin and Tualatin Mountains (Geomatrix, 1995).

The Portland Basin is described by Madin (1990) as "a flat-bottomed basin with faulted southwestern and northeastern margins" produced by large-scale tectonic structures affecting the regional basement rocks.

The folded and faulted basement of the Portland Basin and the Portland West Hills is composed of the Eocene and Oligocene tuffaceous marine sedimentary rocks associated with an accreted terrain that underlies northern Oregon west of the Cascades (Orr and others, 1992). Unconformably overlying these early Cenozoic deposits is the Miocene age, (approximately 15 million year old) Columbia River basalt Group (CRBG); more than 205 meters of basalt has been penetrated beneath portions of the basin (Beeson and others, 1991). In the 15 million years since deposition the CRBG has been extensively folded and faulted as well as deeply eroded. Up to 450 meters of alluvially-derived, moderately- to poorly-lithified siltstone, sandstone, mudstone and claystone of the Troutdale Formation (Beeson and others, 1991) have been deposited into the subsiding basin during late Cenozoic time. The younger tephra, flow and intrusive rocks of the Boring Lavas were deposited in the late Pliocene to Pleistocene in portions of the basin east and west of the subject site (Madin, 1990; Beeson and others, 1991). Coarse sands, gravels and cobbles were deposited in the center of the basin in the

Late Pleistocene by catastrophic glacial outburst floods (jökulhlaups). From forty to as many as ninety of these so-called Missoula Floods inundated the Columbia River drainage from approximately 15,300 to 12,700 years before present (Waitt, 1985; Atwater, 1984). Much of the Portland Basin region stratigraphic column is capped by fine-grained sands and silts, also from these floods (Waitt, 1985).

A portion of the fine-grained Portland basin-fill sediments were blown onto the neighboring mountains to the southwest to form the Portland Hills Silt (Lentz, 1977). The time period of this deposition has been debated, with the 700 ka (maximum) to 34 ka (minimum) age for the PHS argued by Lentz (1977) being generally accepted as of this writing.

The major structural feature of the study area is the Portland Hills fault zone, which trends northwest along the east slope of the Tualatin Mountains (Beeson and others, 1991). The main trend of the zone is located approximately 0.5 to 2 km northeast of the study area. The overall length of the fault zone is approximately 32 kilometers. The Portland Hills fault zone is now considered structurally complex, composed of several series of offsetting, overprinted faults ranging from high-angle normal to thrust-fault in character (Geomatrix, 1995). No movement has been proven to have occurred since Pleistocene time 0.75 Ma. No reliable estimates for overall horizontal or vertical displacement on the Portland Hills fault zone are in the published literature. Slip rates on the Portland Hills fault zone are estimated at approximately 0.117 mm/yr by Geomatrix (1995). Some faults in the Portland Hills fault zone have been mapped displacing Latest Pleistocene (20 ka) sediments (Beeson and others, 1991; Geomatrix, 1995). Although no historical activity on the Portland Hills fault has been noted, Beeson and others (1991) stated that "no evidence is available to determine whether any of the mapped (Portland Hills) faults are still active.

Climate

The Portland region is in the xeric moisture regime typical of the Pacific Northwest. This climate is described as "the typical moisture regime of Mediterranean climates, where winters are moist and cool and summers are warm and dry" (Soil Survey Staff, 1994, p.21). Temperature averages 4.5°C (40°F) in the wet, winter months of the year and 18.5°C (65°F) in the summer, although "at high elevations the average winter temperatures are as much as 10 degrees F (4 degrees centigrade) less than the rest of the area" (Green, 1983).

Temperature extremes of below 0°C and above 40°C have been recorded (Green, 1983).

Rainfall tends to be extremely seasonal, usually beginning in October to November and markedly decreasing in March or April. The annual rainfall is approximately 40 inches (100 centimeters) per year, and higher elevations to the west such as the Portland West Hills may receive up to 1½ times this amount. As much as eight inches of snow has been reported on the West Hills in winter (Green, 1983).

Soils

Not surprisingly, this mild climate and abundant rainfall have combined to produce moderately deep to very deep soils even on the steep upland slopes of the West Hills. The soil map units in the study area include the Cascade-Urban land-Cornelius association and the Goble-Wauld association (Green, 1983). Both map units are described as "moderately deep and very deep, warm, moist soils on uplands". The Cascade-Urban land-Cornelius association soils are predominantly silt loams (a mixture of silt, sand and clay) mapped west of the crest of the West Hills. The Goble-Wauld association soils are shown as mapped to the east of the crest. These soils are "formed in silty materials high in volcanic ash and in residuum and colluvium weathered from basalt." (Green, 1983, p.8). Modern vegetation tends to be dominated by Douglas-fir, western redcedar and western hemlock. Both associations are associated with a silt pan or fragipan.

Previous Work

Prior to the work of Rodney Lentz (1977), investigation of the Portland Hills Silt was dominated by the controversy regarding the nature of deposition of the unit. The conclusive summary of this period is contained in Lentz (1977, pp. 12-22), and this study will not attempt to surpass the clarity of that account; however, it is briefly summarized below.

The Portland Hills Silt is part of a larger group of fine-grained sediments in the Lower Columbia and Willamette Basins that were the subject of disputation between 1896 and the publication of Lentz's data in 1981. This work may be divided into three general periods.

1. The Silt Perplex Period: 1896-1952

Beginning with the investigation of J.S. Diller (1896), the silty sediments of Portland vicinity were a matter of considerable stratigraphic confusion. The silts on the east flank of the Portland Hills were treated as a single unit, which Diller (1896) reported to be "distinctly stratified" and therefore a water-laid sediment. Complicating the matter was the apparently overlapping color, grain size and structure of four major fine-grained deposits found in the Portland Basin and vicinity: the lower portion of the Troutdale Formation (later Sandy River Mudstone), the Helvetia Formation, the Willamette Silt and the Portland Hills Silt. The foundation for disagreement was laid within eleven years of the publication of Diller (1896), when N.H. Darton (1909) suggested that the silt deposits on the highlands in the Portland area were of eolian origin.

Arguments concerning silt sediment deposition in the subsequent forty-five years were not clarified by the polymorphous nature of Portland Basin stratigraphy. Rusek (1919) considered at least part of the Portland Hills Silt as a Columbia River sediment or presumably fluvial origin. Treasher (1942) was not committed to a single form of deposition, proposing instead a combination of fluvial, eolian and residual processes.

Three publications associated with W.D. Lowry: Libbey, Lowry and Mason (1946); Wilkinson, Lowry and Baldwin (1946) and Lowry and Baldwin (1952) consider the presence of rounded pebbles within the Portland Hills Silt as evidence for-water-laid origin for the deposit. For the first time the name "Portland Hills Silt" was suggested (Lowry and Baldwin, 1952, p.7), albeit as a younger, widespread silt member of the Troutdale Formation. This material was correlated with similar deposits east of the Cascade Range, specifically the Ringold and Palouse formations of southeast and south-central Washington.

2. The Transition Period: 1952-1977

With the publication of Theisen (1958), the suggestion of the Portland Hills Silt as a loess was reposited. The work of Howell (1962) effectively buttressed the earlier work by repeating Theisen's distinction between an upper, lighter massive silt above elevation 90-120 meters (300-400 feet) Mean Sea Level (MSL) with a lower, younger, well-stratified fluvial silt observed below 90-100 meters (300-350 feet) MSL.

The next major discussion of this sediment is published in Trimble (1963). Curiously, the deposits identified as loess in this study are defined as being "mainly above an altitude of about 600 feet." Consideration should be given to the possibility that this is a misprint; this elevation is significantly higher than the average topographic low of 90-105 meters (350 feet) mapped for this unit (Beeson and others, 1991). Trimble moves the discussion firmly towards an eolian origin for the deposit as well as reaffirming the formation nomenclature of Lowry and Baldwin (1952). Residual formation on a basaltic parent was discounted due to the "quartzose character" of the Portland Hills Silt; however, the lower Columbia River basin is identified as the loess source.

The age of the Portland Hills Silt was also somewhat problematic: Trimble (1963) proposed an early to middle Pleistocene age for this deposit based on stratigraphic positioning. A Middle Pliocene age is discussed in Baldwin (1964) based on fossil evidence: Beaulieu (1971) considers this evidence dubious at least and is quoted at length to that end in Lentz (1977, p.20).

Schlicker and Deacon (1967) considered that the massive, uniform loessal "Upland Silt" was indistinguishable from Willamette Silt except for elevation. This contact was mapped by the 1967 study at 76 meters (250 feet MSL) elevation in the Tualatin Valley.

In DOGAMI Bulletin #70, J.D. Beaulieu (1971, p.34) described the deposit as a "massive, structureless, yellow-brown to buff, micaceous silt...Lithologically it is quite similar to the Palouse soil of eastern Washington."

3. Towards A Synthesis: 1977-Present

At this point, R.T. Lentz began his investigation into the silty yellow sediment on the crests of the Portland Hills.

It should be noted here that the work of Lentz (1977, 1981) is and must still be considered central to discussion of the Portland Hills Silt. This investigation was conducted with notable thoroughness, collecting and correlating the extent of sedimentologic, petrographic and stratigraphic evidence available at the time. From this research, Lentz proposed that:

1) The Portland Hills Silt was derived from the sediments of the upper Columbia River basin. Grain morphology, type and relative abundance of heavy minerals was used to substantiate this assertion, that;

2) The origin of the sediment was most likely loessal. This assertion was based on "distributional character and its striking physical resemblance to other loess deposits" (Lentz, 1977, p.115), and that;

3) Based on the correlated ages used by Lentz (1977) of the inter-glacial paleosols contained in the deposit, and the stratigraphic relationships with the younger Willamette Silt and underlying Boring Lavas, the age of the Portland Hills Silt can be placed approximately between a maximum of 700,000 years before present (YBP) to a minimum of 34,400 YBP.

These conclusions have dominated discussion of Portland Hills Silt sediments since the release of Lentz's thesis in 1977 and the publication of that study in an abbreviated form in 1981. Subsequent investigations that have dealt with Portland Hills Silt - Schlicker and Findlayson (1979), Madin (1990), Beeson and others (1991) and Mabey and Madin (1993) - have accepted, in one form or another, these three central conclusions of the Lentz work. The present study will follow their example and do likewise for the first two points. The soil chronology of Lentz (1977) is currently accepted by Beeson and others (1991), who consider the Portland Hills Silt to be no younger than 34,000 YBP. This *terminus ad quo* effectively eliminates loess contributions from the last great Missoula flooding, antedating by about 20 ka the 13,000 YBP date assigned to the last great catastrophic flood. I believe that the soil chronology of this study and the stratigraphic evidence provided by the WLRT borings does affect the Lentz (1977) chronology and will be addressed in the appropriate section below.

The Nature of the Portland Hills Silt

Portland Hills Silt is typically described as:

> ...loessial deposits (of) yellowish-brown clayey, sandy silt, which is homogeneous and structureless. No stratification has been observed in this material by the author. A size-distribution analysis of a typical sample from the upper loessial material...indicated 19 percent sand by weight, 64 percent silt and 17 percent clay. (Trimble, 1963, p.51)

Lentz (1977) describes the unit as a massive,-yellowish-brown (10YR 6/4 dry; 10YR 4/4 moist) silt containing diagnostic FeO/MgO shot concretions as well as localized rubefication (as much as 5YR 5/5), mottling and increasing soil structure associated with paleosol development.

The core recovered from the DOGAMI boring east of 53rd Street, which will be described in detail in a subsequent chapter, is typical of the Portland Hills Silt as encountered near the western crest of the West Hills. The modern ground surface is underlain by approximately 26 meters (85 feet) of massive, yellow micaceous silt containing three paleosols at depths of approximately 10 to 13 meters, 16 to 20 meters, and 25 meters below the existing ground surface (bgs). The deposit lies unconformably over a Sentinel Bluffs flow of the Grande Ronde Basalt of the CRBG (Marvin Beeson, personal communication, 1994). The buried soils display physical features associated with soil development: subangular blocky ped structure and few to some clay film coatings on the soil peds. Curiously, the DOGAMI core contains little or no trace of remnant plant material. No root hairs, root traces or soil mineralization associated with plant rooting were observed in the portions of the core containing buried soils. It is unlikely that the Portland Hills lacked groundcover during the middle to late Pleistocene. Soil formation also generally indicates some degree of chemical weathering, typically provided primarily by plant chelation (Birkeland, 1984). The absence of plant remains may reflect lack of preservation rather than absence during soil development.

THE PACIFIC NORTHWEST DURING THE PLEISTOCENE

Before entering into the specifics of the geochemistry, it might be of use to look briefly at the conditions of the northwest portion of the North American plate margin during the time of deposition of the Portland Hills Silt.

Given the association of massive loess deposits with Pleistocene glaciation across much of the northern hemisphere as well as Argentina and New Zealand (Pettijohn, 1975), the start of the most recent cycle of glaciation in North America would be an appropriate period to begin. This has been proposed to have followed soon after the appearance of Antarctic ice sheets in the late Pliocene (Wright, 1989). Uplift of the Himalayan-Tibetan plateau, resulting in glaciation and reduction in albedo has been proposed as a tectonic "trigger" for the initiation of glaciation. This change in overall global albedo would lead in turn to a change in atmospheric energy and cooling of subpolar North America

(Kuhle, 1987). Other possible factors may include changes in ocean circulation; such as the opening of a circum-Antarctic ocean and the resulting oceanic temperature changes, and the termination of the Pacific-Atlantic connection with the emergence of the present-day isthmus of Panama (Wright, 1989).

Northern hemisphere glaciation is believed to have begun about the time of the Gauss-Matuyama polarity reversal, when small continental glacial sheets formed across much of North America, Europe and Asia (Wright, 1989). This Early Pleistocene time lasted from approximately 1.65 Ma to the Matuyama-Brunhes polarity reversal at 0.79 to 0.75 Ma. At this point, the beginning of the Middle Pleistocene, the ice sheets expanded to about twice the size of the earlier glacial cover, at times extending down into and over the Great Lakes Region of North America (Wright, 1989; Dawson, 1992). Glacial advances and retreats during the Early Pleistocene appear to have been on a 41,000-year-cycle influenced mainly by the changes in insolation due to orbital obliquity: after 0.7 Ma the higher summer insolation caused by 19,000- and 23,000-year precessional cycles began to have a stronger effect on glacial expansion (Wright, 1989).

The glacial chronology in North America is poorly documented in land prior to the last glacial maximum (LGM), but $\delta^{18}O$ data leads Wright (1989) to suggest the following:

- a glacial advance from 0.7 to 0.6 Ma (Stage 16)
- an interglacial at about 0.53 Ma
- another advance with a maximum at 0.43 Ma
- a long interglacial from 0.33 to 0.23 Ma
- a glacial maximum at 0.15 Ma
- an interglacial between 0.1 Ma (100 ka) and 40 ka
- a minor glacial advance at 60 ka
- an interglacial period between 40 ka and 30 ka
- the LGM at 20 ka to 18 ka
- deglaciation from 18 ka to 11 ka

The Cordilleran ice sheet appears to have behaved somewhat erratically during the Pleistocene, based on sedimentary evidence from the Puget Sound region (Easterbrook, 1994). Laser-argon, fission-track, magnetic polarity and amino-acid dates from glacial drift places the Orting glaciation at between 2.4 Ma and 1.6 Ma. The Stuck Drift is now placed almost adjacent to the Orting in the stratigraphic column, at 1.6 Ma, with the Salmon Springs Drift dated by the 1.06 Ma Lake Tapps tephra (Easterbrook, 1994). The Double Bluff Drift and associated tills and glaciomarine sediments have been dated between 0.32 Ma and 0.17 Ma (Easterbrook, 1994). The Possession glaciomarine drift yields mean age dates of about 80 ka (Easterbrook, 1994).

These dates represent a significant change from the glacial stratigraphy of Lentz' (1977) time. At that point, the Orting Drift was dated at 0.7 Ma. The Stuck and Double Bluff Drifts were considered contemporaneous in deposition, 0.3 to 0.15 Ma. The Salmon Springs deposits and the Possession Drift were believed to be between 90,000 and 30,000 years old. The significance of these stratigraphic age changes will be addressed in the discussion of soil formation in the 53rd Street Core.

Climatic Effects of Glaciation

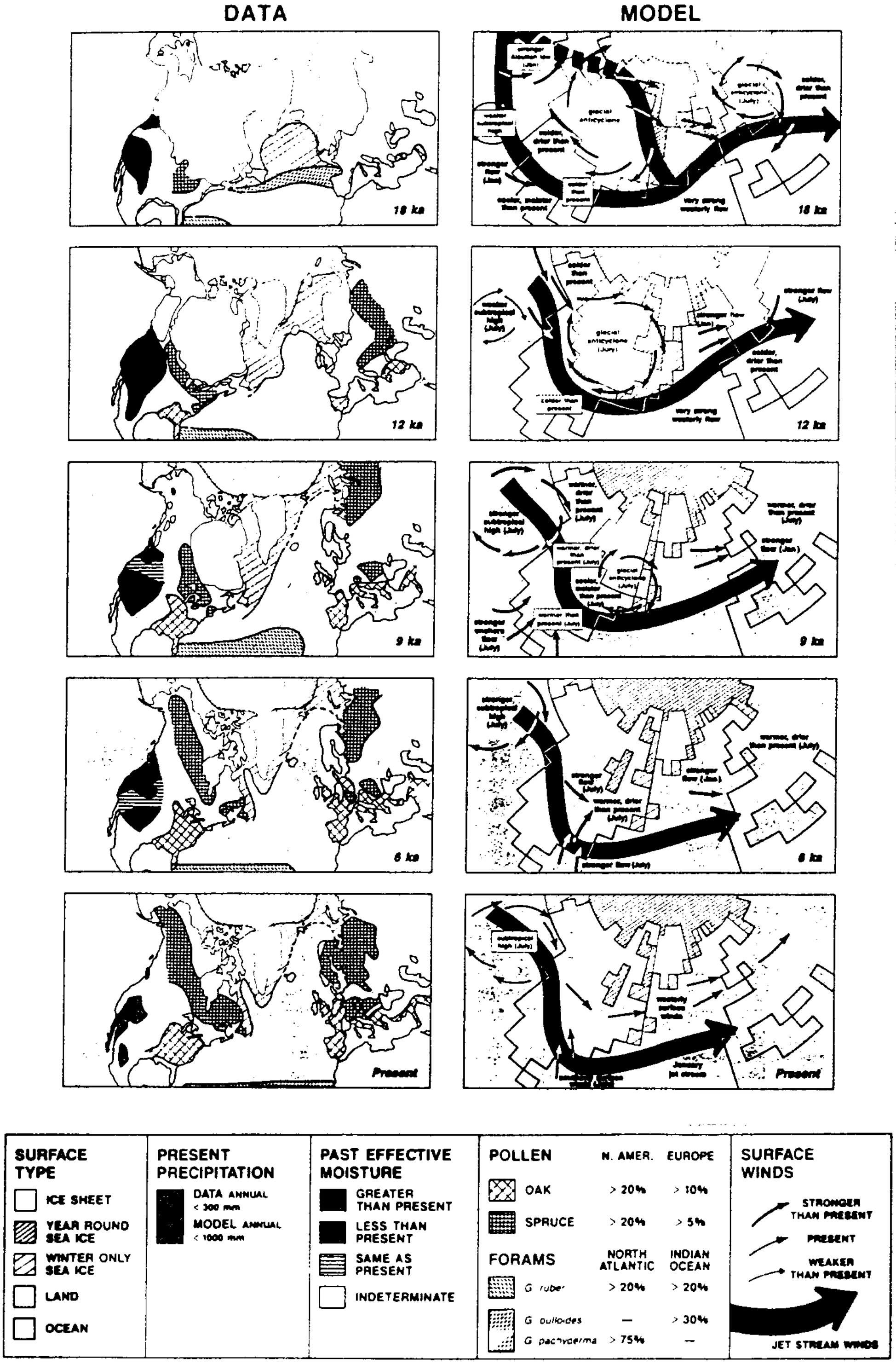
The present-day, interglacial Pacific Northwest climate is dominated by two major topographic features: the Pacific Ocean to the west with consistent, cool water temperatures, and the mountain barrier of the High Cascades to the east that provides a geographic barrier to the frigid air masses moving south from the Arctic. This produces the xeric climatic regime in the Willamette Valley discussed in the *Climate* section above. West-to-east weather patterns typical of Holocene North America are created by the eastward-flowing upper atmosphere jetstream. The weather patterns in the Pacific Northwest are therefore dominated by relatively consistent, cool, moist winds off of the Pacific, varying in direction from northeast to southeast. Pushed south by wintertime polar highs, the jetstream brings a northwest-to-southeast pattern of cold, moist air masses down from the Gulf of Alaska. Summertime patterns tend to move from southwest to northeast, bringing warm, wet weather up from the central Pacific region near Hawaii. The prevailing winds west of the Cascades are generally westerlies (blowing west-to-east).

The effect of the present-day climate regime on sediment is to restrict large-scale, long distance westward eolian transport, while the thick vegetation cover encourages in-place deposition and soil-formation.

Although the climatic record for earlier glaciations is sparse, Late Pleistocene paleoclimate has been reconstructed from the fossil record as well as modeled. One such LGM model:

> "shows that atmospheric circulation around North America was greatly influenced by the presence of the Laurentide ice sheet. Because of its height, the ice sheet at its maximum split the jet stream. One branch passed north of the ice sheet, while the second crossed the west coast at Lat. 45° N, farther south than at present...As a result of low surface temperature over the ice sheet, a "glacial anticyclone developed, which had maximum expression in January.
>
> In the northwestern U.S., easterly winds were stronger and temperatures significantly lower than today's, as were annual precipitation... In the fossil record, these cold dry conditions are evidenced by widespread periglacial steppe and tundra over much of the northwestern U.S., and xerophytic subalpine parkland west of the Cascade Range in Washington." (Barnosky and others, 1987)

This climatic pattern as modeled by Wright (1989) is shown in Figure 6). The picture of the Portland area during the Pleistocene that emerges from the paleoclimatic evidence is one of a cooler, drier climate with a more open landscape than the coniferous forests of the Holocene. It is possible that the stronger westerly winds might have transported some fine loess directly from the great silt reserves in the Palouse region, although it appears that by at least 50,000 years ago prevailing winds east of the Cascades were southwesterlies similar to today's (Busacca and McDonald, 1994). What is quite likely is an increased east-to-west eolian transport of sediments deposited in the Portland Basin in Pleistocene times relative to earlier and later periods. This has implications for the hypotheses concerning the origin of the two major post-Miocene sediments encountered in the Tualatin Mountains stratigraphic section: the Portland Hills Silt and the Sandy River Mudstone-equivalent (Squier, 1993). Before this can be addressed, however, the source material of the Portland Hills Silt should be examined.



from Wright (1989), Figure 9

Figure 6 Paleoclimate field data and models for North America

METHODS

Sample Locations and Procedures

Sample collection and processing for this study was divided into two stages or phases. The first phase was conducted between March and May, 1992, as part of graduate-level class work in geochemistry. In this portion of the investigation the sample field included a total of 19 samples for irradiation. Seven samples were derived from the DOGAMI 53rd Street core; soils were sampled at depths of 1.5, 7.62, 13.7, 18.3, 21.3, 24.4 and 26 meters (5, 25, 45, 60, 70, 80 and 85 feet) bgs. Four samples were derived from West Side Light Rail borings in the eastern margin of the Tualatin Valley near the intersection of Highway 26 and 217, three from boring M102 and a single sample from boring N104. The bulk of the geochemical data from this four-sample suite, referred to as the "Northeast Tualatin Valley" or NETV samples, was lost after INAA was completed. The locations of these sample sites are shown on Figure 2. Partial data from these sediments has been included in Table II found in the Geochemical Data section of this report.

A total of eight samples of glaciofluvial sediments from potential source locations for the Portland Hills Silt were collected. Five were from the silt soils collected by Mr. Dave Cordero in eastern Oregon and Washington. Specifically, three sites in Wasco County, Oregon (Figure 4) and two sites in Whitman County, Washington (Figure 5) were sampled for a mixture of Pleistocene and Holocene silt or loess soils. Three samples of glaciofluvial outwash sediments associated with the Puget Sound glaciation of Washington were collected from the fluvial terraces of the Chehalis River drainage (Figure 3).

The second portion of the study took place between August and November, 1994 and concentrated on the Portland West Hills, using samples derived largely from the Tri-Met West Side Light Rail Tunnel exploratory program. A total of 37 samples from five borings were collected. Of this total, four were additional samples from the DOGAMI 53rd Street core. Five samples were collected in a shallow soil excavation for a residential garage on S.W. Elm Street at S.W. Montgomery Avenue on the Vista Heights section of Portland. The remaining 26 samples were distributed among the five borings chosen along the Canyon Road axis of the WLRT project. Locations of these borings and sample collection sites are also shown in Figure 2.

Sample Collection

Dry core boring samples were taken with a soil knife from the field core boxes. In many cases, the upper ten to fifteen meters of the WLRT borings with a Standard Penetration Test (SPT) 2.75-inch (68.75 mm) split-spoon sampler. These moist samples were removed from their sample jars using clean forceps. Both types of sample were bagged as described in the Sample Preparation and Analysis section below.

Shallow soil samples, such as the silts collected at Elm Street in Portland, along the Chehalis River, and in eastern Washington and Oregon, were removed from banks and cuts with a clean soil knife or trowel and bagged in the same manner as the core and jar samples.

The total sample field collected is summarized in Table I.

TABLE I

SAMPLE IDENTIFICATION, LOCATION AND DESCRIPTION

Notes:
(bgs) - below existing ground surface
(#) - sample descriptions followed by this symbol taken from original formation logs, L.R. Squier & Assoc., 1993

Portland Area Samples:
53rd Street: taken from the topmost 85 feet of the DOGAMI continuous-core boring performed December 1992 on the east side of N.W. 53rd Street approximately 1.5 miles north of N.W. Cornell Road in Forest Park. Eleven samples were taken at the depths indicated:

First irradiation (collected April 1992; irradiated at Corvallis, May 1, 1992; counted May 7-12, 1992)

Sample No.	Irrad. No.	Depth (bgs)	Soil Horizon	Description
NW5305	92A26	1.5m(5ft)	Bwb	SPT sample - Base of paleosol 4
NW5325	92A27	7.62m(25ft)	Cu	Massive, yellow silt, (ML),sand, micaceous
NW5345	92A28	13.7m(45ft)	Cox	Found just below paleosol 3: yellow silt (ML)/ weak sbky structure
NW5360	92A29	18.7m(60ft)	Bwb	In paleosol 2: reddish, many Fe/Mg shot-concretions Strong, sbky structure
NW5370	92A30	21.3m(70ft)	Cox	Yellow silt (ML), weak sbky structure
NW5380	92A31	24.4m(80ft)	Cu	Massive, yellow silt (ML), micaceous
NW5385	92A32	26m(85ft)	Btb	In paleosol 1: reddish, strong angular blocky structure, trace basalt fragments

TABLE I
(Continued)
SAMPLE IDENTIFICATION, LOCATION AND DESCRIPTION

Second irradiation (collected April 1992; irradiated at Reed College, October 1993; counted October 9-28, 1993.)

Sample No.	Irrad. No.	Depth (bgs)	Soil Horizon	Description
NW5337	93F011	1.1m(37ft)	Bwb	In paleosol 3: reddish, weak sbky structure, basalt fragments to 3" max. dim.
NW5352	93F02	15.6m(52ft)	Cu?	Massive, yellow silt (ML), micaceous
NW5365	93F04	19.5m(65ft)	Bwb	In paleosol 2: red, weak sbky structure
NW5375	93F032	2.5(75ft)	Cu	Massive, yellow silt (ML)

Elm Street: Shallow Recent soil samples collected April 11, 1993 from a garage excavation at 2121 S.W. Elm St. in the Vista Heights neighborhood of Portland. All samples processed as part of second irradiation as per note above:

Sample No.	Irrad. No.	Depth (bgs)	Soil Horizon	Description
ES01	93F05	10-20cm	Bw	Modern cambic horizon
ES02	93F06	60-80cm	Cox	Dark yellow to tan silt (ML), massive, root hairs
ES03	93F07	1.1-1.3m	Cox	As above but fine black laminations 1-3mm
ES04	93F09	1.7-1.9m	Btb1	Upper buried soil, dark brown, trace charcoal
ES05	93F08	2.2-2.5m	Btb2	Lower buried soil, dark reddish brown, some charcoal fragments

TABLE I
(Continued)
SAMPLE IDENTIFICATION, LOCATION AND DESCRIPTION

B-525: West Side Light Rail Tunnel (WLRT) exploratory boring performed by L.R. Squier and Associates, September 14, 1992. Sampled July 1, 1993. Second irradiation (1993) as noted above:

Sample No.	Irrad. No.	Depth (bgs)	Soil Horizon	Description
B525S2	93F29	3.3m(11ft)	Cox	Mottled gray/red-brown silt (ML), trace sand, mica (#)
B525S5	93F26	7.8m(26ft)	Bwb	Silty clay to clayey silt tan to light brown(#)
B525S6	93F11	11.1m(37ft)	Cox	Yellow-brown silt (ML), trace sand (#)
B525S8	93F28	12.3m(41ft)	Btb2	Mottled brown/red-brown silty clay to clayey silt: identified as Sandy River Mudstone (SRM) (#)
B525S10	93F14	15.3m(51ft)	Btb2/Cox?	Brown, mottled gray clayey silt, micaceous: identified as SRM (#)
B525S12	93F16	18.3m(61ft)	Cox	As S-10 above (#)

B-527: WLRT exploratory boring performed by L.R. Squier & Assoc. September 14, 1992. Sampled July 1, 1993. Second irradiation (1993) as noted above.

Sample No.	Irrad. No.	Depth (bgs)	Soil Horizon	Description
B527S2	93F23	3.6m(12ft)	Cox	Light brown mottled gray silt (ML), trace sand (#)
B527S6	93F21	6.6m(22ft)	Cu	As above but some clay
B527S7	93F31	8.1m(27ft)	Cu	As S6 above
B527S9	93F191	1.1m(37ft)	Btb	Stiff, orange-brown mottled gray silty clay, identified as SRM (#)

TABLE I
(Continued)
SAMPLE IDENTIFICATION, LOCATION AND DESCRIPTION

B-530: WLRT exploratory boring performed by L.R. Squier & Assoc. March 26, 1992. Sampled July 1, 1992. Second irradiation (1993) as noted above.

Sample No.	Irrad. No.	Depth (bgs)	Soil Horizon	Description
B530S2	93F20	3m(10ft)	Cu	Stiff, brown mottled tan silt (ML), trace sand, massive, sbky,10YR5/4 (dry)
B530S4	93F24	5.1m(17ft)	Cox	yellow to red-brown (#) Otherwise as above
B530S5	93F33	6m(20ft)	Cox	As S4 above
B530S6	93F13	7.5m(25ft)	Bwb	Orange-brown mottled tan and gray silt to silty clay w/ trace "organics" (#)Trace subrounded basalt gravels to 1/4" max. dim.
B530S9	93F27	12m(40ft)	Btb	Stiff, yellow-brown silt (ML), trace sand & clay (#) strong sbky structure, good clay films 7.5YR4/3 (dry)
B530S11	93F32	15m(50ft)	Btb	Becomes orange-brown (#) weak sbky structure, very well-developed clay films, root traces.
B530S12	93F12	16.5m(55ft)	Btb2	Identified as SRM(#) massive, very good clay films, many Fe/Mg shot-conc., tephra frags?
B530S14	93L30	19.5m(65ft)	Btb2	Identified as SRM, mottled silty clay, trace basalt frags.

TABLE I
(Continued)
SAMPLE IDENTIFICATION, LOCATION AND DESCRIPTION

B-574: WLRT exploratory boring performed by L.R. Squier & Assoc. September 12, 1992. Sampled July 1, 1993. Second irradiation (1993) as noted above.

Sample No.	Irrad. No.	Depth (bgs)	Soil Horizon	Description
B574S2	93F25	3m(10ft)	Cu	Stiff, wet, light brown silt (ML)(#) trace sand, massive, 10YR5/4 (dry)
B574S3	93F15	4.5m(15ft)	Cox	As above
B574S6	93F22	7.8m(26ft)	Bwb	Stiff, red-brown mottled gray clayey silt, trace sand (#)
B574S8	93F17	9.3m(31ft)	Bwb	Stiff, orange-brown clayey silt (#)
B574S9	93F17b	10.5m(35ft)	Btb	Dark red-brown silty clay, identified as SRM (#)

B-564: WLRT exploratory boring performed by L.R. Squier & Assoc. September 14, 1992. Sampled July 1, 1993. Second irradiation (1993) as noted above.

Sample No.	Irrad. No.	Depth (bgs)	Soil Horizon	Description
B564R18	93F34	39m(130ft)	Bwb	Hard-baked, brick-red clayey silt, gravel-sized angular basalt fragments at top, wet silt & sand at base - identified as SRM interbedded between normal polarity Boring Lavas(#)
B564R42	93F36	73.8m(246ft)	Cox	Hard, dark green silt, trace clay - SRM found underlying Boring Lava (#)
B564R44	93F35	77.1m(257ft)	Btb	Light orange - many FeO concretions, SRM (#) massive, trace sand & mica

TABLE I
(Continued)
SAMPLE IDENTIFICATION, LOCATION AND DESCRIPTION

B564R51	93F37	85.8m(286ft)	Cu	Light tan to gray silt, micaceous, SRM (#)

M-102: WLRT exploratory boring performed by Oregon Department of Transportation (ODOT) March 17, 1992. Sampled March 28, 1992. First irradiation (1992) as noted above. Soil horizons not identified.

Sample No.	Irrad. No.	Depth (bgs)	Description
M102N21	92A40L	45m(120ft)	Gray, clayey silt (ML), micaceous, FeO concretions
M102N26	92A39L	60m(200ft)	Gray to dark gray, as above
M102N32	92A38L	90m(300ft)	Dark blue-green clay (CL), damp, very stiff, micaceous

N-104: WLRT exploratory boring performed by Oregon Department of Transportation (ODOT) March 17, 1992. Sampled March 28, 1992. First irradiation (1992) as noted above. Soil horizons not identified.

Sample No.	Irrad. No.	Depth (bgs)	Description
N104N12	92A40U	21.3m(71ft)	Light brown mottled gray silt (ML), FeO shot-conc., damp, hard

Source Area Samples:

Palouse Region: Collected by David Cordero from the sites listed below in 1991 and 1992. Samples were hand-dug from existing roadcuts and embankments. First irradiation (1992) as noted above:

Sample No.	Irrad. No.	Depth (bgs)	Soil Horizon	Description
DC-147	92A33	2-3m(10ft)	Bkb	caliche horizon in loess paleosol near The Dalles, Oregon

TABLE I
(Continued)
SAMPLE IDENTIFICATION, LOCATION AND DESCRIPTION

Sample No.	Irrad. No.	Depth (bgs)	Soil Horizon	Description
DC-179	92A34	0-1m(3ft)	Bw?	Modern soil in loess near the town of Dusty, Whitman Co., Washington
DC-107	92A35	0-1m(3ft)	Cu	Recent loess, Wasco Co., Oregon
DC-143	92A36	3-6m(10-20ft)	Cu	Missoula flood silts near The Dalles, Oregon
DC-177	92A37L	3-9m(10-30ft)	Cu	Older (Pleistocene) loess, Whitman Co., Washington

Puget Sound Outwash: Hand dug from existing roadcuts, cut slopes and embankments along the north side of the Chehalis River Valley, Washington in 1992. First irradiation as noted above.

Sample No.	Irrad. No.	Depth (bgs)	Soil Horizon	Description
PS-1	92A37U	.75m(2ft)	Cox	Modern soil in roadcut 0.5mi NW of Satsop, Wash.
PS-2	92A38U	.75m(2ft)	Cox	
PS-3	92A39U	1m(3ft)	Cox	Both samples from modern soil in roadcut 0.75mi north of Montesano, Wash. yellow to tan silty sand (SM) glacio-fluvial outwash.

Choice of Analytical Method

This project was approached as a part of a larger suite of geochemical analyses currently in progress on Portland area geologic materials, notably those of Barnes (MS thesis, 1996) on Boring Lava and sediments of the Tualatin Mountains and Portland and Tualatin Basins, and Wilson (1997) on Tualatin Basin sediments. The petrologic character of the Portland Hills Silt and its relationship with the loess of the North American interior has been well established by Rodney Lentz (1977, 1981). The intent of this study was to use the high resolution of current instrumental geochemical techniques to attempt to determine if this relationship could be established geochemically. If, as indicated in Lentz (1977), the Portland Hills Silt shared a distinct petrologic suite with the glaciofluvial materials of the upper Columbia River basin, then this petrology should be reflected in the geochemistry of both the Portland Hills Silt and the sediments of the source area. In addition, internal changes such as soil formation or contamination could be analyzed by observing geochemical variations within the deposit.

Instrumental Neutron Activation Analysis (INAA)

First proposed in 1936, this geochemical analytical procedure is based on the concept that stable nuclei will produce distinct radioactive nuclides when immersed in a neutron bath, or flux (Meucke, 1980). These nuclides will then decay, emitting electromagnetic radiation (gamma photons) or submolecular particles such as alpha or beta emissions. The reactor chamber of a nuclear facility will produce such a neutron bombardment: the resulting gamma-radiation decay spectrum can then be studied "as a function of energy and time after irradiation, and the original quantities of each element present can be deduced" (Fairbridge, 1972, p.779). This process is known as *scintillation* and is performed in a photo- or gamma-spectrometer such as a scintillation crystal, crystal-phototube combination or solid-state germanium or silicon-lithium detector coupled to a multichannel gamma-ray analyzer. These detectors record the number of gamma radiation emissions at specific energies in electron volts (eV). Each gamma ray energy emission is recorded as a "count" on an energy-range at that energy by the analyzer. This produces individual sample energy spectra composed of distinct "count" peaks that can be matched against a spectrum produced by a standard sample of known element composition and concentration.

Sample Preparation and Analysis

All soil samples were placed in separate zip-lock sealed plastic baggies after collection. Any large organic matter (roots, duff, wood fragments) visible at the time of collection was removed and either discarded (for Recent soils) or retained for examination (paleosols). Samples were examined and logged for texture based on the Unified Soil Classification System (USCS) using the ASTM standard D2488-90 *Standard Practice for Description and Identification of Soils (Visual-Manual Procedure)* (ASTM, 1996) and color by the Munsell Soil Color Index (wet and dry) (Munsell, 1992). If pedogenic features such as soil structure, clay film formation or rubefication with regard to the parent materials were observed, these features were noted in accordance with the Soil Conservation Service (SCS) classification system (Soil Survey Staff, 1994). The total original sample was weighed and placed in a covered, ventilated container to dry.

Once dried, the samples were physically crumbled and wet-sieved through an abbreviated sieve stack consisting of the #230 sieve. This separated the U.S.C.S. sand-sized particles. Certain samples required mechanical crushing in a mortar-and-pestle, which may have produced some small percentage of excessive fines. The weight-percent of each grain-size fraction of each sample was determined. An additional grain size test was performed on the DOGAMI 53rd Street core samples. This consisted of performing further wet-sieving using a #400 sieve to remove the coarse silt fraction, followed by hydrometer analyses to determine the percentage of medium and fine silt-size particles versus the clay-sized fraction for the DOGAMI samples. The sieve analyses were performed in accordance with the ASTM Test D422-63 *Test Method for Particle-Size Analysis of Soils* (ASTM, 1996). The hydrometer tests were performed in accordance with *Test Method for Amount of Material in Soils Finer than the No. 200 (75-μm) Sieve* (ASTM, 1996).

A small amount of the separated sample was collected for mineralogic examination using a binocular or petrographic microscope.

The remaining samples were run through a sample-splitter to assure a random petrologic and grain-size distribution. A small amount of sample, usually between 0.75 gram and 1.1 gram, was encapsulated in a clean, weighed plastic sample vial and the sample vial heat-sealed and marked with an irradiation number (Meucke, 1980). This vial was then placed in a plastic containment vial in preparation for shipment to the irradiation facility.

The samples were irradiated for one hour at 250 kilowatts. The "first irradiation" was performed at the OSU TRIGA reactor in Corvallis, Oregon on May 1, 1992. The "second irradiation" was performed at the Reed College TRIGA reactor on October 4, 1993. In both cases, the batch samples were allowed to decay for five days on the reactor sites to allow for safe handling.

On return from irradiation the samples were held in shielded storage to ensure that hard radiation counts were below the safe-handling limits prior to continued processing. The containment vials were then opened, the sample vials removed and the gamma-spectrometer analysis begun. Counting was performed on the PSU apparatus which contained a EG&G Solid-state Photon Detector with high-purity germanium crystal. This procedure consisted of two stages: a first count, conducted within a week of irradiation and a second count following within a month. This two-stage counting procedure is an artifact of the gamma radiation state of the samples immediately after neutron activation. The delay between counts is sufficient to allow the short half-life nuclides to decay sufficiently that long half-life isotopes may be detected. The first-count spectra were used to collect data for and detect the elements potassium, sodium, uranium, arsenic, gallium, lanthanum and samarium (K, Na, U(as Np), As, Ga, La and Sm). Second-count elements detected included iron, chromium, cobalt, barium, rubidium, strontium, cesium, scandium, thorium, hafnium, tantalum, zirconium, tantalum, zinc, lanthanum, cerium, neodymium, europium, terbium, ytterbium and lutetium (Fe, Cr, Co, Ba, Rb, Sr, Cs, Sc, Th (as Pa), Hf, Ta, Zn, La, Ce, Nd, Eu, Tb, Yb, Lu). The collected spectra were processed by the ORTEC multichannel spectrum analyzer for geochemical element gamma radiation activity and matched against standards to determine elemental concentrations (Meucke, 1980).

Geochemical data were transferred to a spreadsheet (initially Lotus, then Microsoft Excel). The imbedded statistical functions in the Excel spreadsheet were used to run significance analyses on the chemical groups. Based on the significance results of F- and T-tests, X-Y scattergrams of selected elements and rare-earth linear plots were prepared. This graphic analysis was performed in order to attempt to separate samples into fields or groups by geochemistry.

As mentioned above, a data retrieval error resulted in a loss of portions of the element concentration data, particularly in the four samples from the Tualatin Valley (N104, M102).

GEOCHEMICAL DATA: RESULTS AND DISCUSSION

Introduction

The elemental concentration data produced by INAA during this study can be divided into three general groups based on their utility in characterizing separate populations of samples. First, there is that group of elements below or near the detection limit. Second, there is a group of elements detected in most samples with low uncertainties but which do not display statistically reliable geochemical affinities. Third, there is the group of elements that can be used to separate samples geochemically into discrete fields that can be related to lithology or petrology. These latter elements were used in this study to attempt to distinguish internal, stratigraphic or developmental divisions within the Portland Hills Silt.

The first category of elements includes arsenic (As), gallium (Ga), rubidium (Rb), uranium (U), strontium (Sr), zinc (Zn) and zirconium (Zr), as well as Rare Earth Elements (REE) lutetium (Lu), neodymium (Nd) and terbium (Tb). These elements were detected in less than half (an average of 43.1%) of all samples analyzed. The element most commonly detected in this group was terbium, encountered in 53.8% of 52 samples analyzed. Least often encountered was the REE element neodymium, at 26.9%. The highly irregular pattern of detection, coupled with small concentrations displaying high counting uncertainties, make these ten elements less suitable for use in identifying geochemical sample groups. The three REE elements were included in REE sample plots but not used independently in element-to-element scatter plots: the other seven elements were not used further in this study.

In the second group, the elements barium (Ba), cobalt (Co), potassium (K), tantalum (Ta) and samarium (Sm) were found to be statistically unreliable in distinguishing between geochemical groups. This analysis was performed using the statistical function of the Excel spreadsheet, which provided results in the form of the probability (p) that the null hypothesis ($Ho:\sigma 1 = \sigma 2$) is valid between two subject sample groups. The first test performed was the F test, which compares the spread (or variance) of two normal populations. This test is based on the proposition that where two subject groups were taken from the same population, or such similar populations that variance could be statistically attributed to random variation, the F-Test formula would return a probability of Ho = Ho of 100%, or 1.0. If the populations displayed sufficient and consistent variance differences, that is, $Ha: \sigma 1 \neq \sigma 2$, then the p-value returned should be 0%

or 0.00. This test is extremely sensitive to nonnormal distributions, so in addition, a Student t test was run on the same sample groups. An example of this is the statistical analysis of the element barium:

TABLE II

STATISTICAL ANALYSES OF BARIUM, THREE LOCATIONS
(probability (p) = 1.0 if Ho = Ho)

Sample	Probability of Ho=Ho (F-Test)	Probability of Ho=Ho (T-Test)
53rd v. Boring	0.05	0.05
Palouse v. Boring	0.01	0.16
53rd v. Palouse	0.28	0.47
53rd v. B530	0.40	0.48
Palouse v. B530	0.63	0.12
53rd v. Elm St.	0.02	0.42
Elm St. v. Palouse	0.02	0.38
53rd v. Puget Sd.	0.60	0.25
53rd v. B525	0.46	0.01
Palouse v. B525	0.61	0.00
53rd v. B574	0.07	0.69

If the first two samples display the anticipated dissimilarity between the Boring Lava volcanics and the silts sampled from both the 53rd Street core and the Palouse source regions, the next three samples typify the difficulty of using barium to distinguish between geochemical groups. The f-tests show a wide range of variability: this is probably due to the variations in barium concentration found in the 53rd Street samples. Although the mean is 556 ppm, the extremes are 449 ppm in the 5 ft/1.4 m sample and 729 ppm in the 65 ft./19.5 m sample. The standard deviation (s) of 81 ppm for this group of samples is twice the s value for the Palouse samples and 30% larger than that of the B-530 samples. Given the sensitivity of the F-test to these "outliers", the preferred analytical method is the more robust t-test (Moore and McCabe, 1993). The t-test suggests that the barium concentration means of the 53rd Street core are similar to the means detected in the Palouse samples at a 47% confidence level. This rather indeterminate level is similar to the 48% probability of similarity between the 53rd Street sample mean and the mean barium concentration of the samples from the WLRT B-530 samples. In themselves, these intermediate values are problematic, falling near the middle of the range of probabilities and therefore not helpful in either validating or disproving the null hypothesis. To add to the difficulty in interpreting the data, the test of means between the Palouse samples and the B-530 core samples is dissimilar to both the preceding groups and shows a rather low 12% confidence level, that is, that it is likely that the mean barium concentrations of these two sample groups are different populations at a 88% confidence level. Given that the Palouse silts show similar barium mean concentrations to the 53rd Street samples and that the 53rd Street samples are somewhat similar to the samples taken from B-530, the failure to "close" the barium means between B-530 and the Palouse samples raises questions about the reliability of barium as an indicator element for defining sample group affinities.

Due to similar statistical uncertainties, the elements barium, cobalt, potassium, tantalum and samarium were used sparingly to distinguish between the groups. Sodium proved to be useful for certain internal distinctions, but was not a statistically reliable element for distinguishing between the major geochemical groups.

The remaining elements were used in this study to characterize the geochemistry of the Portland Hills Silt. This group of elements included the major elements iron and sodium; the metallic element chromium; trace elements hafnium, scandium and thorium, and the REE elements, but particularly lanthanum, cerium, europium, terbium, ytterbium and lutetium.

First, the average element concentration of each of the proposed sample groups was plotted as abundances on an X-Y graph, with average concentration plotted against element type. The major, trace and metallic element concentration data were evaluated in point scatter plot diagrams that plotted element concentrations on separate axes. REE abundance was plotted as element concentrations on a linear plot to show distinctive REE anomalies. These plots are included in the discussion portions of the following sections. Table III contains the INAA geochemistry obtained for this study. Table IV contains INAA geochemistry of selected samples analyzed by Barnes (1996) used for comparison.

TABLE III

ELEMENT CONCENTRATIONS

Notes:

Concentrations in parts per million (ppm) except for Fe, K and Na, listed as percent (%).

Elements not detected by indicated as "ntd"

Elements detected but data subsequently lost indicated by blank space in column

Sample Number	As	Ba	Ce	Co	Cr
53d 5'		449	59.1	14.3	49
53d 25'		522	69.4	8.5	44
53d 37'	6.82	565.9	87.7	8.06	100.3
53d 45'		593	91.8	15.8	63
53d 52'	10.06	ntd	96.48	17.05	63.08
53d 60'		512	80.4	10.9	57
53d 65'	7.5	728.7	103.3	14.78	120.7
53d 70'		610	93.1	13.1	61
53d 75'	6.88	ntd	96.4	17.0	63.1
53d 80'		524	70.5	10.6	52
53d 85'		500	93.2	24.5	80
ES10-20cm	9.78	729	67.6	18.68	131.2
ES60-80cm	4.45	933	63.3	23.9	165.5
ES110-130cm	8.07	573.7	64.5	20.2	150.2
ES170-190cm	8.23	410.8	52.2	10.78	146.3
ES220-250cm	9.13	ntd	48.1	5.5	90.3
DC-147	7.35	563	71.9	14.8	58
DC-179	5.51	525	83.1	11.5	60
DC-107	9.68	559	68.9	12.1	59
DC-143	6.03	475	54.8	13.5	36
DC-177	7.86	ntd	ntd	22.2	82
PS-1		361	45.7	19.4	102
PS-2		ntd	ntd	ntd	110
PS-3		488	45.7	9.2	54
B525S2	10.3	668	74.6	16.1	80.5
B525S5	12.5	646.8	64.1	8.38	87
B525S6	9.03	630.6	91.5	12.6	113.5
B525S8	8.42	639.1	101.5	14.1	113.8

TABLE III
(Continued)
ELEMENT CONCENTRATIONS

Sample Number	As	Ba	Ce	Co	Cr
B525S10	8.0	617.3	91.1	12.4	58.8
B525S12	7.64	774.7	72.7	19.2	118.8
B527S2	8.05	ntd	82.6	17.6	98.8
B527S6	4.7	644.3	83.9	17.8	126.6
B527S7	7.5	ntd	83.3	16.7	129.3
B527S9	8.47	567.7	60.6	8.3	11.5
B574S2	10.4	867.6	73.8	16.5	93.1
B574S3	6.5	ntd	65.5	19.3	117.3
B574S6	8.02	459.8	89.8	49.6	116.7
B574S8	13.0	633.5	72.9	12.5	121.9
B574S9	11.6	535.5	63.8	8.54	73.03
B530S2	11.5	537.5	82.8	15.9	108.3
B530S4	6.9	650.1	94.6	9.08	65.0
B530S5	7.03	568.1	94.4	16.3	107.5
B530S6	7.64	593.2	85.0	9.8	77.0
B530S9	9.89	482.8	78.9	10.5	118.9
B530S11	5.37	618.6	103.5	23.2	94.3
B530S12	7.16	617.0	75.9	12.4	10.8
B530S14	6.34	ntd	72.3	6.06	96.9
B564R18	4.1	614.8	63.7	16.5	118.9
B564R42	5.3	ntd	68.9	18.9	85.5
B564R44	7.9	669.9	69.4	47.7	83.7
B564R51	ntd	667.2	82.6	21.2	87.5
N104N12		460	30.1	21.5	113
M102N21		445	37.2	27.6	143
M102N26		581	70.1	35.2	66
M102N32		820	218	15.7	69

TABLE III
(Continued)
ELEMENT CONCENTRATIONS

Sample Number	Cs	Eu	Fe(%)	Ga	Hf
53d 5'		1.42	3.75		7.4
53d 25'		1.28	2.6		7.19
53d 37'	3.35	1.41	3.8	8.17	8.25
53d 45'		1.62	3.34		8.1
53d 52'	3.46	1.65	3.95	18.8	9.1
53d 60'		1.56	3.23		7.4
53d 65'	3.95	1.61	3.79	12.6	9.72
53d 70'		1.8	3.61		7.8
53d 75'	4.38	1.83	4.07	17.3	8.6
53d 80'		1.48	2.95		8.3
53d 85'		1.43	4.5		9.2
ES10-20cm	2.49	1.65	4.46	10.8	6.82
ES60-80cm	1.99	1.65	4.94	ntd	6.7
ES110-130cm	2.45	1.54	4.57	ntd	5.78
ES170-190cm	3.24	1.17	5.13	7.74	6.77
ES220-250cm	3.02	0.90	4.82	8.6	8.08
DC-147	3.29	1.6	3.8		7.6
DC-179	3.02	1.5	3.06		8.35
DC-107	3.13	1.3	3.13		7.5
DC-143	3.65	1.27	3.48		5.8
DC-177		ntd	3.57		ntd
PS-1		1.91	5.93		4.7
PS-2		ntd	3.57		ntd
PS-3		ntd	2.86		5.0
B525S2	4.14	1.53	4.07	18.7	8.49
B525S5	4.19	1.31	5.09	10.8	7.66
B525S6	3.91	2.15	4.22	7.71	8.96
B525S8	3.17	1.68	3.86	9.36	8.63
B525S10	3.67	1.81	3.77	13.05	7.73
B525S12	2.91	1.80	5.00	8.6	6.99
B527S2	4.51	1.81	4.55	ntd	9.41
B527S6	2.92	1.44	4.23	9.95	8.53
B527S7	3.61	0.96	5.86	7.00	7.35

TABLE III
(Continued)
ELEMENT CONCENTRATIONS

Sample Number	Cs	Eu	Fe(%)	Ga	Hf
B527S9	3.51	0.96	5.86	7.00	7.35
B574S2	3.92	1.56	4.08	13.4	7.99
B574S3	3.42	1.61	4.61	ntd	6.8
B574S6	4.10	1.16	5.50	8.56	8.94
B574S8	4.32	1.20	5.19	7.79	9.69
B574S9	5.78	1.39	6.24	9.72	9.00
B530S2	2.85	1.61	4.20	21.5	7.55
B530S4	3.34	1.76	3.41	8.04	8.86
B530S5	4.44	1.66	4.29	12.5	8.28
B530S6	2.98	1.30	4.02	9.59	8.11
B530S9	4.49	1.38	4.87	8.37	7.92
B530S11	2.76	2.09	4.47	11.09	8.92
B530S12	2.64	1.69	6.57	9.28	10.65
B530S14	3.32	1.93	4.96	10.39	11.26
B564R18	5.42	1.51	6.69	9.34	6.76
B564R42	3.56	1.94	5.25	8.43	3.92
B564R44	5.68	1.29	3.73	ntd	9.15
B564R51	4.10	1.59	3.12	ntd	8.66
N104N12		1.1	3.5		2.8
M102N21		1.2	4.1		3.5
M102N26		1.81			8.4
M102N32		6.7	7.6		4.9

TABLE III
(Continued)
ELEMENT CONCENTRATIONS

Sample Number	K(%)	La	Lu	Nd	Rb
53d 5'	1.91	35.9	0.44	30	46
53d 25'	1.66	47	0.54	29	50
53d 37'	1.53	39.11	0.45	31.3	58.7
53d 45'	2.60	48.2	0.44	36	60
53d 52'	2.06	52.2	0.42	ntd	68.04
53d 60'	2.30	54.6	0.42	32	73
53d 65'	2.08	50.2	0.60	ntd	74.1
53d 70'	2.80	50.5	0.5	42	74
53d 75'	1.87	47.4	0.56	41.5	78.6
53d 80'	2.30	48.5	0.39	34	63
53d 85'	2.10	40.7	0.48	ntd	83
ES10-20cm	1.58	32.47	0.44	ntd	60.5
ES60-80cm	1.57	31.6	0.50	ntd	57.3
ES110-130cm	1.49	31.3	0.61	ntd	ntd
ES170-190cm	1.00	28.3	0.34	ntd	ntd
ES220-250cm	1.08	23.2	0.30	45.5	58.4
DC-147	1.97	38.8	0.46	30	64
DC-179	1.60	30.9	0.8	ntd	
DC-107	1.90	40.4	0.46	ntd	60
DC-143	1.98	37.9	0.39	30	45
DC-177	2.20	46.1	ntd	ntd	ntd
PS-1	0.60	21.2	0.47	ntd	60
PS-2	2.36	39.1	ntd	ntd	ntd
PS-3	ntd	ntd	ntd	ntd	49
B525S2	2.04	35.9	0.52	ntd	51.6
B525S5	1.38	32.9	0.39	ntd	52.9
B525S6	1.65	51.1	0.48	ntd	83.8
B525S8	1.67	48.6	0.55	ntd	78.1
B525S10	1.88	52.2	0.51	ntd	49
B525S12	1.17	35.5	0.36	ntd	71.5
B527S2	1.71	39.8	0.67	ntd	60.1
B527S6	1.55	39.8	0.41	ntd	64.6
B527S7	1.40	39.4	0.34	ntd	79.6

TABLE III
(Continued)
ELEMENT CONCENTRATIONS

Sample Number	K(%)	La	Lu	Nd	Rb
B527S9	1.22	33.2	0.28	ntd	68.4
B574S2	2.01	36.7	0.50	ntd	66.3
B574S3	1.47	31.5	0.37	36.7	44.8
B574S6	1.23	34.7	0.33	38.5	ntd
B574S8	1.68	33.5	0.37	ntd	59.6
B574S9	1.71	36.2	0.48	57.8	60.0
B530S2	1.86	39.44	0.43	ntd	69.2
B530S4	2.09	52.1	0.47	ntd	111.4
B530S5	1.88	45.9	0.504	ntd	ntd
B530S6	1.81	33.8	0.35	ntd	70.8
B530S9	1.31	34.2	0.35	ntd	62.14
B530S11	1.43	55.5	0.47	ntd	59.6
B530S12	1.31	45.8	0.45	37.6	7.06
B530S14	1.21	48.9	0.55	ntd	59.4
B564R18	1.30	30.6	0.43	48.9	ntd
B564R42	1.47	34.5	0.35	ntd	84.9
B564R44	1.49	36.6	0.51	ntd	ntd
B564R51	2.07	44.0	0.40	35.7	82.1
N104N12	ntd	19.2	ntd	ntd	38
M102N21	ntd	20	ntd	ntd	57
M102N26			0.54	ntd	48
M102N32	1.46	84.7	1.78	99	69

TABLE III
(Continued)
ELEMENT CONCENTRATIONS

Sample Number	Na(%)	U(Np)	Th(Pa)	Sr	Ta
53d 5'	1.63		8.6	292	
53d 25'	1.66		9.9	353	
53d 37'	0.88	ntd	15.9	ntd	1.31
53d 45'	1.38		13.5	260	
53d 52'	1.26	3.64	14.1	566.3	1.21
53d 60'	1.18			ntd	
53d 65'	0.96	4.74	13.2	446.8	1.29
53d 70'	1.15			368	
53d 75'	1.22	3.63	14.4	545	1.28
53d 80'	1.39			331	
53d 85'	0.74			ntd	
ES10-20cm	1.85	2.20	8.28	707.8	0.79
ES60-80cm	1.99	2.65	8.38	ntd	0.99
ES110-130cm	1.88	ntd	8.55	444.5	1.00
ES170-190cm	0.97	ntd	8.45	767.3	0.85
ES220-250cm	0.58	3.40	9.50	ntd	1.09
DC-147	1.70		10.7	432	1.16
DC-179	1.50		12.4	249	0.98
DC-107	1.76		10.1	505	0.91
DC-143	1.50		7.8	307	0.76
DC-177	1.48			ntd	ntd
PS-1	0.47		4.5	ntd	
PS-2	1.56			ntd	
PS-3	ntd			437	
B525S2	1.70	ntd	10.3	469.2	1.18
B525S5	0.95	3.79	10.6	471.6	1.19
B525S6	1.23	5.53	11.9	783.8	ntd
B525S8	1.16	4.10	13.5	ntd	ntd
B525S10	1.19	3.08	11.9	584.7	0.95
B525S12	0.85	4.54	10.4	ntd	ntd
B527S2	1.68	ntd	11.9	ntd	1.07
B527S6	1.31	3.29	11.3	ntd	1.44
B527S7	1.24	3.58	10.45	413.5	1.17

TABLE III
(Continued)
ELEMENT CONCENTRATIONS

Sample Number	Na (%)	U(Np)	Th(Pa)	Sr	Ta
B527S9	0.41	ntd	13.4	ntd	1.18
B574S2	1.69	3.37	9.54	ntd	ntd
B574S3	1.63	ntd	8.45	901.2	ntd
B574S6	0.37	3.66	13.4	ntd	1.50
B574S8	0.78	4.04	11.8	ntd	1.34
B574S9	0.66	4.42	14.0	ntd	1.20
B530S2	1.52	ntd	10.65	861.2	1.23
B530S4	1.41	3.88	13.5	655	1.24
B530S5	1.10	4.87	13.8	ntd	1.26
B530S6	0.99	4.31	13.5	ntd	1.37
B530S9	0.68	4.37	12.9	ntd	1.25
B530S11	1.09	ntd	13.4	474.5	ntd
B530S12	0.45	4.47	14.0	ntd	1.29
B530S14	0.45	ntd	14.3	ntd	ntd
B564R18	1.11	3.02	9.36	ntd	1.07
B564R42	0.89	2.13	7.52	ntd	ntd
B564R44	1.11	3.52	11.6	ntd	1.19
B564R51	1.57	3.59	12.8	622.7	1.26
N104N12	1.64			ntd	
M102N21	1.84			581	
M102N26				ntd	
M102N32	2.7			ntd	

TABLE III
(Continued)
ELEMENT CONCENTRATIONS

Sample Number	Zn	Sc	Yb	Tb	Sm
53d 5'			3.3	0.91	6.47
53d 25'			2.9	0.8	7.19
53d 37'	ntd	14.3	3.16	ntd	6.32
53d 45'			3.6	ntd	7.8
53d 52'	95.0	13.1	3.68	1.14	8.23
53d 60'			3.2	0.95	8.49
53d 65'	85.7	12.5	3.45	1.08	7.84
53d 70'			4.0	1.06	8.46
53d 75'	77.7	13.8	3.15	ntd	7.64
53d 80'			2.9	ntd	7.74
53d 85'			3.1	ntd	6.39
ES10-20cm	84.0	15.8	2.65	ntd	5.84
ES60-80cm	101.9	18.0	2.65	ntd	5.77
ES110-130cm	ntd	16.1	2.67	ntd	5.46
ES170-190cm	ntd	12.7	2.09	ntd	4.44
ES220-250cm	ntd	11.6	2.29	ntd	3.30
DC-147	76	13.2	3.1	0.95	6.89
DC-179	64	10.6	3.4	1.01	8.03
DC-107	59	10.8	3.3	0.91	7.03
DC-143	60	12.3	2.9	0.76	6.45
DC-177		11.2	3.2		6.93
PS-1			3.4	ntd	6.68
PS-2			ntd	ntd	5.12
PS-3			2.3	ntd	ntd
B525S2	94.8	14.5	3.22	1.20	6.6
B525S5	82.5	14.7	2.47	0.74	5.29
B525S6	84.8	16.7	3.9	ntd	9.13
B525S8	ntd	13.7	3.88	1.01	7.49
B525S10	103.4	13.2	3.36	1.14	8.35
B525S12	93.9	17.5	2.74	ntd	6.15
B527S2	ntd	15.7	4.33	ntd	7.08
B527S6	ntd	12.6	2.61	0.89	6.16
B527S7	ntd	15.3	2.68	0.92	5.97

TABLE III
(Continued)
ELEMENT CONCENTRATIONS

Sample Number	Zn	Sc	Yb	Tb	Sm
B527S9	82.8	15.0	2.43	ntd	4.12
B574S2	ntd	14.7	3.33	ntd	6.42
B574S3	105.3	16.3	2.99	0.82	5.69
B574S6	ntd	15.1	2.53	ntd	5.02
B574S8	84.0	17.1	3.89	0.82	5.38
B574S9	ntd	15.0	3.02	ntd	4.67
B530S2	ntd	13.5	3.08	1.00	6.55
B530S4	ntd	11.66	3.96	1.15	8.02
B530S5	ntd	13.5	3.47	1.14	7.26
B530S6	79.1	13.4	2.91	0.90	5.50
B530S9	84.3	14.6	3.57	0.98	5.78
B530S11	92.4	15.5	3.41	1.15	8.59
B530S12	ntd	17.33	3.71	1.24	7.34
B530S14	ntd	18.3	2.96	ntd	7.74
B564R18	ntd	18.8	4.06	1.00	5.37
B564R42	107.21	20.1	2.77	1.00	7.25
B564R44	ntd	11.7	2.77	0.87	5.94
B564R51	ntd	12.9	3.41	0.94	6.67
N104N12			2.3	0.53	4.04
M102N21			2.4	0.68	4.51
M102N26			3.2	ntd	ntd
M102N32			13.7	3.82	25.6

TABLE III
(Continued)
ELEMENT CONCENTRATIONS

Sample Number	Zr
53d 5'	478
53d 25'	ntd
53d 37'	ntd
53d 45'	390
53d 52'	ntd
53d 60'	265
53d 65'	ntd
53d 70'	419
53d 75'	189
53d 80'	387
53d 85'	354
ES10-20cm	ntd
ES60-80cm	ntd
ES110-130cm	ntd
ES170-190cm	201.1
ES220-250cm	242.5
DC-147	327
DC-179	308
DC-107	ntd
DC-143	319
DC-177	ntd
PS-1	ntd
PS-2	ntd
PS-3	ntd
B525S2	210.0
B525S5	ntd
B525S6	ntd
B525S8	204.0
B525S10	437.6
B525S12	272.9
B527S2	ntd
B527S6	165.5
B527S7	ntd

TABLE III
(Continued)
ELEMENT CONCENTRATIONS

Sample Number	Zn
B527S9	188.2
B574S2	ntd
B574S3	ntd
B574S6	375.1
B574S8	259.2
B574S9	ntd
B530S2	ntd
B530S4	192.6
B530S5	299.7
B530S6	157.6
B530S9	ntd
B530S11	ntd
B530S12	ntd
B530S14	195.7
B564R18	306.2
B564R42	ntd
B564R44	ntd
B564R51	216.6
N104N12	ntd
M102N21	ntd
M102N26	517
M102N32	601

TABLE IV

ELEMENT CONCENTRATIONS

Sample data from Barnes (1996) used for comparison. Partial element concentration data. For complete data see Barnes (1996)

Sample Number	Fe(%)	Na(%)	K(%)	Cr	Hf
Boring Lava Samples					
b556-57	6.18	3.08	1.09	159	3.60
b538-176	6.57	2.96	1.20	205	3.70
b538-28.5	6.09	2.95	1.30	178	3.70
b540-90	5.94	3.06	1.40	179	4.00
KA1	7.44	2.25	2.05	321	4.31
HWY26-2	6.60	3.08	1.62	194	3.74
ODOT-K108	5.83	3.06	1.32	153	3.37
b13-104.7	6.58	2.75	1.57	300	3.97
Columbia River basalt Sediment Samples					
b563-212	12.2	3.85	0.7	56	5.56
b565-226	10.4	70.29	0.4	26	8.97
BVD4-36.5	10.3	90.35	0.82	70	8.31
High Cascades Sediments					
b561-135	5.70	1.97	0.91	255	3.34
b557-211	6.35	2.77	0.89	224	3.43
GSD2-10	5.14	2.26	1.27	64	4.22
Columbia River Source Sediments					
b557-114	4.05	1.33	1.14	83	7.90
b538-128	3.65	1.40	1.76	71	8.03
b565-214	4.40	1.22	1.84	64	6.62
BVD4-91.4	3.82	0.76	1.85	39	5.87
DHW-330	4.34	1.53	1.31	59	5.58
Blue	4.50	0.59	1.40	72	3.80
PHS	3.66	1.83	1.73	59	8.71
SRM	4.08	0.96	1.89	76	6.24
Young Columbia River Sediments					
MTD2-145	3.29	2.23	2.03	42	3.40
MTD1-50	3.26	3.44		29	3.72
MTD1-155	2.69	2.64		35	3.44
Hillsboro Drill Hole					
HBD1-60.5	3.20	1.51	1.90	64	9.44
HBD1-84	2.84	1.03	1.64	46	11.09

TABLE IV
(Continued)
ELEMENT CONCENTRATIONS

Sample data from Barnes (1996) used for comparison. Partial element concentration data. For complete data see Barnes (1996)

Sample Number	Fe(%)	Na(%)	K(%)	Cr	Hf
HBD1-131	7.66	0.70	1.06	61	8.49
HBD1-405.5	3.33	2.63	2.99	71	10.40
HBD1-714.8	13.1	40.52	1.06	49	7.37
HBD1-938.5	13.1	10.01	0.21	61	12.00

TABLE IV
(Continued)
ELEMENT CONCENTRATIONS

Sample data from Barnes (1996) used for comparison. Partial element concentration data. For complete data see Barnes (1996)

Sample Number	Th(Pa)	Sc	La	Ce	Nd
Boring Lava Samples					
b556-57	1.60	19.3	17.7	41.4	36
b538-176	0.50	21.9	14.8	33.0	3
b538-28.5	ntd	18.2	17.3	39.0	3
b540-90	0.45	17.6	17.3	38.0	22
KA1	2.6	22.2	30.0	51.3	27
HWY26-2	1.9	6.60	20.4	46.8	3
ODOT-K108	1.6	16.0	21.8	42.6	3
b13-104.7	3.6	17.0	26.9	59.2	40
Columbia River basalt Sediment Samples					
b563-212	4.4	45.3	51.6	30.8	ntd
b565-226	7.9	55.5	38.2	159.2	52
BVD4-36.5	11.8	37.3	40.5	82.6	ntd
High Cascades Sediments					
b561-135	3.4	18.8	19.4	42.4	ntd
b557-211	2.6	17.4	32.3	62.2	40
GSD2-10	4.9	18.4	24.4	46.0	28
Columbia River Source Sediments					
b557-114	8.7	11.3	34.6	68.3	30
b538-128	10.8	12.5	41.3	78.0	40
b565-214	11.0	16.1	41.7	78.4	40
BVD4-91.4	17.7	14.2	31.9	64.8	29
DHW-330	7.9	15.7	28.4	54.9	ntd
Blue	5.6	18.9	22.5	42.0	22
PHS	10.3	13.0	37.9	78.0	ntd
SRM	11.8	16.4	40.7	91.0	ntd
Young Columbia River Sediments					
MTD2-145	4.7	10.9	21.2	38.7	20
MTD1-50	3.3	9.9	20.3	35.3	19
MTD1-155	4.3	9.2	17.9	34.5	ntd
Hillsboro Drill Hole					
HBD1-60.5	10.6	11.6	43.8	2.5	42
HBD1-84	10.8	14.9	44.7	91.8	46

TABLE IV
(Continued)
ELEMENT CONCENTRATIONS

Sample data from Barnes (1996) used for comparison. Partial element concentration data. For complete data see Barnes (1996)

Sample Number	Th(Pa)	Sc	La	Ce	Nd
HBD1-131	9.2	25.0	27.3	56.7	26
HBD1-405.5	10.4	12.9	38.2	91.3	41
HBD1-714.8	8.1	13.14	30.8	70.8	38
HBD1-938.5	12.8	45.6	47.8	93.6	ntd

TABLE IV
(Continued)
ELEMENT CONCENTRATIONS

Sample data from Barnes (1996) used for comparison. Partial element concentration data. For complete data see Barnes (1996)

Sample Number	Sm	Eu	Tb	Yb	Lu
Boring Lava Samples					
b556-57	5.15	1.80	0.62	1.80	0.26
b538-176	4.15	1.50	0.60	2.20	0.31
b538-28.5	4.94	1.70	0.66	1.80	0.33
b540-90	4.60	1.70	0.57	1.60	0.25
KA1	6.70	2.01	0.84	2.35	0.46
HWY26-2	5.40	1.90	0.68	1.76	0.28
ODOT-K108	5.70	1.71	0.59	1.48	0.22
b13-104.7	5.67	1.79	0.69	1.44	0.34
Columbia River basalt Sediment Samples					
b563-212	9.73	3.07	1.41	4.56	0.64
b565-226	13.59	3.76	1.65	3.74	0.68
BVD4-36.5	8.68	2.32	1.80	3.50	0.59
High Cascades Sediments					
b561-135	4.54	1.30	0.54	1.32	0.22
b557-211	7.23	2.18	0.79	1.81	0.24
GSD2-10	5.59	1.66	0.80	2.51	0.42
Columbia River Source Sediments					
b557-114	5.49	1.29	0.77	2.40	0.37
b538-128	6.40	1.48	0.91	2.68	0.42
b565-214	7.18	1.61	0.97	3.04	0.56
BVD4-91.4	6.54	1.20	1.14	2.94	0.47
DHW-330	5.92	1.36	0.83	2.83	0.50
Blue	5.53	1.23	0.64	2.10	0.33
PHS	6.50	1.36	1.06	2.63	0.53
SRM	7.70	1.53	1.14	3.08	0.55
Young Columbia River Sediments					
MTD2-145	3.81	1.02	0.57	1.74	0.33
MTD1-50	3.77	1.05	0.48	1.42	0.21
MTD1-155	3.36	0.95	0.51	1.53	0.23
Hillsboro Drill Hole					
HBD1-60.5	7.01	1.49	0.90	2.85	0.49
HBD1-84	8.37	1.92	1.15	3.24	0.56

TABLE IV
(Continued)
ELEMENT CONCENTRATIONS

Sample data from Barnes (1996) used for comparison. Partial element concentration data. For complete data see Barnes (1996)

Sample Number	Sm	Eu	Tb	Yb	Lu
HBD1-131	5.57	1.45	0.85	2.87	0.53
HBD1-405.5	6.52	1.76	0.96	2.91	0.49
HBD1-714.8	7.88	2.22	1.23	4.18	0.78
HBD1-938.5	8.64	2.28	1.06	2.73	0.53

SILT OF THE PALOUSE REGION

The Pleistocene history of the Columbia Plateau is dominated by the great jökulhlaups or glacial outburst floods of the Lake Missoula system (Bretz, 1928). This record includes the alluvial soils and related loess of the Channeled Scablands of eastern Washington and northeastern Oregon. The core area of this loess, identified by the name of the Palouse region of eastern Washington and Northern Idaho where it was first recognized, exceeds an area of 8,000 square kilometers and reaches a thickness of up to 75 meters (Busacca, 1991). The deposit is further described as:

> "...extending approximately from Waterville on the northwest, to Spokane on the northeast, beyond Walla Walla and Pasco on the south, and into the adjacent northernmost part of Oregon, between Pendleton and The Dalles.
>
> Beneath the surface of the Palouse, dozens of paleosols are interstratified with sheets of loess. Paleomagnetic measurements now prove that the geologic record in the loess spans at least the last 1 m.y. (Busacca, 1991, p.216)

The relationship between the sandy to silty alluvial (later recognized as catastrophic flood) sediment parent and the product Palouse soils was recognized by Bryan (1927). Three sources of generally similar mineralogy produced the Palouse loess: the late Miocene to Pliocene Ringold Formation of the Pasco and Quincy Basins, the Touchet Beds and associated pre-Wisconsin flood sediments, and Columbia River alluvium derived from the front of the Cordilleran Ice Sheet (Busacca, 1991). Busacca and McDonald (1994) detail the transport and deposition of what they refer to as the L1 loess from source sediments in the Walla Walla Valley and Pasco Basin during latest Pleistocene and Holocene times, and a similar genesis for the so-called L2 loess in the early Wisconsin (50 ka to 25 ka).

The hypothesis presented by Lentz (1977), that the petrology and hence the provenance of Portland Hills Silt could be associated with the Palouse loess seems well supported by the petrologic and sedimentary evidence contained in that work. To serve as a check on the Lentz (1977) theory, a total of 5 samples were taken from these areas for this study. The sample locations are shown on Figures 4 and 5: two samples were taken from shallow loess deposits, and a third from Missoula flood silts, in roadcuts in Oregon locations (Figure 4) and two from Whitman County, Washington (Figure 5). Note that the location and the shallow depth of these samples would appear to place them in the youngest (L1) loess of Busacca and McDonald (1994). The overall geochemistry of these samples is shown in Figure 7. Since this loess material will be considered the "type" parent material for loess generated from Pleistocene Columbia Basin sediments, this geochemical profile becomes the "baseline" Columbia River/continentally-derived loess geochemical signature.

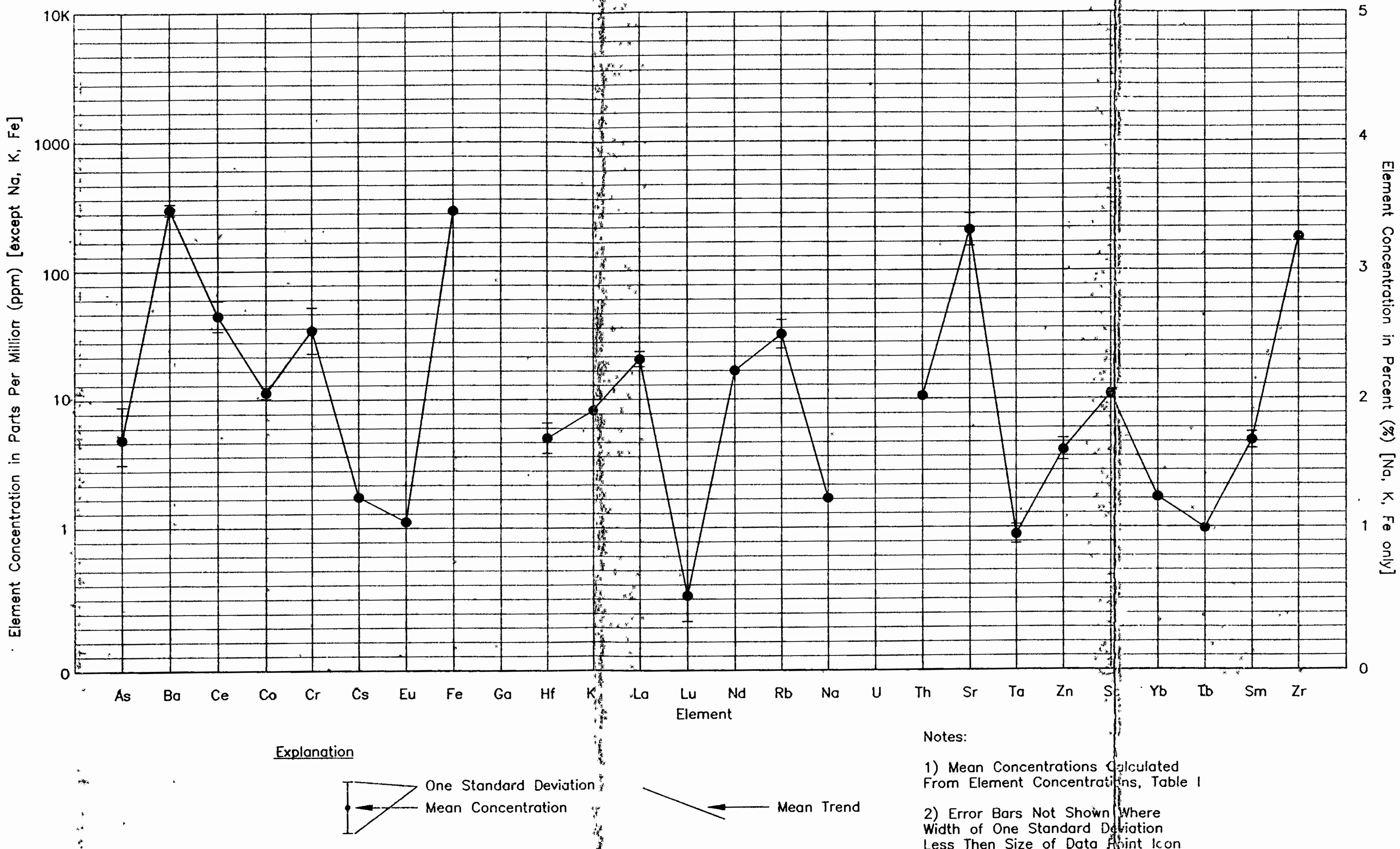


Figure 7: Average Element Concentration, Palouse Loess

EFFECTS OF DIFFERENTIAL TRANSPORT AND DEPOSITION, PORTLAND HILLS SILT AND SANDY RIVER MUDSTONE

Among the issues this study was designed to address is the geochemical relationship between those sediments on the Tualatin Mountains recognized as Portland Hills Silt and those identified as Sandy River Mudstone-equivalent by Squier (1993). These Portland-area sediments are separated by time as well as depositional type. The late Miocene Sandy River Mudstone is described by Trimble (1963) as subhorizontal (dips usually less than 2 degrees), parallel-bedded, moderately lithified, very fine sand and silt with occasional conglomerate. This fine-grained deposit was dated by Trimble (1963) as Pliocene in age, but more recent studies have placed this sediment at the end of the Miocene, approximately 10.5 Ma to 5.3 Ma (Orr and others, 1992).

The possible similarities of these sediments are based on erosion from a similar source: the interior of the North American continent. Lentz (1977) notes the similarity in the heavy mineral suites between the Portland Hills Silt and the Troutdale Tualatin Valley equivalent of Schlicker and Deacon (1967), which includes the Sandy River Mudstone.

Differences in sediment character may be drawn from the difference in the modes of deposition of these sediments. Both sediments are usually yellowish brown to brown and fine-grained. Lentz (1977) typifies the eolian Portland Hills Silt as:

- showing little or no stratification, massive texture;
- uniform in textural classification at around 70% to 80% silt, but fining and thinning downwind of the Portland Basin source.
- containing numerous or common iron-magnesium shot concretions.
- non-calcareous

The Sandy River Mudstone generally appears as:

- stratified to massive, but usually with some form of bedding, including lenses and discrete beds of sand-size and coarser particles (Lentz, 1977).
- uniform texturally over the deposit area, with variations in textural class in relation to distance from paleochannel axes.
- contain few to no shot concretions (Lentz, 1977).
- calcareous (Lentz, 1977).

It is difficult to distinguish between these depositional environments geochemically. Subaerial deposition under reducing conditions is suggested by the enrichment of trace elements uranium (U) and vanadium (V) (Fairbridge, 1972), but subsequent redox fluctuations, coupled with the erratic detection of uranium encountered in this study, make this evidence hard to use effectively. Calcium (Ca) might have been more helpful in distinguishing calcareous from non-calcareous sediments but, like vanadium, was not measured.

Generally speaking, the geochemistry performed in this study is not useful in separating lacustrine from eolian modes of sediment deposition. However, the physical evidence such as presence or absence of bedding, or shot concretions, are useful in classifying suspect sediments, especially the Sandy River Mudstone-equivalent identified by Squier (1993) in the WLRT cores, as will be discussed later.

DOGAMI N.W. 53^{rd} STREET CORE BORING (TB-810)

This geotechnical boring was drilled in April, 1992 by the Oregon Department of Transportation (ODOT) for the Oregon Department of Geology and Mineral Industries (DOGAMI) as a part of the field investigation for the work that was published as the *Seismic Hazard Maps for the Portland Quadrangle* (Mabey, 1996). The borehole was located in Multnomah County in the northeast quarter of the southwest quarter of Section 30, Township 1 North, Range 1 East of the Willamette Meridian. The boring site is a traffic pullout on the south side of Northwest 53rd street approximately 0.8km (1/2 mile) north of the intersection of N.W. Cornell Road and N.W. 53rd Street. This site is a levelled grade located on a gently to moderately gently-sloping ridgetop that forms the eastern crest of the Tualatin Mountains. Ground-surface elevation at the boring site is shown on the U.S.G.S. Portland 7.5 minute quadrangle as approximately 850 feet (285 meters) MSL.

DOGAMI performed this boring primarily to establish underlying geology of the West Hills for use in the shear-wave seismicity study performed by DOGAMI (Mabey, 1996) for the Portland area.

The boring was performed using a B-53 truck-mounted rotary drilling rig using with a HQ3 wireline 4-inch ID diamond crown bit with a 4 inch diameter core barrel to the termination of the boring at 100 meters (300 feet) below the ground surface, approximately elevation 185 meters (550 feet MSL). The field conditions were logged at the site by Mr. Dermot O'Keefe of ODOT and the core then placed in wooden core boxes by the driller. The core was held by DOGAMI until completion of the study and then transferred to the Oregon Department of Transportation (ODOT) for storage at the ODOT core facility at Highway 217 and Allen Boulevard in Progress, Oregon. It remained at that location until May, 1994 when four boxes comprising the uppermost portion were removed to the core laboratory at Portland State University for further examination where it was located at the time of writing.

Sampling and Analysis

For the purposes of this study only the uppermost 25.9 meters (85 feet) of this boring was subjected to detailed analysis. The boxed core was logged to detail color of the dried soil, mineral composition and soil structure, and photographs of the core were taken (Appendix B). Based on this observation, samples were removed from the core for irradiation and/or grain size analysis.

Of the approximately 26-meters of PHS drilled, the uppermost five meters (15 feet) were saturated and extremely soft. This portion of the boring could not recovered as continuous core (Scott Burns, personal communication, 1997). Grab samples from this saturated core interval were taken and placed in sample jars during drilling. A single sample from a depth of 1.4 meters (5 feet) was used for INAA testing.

Samples for INAA were taken from the extant 18.3 meters (60 feet) of core as detailed in Section 3 (Methods) and at the depths specified in Table I. This sampling and analysis were performed in 1992 and 1993.

Additional samples were taken from the core in 1996 for grain size analysis. The sample depths and results of this phase of the investigation are detailed in Table III.

Visual logging of the boxed core was performed using ASTM D2488-85, *Practice for Description and Identification of Soils (Visual-Manual Procedure)* (ASTM, 1996) for preliminary textural classification. Color of the dry soil was quantified using the Munsell Soil Color Handbook (Munsell, 1992) as specified in the U.S.D.A. *Soil Survey Manual* (Soil Survey Staff, 1994) Soil characteristics were used to develop Harden Indices (Harden, 1982) as a measure of soil development in the four recognizable paleosols. To further investigate this process, the grain size analysis was performed to determine the degree of clay mineral formation.

This parameter has been used as a method of determining maturity in soils. In this study, clay content was analyzed in an attempt to add a physical means of refining internal loess-paleosol stratigraphy difficult to resolve by geochemistry alone.

Silt Sediments and Parent Materials

Within the approximately 85-feet (26 meters) thick Portland Hills Silt sediment cored at this location, a total of four loess intervals were observed. The uppermost loess, from the base of the modern soil to approximately 15 meters bgs, exists only as isolated jar samples. Of the 70 meters of core recovered, three loess intervals could be identified that did not appear to show visual evidence of significant soil development. The silty sediment contained in these intervals will be identified in this study as less weathered or parent material (loess) zones. Four paleosols are encountered within the DOGAMI core which divide the loess into three unweathered or parent material intervals. The first task is to examine the characteristics of the parent loess material.

The loess intervals, in order of increasing age are: first, from just below the top of the existing core at about 6.1 meters (20 feet) bgs from the base of Paleosol 4 to the top of Paleosol 3 at a depth of approximately 10.6 meters (35 feet) bgs; second, from the base of Paleosol 3 at approximately 12.8 meters (42 feet) bgs to the diffuse upper edge of Paleosol 2 at between 15.5 to 18 meters (51 to 59 feet) bgs (Figure 8; Appendix B). The third less weathered interval is also somewhat indistinct, extending from a diffuse contact with the bottom of Paleosol 2 somewhere between 20 to 22 meters (65 to 72 feet) bgs to the top of the basal soil horizon (Paleosol 1) at 25.3 meters (83 feet) bgs. The lowermost Paleosol 1 appears to be a residual soil developed on loess mixed with the weathered top of a Sentinel Bluffs basalt flow of the Grande Ronde Basalt of the CRBG that underlies the Portland Hills Silt at this location. For a complete description of the boxed core, see Appendix B.

In general, the grain size distribution of the 53rd Street core is remarkably uniform. Table V shows a complete breakdown of this information, which is summarized here.

TABLE V.

GRAIN SIZE ANALYSIS
DOGAMI 53rd STREET CORE (TB-810)

Depth of Sample (m)	(ft)	Horizon	% Sample by Wt. Sand (+.065mm)	Silt (.065-.002mm)	Clay (<.002mm)	USCS Class	USDA Class
4.5	15	PS4/L3	5.7	77.5	16.7	ML	SiCL
6.1	20	Loess 3	12.1	83.7	4.2	ML	SiL
7.6	25	Loess 3	3.8	87.0	9.2	ML	SiL
9.1	30	Loess 3	2.8	82.9	14.3	ML	SiCL
11.4	37½	PS3	2.0	82.2	15.8	ML	SiL
12.2	40	PS3	6.6	81.7	11.7	ML	SiL
13.7	45	Loess 2	11.5	78.5	10.0	ML	SiL
15.3	50	Loess 2	5.1	83.6	11.3	ML	SiL
15.8	52	Loess 2	1.6	75.9	23.1	ML	SiCL
16.7	55	Loess 2	8.2	79.7	12.1	ML	SiCL
18.3	60	PS2	1.9	82.6	15.5	ML	SiCL
18.9	62	PS2/L1	1.2	89.9	8.9	ML	SiL
19.8	65	PS2/L1	5.3	76.0	18.7	ML	SiCL
21.3	70	PS2/L1	3.5	77.0	19.5	ML	SiCL
22.8	75	PS2/L1	4.6	79.9	15.5	ML	SiCL
24.4	80	Loess 1	1.8	84.2	14.0	ML	SiCL
26	85	PS1	1.1	73.0	25.9	ML	SiCL
		Average soil grain size content percent					
			4.6	80.9	14.9		
			Sample variance by percent				
			3.3	4.2	5.2		

Grain size analysis shows the total core to have an average of 80.9±4.2 percent silt-sized particles. Silt content in the loess intervals averaged 82.1±5.1 percent. Silt content variability in the loess intervals ranges from a low of 75.9 percent total silt at 15.8 meters (52 feet) in Loess 2 to the high of 87.0 percent as 7.6 meters (25 feet) in Loess 1.

Sand (greater than 0.065 mm size) composes an average of 4.6±3.3 percent of the whole core and 5.8±5.2 percent of the loess intervals. Sand-size content of the loess deposits shows some variability, ranging from a low of 1.6 percent at 15.8 meters (52 feet) to a maximum of 12.1 percent at 6 meters (20 feet). Visual inspection of the sand-sized particles showed that a significant portion of this group is composed of secondary mineralized particles, especially manganese nodules. These "shot-concretions" were present in all the paleosol horizons, often forming up to 50-60 percent of the total sand fraction in many of the soil horizons, particularly noticeable at depths of 15.8 meters (52 feet) and 25.9 meters (85 feet).

Average clay content of the entire core averaged 14.9±5.2 percent, with clay fraction of the loess intervals averaging 12.3±9.5 percent, from a low of 4.2 percent at 6 meters (20 feet) to a high of 23.1 percent at a depth of 15.8 meters (52 feet).

In general, the less weathered, or parent material (loess) zones appeared predominantly silty, with a trace of some fine sand. Much mica was observed in these intervals, along with trace ferromagnesian shot-concretions. Dry soil colors ranged from very pale brown (10YR 7/4) and brownish yellow (10YR 6/6) to yellow (10YR 7/6). Remoistened, soil colors ranged from yellowish brown (10YR 5/4) to dark

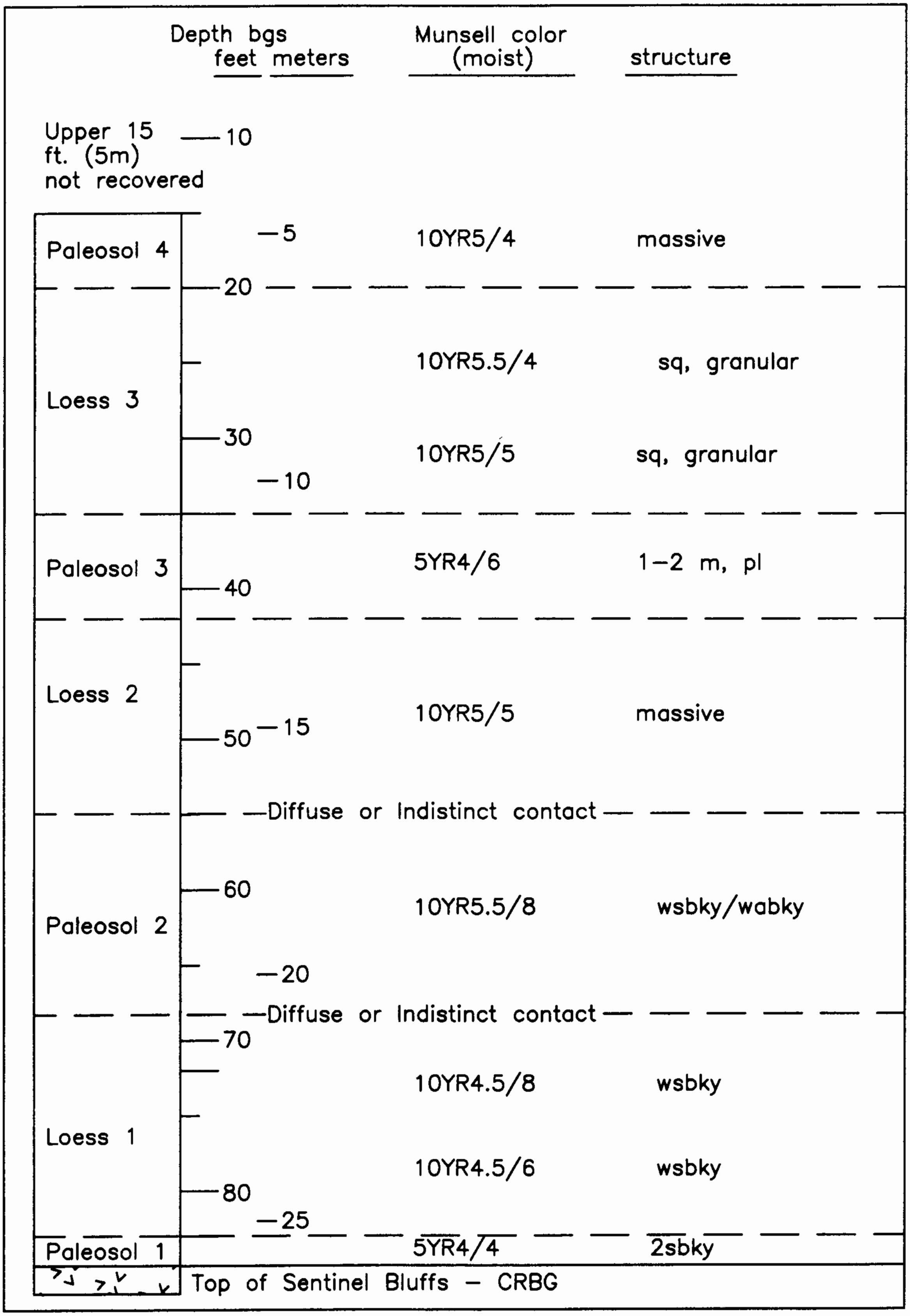


Figure 8 Schematic Diagram, 53rd St. Core (TB-810)

yellowish brown (10YR 4/6). The parent material intervals showed no depositional structures. A massive structure was more typical of these intervals. Dry consistencies ranged from soft to hard; as is common with silt soils, the dried loessal silt tended to crumble under moderate finger pressure. Wet consistency was generally loose to very friable. A single dark gray, angular basalt fragment 0.65 cm (2 inches) dimension was collected from the uppermost parent material interval (Loess 3) at a depth of approximately 10 meters (30 feet) bgs during examination of the core.

The lowest parent material interval, Loess 1, from the base of Paleosol 2 to the top of Paleosol 1 at the contact with the underlying CRBG, differs visibly from the two upper less weathered zones above it. This interval displays increased rubefication of up to one Munsell value and chroma level. Dry Munsell soil value decreases from an average of 7 to 6: chroma increases from 4.5 to 6. Increased weathering is also indicated by the increased clay content of the interval: averaging 16.9 percent over the lowermost 6 meters (20 feet) including the basal soil zone. Soil structure appears to be slightly better developed throughout much of this portion of the core, ranging from massive granular to weak angular blocky. Dry consistency increases from hard to very hard.

The average geochemistry of the loess intervals is quite similar to the average geochemistry of the Palouse region samples, as shown in Figure 9. All five Palouse samples are averaged against six of the 53rd Street samples: 1.4 meters (5 feet) representing Loess 4; 7.5 meters (25 feet) representing Loess 3; 13.5 meters and 15.7 meters (45 feet and 52 feet) representing Loess 3, and; 21 meters, 22.5 meters, and 25 meters (70, 75 and 80 feet) taken from the Loess 1/Paleosol 2 intergrade area.

Paleosol Development

Four buried soil horizons were encountered in the 53rd Street core, with the traces of the base of the uppermost, Paleosol 4, encountered at the top of the core at a depth of 4.5 meters (15 feet) bgs (Appendix B). This appears to be the lower portion of a Bwb horizon of a weakly developed paleosol, with only the increased clay content (14.5 percent compared to 3.5 percent and 8.5 percent in the 6.1 meter and 7.6 meter intervals, respectively) to distinguish it from the 1Cu horizon loess beneath it. Paleosol 4 displays no clay films and a massive, granular structure, grading into the underlying Loess 3 by 6.1 meters (20 feet) bgs. This geologically youthful soil appears to have been pedologically immature, as well.

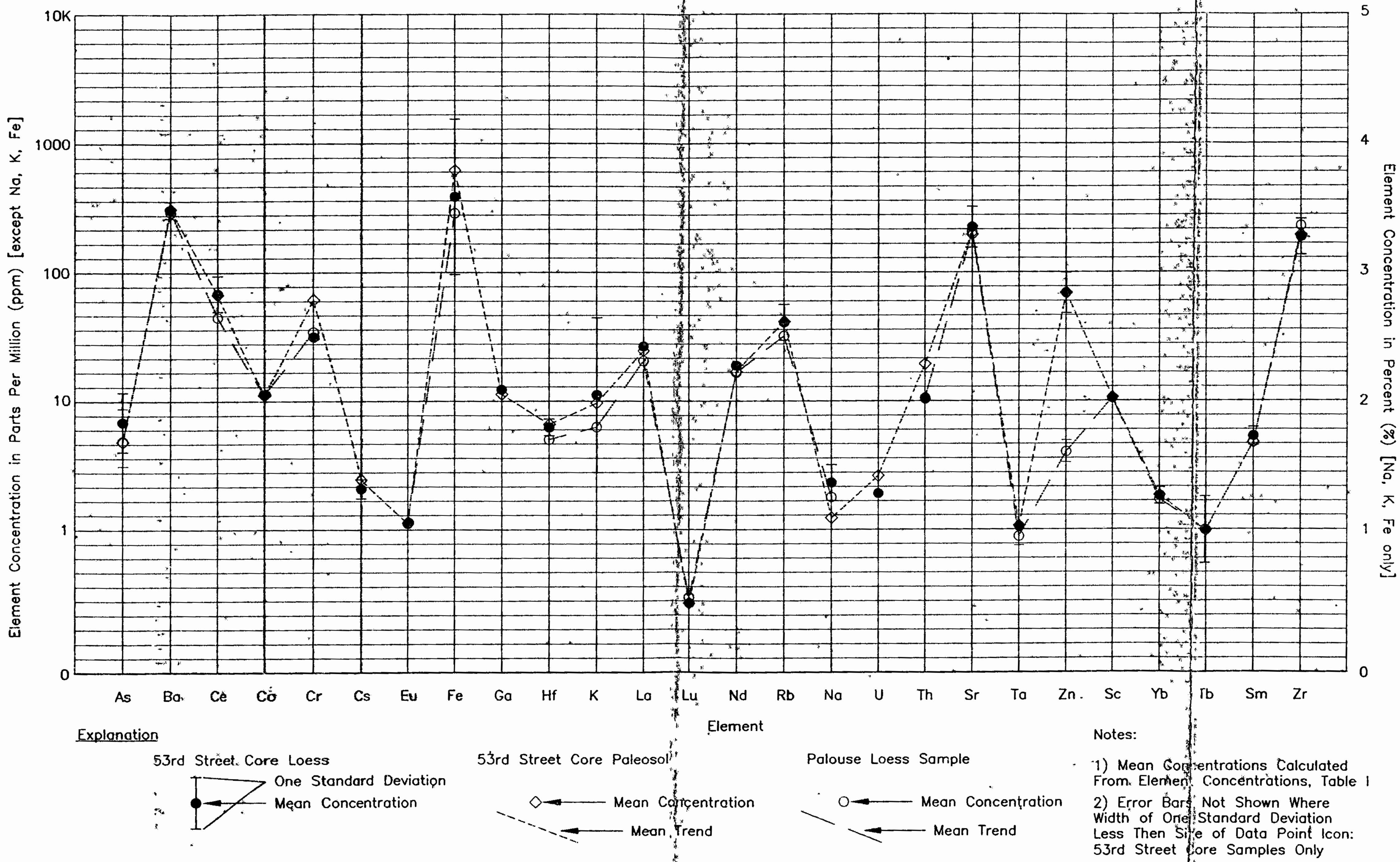


Figure 9: Average Element Concentration, Palouse Loess vs. 53rd Street Loess vs. 53rd Street Paleosols.

Paleosol 3 is encountered centered around 12 meters (40 feet) bgs. This interval is first recognized just below 10 meters (about 35 feet) bgs. The upper contact, as is the case with all the paleosol contact zones observed in this core, is diffuse. The indications of transition from the overlying Loess 3 zone are a gradual reddening from pale yellow (2.5Y 7/5 dry) of the Loess 3 1Cu horizon to yellow (10YR 7/7 dry), and the development of moderately strong, platy to subangular blocky structure in the 3Bw horizon of Paleosol 3. By 11.5 meters (38 feet) bgs Paleosol 3 shows signs of a buried argillic (2Btb) horizon, as evidenced by some well developed clay films bridging soil peds and forming lamella waves, strong platy to subangular blocky structures and increased rubefaction. Thirty to forty percent reddish yellow (7.5YR 7/8 dry) mottling is present, along with faint root trace or krotovina impressions. An angular, very pale, yellow decomposed rock or ash fragment approximately 1.2 cm (1/2 inch) maximum dimension was encountered at 12 meters (40 feet) bgs.

Paleosol 3 development decreases or weakens by 12.8 meters (42 feet) bgs, and no noticeable reddening and soil structure could be observed in the core by a depth of 15.8

meters (52 feet) bgs. This represents the transition from the soil zone into the 3Cu horizon of Loess 2.

Paleosol 2 is encountered at a depth of 17.8 meters (59 feet) bgs. This buried soil is slightly yellower (10YR 5/6 dry, yellowish brown) and structurally less mature (weak subangular to angular blocky structure) than the overlying Paleosol 3. Reddening peaks in the 4Bwb horizon at 10YR 5.5/6 dry (yellowish brown) at 17.8 meters (59 feet) bgs. Both rubefication and structure weaken below a depth of 18 meters bgs as the 4Bwb gives way to the 4Cu horizon of Loess 1. Iron/magnesium "shot-concretions" make up as much as 2 percent of this paleosol horizon. The size of these concretions is likewise notable - up to 4mm. Concretions compose roughly half of the sand-size and larger fraction of this soil.

Low clay content appears to reflect the apparent lack of pedologic maturity of Paleosol 2. Clay particle content rises from 12.1 percent at 16.7 meters (55 feet) bgs to 15.5 percent at 18.3 meters (60 feet), but then drops to 8.9 percent at 18.9 meters (62 feet). Although the soil at this depth does appear slightly more mature in soil development indices such as color, structure and clay film formation than the parent material core intervals above and below it, this 8.9 percent clay is the lowest clay content encountered in the lower 20.5

meters of core. This clay variability is consistent within the range of average clay content of the core.

Higher overall clay content levels in the parent materials may be reflected by the lack of sharp visual distinction between the lowest parent material zone (Loess 1) and the Paleosol 2 formed on it. The contact between Loess 1 and the basal soil horizon of the Portland Hills Silt sequence, Paleosol 1, however, is distinctive and immediately recognizable. Encountered at the diffuse but noticeable contact at 25.3 meters (83 feet) bgs, this soil is extremely red (5YR 4/4 moist) and contains the highest clay percentage (23.1) of any of the soils; for that matter, of the entire Portland Hills Silt portion of the core. The weak to moderate subangular blocky structure and up to four percent by weight shot-concretions likewise indicate that this soil has obtained some degree of maturity.

Harden indices for these paleosols are listed in Table VI. For paleosols 2 through 4, the Harden indices were developed by contrasting the paleosol to the parent loess upon which it developed: Loess 3 for Paleosol 4, for example. Paleosol 1, which developed at the contact with the underlying Sentinel Bluffs basalt, was contrasted to a "representative" loess sample, in this case from a depth of 30 feet in the middle of Loess 3.

TABLE VI.

HARDEN INDICES FOR PALEOSOLS, 53^{RD} STREET CORE

Paleosol	Horizon Development Index
Paleosol 4	0.09
Paleosol 3	0.26
Paleosol 2	0.42
Paleosol 1	1.05

Using the description of the Goble series soils mapped at this location (Green, 1983), the estimated Harden index for the modern soil ranges between 0.40 and 0.68. This variation is dependent on the soil properties chosen to represent Loess 4.

The implications of these values will be discussed below.

The average geochemistry of the paleosol intervals of the 53^{rd} Street core is shown in Figure 10. The samples averaged for this are 11.2 meters (37 feet) from Paleosol 3, 18 meters and 19.5 meters (60 and 65 feet) from Paleosol 2; and 25.9 meters (85 feet) from Paleosol 1. Figure 11 shows the average bulk geochemistry of all the 53^{rd} Street core samples compared to the five Palouse loess samples as well as eight selected Boring Lava samples of Barnes (1996) listed in Table IV.

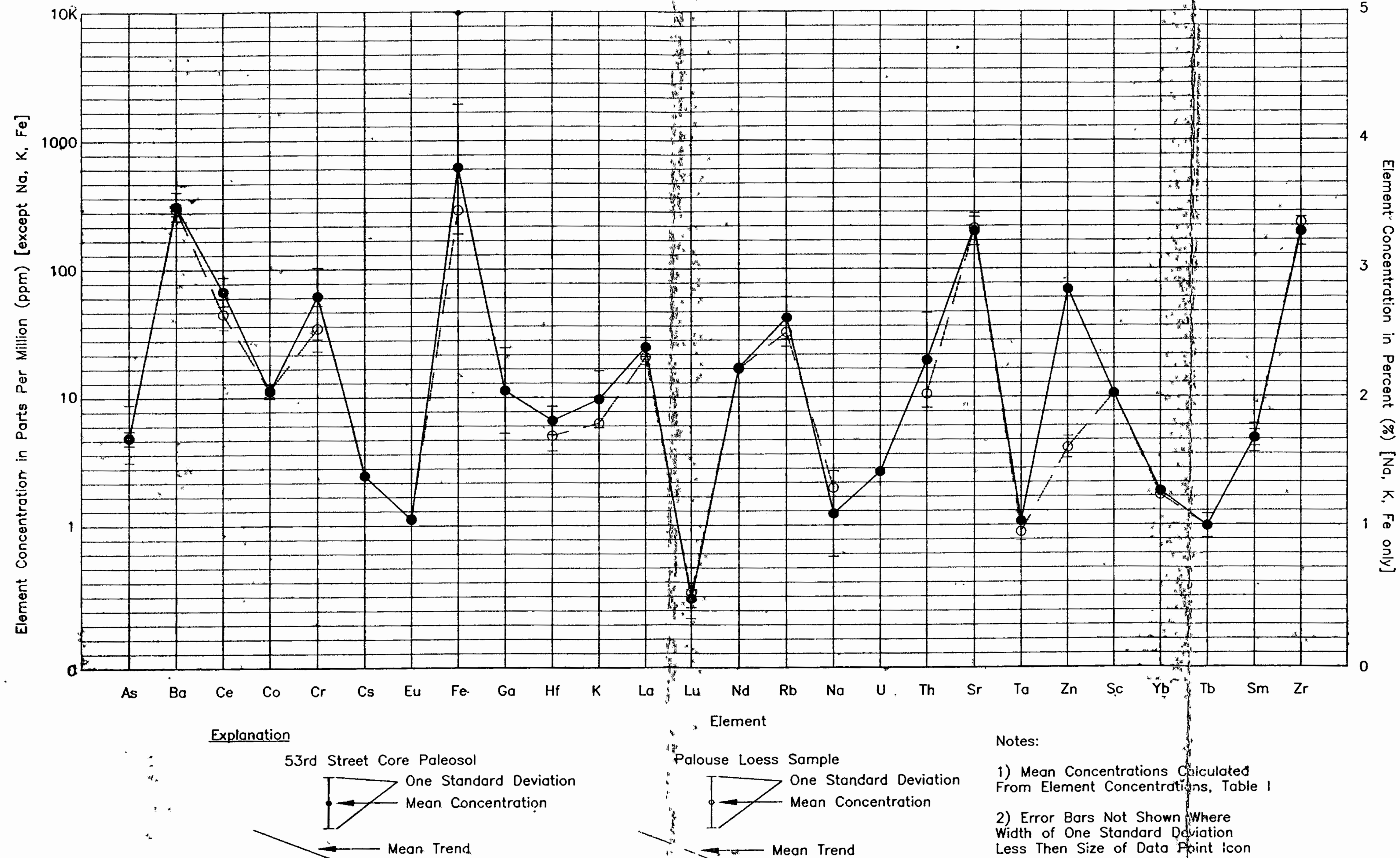


Figure 10: Average Element Concentration, Palouse Loess vs. 53rd Street Paleosols

Results and Discussion

When the average geochemical element concentrations (Figures 9, 10 and 11) are analyzed, several broad trends in the geochemistry of the 53rd Street core can be observed.

First, the geochemical similarity between the average element concentrations in Palouse soils and in the 53rd Street core is marked. Statistical analysis indicates that the concentration of the elements cerium, cobalt, europium, lanthanum, and strontium show a similarity between the two areas with confidence levels ranging between 86 percent (for cerium) to 99 percent (for lanthanum). Both the absolute abundances of thorium and scandium and the thorium/scandium ratio between the two populations are similar, and show clear differences from the data from the Boring Lava samples of Barnes (1996), as shown in Table VII.

TABLE VII.

THORIUM-SCANDIUM RATIOS FROM EIGHT SAMPLE GROUPS

Sample No.	Th (conc. Ppm)	Sc (conc. Ppm)	Th/Sc ratio
53rd St. Samples:			
5'/1.4m	8.6	13.2	0.65
25'/7.5m	9.9	9.8	1.01
37'/11.2m	15.9	14.4	1.10
45'/13.5m	13.5	11.7	1.15
52'/15.7m	14.2	13.1	1.08
60'/18m	11.5	11.1	1.03

TABLE VII.
(continued)
THORIUM-SCANDIUM RATIOS FROM EIGHT SAMPLE GROUPS

Sample No.	Th (conc. Ppm)	Sc (conc. Ppm)	Th/Sc ratio
53rd St. Samples (con't):			
65'/19.5m	13.3	12.5	1.06
70'/21m	13.4	12.7	1.05
75'/22.5m	14.4	13.9	1.03
80'/24m	11.1	10.3	1.07
85'/25.9m	12.8	13.8	0.92
Average 53rd St.:	12.6	12.4	1.01
Palouse Samples:			
DC-147	10.7	13.2	0.81
DC-179	12.4	10.6	1.16
DC-143	10.1	10.8	0.93
DC-107	7.8	12.3	0.63
DC-177	data not recovered		
Average Palouse:	10.25	11.7	0.88
Selected Boring Lava samples (Barnes, 1996):			
b556-57	1.6	6.18	0.25
b358-176	1.4	6.57	0.21
b358-28.5	1.7	6.09	0.27
b540-90	1.6	5.94	0.27
KA1	2.6	7.44	0.34
HWY26-2	1.9	6.6	0.28
ODOT-K108	1.6	5.83	0.27
B13-104.7	3.6	6.48	0.55
Average BL:	2.0	6.39	0.30
Selected Columbia River basalt sediment samples (Barnes, 1996):			
b563-212	4.4	45.3	0.09
B565-226	7.9	55.5	0.14
BVD4-36.5	4.9	37.3	0.31
Average CRB:	5.8	46.0	0.18
Selected High Cascades sediments (Barnes, 1996):			
b561-135	3.4	18.8	0.18
b557-211	2.6	17.4	0.14

TABLE VI.
(continued)
THORIUM-SCANDIUM RATIOS FROM EIGHT SAMPLE GROUPS

Sample No.	Th (conc. Ppm)	Sc (conc. Ppm)	Th/Sc ratio
High Cascades Sediments (Barnes, 1996) (Con't):			
GSD21015	4.9	18.4	0.26
Average HCS:	3.6	18.2	0.19
Columbia River Source Sediments (Barnes (1996):			
b557-114	8.7	11.3	0.77
b538-128	10.8	12.5	0.86
B565-214	11	16.1	0.68
BVD4-91.4	17.7	14.2	1.24
DHW-330	7.9	15.7	0.50
Blue Mud	5.6	18.9	0.29
PHS	10.3	13	0.79
Sand R. Mdstn	11.8	16.4	0.72
Average CRSS:	10.5	14.7	0.73
Young Columbia River Sediments (Barnes, 1996):			
MTD1-50	3.3	9.9	0.33
MTD1-155	4.3	9.2	0.46
MTD2-145	4.7	10.9	0.43
Average YCRS:	4.1	10.0	0.41
Hillsboro Drillhole samples (Barnes, 1996):			
60.5'(18.5m)	10.6	11.6	0.91
84'(25.6m)	10.8	14.9	0.72
131'(40m)	9.2	25	0.37
404.5'(123.6m)	10.4	12.9	0.80
714.8'(218m)	8.1	23.6	0.34
938.5'(286m)	12.8	45.6	0.28

The Hillsboro samples are two discrete materials: Willamette Silt above about 20 meters, underlain by Neogene sediments. It is inadvisable to average these groups.

Figure 12 shows the above relationship graphically in the scatterplot of the thorium-scandium ratio for all samples

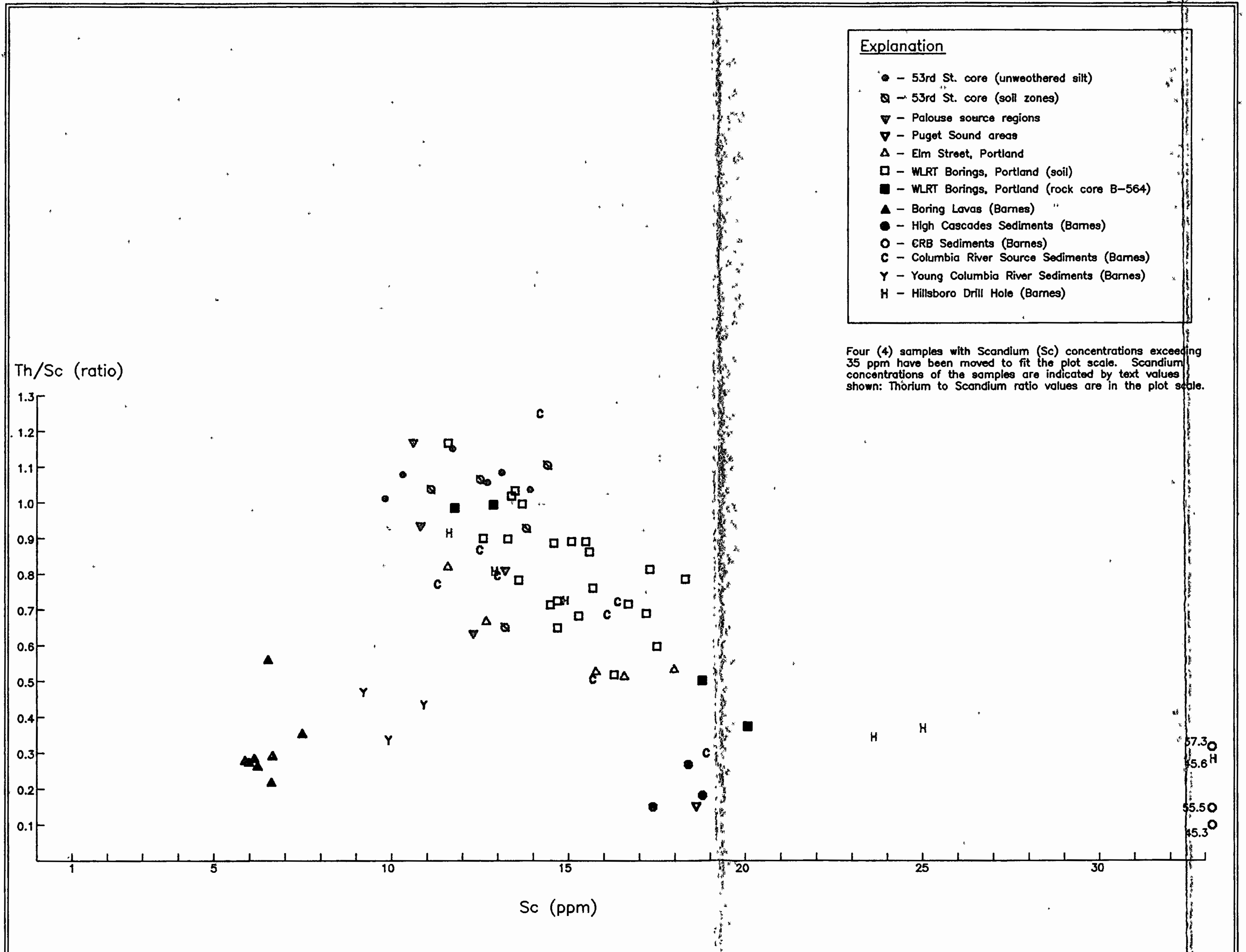


Figure 12

Scatter Plot: Thorium/Scandium Ratio v. Scandium Abundance (All Samples) in this study plotted against scandium abundance. The thorium-scandium plot can be referenced to Figure 11 to produce the second overall geochemical trend observed in this study so far. This is the overall geochemical dissimilarity between the "continental signature" sediments, typically showing a ratio of 0.75 to 1.1 Th/Sc. These "continental" sediments are composed of the Palouse, 53rd Street, the CRSS sediments and the upper 20 meters of the Hillsboro drillhole samples of Barnes (1996), versus the "arc-magmatic signature" of less than 0.5 to 0.15 Th/Sc observed in the basalts and basaltic andesites of the Boring Lavas, sediments derived from the Columbia River basalt and the High Cascades, and to a lesser extent the Younger Columbia River Sediments of Barnes (1996). The thorium-scandium ratio is not the only place in this study in which this distinction between the "continental" versus "arc-magmatic" samples is seen. The trend is observed in the scatterplot of the concentration of iron versus sodium shown in Figure 13, and in the scatterplot of thorium concentration versus hafnium concentration shown in Figure 14. In both plots the Boring Lava samples plot in a tight group, lower in thorium and hafnium, higher in iron and sodium, than the "continental" group of samples. Both plots show the affinities of the YCRS and HCS groups of Barnes (1996) to the more similar Boring Lava samples. T-test analysis shows that

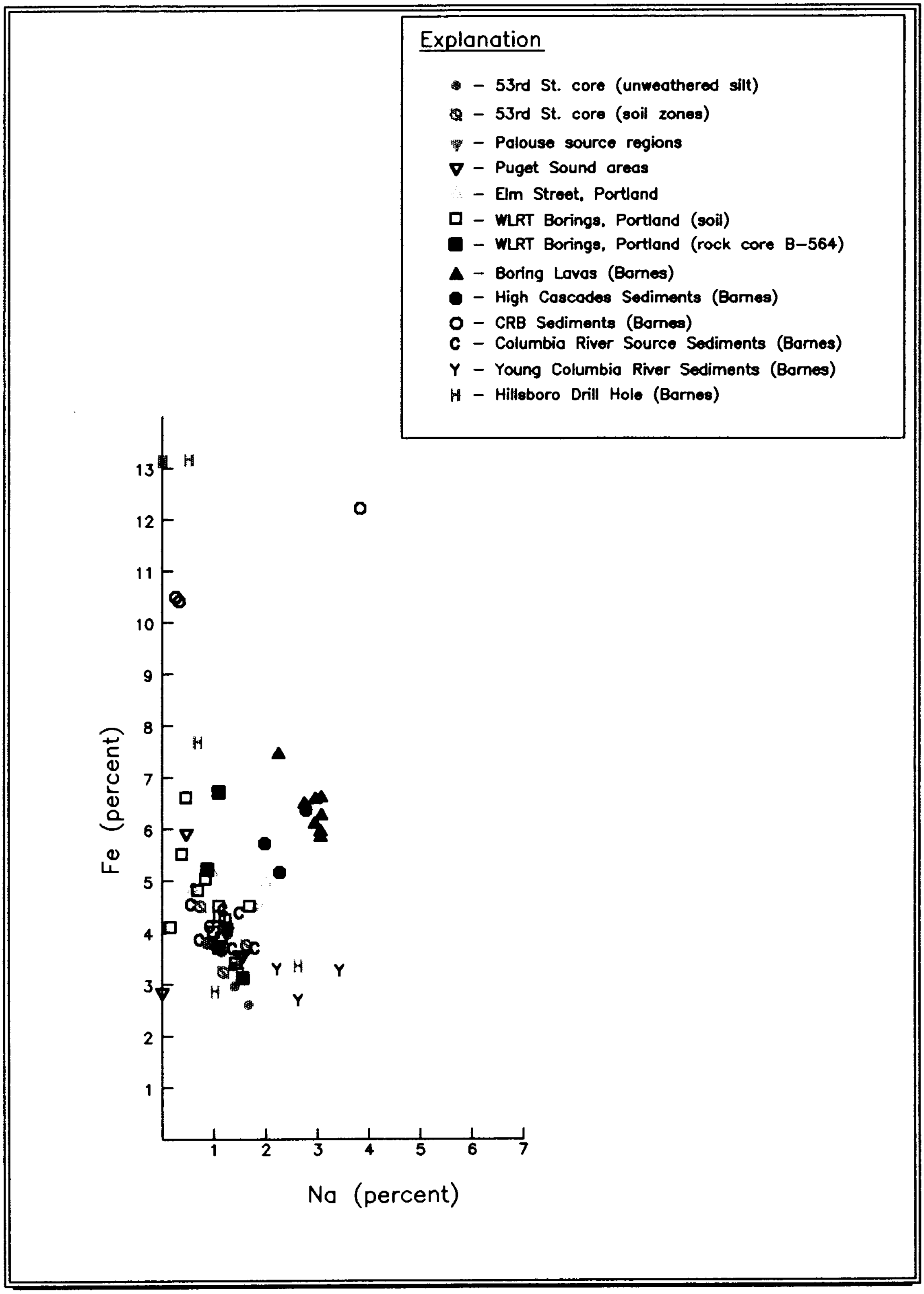


Figure 13

Scatter Plot: Iron v. Sodium (All Samples)

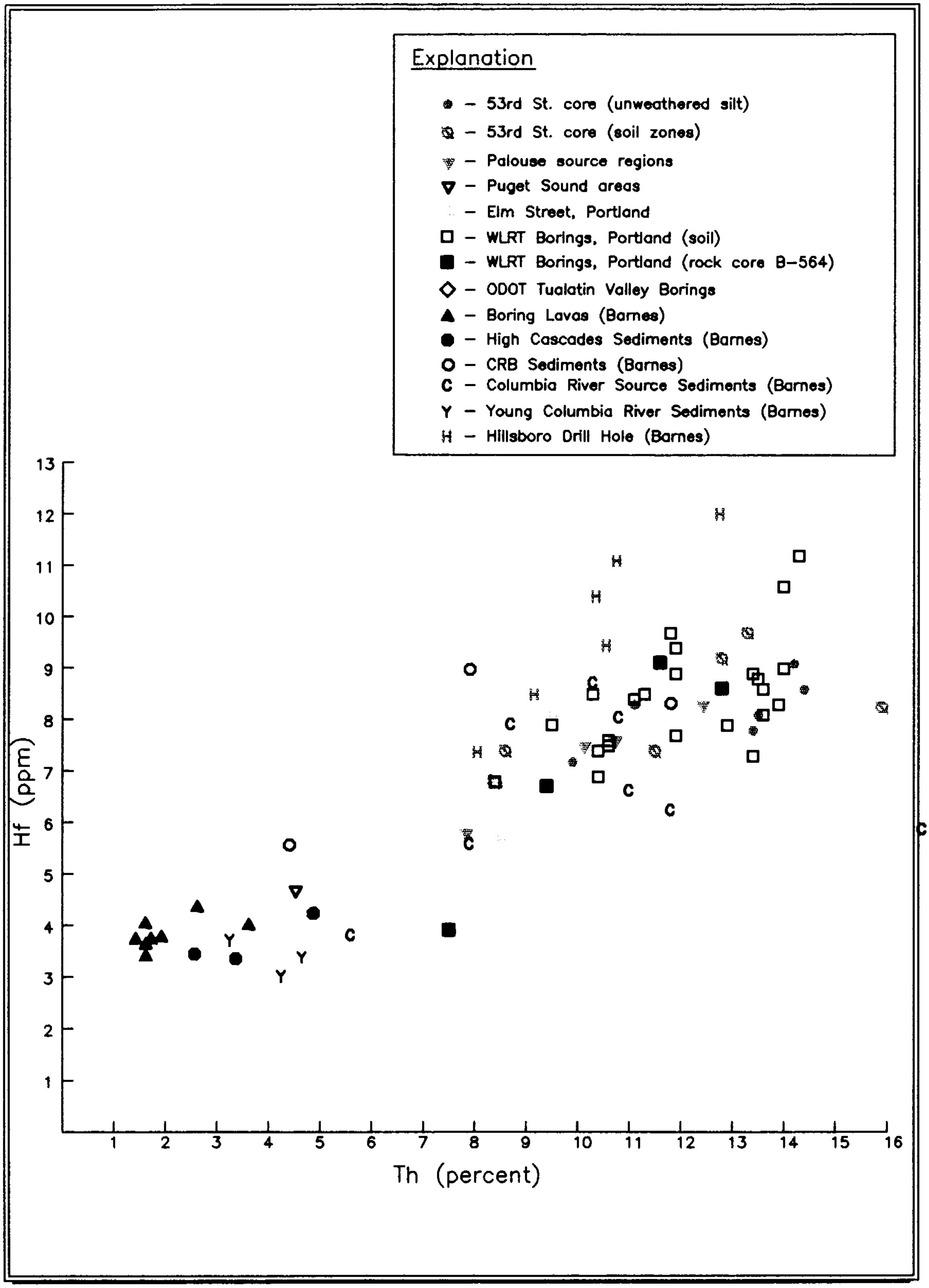


Figure 14

Scatter Plot: Thorium v. Hafnium (All Samples) the differences between the "continental" and "arc-magmatic" populations are statistically significant at a 100% confidence level.

Internal geochemistry in the 53rd Street core is more ambiguous. The core samples appear to "clump" together where iron, sodium, thorium-scandium or hafnium are plotted. Iron content appears to fall within a three percent range centered on 3.5 percent concentration. Hafnium content plots within a three ppm range, from 7 ppm to 10 ppm, inclusive. A scatter plot of the concentration of the element hafnium versus chromium is shown in Figure 15. Chromium content is somewhat more variable than iron or sodium, but still falls with a range between 50 and 100 ppm. Within these elements one finds no apparent geochemical segregation of the paleosols.

The element that does appear to show a systematic variation between loess and the paleosols produced in the loess is sodium. This segregation is not immediately recognizable from Figure 13, but does appear if the concentrations of this element are analyzed in detail, as in Table VIII:

TABLE VIII.

SODIUM CONCENTRATIONS, 53RD STREET LOESS VS. PALEOSOLS

Sample No.	Horizon	Sodium Concentration (ppm)
5'/1.4m	2Bwb	1.63
37'/11.2m	3Bwb	0.88
60'/18m	4Bwb	1.18

TABLE VIII.
(continued)
SODIUM CONCENTRATIONS, 53RD STREET LOESS VS. PALEOSOLS

Sample No.	Horizon	Sodium Concentration (ppm)
65'/19.5m	4Bwb/Cox?	0.96
85'/25.9m	5Btb	0.74
Average sodium concentration, paleosols:		1.08
25'/7.5m	Cu	1.66
45'/13.5m	Cox	1.38
52'/15.7m	Cu?	1.26
70'/21m	Cox/Cu	1.15
75'/22.5m	Cu	1.22
80'/24m	Cu	1.36
Average sodium concentration, loess:		1.34

Probability that these samples are derived from the same population (i.e., the null hypothesis Ho = Ho is valid):

f- test: 0.18 or 18%
t-test: 0.18 or 18%

Both f- and t-test results suggest that the variation in average sodium concentration between the loess intervals (1.34±.25 ppm) and the paleosols (1.08±.45 ppm) is statistically significant to an 82% confidence level. The depressed sodium concentrations of the paleosols would suggest leaching during soil formation. Movement of the alkali elements such as sodium, potassium, rubidium and cesium are "caused by an interplay of their high solubilities and absorption on colloidal materials" (Fairbridge, 1972, p.20).

The basal Paleosol 1 shows an increase in iron content, to 4.5 percent. This in itself is unsurprising, given the high iron content of the underlying basalt and the amount of basaltic residual soil that appears to be incorporated in this paleosol horizon. In addition, an increase in iron concentration is not diagnostic for soils, however, no such iron content increase is evident for Paleosol 3 or Paleosol 2 (3.3 and 3.2 percent iron, respectively). At a depth of 22.8 meters (75 feet) bgs, a portion of a pedologically immature loess zone, the deposit contains four percent iron. Other geochemical species show a similar lack of overall segregation into "soil" and "parent material" chemical suites. The lack of segregation or concentration of elements that are typical indicators of weathering, such as iron, in the paleosols suggests that these elements have not been eluviated. This conflicts with the observed rubification and structural changes observed in the soil zones: clearly some translocation of iron has occurred. This disparity between visual and geochemical analyses may be an indicator that the iron films and coatings, although pedologically apparent, are not being visualized by INAA.

In addition to the geochemical data, grain size analyses indicate that the distinction between paleosol and loess is not sedimentologically large. Clay content never exceeds twice the overall core average of 12.6 percent, and is seldom located consistently in otherwise recognizable paleosol zones (see Table IV). Paleosols 4 and 1 do indeed show increased clay materials ranging from 2 to 9 percent above the average, but no such clear distinction is seen in the core interval between the top of Paleosol 2 at 10 meters bgs and the top of Loess 1 at 19 meters bgs. This interval is distinguished by:

- low clay content throughout Paleosol 3, indistinguishable in this respect from the 8 to 9 percent clay content observed in the underlying upper 2 meters of Loess 2.
- A sudden increase in clay mineral content at a depth of 15.8-16 meters bgs, is a portion of Loess 2 that shows little or no other pedogenic structure.
- Little clay content differential between Paleosol 2, the base of Loess 2 and the upper portion of Loess 1 (the interval between 15.8 meters and 19.8 meters bgs).

Conclusions

The geochemistry of the DOGAMI 53rd Street borehole allows us to place this group of samples into the somewhat amorphous geochemical grouping of silty sediments of a "continental" (0.8 to 1.15 Th/Sc thorium-scandium ratio) signature. This group includes potential source area sediments such as the Palouse soils of eastern Oregon and Washington as well as the Columbia River Source Sediments of Barnes (1996). This is in accord with the conventional assessment of the Portland Hills Silt as a silty loessal deposit of continental origin.

Can anything be deduced about the age and pedologic history of the silt cored in this boring, along the western crest of the Tualatin Mountains? The question of the immaturity of the 53rd Street paleosols is raised by several factors: the generally homogeneous geochemistry of the core, the relatively low variability of silt and clay content between the paleosol zones and the loess parent materials, and the indications of pedologically juvenile paleosols.

Pedologically, physical indicators of soil maturity such as structure, darkening, increased hardness/firmness, reddening and clay films suggest that the 53rd Street paleosols have reached a level of soil development consistent with Inceptisol soils (Birkeland, 1984). These soils require approximately 10,000 to 15,000 years to develop, depending on the climate, vegetation and a variety of other factors (Birkeland, 1984).

One early indicator of geochemical weathering, alkali element concentration, suggests that relatively little eluviation has occurred in the 53^{rd} Street paleosols. Sodium, least strongly sorbed, is among the first of these alkali cations to be leached. Although the depressed sodium anomaly can be clearly seen in the 53rd Street paleosols, there are other alkali elements that are progressively leached with increased time and weathering. The sequence of this eluviation is determined by the relative ratios of ionization potential vs. hydrated ion radius (Fairbridge, 1972). It is instructive to observe that while the ratio of sodium concentration in the paleosols to the parent loess is 1.08 ppm to 1.34 ppm (0.8:1), the ratio of the more strongly sorbed alkali cations shows little if any variation:

TABLE IX.

ALKALI ELEMENT CONCENTRATION, PALEOSOLS VS. LOESS, 53RD STREET BORING

Sample type	Element	Average Concentration
Paleosol	potassium	1.98±.38
Loess	potassium	2.04±..77
	potassium P/L ratio:	0.97:1
Paleosol	rubidium	66.9±.18.5
Loess	rubidium	65.6±14.3
	rubidium P/L ratio:	1.01:1

These cations are listed in increasing sorption potential: cesium is not analyzed due to the small sample field. The higher-ionic potential cations, theoretically eluviated in turn as weathering increases, do not show the depressed sodium concentration observed in the 53rd Street paleosols. Thus, geochemistry appears to argue for geologically young or pedologically immature soils.

The clay content evidence appears to compliment this assessment. When compared to similar studies of loessal soils (Ruhe, 1969; Norton and others, 1988), little increase in clay content is seen in the cambic and argillic horizons in the 53rd Street boring paleosols. Ruhe (1969) showed that clay fraction in argillic horizons formed in Wisconsin (modern) soils increase by between two and three times, from 25 percent to between 35 and 55 percent. This study shows a similar degree of clay content increase in Sangamon soils formed in older (Illinoian) loess. In a study of three Midwestern loess deposits, Norton and others (1988) observed similar intense illuviation in the Sangamon paleosols, with argillic development reaching 40 percent. In contrast, clay content increases of 6 to 12 percent seen in the 53rd Street paleosols suggest that soil development at this location was not as well developed as even the younger (Wisconsin) loess soils of Ruhe (1969). These clay mineral concentration anomalies are difficult to explain unless one assumes the hypothesis that a low degree of soil development and clay illuviation has occurred through the period during which Paleosols 2 through 4 were developed. The general pedologic features are similar to those reported for the paleosols in the eastern Palouse region by Busacca (1991), in particular the Palouse cambic horizons, colored 10YR to 7.5YR, with clay contents between 5 percent and 20 percent higher than the inferred clay content of the parent loess.

Harden horizon development indices (HDI) for the 53rd Street paleosols are 0.09, 0.26, 0.42, and 1.05, in order of youngest to oldest. This compares favorably with the 0.1 to 0.3 HDI values derived by Harden (1982) for Holocene soils and values of 0.2 to 0.4 for late Pleistocene Riverbank Formation soils. The typical horizon index values of 0.4 to 0.8 for the 3 Ma Turlock and Laguna Formation soils are consistently higher than those observed for the three upper 53rd Street paleosols (Harden, 1982).

Care should be taken with the use of soil maturity as in indication of age, and the pedologic evidence presented in this study is intended as no more than support for the geochemical data analysis. Rates of soil development differ markedly with climate and are both intrinsically variable and tend to increase with increased precipitation (Vidic, 1997). The Harden (1982) HDI values are from a thermic, xeric climate zone with mean annual temperatures of 16 degrees Celsius and mean annual precipitation of 41 centimeters, less than half the modern rainfall of the Portland region.

The low HDI values observed in the 53rd Street paleosols may well point towards even younger, less mature soils than the comparison with the Harden (1982) HDI values for the

Merced River soils would suggest. These data do not stand alone, however, given the problems of age control and small differences observed between soils of advanced ages (Vidic, 1997).

Development in soil dating and revision of Puget Sound glacial drift stratigraphic column (Easterbrook, 1994) adds complications to the soil stratigraphy proposed by Lentz (1977). This is illustrated in Figure 15, contrasting the two stratigraphic columns. The revised age-dates of Easterbrook (1994) in the Puget Sound and Busacca (1991) suggest paleosol formation in the Portland Hills Silt should be considered to have begun as early as the early Pleistocene (before 1 to 1.6 Ma). This brings Lentz's (1977) identification of the ages of his paleosols in question. If, for example, the oldest paleosol is associated with climatic conditions in Orting Drift time, why is this paleosol not more mature? Million-year-old soils on the Tertiary marine sediments associated with the Eola surface in the Willamette Valley are Oxisols and Ultisols, very mature soils (Michael Cummings, personal communication, 1993). The implications for Lentz's (1977) soil stratigraphy are inauspicious: it is the opinion of this investigator that that stratigraphy should be abandoned.

Another source of variability in PHS soil development should be considered. Recent observations of soil and

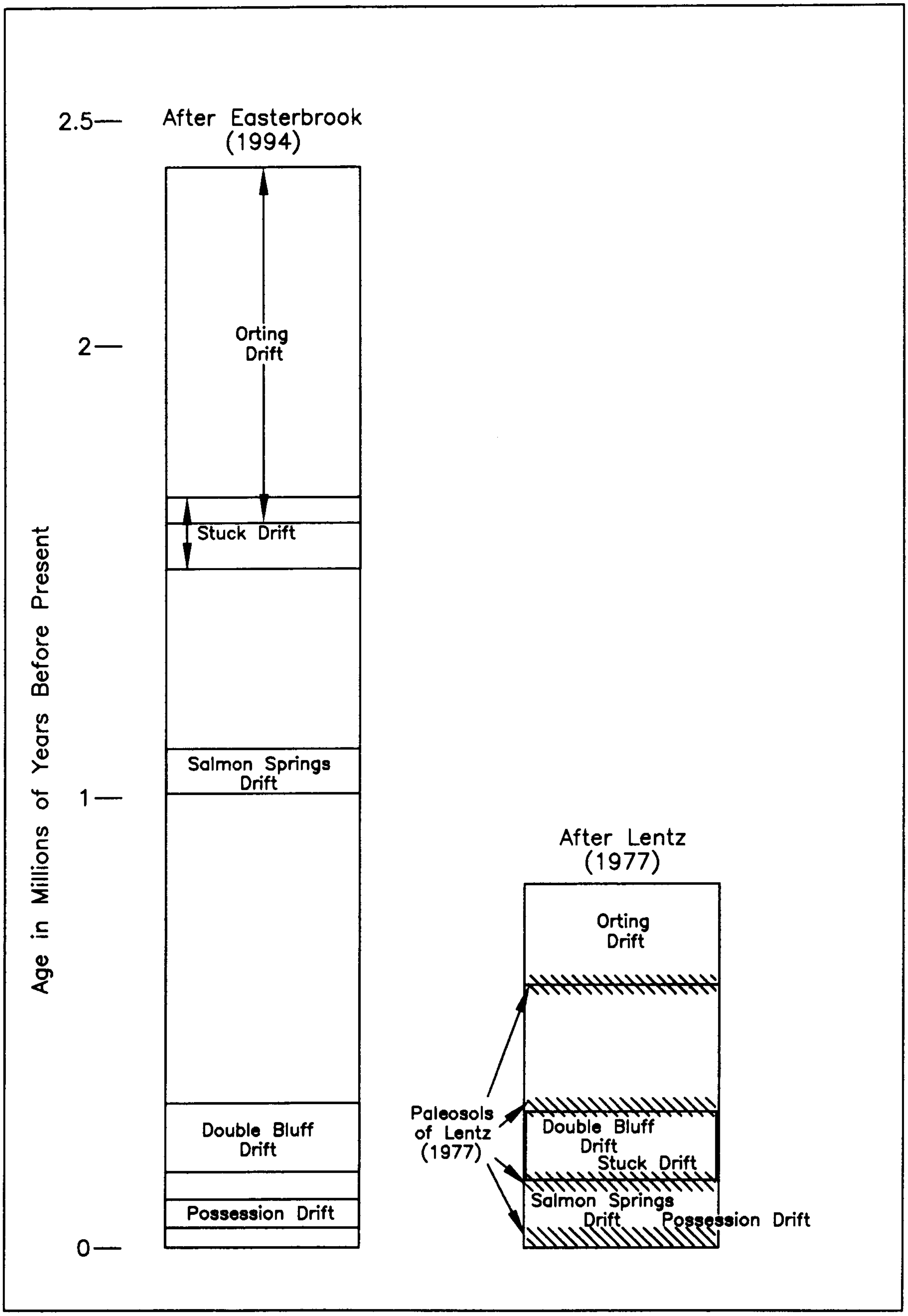


Figure 15 Comparative Puget Sound Glacial Chronology

paleosol development in the Portland Hills Silt have raised questions about the effect of microclimates on soil development. Soils developed in Portland Hills Silt observed at other locations, have shown higher clay content as well as the better rubefication and clay film development. It is interesting to speculate on the reasons that these sites have been located on south- and southwest-facing slopes such as the S.W. Highland Terrace site, where a landslide headscarp was observed on what was identified as the more mature of two paleosols in the uppermost five meters of Portland Hills Silt. (Scott Burns, personal communication, 1996). Soil formation in this sediment appears to be influenced by small-scale variations in rainfall, sunlight and slope angle. The location of the 53rd Street site in a shaded canyon on the "rain-shadowed" eastern slope of the West Hills may well be the major factor behind the contrast between the soil development at that location versus that occurring on the warmer, moister west slope side.

Pedogenic processes alone appear inherently too variable to permit speculation on absolute age and maturity of the 53rd Street paleosols. The combination of geochemistry and soil development is a strong argument looking at the 53rd Street paleosols in a similar light to the paleosols studied by Busacca (1991). These soils are Inceptisols developed in a loess parent material during periods of cool temperatures and relatively little rainfall. Interestingly, this would correspond to the working hypothesis of Foley (1982), which postulates that interglaciation and flooding result in high sediment supply and rapid loess deposition, while glacial maxima are times of sediment stability and soil development. For all of the above reasons, this investigator believes that the soil stratigraphy of Lentz (1977) should be revised. Additional work is required to produce an updated chronosequencing Portland Hills Silt soils - this is discussed in Recommendations for Future Work.

The 53rd Street core can be seen as a record of four periods of loess deposition starting with a basalt paleosol developed on the underlying basalt. Each of these periods was separated by a depositional hiatus in which a soil was developed on the loess parent material. These soils are better seen morphologically than geochemically, but in both cases appear to be less mature than many other PHS soils and paleosols observed elsewhere, particularly on the south- and southwest-facing slopes of the Sylvan area. Why are these soils so poorly developed. One key observation may be the mottling observed in Paleosol 3 and the saturation of the upper 15 meters of the site. This location appears to be relatively poorly drained. The site is also on the shaded, east- to northeastern slopes of the Tualatin Mountains. The combination of a poor drainage and cool soil temperatures may well have led to the low level of soil development observed at this location.

WEST SIDE LIGHT RAIL PROJECT TUNNEL (WLRT) BORINGS

The WLRT Project Area

The geotechnical investigation for a proposed commuter light rail (this being the current euphemism for "trolley") line tunnel under the West Hills produced more than eighty geotechnical borings and core drillholes (Squier, 1993). These borings were performed over the two year investigation period by a combination of private drillers and crews from ODOT and Tri-Met; the borings being observed and logged by geologists from the private geotechnical firm of L.R. Squier and Associates (Squier, 1993). These borings represent a unique look at the geology of the Portland West Hills, both in cross-section and map coverage of the approximately 2.9-mile (4.7 kilometer) -long section of the West Hills proposed for the site of a twin-tube railroad tunnel. The east entrance of this tunnel is located in the northeast slopes of a ridge located west of the S.W. Jefferson Street/Highway 26 onramp (Figure 1). The tunnel roughly parallels Canyon Road (State Highway 26) between this so-called "east portal" and the western entrance ("west portal") located immediately north of Highway 26 at S.W 76th Avenue in the Sylvan Hills district of the city of Portland. The WLRT borings are located along this

15,500-foot-long (4,725 meter) alignment, ranging in depth from less than 30 feet (10 meters) to several borings in excess of 250 feet (80 meters). These borings penetrate the stratigraphic record of the West Hills from the Holocene surface soils to the 15.8 Ma Winter Water Unit of the Grande Ronde Basalt of the CRBG (Squier, 1993).

The Sandy River Mudstone-Equivalent in the WLRT

Within the data field amassed by these borings are some interesting stratigraphic questions. One of these questions is shown graphically in Figure 16, adapted from a portion of the stratigraphic cross-section of the West Hills contained in the WLRT geotechnical report (Squier, 1993, Figure 5). Specifically, this question pertains to the material identified in Squier (1993) as "Sandy River Mudstone equivalent". This sediment is labeled "SRM" and colored magenta in Figure 16. Note the location of the SRM-equivalent materials in Borings B-564 and B-563 in Figure 16, particularly the thick sequence of material logged in the former from elevation 550 feet to 480 feet MSL, above the Basalt of Frenchman Springs. To the west, B-563 records SRM-equivalent immediately below the Portland Hills Silt, around elevation 700 feet MSL. The identification of this sediment

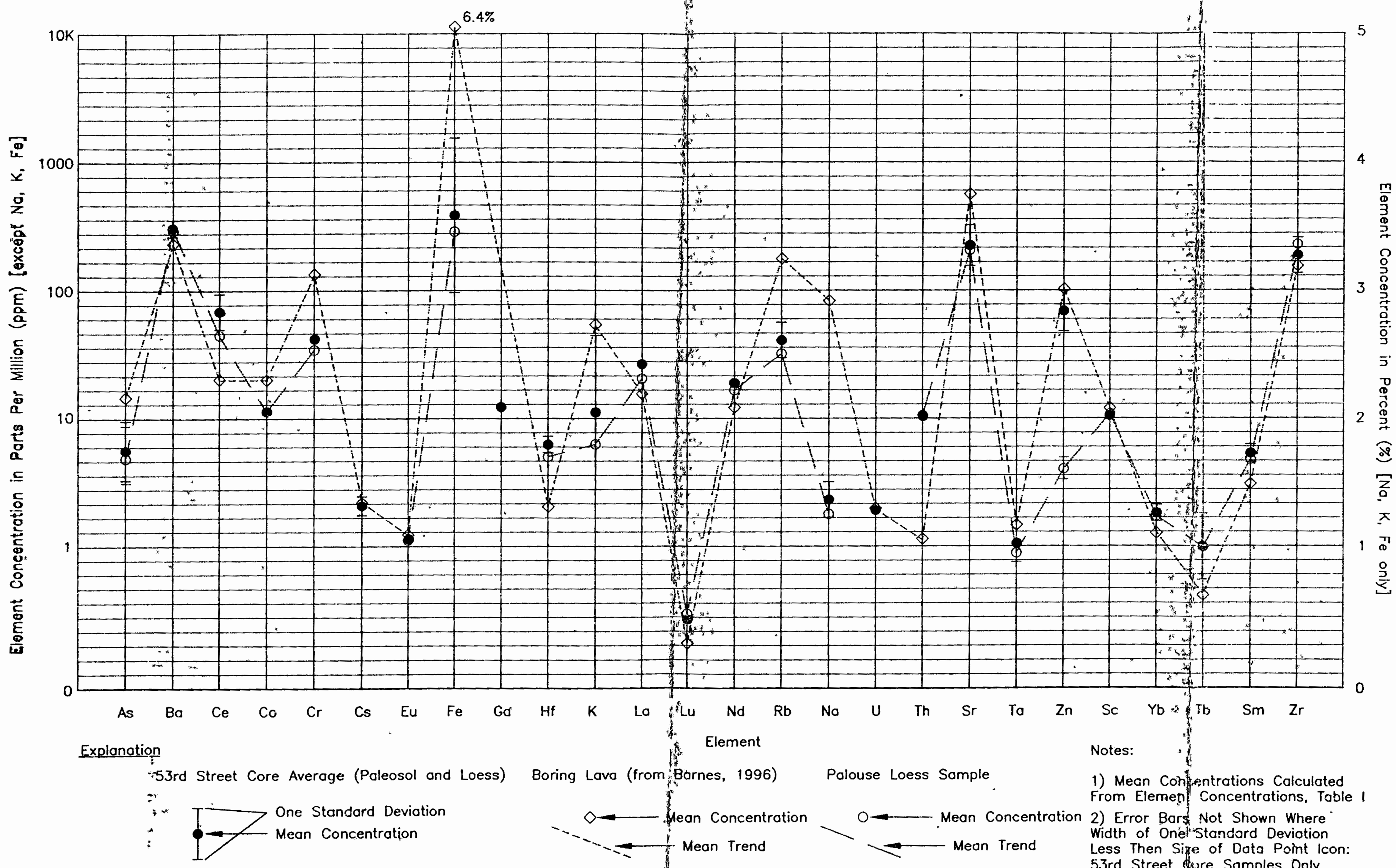


Figure 11: Average Element Concentration, Palouse and 53rd St. vs. Boring Lavas of Barnes (1996)

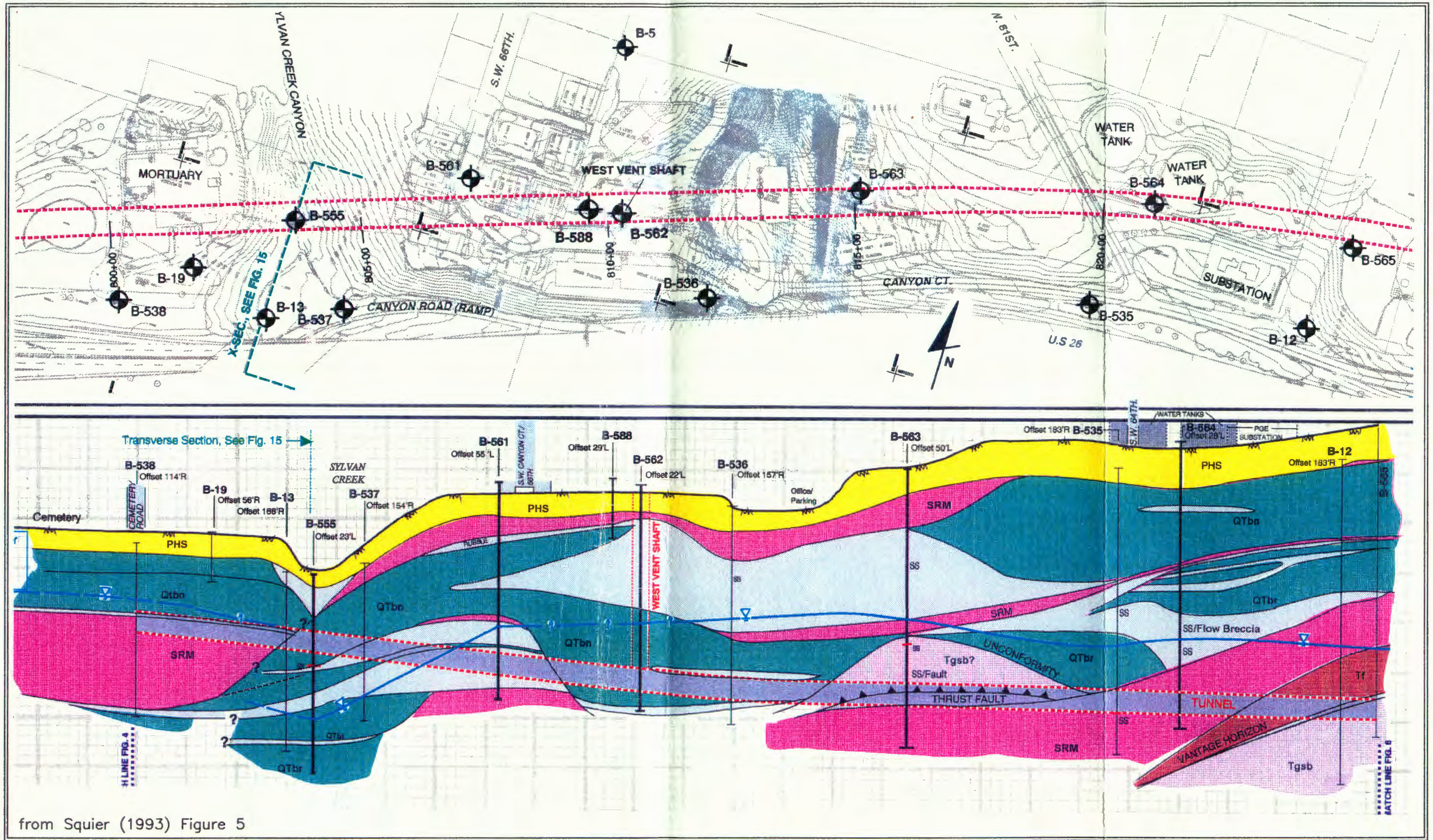


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Figure 16 Geologic Cross-Section of Squier (1993) raised the question: what were materials associated with Pliocene "lake beds of silt or very fine sand" (Trimble, 1963, p.27) doing at or near the crest of what has been reported as a topographic highland as early as 15 to 20 millions years old (Beeson and others, 1989)? Could these fine-grained sediments be high-water onlaps of SRM, or is it more likely that these are loessal silts and fine sands of the Portland Hills Silt?

To attempt to help answer this question, a total of 26 samples was taken from five of the geotechnical borings drilled for the WLRT Project. These borings and a summary of the samples taken from each are described below in order of east to west. A detailed description of the samples taken from this suite of borings is contained in Table I.

WLRT Boring B-574

This boring was drilled September 12, 1992 on the upper slopes of the northeast-sloping ridge overlooking the WLRT East Portal, at WLRT tunnel station number 927+81.2 (Appendix A, Figure A-1). The ground surface elevation at the drillhole is recorded as 336.9 feet (102.6 meters) MSL. The boring penetrated 35.2 feet (10.7 meters) of Portland Hills Silt overlying 10.4 feet (3.1 meters) of dark red-brown silty clay which is identified on the log as Sandy River Mudstone equivalent. At the base of this sediment the boring encountered basalt identified as the Sentinel Bluffs unit of the Grande Ronde Basalt (Figure A-1). The boring is recorded as terminating in this basalt at a depth of 135.9 feet (41.2 meters) in the Sentinel Bluffs unit.

Five samples were taken from this boring; two, S-2 and S-3, from what is clearly Portland Hills Silt; another two, S-6 and S-8 from a mottled, clay-enriched zone between 21.2 feet and 35.2 feet (6.4 meters and 10.7 meters) bgs; and the bottom sample, S-9, from the top of the "SRM-equivalent" zone at 35.2 feet (10.7 meters) bgs.

These samples were intended to provide geochemical data for a known PHS as well as "SRM-equivalent" in apparent depositional contact with the loess.

WLRT Boring B-525

This boring was drilled March 14, 1992 on a gently-sloping south-trending ridge along the former Kingston Drive (current alignment of the Portland Zoo railroad) near WLRT tunnel station number 911+26.3 (Appendix A, Figure A-2). The boring was drilled with a hollow stem auger to auger refusal on basalt at 74.9 feet (22.8 meters) bgs and cored from that depth to TD. The ground surface elevation at the drillhole is recorded as 539.5 feet (164.4 meters) MSL. The boring penetrated 39.0 feet (11.8 meters) of mottled red-brown and gray Portland Hills Silt overlying 27.0 feet (8.2 meters) of dark red-brown silty clay which is identified on the log as

Sandy River Mudstone equivalent. At the base of this sediment the boring encountered an 8.9 feet (2.7 meters) thick residual soil layer developed on basalt identified as the Sentinel Bluffs (M2) unit of the Grande Ronde Basalt (Figure A-2). The boring is recorded as terminating in this basalt at a depth of 280.0 feet (85.43 meters) in the Winter Water unit of the Grande Ronde Basalt.

Six samples were taken from this boring: three, S-2, S-5 and S-6, from what is identified as Portland Hills Silt above 35 feet (10.5 meters), and three more; S-8, S-10 and S-12, from the "SRM-equivalent" zone ranging in depth from S-8 at 41 feet (12.4 meters) to S-12 at 61 feet (18.5 meters). Interestingly, the boring log records sample S-10, taken from 51 to 52.5 feet (15.5 to 16 meters), as a "stiff, mottled gray clayey silt, *micaceous;* moist".

These samples were intended to provide geochemical data for a stratigraphic section similar to that in B-574.

WLRT Boring B-527

This boring was drilled February 18, 1992 on the southwest-facing slope of the broad hilltop northeast of the Washington Park Zoo, at Light Rail station number 893+44.5 (Appendix A, Figure A-3). The ground surface elevation at the drillhole is recorded as 683.1 feet (208.2 meters) MSL. The boring penetrated 35.0 feet (10.6 meters) of light brown to brown mottled gray and red-brown Portland Hills Silt overlying 8.8 feet (2.7 meters) of orange-brown silty clay to lean clay which is identified on the log as Sandy River Mudstone equivalent. At the base of this sediment the boring encountered basalt identified as the Sentinel Bluffs (M1) unit of the Grande Ronde Basalt (Figure A-3). The boring is recorded as terminating in this basalt at a depth of 340.0 feet (103.6 meters) in the Winter Water unit.

Six samples were taken from this boring but only four were irradiated. Three, S-2, S-6 and S-7 were taken from what is identified on the boring log as Portland Hills Silt. An fourth sample, S-9 was taken from a stiff, orange-brown mottled gray, silty clay to (lean?) clay zone between 35.0 feet and 43.8 feet (10.6 meters and 13.3 meters) bgs identified on the log as the SRM-equivalent.

These samples were intended to provide geochemical data for a known PHS sequence, with the additional sample S-9 included to serve as both a check on the "SRM-equivalent" as well as the possible effect of mixing of PHS with residual soils formed on basalt.

WLRT Boring B-530

This boring was drilled in February, 1992 on a level plateau or cut bench on the southwest-facing slopes of the hilltop in the Highland District of Portland. The boring is located southeast of S.W. Highland Road approximately 80 feet (24 meters) southwest of the intersection with S.W. Strathfell Lane, near WLRT tunnel station number 864+20.3 (Appendix A, Figure A-4). The boring is believed to have been drilled with a hollow stem auger to auger refusal on basalt at 145.4 feet (44.3 meters) bgs, and cored from that depth to TD. The ground surface elevation at the drillhole is recorded as 724.6 feet (220.8 meters) MSL. The boring penetrated 54.0 feet (16.4 meters) of yellow, yellow-brown and brown Portland Hills Silt overlying 66.0 feet (20.1 meters) of orange-brown, yellow-brown, brown and gray silt, silty clay and (lean?) clay which is identified on the log as Sandy River Mudstone equivalent.

It must be added that at least the location of, if not the stratigraphy below, this contact is clearly in error. The description for sample S-12 mentions "iron oxide nodules", that is, the Fe/Mg shot concretions typical of the Portland Hills Silt. The identification of the underlying unit as "SRM-equivalent" appears to have been based on the amount of clay as well as the presence of sand and gravel debris described as "rock fragments" (observed during the sampling for this study to be largely basaltic appearance). Based on observation of these samples, as well as conversations with the geologist preparing the as-built report for Parsons-

Brinckerhoff (Ken Walsh, Parsons Brinckerhof, personal communication, 1996), it is proposed that this entire interval from 54 to 120 feet (16.4 to 36.5 meters) bgs be classified as reworked PHS colluvial or slope deposits.

At the base of the slope deposits, B-530 encountered a 25.4 feet (7.7 meters) thick residual soil layer developed on basalt identified as the Basalt of Ginkgo of the Frenchman Springs Member of the Wanapum Basalt (Figure A-4). The boring is recorded as terminating at a depth of 305.0 feet (92.9 meters) in the Sentinel Bluffs unit of the Grande Ronde Basalt.

Seven samples were taken from this boring, all but the lowermost from what is identified on the boring log as Portland Hills Silt. Of these samples, S-2, S4 and S-5 are taken in the uppermost interval of silt from the surface to a depth of 24 feet (7.3 meters). Sample S-6 was taken from what is interpreted as a buried soil (Btb) horizon at 25 to 26.5 feet (7.6 to 8.1 meters). Sample S-9 was taken from the yellow-brown, silty loess interval (Cub) that was encountered from the base of the upper buried soil to the top of the slope deposits at 54 feet (16.4 meters) bgs. Sample S-11 was taken from what appears to be another paleosol (Bt2b) on the top of the slope deposits at 50 to 51.1 feet (15.2 to 15.6 meters). The lowest sample, S-12, was taken from the upper portion of the slope deposits at 55 to 56.5 feet (16.7 to 17.2 meters) bgs.

These samples were intended to provide geochemical data for a "pure" PHS stratigraphic section including at least two paleosols, similar to the section encountered in the 53rd Street core.

WLRT Boring B-564

This boring was drilled September 14, 1992 on the western portion of the broad top of the West Hills in the Sylvan district of Portland. The boring is located immediately southwest of and adjacent to the eastern of the two water reservoir tanks east of S.W 61st Street near WLRT tunnel station number 821+4.9 (Appendix A, Figure A-5). The boring was drilled with a hollow stem auger to auger refusal on basalt at 45 feet (13.7 meters) bgs and cored from that depth to TD. The ground surface elevation at the drillhole is recorded as 782.3 feet (238.4 meters) MSL. The boring is logged as penetrating 42 feet (12.8 meters) of stiff, gray-brown Portland Hills Silt. At the base of this sediment the boring encountered 84.6 feet (25.7 meters) of basalt identified as 0.86 Ma, normal polarity Boring Lava (Conrey and others, 1996) (Figure A-5). A 6.3 feet (1.9 meter) thick interval of "SRM-equivalent" is recorded from 125 feet to 131.9 feet (38.2 to 40.2 meters) bgs. Below this sediment, the log records penetration of basalt flows and flow breccias of a 0.96/0.97 Ma reversed-polarity Boring Lava (Conrey and others, 1996) to a depth of 228.5 feet (69.6 meters) bgs. At this depth the boring begins coring a dark gray-green to light orange and light tan micaceous silt that is identified as "SRM equivalent". The boring is recorded as terminating in this sediment at a depth of 296.8 feet (90.4 meters).

Four samples were taken from this boring. One, R-18, was taken from the upper "SRM-equivalent" interval interbedded between the Boring Lava units at a depth of 130 feet (39 meters) bgs. The other three samples were all taken from the lower "SRM" interval underlying the 0.96/0.97 Ma Boring Lava (Conrey and others, 1996) ranging in depth from R-42 at 246 feet (73.8 meters) to R-51 at 286 feet (85.8) meters. The boring log also records both the presence of mica and "nodules of FeO" in this cored interval.

These samples were intended to provide geochemical data for much older silts, currently identified as "SRM-equivalent" but believed to be more accurately an older, "PHS-equivalent" loess deposit.

Sample Characteristics

U.S.C.S. classification of the WLRT soil samples ranges from silt (ML) through clayey silts and silty clay to lean clay (CL). Trace amounts of fine sand are commonly observed as well as ferromagnesian shot-concretions and what Squier (1993) describes as "organics", presumably traces of woody plant debris such as bark or wood fragments, root traces and remnants of leaf litter. In an interesting coincidence, what is described as a "cobble" is reported at a depth of 29.5 feet (approx. 10 meters) bgs in B-527, similar depth to the 65mm basalt gravel found during sampling of the DOGAMI 53rd Street core.

Portland Hills Silt is logged in four of the five WLRT borings sampled in this study at or near the ground surface. The log of B-564 does not record the nature of the uppermost 42 feet (12.5 meters), but the description of the auger cuttings suggests that PHS was encountered in this boring, as well. The sediments drilled in these borings are typical PHS: brown to yellowish brown, massive, micaceous silts.

Several possible paleosol zones are recorded on the boring logs as having been encountered within the PHS. A 1.6 meter (5 feet) red-brown and gray mottled clayey layer is logged at between 24 feet (8 meters) and 29 feet (9.6 meters) bgs in B-525. Sample S-5 was taken from the middle of this interval. Another, 1.2 meter (4 feet) suspected paleosol is shown from 24 feet (8 meters) to 28 feet (9.2 meters) in B-530. It is worth noting that samples S-11 and S-12, split-spoon samples taken from Boring B-530 at a depth of 15 meters and 16.5 meters bgs, respectively, displayed a weak subangular blocky structure, ferromagnesian shot-concretions and well-developed, thick clay films. Both samples were an orange-brown color. The former sample is identified as having been taken from the base of the PHS, while the latter is identified as SRM.

Squier (1993) divides these silty and clayey soils between an overlying Portland Hills Silt and an underlying Sandy River Mudstone by what appears to be the clay content and physical appearance of the sediments. The contact does not appear to be fixed vertically. In B-525, "SRM-equivalent" is encountered below PHS at 39 feet (12 meters) bgs. The mudstone extends from that depth to the top of the Sentinel Bluffs (M2) unit of the Grande Ronde Basalt. In B-527 an three-meter thick sequence of SRM is interbedded between PHS and the top of the Sentinel Bluffs (M1) flow at 44 feet (13 meters) bgs. A 3.2 meter (10 feet) thick interval of SRM is encountered in B-574 between the bottom of the PHS at 35 feet (11.5 meters) bgs and the top of the Sentinel Bluffs basalt at

45.6 feet (14.7 meters) bgs. The top of the SRM is logged at 54 feet (16.5 meters) bgs in Boring B-530

The "Sandy River Mudstone" logged in the rock core of Boring B-564 is variable in color, from the approximately 6-feet thick baked red interbed of sample R-18 to the dark green to light tan massive, micaceous silts of samples R-42, R-45 and R-51. All of these samples share a similar silty to clayey silt (ML) texture and the presence of ferromagnesian concretions and mica. The lowermost sample, R-51, is in a zone that has been observed during the Light Rail tunnel construction. This portion of the deposit appears to be finely stratified or laminated and contains some small rip-up clasts of the underlying, massive micaceous siltstone that appears remarkably similar to the PHS. The geologist logging this section of the tunnel considers this sample to be part of a reworked local fluvial deposit predominantly derived from PHS materials (Ken Walsh, Parsons Brinckerhof, personal communication, 1996).

RESULTS AND DISCUSSION

Samples Grouped by the Lithology of Squier (1993)

The WLRT samples can be split into two groups, whose sample composition depends on the hypothesis used in this division. Initially, the samples were broken down into two lithologic groups, as they are in the cross-section stratigraphy of Squier (1993), by apparent stratigraphic relationship. In this system, the first group consists of samples identified by Squier (1993) and confirmed by observation during sampling for this study as Portland Hills Silt. These soil materials are, generally speaking, silts (ML) to lean clays (CL) encountered in the uppermost 10 to 15 meters of the first four of the five borings listed above.

The colors of the moist soils recorded on the boring logs include a range from brown through light brown, yellow-brown and orange to gray. Some mottling is reported on the original logs, while dry colors observed during INAA sample collection ranged from brown (10YR 5/4) to strong brown (7.5YR 4/3). Standard penetration test (SPT) blow-counts indicate consistency ranging from firm to stiff. This group includes a total of fifteen samples; fourteen immediately acceptable as PHS as well as one of the two problematic samples from B-530.

The samples included in this "Portland Hills Silt" or "PHS" group are: S-2 and S-3 from B-574; S-2, S-5, and S-6 from B-525; S-2, S-6 and S-7 from B-527; S-2, S-4, S-5, S-6, S-9, and S-11 from B-530.

Samples S12 and S14 from B-530 are problematic. Although this study does not accept them as "SRM-equivalent" as identified in the boring logs of Squier, (1993), these samples are clearly reworked. Both contain some allocthonous sand and gravel material, and the lower of the two (S-14) lacks the PHS-like shot concretions of the upper (S-12). To avoid tiresome discursiveness, Sample S-12 has been added to the above group based on the observed lithologic similarities. Sample S-14 is lumped in the second group described below.

The second lithologic group consists of the silty and clayey sediments identified by Squier (1993) as belonging to Sandy River Mudstone, or, more accurately, as "SRM-equivalent". The colors and textures of these samples appear to be similar to the Portland Hills Silt group described above, but with several distinctive features. Soil color in the "SRM-equivalent" samples is often more orange, or reddish, than observed in the "Portland Hills Silt" group. Soil texture is typically described in the field logs as clayey, or clayey silt (CL to CL/ML) in "SRM-equivalent" samples. Where silty sediments were encountered underlying older volcanic rocks such as Boring Lava they were commonly identified, based apparently on this stratigraphic relationship, as "SRM-equivalent".

A total of twelve samples are included in the "SRM-equivalent" group. Seven split-spoon samples from four borings; S-8 and S-9 from B-574; S-8, S-10 and S-12 from B-525; S-9 from B-527; S-14 from B-530, as well as the four core samples R-18, R-42, R-45 and R-51 taken from B-564.

The average geochemical makeup of the above two PHS and SRM-equivalent groups from the WLRT cores is shown in Figure 17, with the mean composite geochemistry of the 53rd Street core included as the "typical" Portland Hills Silt profile.

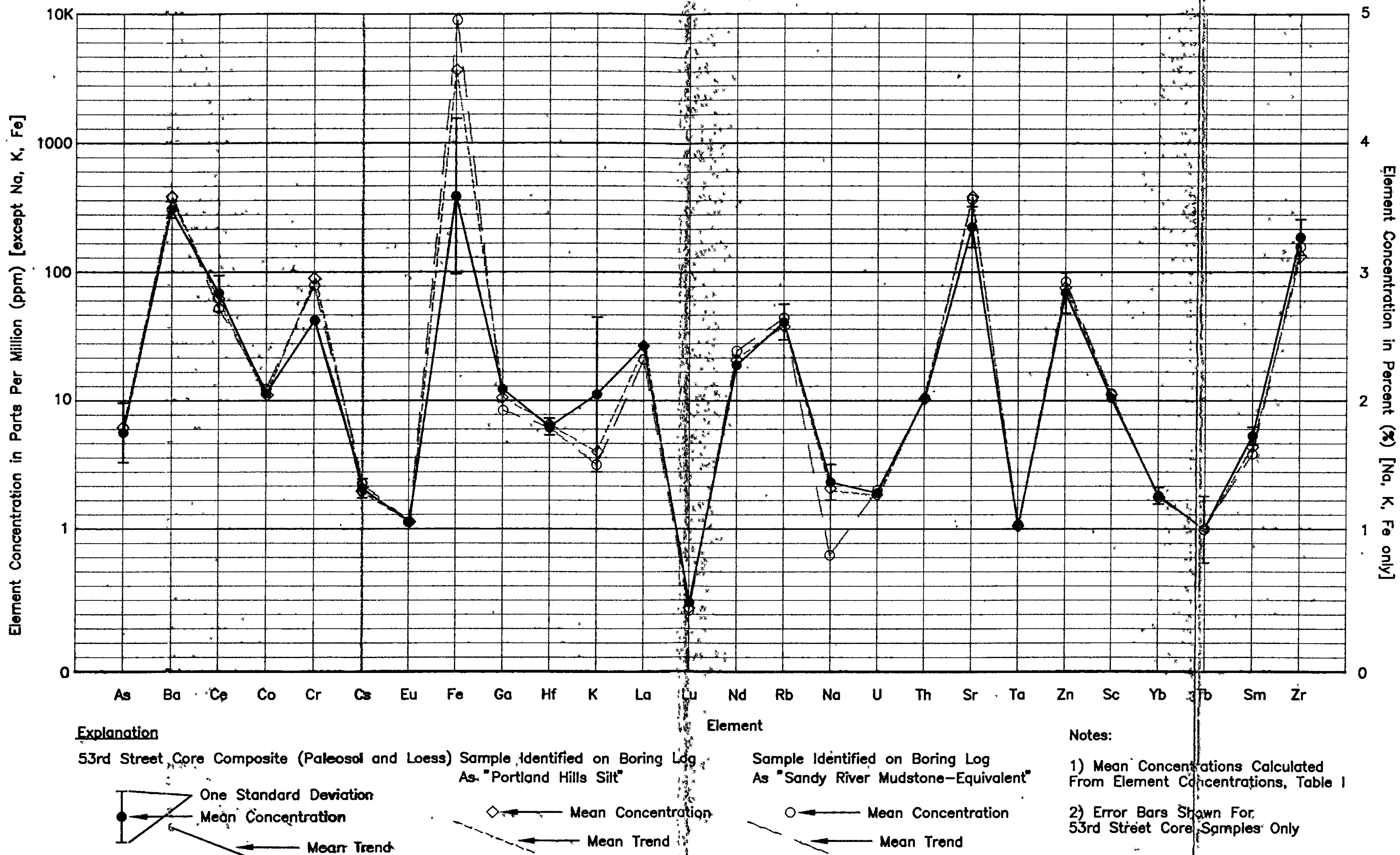


Figure 17: Average Element Concentration, WLRT Boring Samples Grouped By The Lithology of Squier (1993) [53rd Street Composite as Control]

Samples Grouped by Lithologic/Pedologic Appearance

One alternative to the "Sandy River Mudstone - equivalent" hypothesis is to postulate that the redder, finer-grained, stratigraphically-lower silty sediments encountered in the Light Rail Tunnel borings are older Portland Hills Silt that has undergone more prolonged weathering as well as localized soil formation, or has been reworked. This hypothesis would explain the increases in clay content, rubefication as pedogenic; and lithologic changes such as stratified or laminated silt and sands, or the addition of allocthonous debris such a basalt gravel as the product of alluvial or colluvial actions after deposition of the wind-blown silts.

Under this hypothesis, the WLRT samples were observed for signs of apparent pedogenic maturity; increased clay content as films and coatings, heightened rubefication, soil structure, as well as an increased percentage of ferromagnesian shot concretions. Any sample that showed these characteristics was placed in a group of "suspected paleosols". Samples that appeared more similar to unweathered, massive, structureless silt were placed into a "suspected loess" group.

The effect of this rearrangement of lithologic groups produces a "loess group" composed of fifteen samples: S-2, S-6 and S-12 from B-525; S-2, S-6, and S-7 from B-527; S-4, S-5, S-9 and S-11 from B-530; S-2, and S-3 from B-574. Two of the core samples from B-564 are included in this group; R-42 and R-51.

A "paleosol group" produced by this rearrangement consists of eleven samples: S-5 and S-10 from B-525; S-9 from B-527; S-6 from B-530, and S-6, S-8 and S-9 from B-574. Two core samples taken from silt sediments in B-564 are included in this group: R-18 and R-44. This group also includes the two "reworked" sediment samples S-12 and S-14 from B-530.

Figure 18 shows the average geochemistry of the "loess" and "paleosol" groups of WLRT samples, again with the average geochemistry of the 53rd Street core serving as a Portland Hills Silt "control" group.

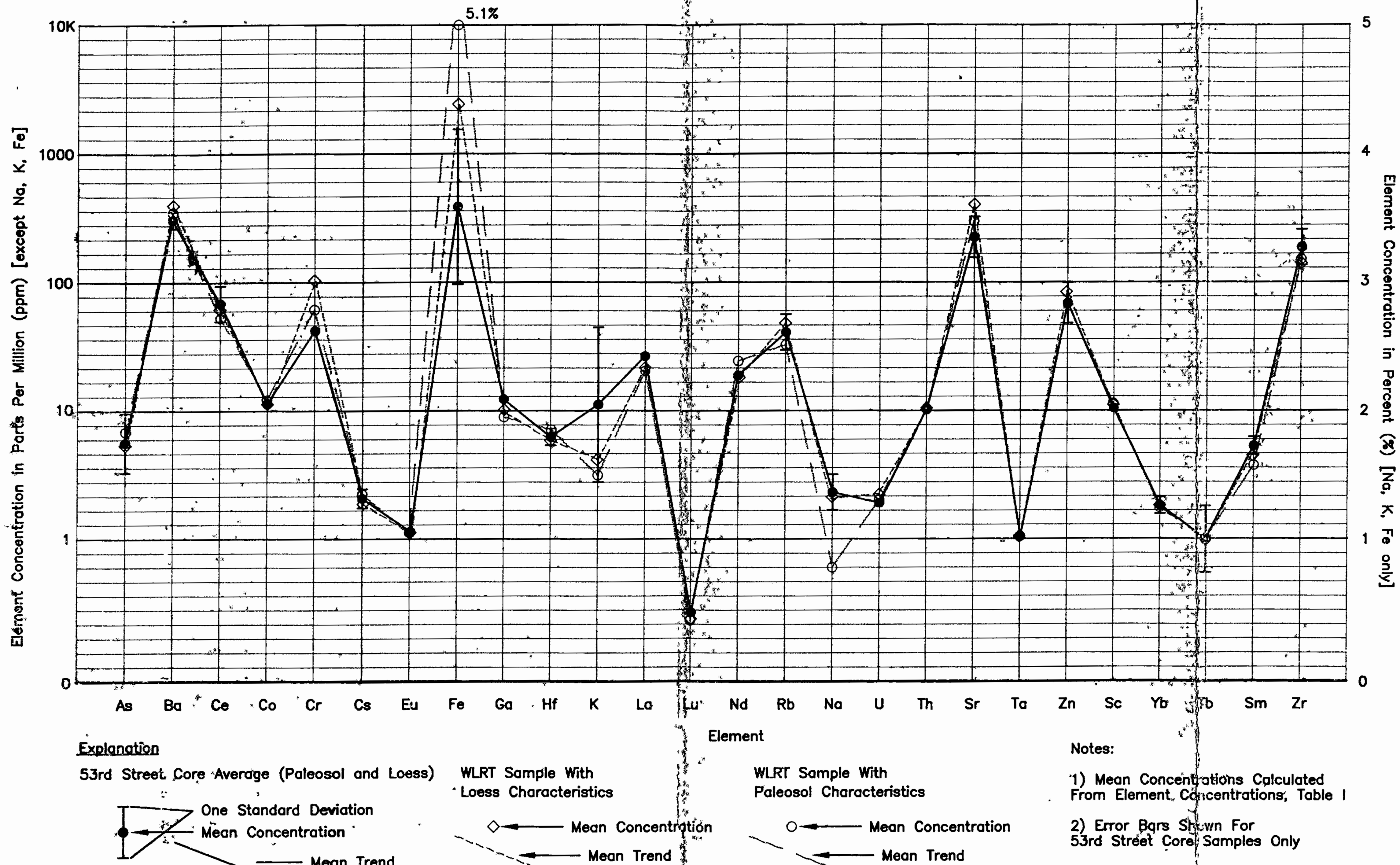


Figure 18: Average Element Concentration, WLRT Boring Samples Grouped By Soil Development [53rd Street Composite as Control]

Instrumental Neutron Activation Analysis Results

Looking that the average geochemistry of all four sample groups ("PHS", "SRM-equivalent", "loess" and "paleosol") what is most immediately striking about Figures 17 and 18 are the degree of similarity between all the groups and the average geochemical makeup of the 53rd Street core sample. Using this first glance, it is tempting to state that all of these silty sediments are, or are reworked from, Portland Hills Silt, quod erat demonstrandum - thus it is proven!

However, statistical analysis does not show this correspondence quite as neatly. Certain element concentrations appear to show high probabilities of similarity, while others do not fall into line so neatly. Average hafnium concentrations in this group are shown in Table X below. Where the statistical tests indicate that the samples are from the same population (Ho = Ho), the probability (p) value equals 1.0, with decreasing values indicating more extreme population variability.

TABLE X.

AVERAGE HAFNIUM CONCENTRATIONS AND STATISTICAL ANALYSES

Sample Group	Avg. Hf Conc. (ppm)	probability (p) (Ho = Ho = 1.0)
53rd Street (Avg) "PHS" group	8.28 8.37	F Test: 0.05 T Test: 0.80
53rd Street (Avg) "SRM-equiv." group	8.28 8.17	F Test: 0.11 T Test: 0.86
53rd Street (Avg) "loess" group	8.28 7.91	F Test: 0.12 T Test: 0.40
53rd Street (Avg) "paleosol" group	8.28 8.74	F Test: 0.13 T Test: 0.32
"PHS" group "SRM-equiv." Group	8.37 8.17	F Test: 0.02 T Test: 0.75
"PHS" group "loess" group	8.37 7.91	F Test: 0.19 T Test: 0.29
"PHS" group "paleosol" group	8.37 8.74	F Test: 0.21 T Test: 0.42
"SRM-equiv." group "loess" group	8.17 7.91	F Test: 0.27 T Test: 0.68
"SRM-equiv." Group "paleosol" group	8.17 8.74	F Test: 0.31 T Test: 0.39
"loess" group "paleosol" group	7.91 8.74	F Test: 0.99 T Test: 0.12

Hafnium concentrations appear to show gross similarity between the groups of soil samples, the statistical analysis suggests that these data should be viewed as a suggestion rather than a proof. It is suggested that F-test values should be used with care. In this case, this test appears to be affected by the wide distribution of outlying values for hafnium in the relatively small overall population size. T-test confidence levels in the overall similarity of these samples range from an 86% probability of similarity between the "SRM-equivalent" group and the average hafnium concentration of the 53rd Street core samples to the 12% probability that the "loess" and "paleosol" hafnium concentrations represent parts of a single population.

Although statistical analysis discourages concluding that these groups are part of a uniform Portland Hills Silt geochemistry, the gross hafnium concentration similarities between the groups are marked, whether observed as average concentration (Figures 17 and 18) or in individual sample abundance as shown in the thorium v. hafnium scatter plot (Figure 14).

Other lithologic distinctions can be made by adding in the hafnium concentration values provided in Barnes (1996) for the Boring Lava samples derived from the West Hills. These data are found in Table III. The difference in hafnium content between the group of Boring Lavas sampled by Barnes (1996) and the WLRT sediments used in this study is immediately apparent. Hafnium concentration appears to be a useful indicator of provenance: Boring Lavas generally contain roughly half the average concentration of hafnium seen in all of the WLRT boring sample groups of this study. Figure 14 shows this well: the eight Boring Lava samples taken from the larger Barnes (1996) Boring data field contain between 3.37 ppm and 4.31 ppm hafnium (average 3.79 ppm) compared to the 7.91 ppm to 8.74 ppm range (average 8.25 ppm) for the WLRT sample fields.

Iron (Fe) displays reversed tendencies as an indicator: greater average concentrations in the Boring Lava samples (6.4%) than in the silty WLRT sediments (4.5%).

Iron **does** show a good correspondence with the four WLRT samples as an indicator of relative soil maturity. Whether divided by "loess"-"paleosol" or "PHS"-"SRM" definitions, in both cases the visibly redder, structurally mature "paleosol" and "SRM" groups are significantly higher in average iron concentration, between 0.5% to 1.5%, than the "loess" or "PHS" groups. This geochemical trend will be seen again.

In this study, the Rare Earth Elements (REE) were not found to be generally useful for distinguishing geologic or lithologic affinities. Among rare earths, however, cerium (Ce) does appear in this case to be a useful indicator element. Cerium content in the Boring Lava is between 33 ppm and 59 ppm, typically averaging around 40 ppm. Average cerium concentrations for all of the WLRT sample groups fall between

75.8 and 85.6 ppm (overall average: 80.3 ppm). Cerium content of the WLRT boring sample groups are much more alike the 90 to 100 ppm observed in the Cenozoic Portland Basin deposits sampled by Barnes (1996) and identified by that investigation as "Columbia River Source Sediments" (CRSS). The subset of these sediments used for comparison in this study consists of three silty sediment samples ("SRM-equivalent" or slope deposit) from three WLRT borings B-38, B-557 and B-565; one sample from a DOGAMI boring located in the east edge of the Tualatin Basin, BVD4; a deep sedimentary sample from the David's Hill Well on the west edge of the Tualatin Basin; and three "type" locality sediment samples, one each of the Willamette "Blue Mud", Portland Hills Silt and Sandy River Mudstone". Provenance, sampling and analysis of these sediment samples are discussed in Barnes (1996), and the geochemical data are presented in Tables II and III. This high cerium anomaly may be produced by the increased amount of continental silica in sediments deposited by, or derived from, the Columbia River (Fairbridge 1972). Certainly, the Boring Lavas of Barnes (1996) are notably lower in cerium (averaging 43.9±8 ppm) than the 53rd Street sample average. The average 53rd Street cerium concentration of 85.6±13 ppm is more typical of the PHS.

Geochemical variation can also be seen to rule out other affiliations. Sediments derived from CRBG sources are shown by Barnes (1996) to display a distinctive iron (Fe) content of between 10 and 13 percent. The ratio between thorium (Th) and scandium (Sc) concentrations (Figure 12) is another diagnostic difference between the groups: Boring Lavas tend to show scandium enrichment relative to thorium on the order of 10S:1T to 20S:1T. CRBG sediments display this relationship, to a somewhat lesser degree, with scandium-thorium concentration ratios on order of 3S:1T to 10S:1T (Barnes, 1996). A similar, low-thorium, high-scandium relationship is also observed in two other groups of sediment analyzed by Barnes (1996): those from High Cascade sources (HCS) as well as younger Neogene sediments from the Columbia River (YCRS).

In contrast, the concentration of scandium to thorium in the WLRT silt sediments, as well as the Barnes (1996) CRSS, including SRM and PHS, is roughly 1S:1T. The upper limit of this ratio is commonly between 2S to 1T. In these sediments, a scandium-thorium ratio of 3S:1T is rare; it is observed in these studies only twice, in the sample R-42 of WLRT Boring B-564 and in the "Blue Mud" of Barnes (1996).

Sodium content shows an interesting trend suggestive of the eluviation of sodium seen in the paleosols in the 53rd Street core. In the case of the "paleosol" and "SRM" WLRT sample groups this leaching of sodium is greater than that observed in the 53rd Street core. The two former WLRT groups (related in that nine of the eleven "SRM" samples are also identified as "paleosols") show a decline in average sodium concentration from the 1.24% to 1.31% values observed in the "PHS" and "loess" WLRT groups, respectively, to between 0.80% for the "paleosol" group, and 0.86% for the "SRM". This is a forty percent loss of sodium, compared to the average sodium depletion of twenty percent observed between the 53rd Street paleosols and the parent loess. This in turn suggests a more extensive weathering in these WLRT samples relative to the 53rd street core.

In what appears to be a potentially related geochemical anomaly, the average potassium concentration in all of the four WLRT groups is reduced, from the 2% potassium content in the 53rd Street core, to 1.58%. Values range from a low of 1.49% potassium content in the "paleosol" group to a high of 1.67% in the "loess" group. This data field is shown in Table XI.

TABLE XI.
POTASSIUM CONCENTRATIONS, 53RD STREET AND WLRT SAMPLES

Sample Number (53rd Street)	WLRT Group	Horizon	K Concentration (%)
5'/1.4m	N/A	Bwb	1.9
25'/25.9m		Cu	1.6
37'/11.2m		2Bwb	1.5
45'/13.5m		Cox	2.6
52'/15.7m		Cu?	1.0

TABLE XI.
(continued)
POTASSIUM CONCENTRATIONS, 53^{RD} STREET AND WLRT SAMPLES

Sample Number	WLRT Group	Horizon	K Concentration (%)
53rd Street (continued)			
60′/18m		3Bwb	2.3
65′/19.5m		3Bwb/Cox	2.1
70′/21m		Cox/Cu	2.8
75′/22.5m		Cu	1.9
80′/24m		Cu	2.3
85′		4Btb	2.1
(WLRT Borings)			
B-525 S-2	PHS/loess	Cox	2.0
B-527 S-2	PHS/loess	Cox	1.7
B-530 S-2	PHS/loess	Cu	1.8
B-574 S-2	PHS/loess	Cu	2.0
B-574 S-3	PHS/loess	Cox	1.5
B-530 S-4	PHS/loess	Cox	2.1
B-525 S-5	PHS/paleosol	Bwb	1.4
B-525 S-6	PHS/loess	Coxb	1.6
B-527 S-6	PHS/loess	Cu	1.5
B-530 S-6	PHS/paleosol	Bwb	1.8
B-574 S-6	SRM/paleosol	Bwb	1.2
B-527 S-7	PHS/loess	Cu	1.4
B-525 S-8	SRM/paleosol	2Bwb	1.7
B-574 S-8	SRM/paleosol	Bwb	1.7
B-530 S-9	PHS/loess	Cub	1.3
B-574 S-9	SRM/paleosol	Btb	1.7
B-525 S-10	SRM/paleosol	2Btb	1.9
B-530 S-11	PHS/loess	Cub	1.4
B-525 S-12	SRM/loess	2Coxb	1.2
B-530 S-12	PHS/paleosol	2Bwb	1.3
B-530 S-14	SRM/paleosol	2Btb	1.2
B-564 R-18	SRM/paleosol	Bwb	1.3
B-564 R-42	SRM/loess	Cox	1.5
B-564 R-44	SRM/paleosol	Btb	1.5
B-564 R-45	SRM/loess	Cu	2.1

The potassium concentration averages in these groups are 79% of the average 53^{rd} Street value, that is, an approximately 20% loss of potassium. Could this be an indication of overall increased age of these sediments, relative to a younger loess cored at 53rd Street? T-test statistical analysis suggests that this variation is not random, assessing the probability that the difference in average potassium concentration represents two populations at between a 95% (for 53rd Street vs. the "PHS" WLRT group) to 99% (for 53rd Street vs. both "paleosol" and "SRM" groups) confidence level.

It is useful to observe the progressive leaching of potassium in the deeper soils in the WLRT borings, and in the paleosol zones at shallower depths such as sample S-5 in B-525. This is a reminder that leaching of potassium will be highly variable and dependent not only on age but also on the degree of exposure of the soil to weathering.

The cation next strongest in sorption potential, rubidium (Fairbridge, 1972), did not show statistically significant variation, either between or within any of the sample groups. Average rubidium content is 66.2 ppm for 53rd Street, and within the WLRT groups ranges from 56.1 ppm in the "paleosol" group to 70.8 ppm in the "loess" group. This 20 ppm difference in means between the latter groups does appear to suggest some degree of rubidium leaching in the WLRT "paleosols". However, F-test p values show no better than a 50% confidence level that the rubidium variation between these two groups is statistically valid. The t-test suggests that these WLRT samples should be considered one population when analyzed for rubudium at a 94% confidence level.

The mean average of all four groups of 64.5 ppm.

Two other element concentrations show a small average increase in concentration in the "paleosol" and "SRM" groups relative to the "loess" and "PHS". The accumulation of chromium and strontium in soil or paleosol horizons would be consistent with the trend of these elements in the sedimentary sequence (Fairbridge, 1972). Unfortunately, statistical analysis of the variation of chromium and strontium cannot confirm this apparent buildup of these elements in the more weathered groups of samples. As such, it can be viewed as another possible geochemical indicator of weathering and soil development.

Discussion

Geochemical distinction between Boring Lavas and the WLRT sediment sample groups is particularly important due to the stratigraphic relationship between the Boring Lavas and the rock core samples taken from Boring B-564. Sample R-18 is interbedded between Boring Lava flows between 0.86 Ma and 0.96/.97 Ma (Conrey and others, 1996), while samples R-42, R-44 and R-45 underlie the older flow. The proximity of these sediments to the lava initially suggested the possibility that these samples may be derived from residual soils developed on Boring Lava, in the case of R-18, or contain substantial Boring Lava constituents. The nature of these sediments is complicated by their identification as Sandy River Mudstone in the WLRT Geotechnical Report (Squier, 1993). Based on the lack of overall geochemical similarity observed in this study as well as in the related work of Barnes (1996), it seems unlikely that either of these possibilities are correct.

The clear segregation between the geochemistry of the Boring Lavas and the WLRT sediment samples used in this study, including all four of the rock core samples from B-564, make a parent-product association of the two units at best difficult. Average and bulk element concentration differences, and the variant scandium-thorium ratio are unmistakably suggestive of the difference between the continental margin volcanic geochemistry of the Boring Lavas and the continental metamorphic/granitic parent materials of the sediments.

The relationship between hafnium concentration and lithology has been mentioned in the Results section above. Hafnium concentration appears to provide a good indicator of provenance, tending to be less than half as abundant in the Boring Lava basalts as in the PHS.

As a matter of speculation, it is interesting that a slightly higher hafnium concentration is also seen in the two suspected slope- or alluvially-reworked samples, S-12 and S-14 from B-530, both taken from the boring immediately above the contact between the base of the PHS and the underlying Basalt of Ginko flow of the CRB.

The zirconium-hafnium relationship is described by Fairbridge (1972) as extremely constant in igneous rocks, and that the weathering out of zircon and subsequent sedimentation leads to hafnium conforming to "the same course as the zirconium in sedimentation processes" (Fairbridge, 1972, p.489). This relationship suggests that the hafnium anomalies observed both in the reworked zone in B-530 as well as in the HBDH may be caused by some zircon enrichment taking place, either through accumulation of alluvial zircon or by weathering of in-place basalt. One attractive speculation for the origin of this hafnium anomaly in the reworked zone of B-530 S-12 and S14 might be that the stream (and slope) processes were working on the underlying volcanics as the loess was being deposited, accumulating placer-deposited zircon in paleochannels on the Basalt of Ginko, and the gradual admixture of this alluvium with accumulating loess enriched the basal portion of the PHS with hafnium.

Paleosol development in the PHS, as noted in the section covering the DOGAMI 53rd Street core, is a difficult subject to generalize. The problems presented by variable slope, insolation and vegetation are increased in the case of several suspected soil horizons, particularly S-12 and S-14 in B-530, by the possibility of localized slope or alluvial processes working on the deposits. The increased sodium depletion in the WLRT sample groups, relative to the 53rd Street core, suggests a longer period of eluviation for these sediments. The possibility that there may be the beginnings of eluviation in the element potassium tends to reinforce this. It would be interesting to study the relative depletion levels of the sodium-potassium-rubidium series in, for example, the 1 Ma Ultisols developed on the Eola geomorphic surface in the Willamette Valley (McDowell, 1991) to assess the relative age of these deeper West Hills soils.

The problem of the "Sandy River Mudstone-equivalent" is more difficult, in part due to my own failure to include samples known to be SRM in the sample field. The single sample of recognized SRM, from the Barnes (1996) database, is not enough to establish an SRM "baseline" from which to contrast the known Portland Hills Silt sediments and, therefore, to evaluate the position of the suspect "SRM-equivalent" samples in the WLRT group. The geochemistry of the Barnes (1996) SRM is not particularly distinctive: all geochemical properties fall within the overall trend of what Barnes (1996) has grouped into "Columbia River Source Sediments" that include the PHS.

Two general statements seem safe to make, given the INAA data and physical characteristics of the "SRM-equivalent" sediments observed during WLRT construction.

First, it may be said that the geochemistry of the "SRM-equivalent" of Squier (1993) is much more like the PHS geochemistry of this study and other PHS-related groups (such as the CRSS of Barnes, 1996) than any other geochemical species, including the Boring Lava and the CRBG-related sediments.

Second, although localized reworking and paleosol development have altered the appearance of the older loess in a few places, producing bedding laminations and local sandy to gravely interbeds, the portions of this sediment observed during tunnel construction retain much of the gross physical characteristics of Portland Hills Silt. This material is largely silty and micaceous. In the bedded portions, it contains rip-up-like inclusions of massive, yellowish brown silt. Based on the physical appearance and geochemical similarity, it would seem much more probable that these sediments are Portland Hills Silt.

The WLRT borings allow observation of the PHS beyond the four episodes of loess deposition observed at 53rd Street. In the WLRT stratigraphy, we can observe:

- A series of basal paleosols developed on the Columbia River Basalt, as observed at 53rd Street.
- An interval of silty, micaceous loess-appearing sediment deposited on this basalt that is overlain by Boring Lavas dated at 0.96/0.97 Ma by Conrey and others (1996).
- additional loess deposition that can be spanned from 0.96 Ma to 0.86 Ma by the dated Boring Lavas over- and underlying the sediment.
- Younger loess deposited above the Boring Lavas that is recognizably Portland Hills Silt.
- The geochemistry of this PHS relates to the "older loess" or "SRM-equivalent" in a similar way that the loess parent materials at 53rd Street can be related to their paleosols.

OTHER PORTLAND BASIN SEDIMENTS AND POTENTIAL SOURCE AREAS

S.W. Elm Street, Portland

A total of five samples were taken from a residential garage excavation at 2121 S.W. Elm Street in the Vista Heights neighborhood of Portland at depths ranging from 10cm to 2.5m from the ground surface. This suite of samples will be referred to as "Elm Street" (ES) for convenience.

The Elm Street location consists of the portion of the lawn and grounds that had been excavated during March and April, 1993 to construct a below-ground garage. The dimensions of the excavation were approximately 25 meters east-to-west (along Elm Street) by 32 meters north from the existing sidewalk pavement. The completed cut was approximately 3 to 3.2 meters deep.

The cut appeared to be entirely in native Portland Hills Silt. No disturbed soils, buried debris or irregular areas of atypical texture and color were observed during sampling on April 11, 1993. Although the Vista Heights district has been extensively graded, including cut-and-fill leveling of residential and street grades, there does not appear to be any indication of non-native backfills on this site. Site grading, if more than superficial, appears to have been confined to cut-and-remove grading for the building pad.

From this excavation, a total of five samples were removed from the north cut bank of the garage excavation. The samples are listed in Table I. The uppermost sample (ES-01) was taken from the cambic (Bw) horizon immediately underlying the modern organic topsoil as a depth of 10 to 20 cm bgs. This sample was a strong brown (7.5YR 5/6) massive, micaceous silt, distinguishable from yellowish brown (10YR 5/6) loess (Cu/Cox) sample ES-02 only in the slightly redder hue. Both samples contained trace to few small organic fragments including root hairs from the superposed landscape plants. The PHS deposit appeared uniform from 60 cm bgs (the depth of collection of ES-02) to approximately 1 meter bgs, where a series of thin black horizontal laminations were encountered (Appendix C).

These laminations were observed to be composed of dark mineral grains, with some angular, lightweight carbonized material that appeared to be either ash or charcoal. Sample ES-03 was taken from the portion of the loess containing several of these one- to three-millimeter-wide laminations. A buried soil horizon underlay the black-laminated loess at a depth of 1.7 meters. This approximately 20- to 30-centimeter-thick buried argillic (Btb) horizon, distinguished by a dark brown color (value 3) and thin clay coatings, was sampled between 1.7 meters and 1.9 meters bgs as sample ES-04.

A thin loess (Cu) horizon separated the upper buried soil from a lower paleosol (Btb2) sampled between 2.2 meters and 2.5 meters bgs for sample ES-05. This buried soil was both redder in hue (5YR) and appeared to be more clayey than the upper paleosol. Both paleosols contained trace to some charcoal fragments to 5 millimeters dimension.

The base of the cut bank outcrop was founded in massive, yellowish brown, micaceous Portland Hills Silt at a depth of 3 meters bgs. CRBG bedrock was not observed in this cut, but has been encountered at depths averaging between 3 to 8 meters bgs in adjacent explorations in the Vista Heights neighborhood; both in geotechnical borings on file with the city of Portland, as well in the logs of a refraction seismic investigation performed during the summer of 1992 as a part of map preparation for Mabey and others (1993).

The average geochemistry of the Elm Street suite of samples is shown in Figure 19. In this figure the average ES geochemistry is shown against the average element concentrations of two very different geologic groups: the 53rd Street core samples, and the Boring Lava data of Barnes (1996). Some Elm Street element concentrations are similar to the PHS "type", notably sodium, thorium and cesium, as well as the thorium-scandium ratio (Figure 12). It is instructive

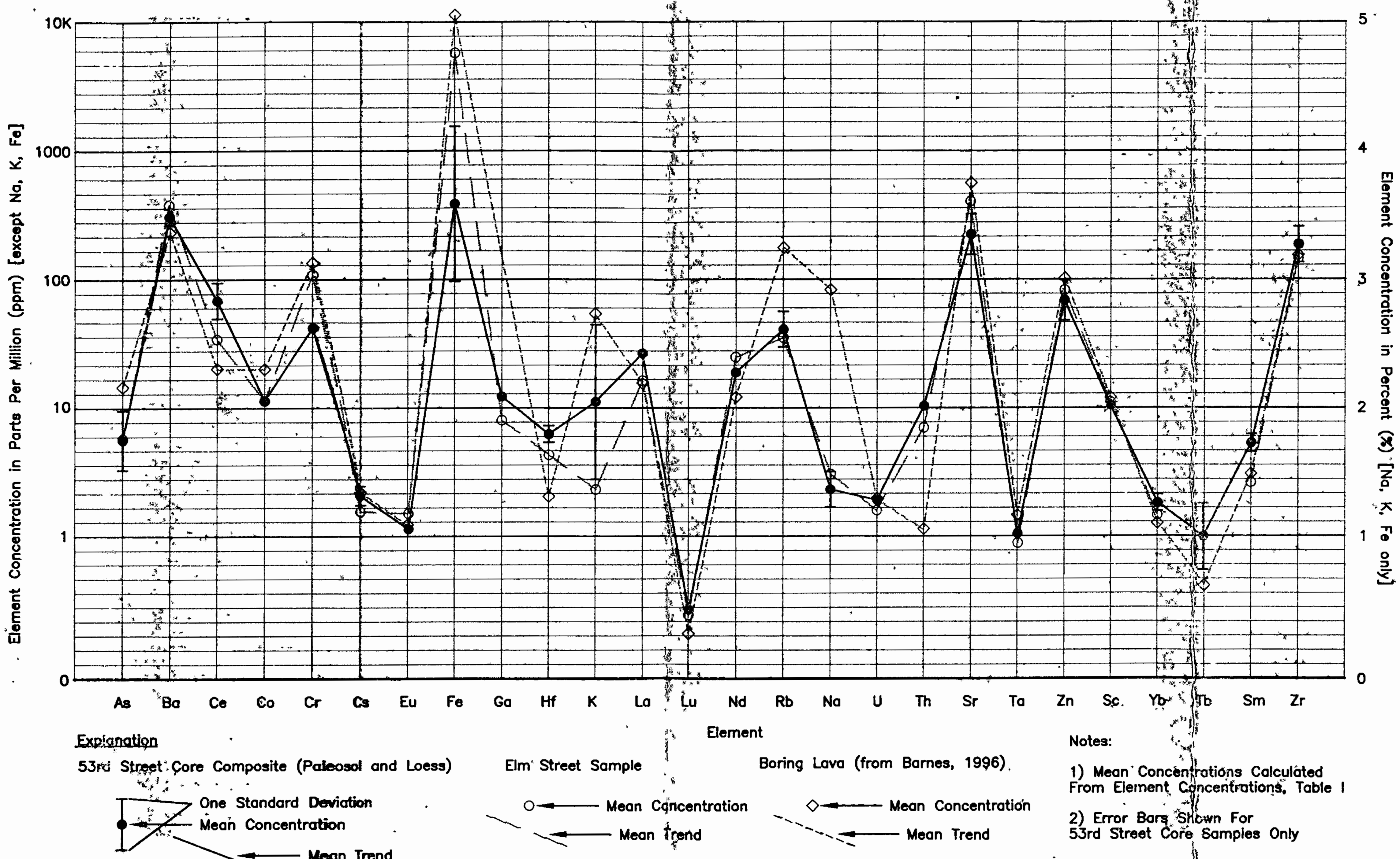


Figure 19: Average Element Concentration, 53rd Street Composite vs. Elm Street vs. Boring Lava of Barnes (1996)

to observe how the PHS geochemistry of Elm Street displays some interesting anomalies when compared to the "type" average concentrations of 53rd Street.

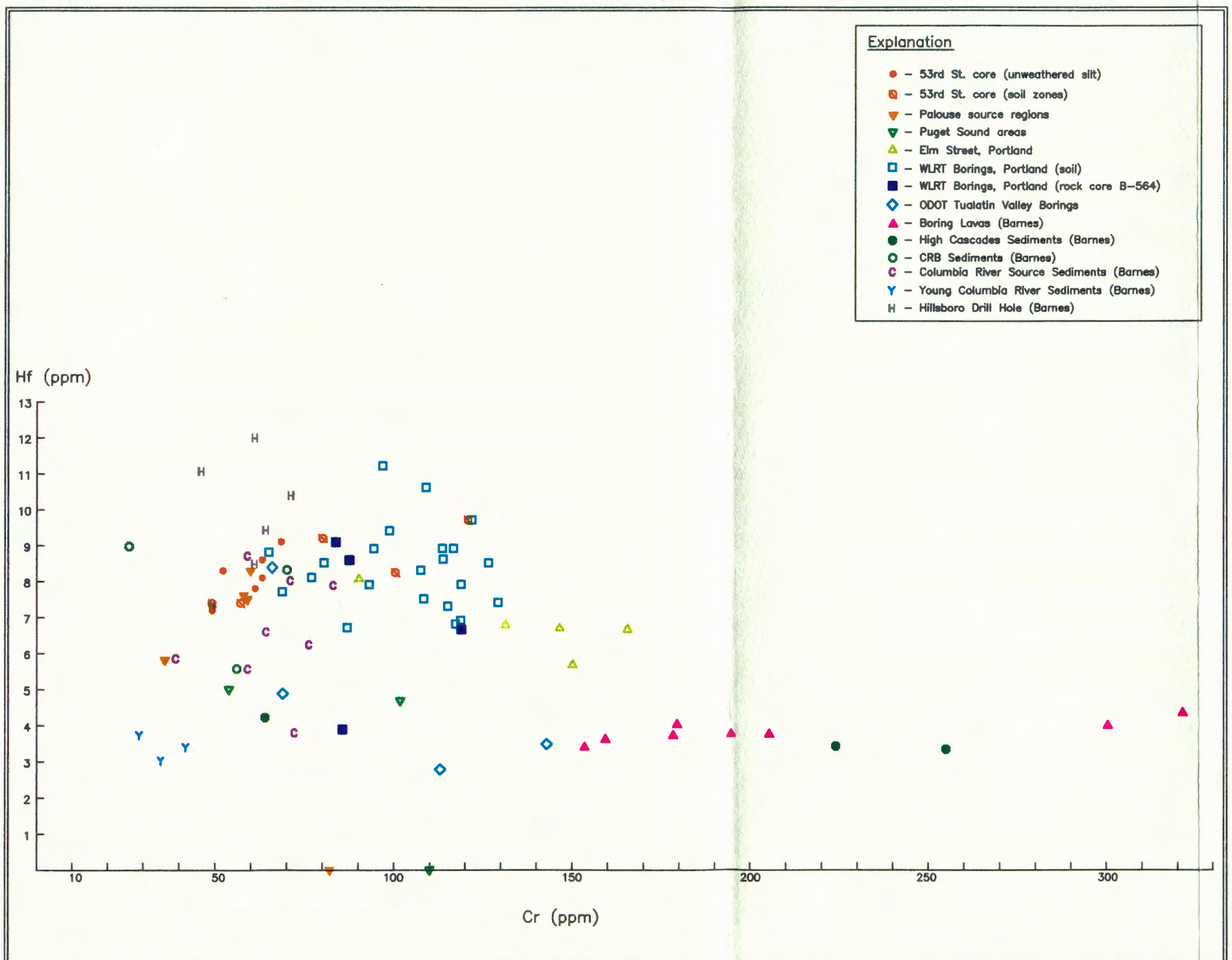
Average ES iron concentration (4.8%) appears closer to the average 6.4% iron of the Boring Lava than the 3.8% iron of the average 53rd Street sample, although statistical analyses show no strong correlation between any of the lithologies. This increased iron concentration is also similar to the levels of iron found in the "paleosol" and "SRM" WLRT groups, suggesting that this enrichment may well be a pedologic feature.

Average cerium concentrations are almost exactly intermediate between the 53rd Street average and that of the Boring Lava. This trend is not observed in the WLRT groups.

More of this sort of neither-one-nor-the-other behavior is observable in the scatterplot of hafnium vs. chromium (Figure 20). Elm Street samples average 6.8 ppm hafnium. This appears to be closer to the 8.28 ppm hafnium typical of 53rd Street: statistical analysis shows a 89% f-test confidence of similarity. However, both f- and t-test analyses suggest that the ES average of 135 ppm chromium is dissimilar to both the average of 211 ppm chromium of the Boring Lavas *and* the 80-90 ppm of the average 53rd Street sample.

Figure 20

Scatter Plot: Hafnium v. Chromium (All Samples)



A look at the Rare Earth Element plot (Figure 21) provides another interesting look at the relationship of these Elm Street soils to the other samples. Note the concentration trend line for the Elm Street samples, both in Y-axis location (average concentration) and slope (relative concentration) in the region between the average of the plotted concentrations of the elements cerium and neodymium. Three of the geologic groups (Elm Street, and the HCS and YCRS of Barnes (1996)), display a relatively low-cerium, high-neodymium relationship. This is expressed as a line representing average REE-element concentrations of these three groups that originates lower on the Y-axis, below approximately 55 ppm cerium. This trend is seen in the gentler slope of the regression or trend line connecting cerium-neodymium averages of these groups relative to the other lithologies of this study and Barnes' (1996).

The slope of the cerium-to-neodymium trend line tends to be 1V:1H or steeper for most of the geologic groups. (Indeed, the cerium-neodymium regression line for sample M102N32 is steeper than 3V:1H, the most exaggerated high-cerium anomaly

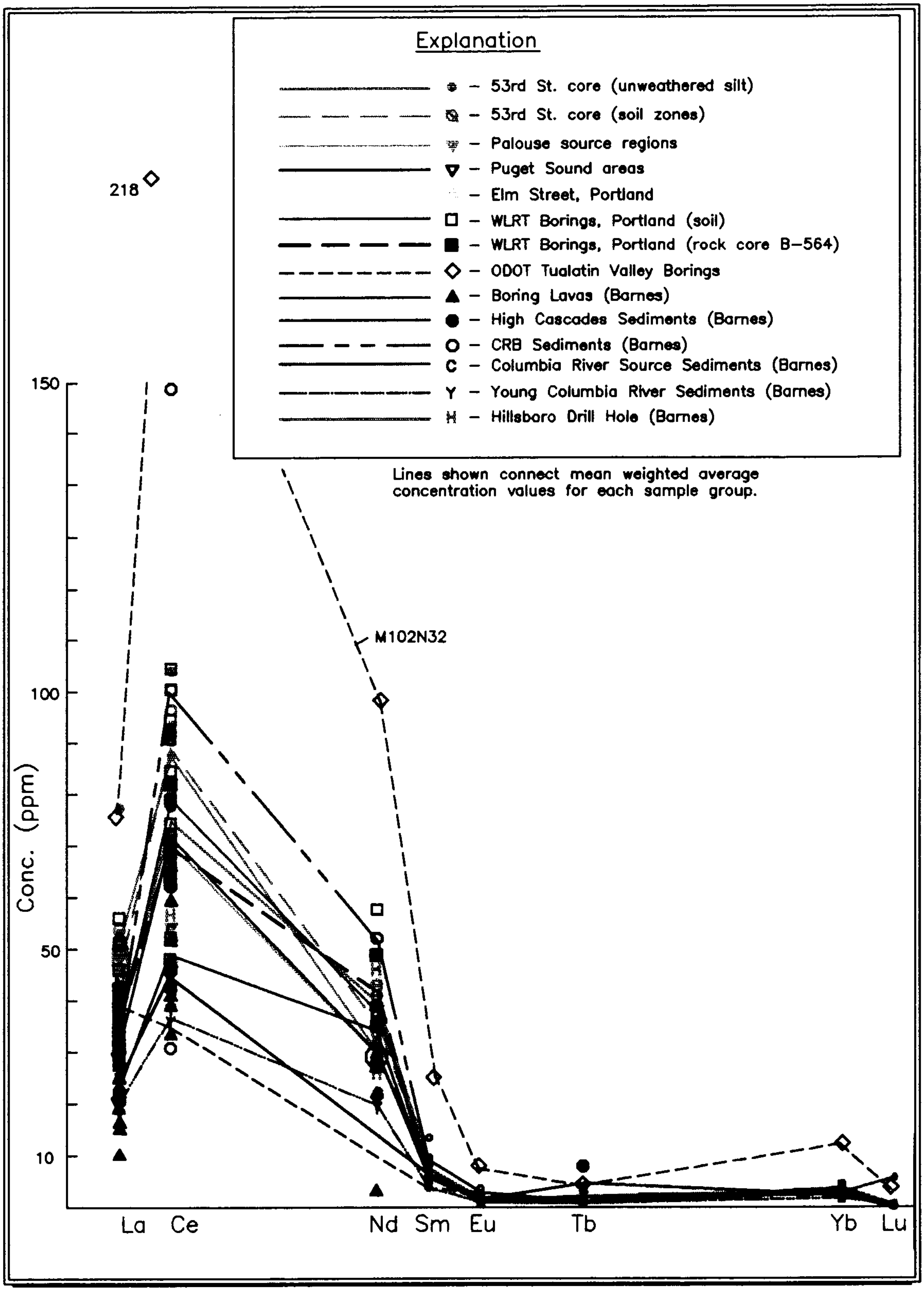


Figure 21

Rare Earth Element Plot – All Samples

(218 ppm) seen in this study. The geochemistry of these odd samples will be discussed further in the following section.)

The average Elm Street cerium-neodymium anomaly is the smallest of any of the lithologic groups, with the slope of the regression between the average ES cerium and neodymium concentration about 1V:4H. Both Barnes' (1996) YCRS and HCS sediments show a similar (1V:3H) REE trend in this location.

Conclusions

The Elm Street sample location appeared to be undisturbed. However, given the extensively developed nature of the Vista Heights area, it is not inconceivable that the PHS in this location contains some anthropogenic contamination that contributes to this anomalous geochemical behavior. The explanation may be even more simple - a random or experimental error, contamination during collection, or during preparation.

While the geochemistry of the Elm Street site is not conclusive, the sediment and soil morphology are more enlightening.

The modern soil is an Inceptisol, generally considered a relatively immature soil in the xeric Portland climate, approximately 10,000 to 15,000 years old (Birkeland, 1984). This has developed on a one-meter-thick massive, micaceous loess that appears similar to the other "type" PHS locations observed, including the WLRT and 53rd Street cores. Based on the age of this modern soil, this uppermost loess was probably formed from continental sediment deposited in the adjacent Portland basin by the last Missoula Flood episode.

Below this loess are a pair of paleosols that are noticeably better developed than the modern soils, or, for that matter, than any of the upper three paleosols observed in the 53rd Street core. The well-developed argillic horizons observed in these buried soils suggests that the loess in which they developed was exposed to weathering for a long period, possibly as long as 10^4 years (Birkeland, 1984). This suggests that the underlying loess may well be contemporaneous with the "SRM-equivalent" loess of the WLRT borings.

Perhaps another factor causes the Elm Street samples to behave idiosyncratically. In some combinations of geochemical species this suite appears to contain a Boring Lava component; in others, no such relationship is seen. The Elm Street site was observed to show multiple bands or layers of a dark, ash- or charcoal-like material interbedded with the silty sediments. Is this banding evidence of depositional contamination of the PHS at the Elm Street location by some Boring Lava-related material such as ash from a nearby Boring Lava cone such as Mount Tabor, or perhaps an east wind-blown ashfall from the nearby Sylvan vent? While the Elm Street soils are physically and geochemically clearly similar to the surrounding Portland Hills Silt, this location provides a cautionary tale in assuming that geochemical homogeneity will accompany lithologic similarity.

Northeast Tualatin Valley (NETV) Sediments

A total of four samples were taken from two borings performed by ODOT along State Highway 217, between the intersection of Highway 217 and State Highway 26 to the north and the intersection of 217 and S.W. Canyon Road to the south, in the Cedar Hills district of Portland. This area lies in the northeast basin margin of the Tualatin Basin, a fault-bounded, structural basin separated from the Portland structural basin by the Tualatin Mountains (Geomatrix, 1995).

This shallow synclinal basin has been filled with tens to hundreds of feet of Cenozoic alluvial and colluvial sediments over a basin floor formed from CRBG basalt (Wilson, 1997). The two ODOT borings were drilled in the northeast portion of the Tualatin Valley, where the valley fill contains fine-grained sediments of Neogene age as well as massive, micaceous silts of the Tualatin Valley equivalent of the Willamette Silt, known informally as Tualatin Silt (Hart and Newcomb, 1965; Beeson and others, 1991).

Three samples were taken from one boring, M-102. These samples are: N-21, taken from a massive, micaceous, gleyed clayey silt at 45 meters (120 feet) bgs; N-26, from a similar gray silt at 60 meters (200 feet) bgs; and N-32, sampled from a massive, micaceous lean clay as 90 meters (300 feet) bgs. No sense of soil formation or paleosol development could be derived from the samples, and none is noted on the original driller's log (Appendix A) The boring was completed at a depth of 96 meters (320 feet) in Neogene sediments.

A single sample was taken from a second boring located within 500 meters of M-102. Sample N-12 was taken from a depth of 21.3 meters (71 feet) bgs in boring N-104. This sample was a brown (mottled with gray), massive, micaceous silt containing scattered two- to three-millimeter iron shot concretions. The log of this boring could not be obtained.

Figure 22 shows the average concentration of the NETV samples. Looking at the behavior of elements as disparate as iron, rubidium, potassium and lutetium, the NETV sediments appear to range from somewhat to quite different from the "typical" PHS as shown by the 53rd Street averages on the same figure.

Figure 22 and statistical analyses show that NETV concentrations are not particularly similar to the geochemistry of the Boring Lavas. Several species, notably cerium, iron, hafnium, lanthanum, terbium and samarium are

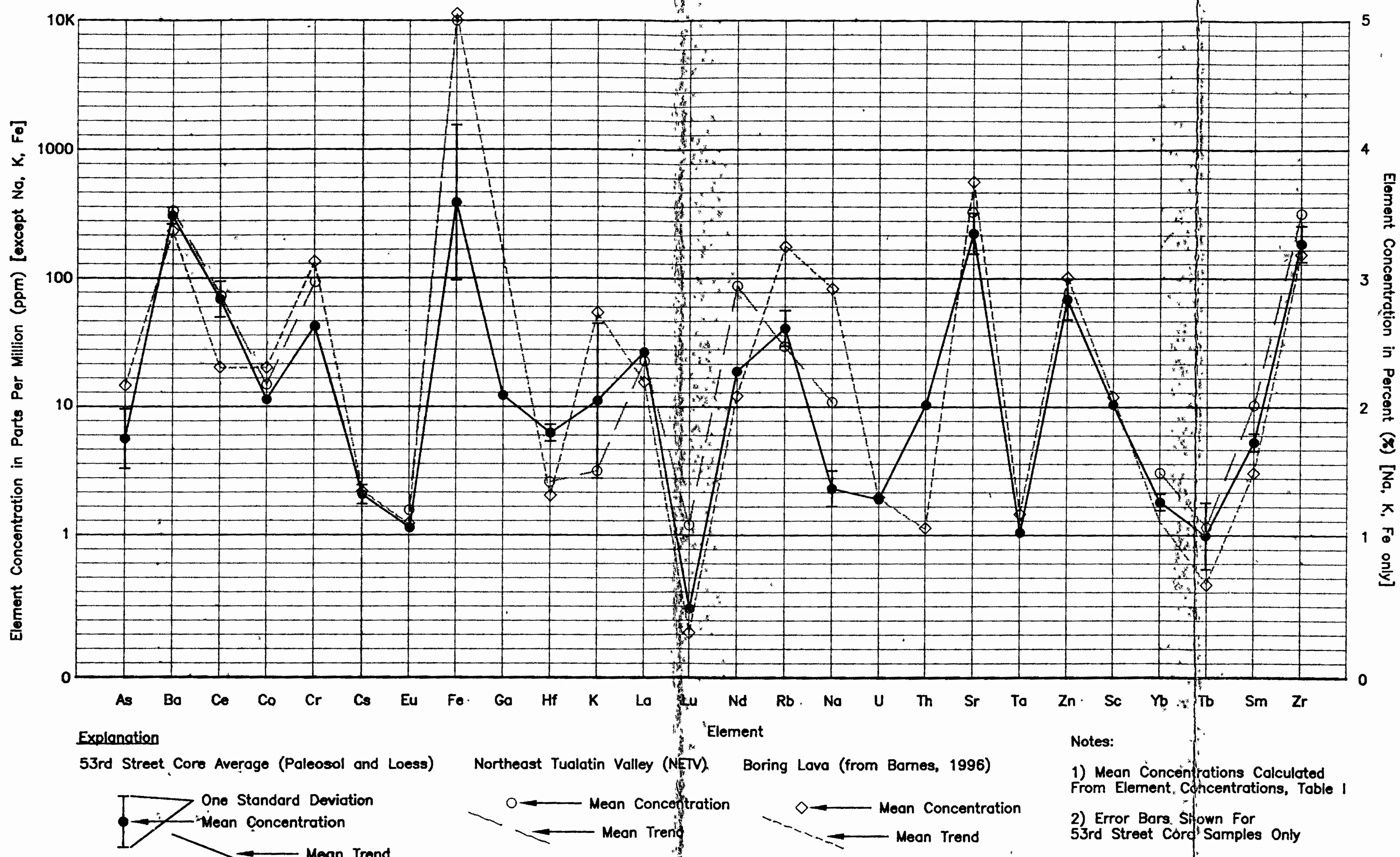


Figure 22: Average Element Concentration, 53rd Street Composite vs. Tualatin Valley Borings (NETV) vs. Boring Lavas of Barnes (1996)

evaluated at no more than between a 40% and 50% confidence level of similarity with Boring Lava.

In several instances, such as the average geochemistry of elements such as lanthanum and cerium, the NETV samples are more similar to a PHS-type geochemistry. Statistical analysis supports this assertion; average cerium concentration is similar at the 95% confidence level, lanthanum at the 83% confidence level. F-test analyses must be approached carefully, as the bizarre cerium behavior of sample N-32 from M-102 tends to affect the less-robust f-test disproportionally.

This might well be the time to discuss this troubling sample. N-32 is, in geochemical terms, rather erratic. Several elemental concentrations are quite conformable within the NETV group, but several others are wildly aberrant as the table below demonstrates:

TABLE XII.
SAMPLE N-32 COMPARED TO NETV AVERAGE GEOCHEMISTRY
(Element Detected in Minimum of 3 Samples)

Element Conc.(ppm)	N-32	NETV Avg.	% of Average
Barium	**820**	**576.5**	**142**
Cerium	**218**	**88.8**	**245**
Cobalt	15.7	25.0	62
Chromium	69	97.7	70
Europium	**6.7**	**2.7**	**248**
Iron	**7.6(%)**	**5.1(%)**	**149**
Hafnium	4.9	4.9	100
Lanthanum	**84.7**	**41.3**	**205**
Rubidium	69	53	130
Sodium	2.7(%)	2.1(%)	128

TABLE XII.
(continued)
SAMPLE N-32 COMPARED TO NETV AVERAGE GEOCHEMISTRY
(Element Detected in Minimum of 3 Samples)

Element Conc.(ppm)	N-32	NETV Avg.	% of Average
Terbium	**3.8**	**1.7**	**223**
Samarium	**25.6**	**11.4**	**224**

Elements exceeding the average NETV concentration by 140% or more are shown in bold. The lanthanum, terbium and samarium anomalies are even more marked than they appear: the other two samples returning values for these three elements(N-104 N-12 and M-102 N-21) are 19.2 ppm and 20 ppm for lanthanum (average 19.6 ppm), 0.53 ppm and 0.68 ppm (average 0.60 ppm) for terbium, and 4.0 and 4.5 (average 4.25) for samarium, respectively. When this mixture of nominal average element concentrations with large variations is combined with post-irradiation data loss, this sample becomes a demonstration point for the difficulty in reconciling the NETV suite internally, and with any of the other lithologic groups in this study. Based on these difficulties, the most that this study will venture about these silty to clayey, micaceous sediments is that they appear to be similar in certain elemental concentrations to the silty, micaceous sediments of the Portland Hills Silt, but show considerable variation in several other elements. It would appear that the PHS, its' parent Palouse loess, and a portion of the "archetype" sediments of the NETV are derived from a continental source. The NETV, however, contains a great amount of non-continental sediment. In addition, such variations as alluvial versus eolian deposition, elevation and the subsequent effect on precipitation and weathering, and the addition of materials from further north and western regions of the Tualatin Valley into the NETV samples all will have contributed to produce the aberrant NETV geochemistry observed in this study.

Outwash of the Puget Sound Region

In the interest of comparing the Portland-area, and Palouse-region source sediments with a discrete source of glacial or glaciofluvial sediments, three samples were taken from the Chehalis River drainage of the Puget Sound region (Figure 3). Based on A.S.T.M. standards, these samples are sandy alluvium rather than loess and are silty sand (U.S.C.S. Classification SM) rather than silt (U.S.C.S. ML) in texture (A.S.T.M., 1996).

This difference in sediment type is regrettable, but not, perhaps, fatal. These samples were intended more to establish the general geochemical character of sediments associated with the latest Puget glaciation than to directly contrast Puget Sound loess to loess of the Portland Hills.

Of the three Puget region samples, one (PS-1) was dug by hand from a 1.2-meter-high roadcut just north of the town of Satsop, Washington. This location is a southeast-facing slope incised into the broad, nearly level, lowermost north terrace of the Chehalis River. The sample was taken from what appeared to be the slightly weathered parent material (Cu/Cox) of a juvenile modern soil. Cursory examination would place the soil development at this location as a Typic Xeripsamment (Soil Survey Staff, 1994).

Two additional samples were removed from a similar roadcut approximately 16 kilometers west of the location of PS-1, near the town of Montesano, Washington. PS-2 was sampled at a depth of 0.75 meters bgs, while PS-3 was taken from the cut approximately one meter bgs. This locality was similar, both in topography and soil development, to the outcrop sampled for PS-1. Both of these locations are mapped by Carson (1970) as a part of the lower Chehalis River terrace formed during the Fraser glaciation.

All three samples are typically light yellowish brown (2.5Y 6/3), moist, loose silty sand (SM). The sand grain mix is generally 60% to 80% quartz and feldspar with minor ferromagnesian mineral grain constituents. PS-2, sampled near the base of the "A" horizon, contained up to 25% organic materials by weight. The other two samples were mineral soils.

Figure 23 shows the average element concentrations of the three PS samples. These data should be treated with care, as frequent non-detection, high counting uncertainties and small sample field combine to produce "averages" that often consist of a single data point. This is the case for the elements europium, lutecium and thorium. The elements barium, cerium, cobalt, hafnium, potassium, lanthanum, rubidium, sodium, ytterbium and samarium were detected in two out of the three-sample field. Several elements were either not detected

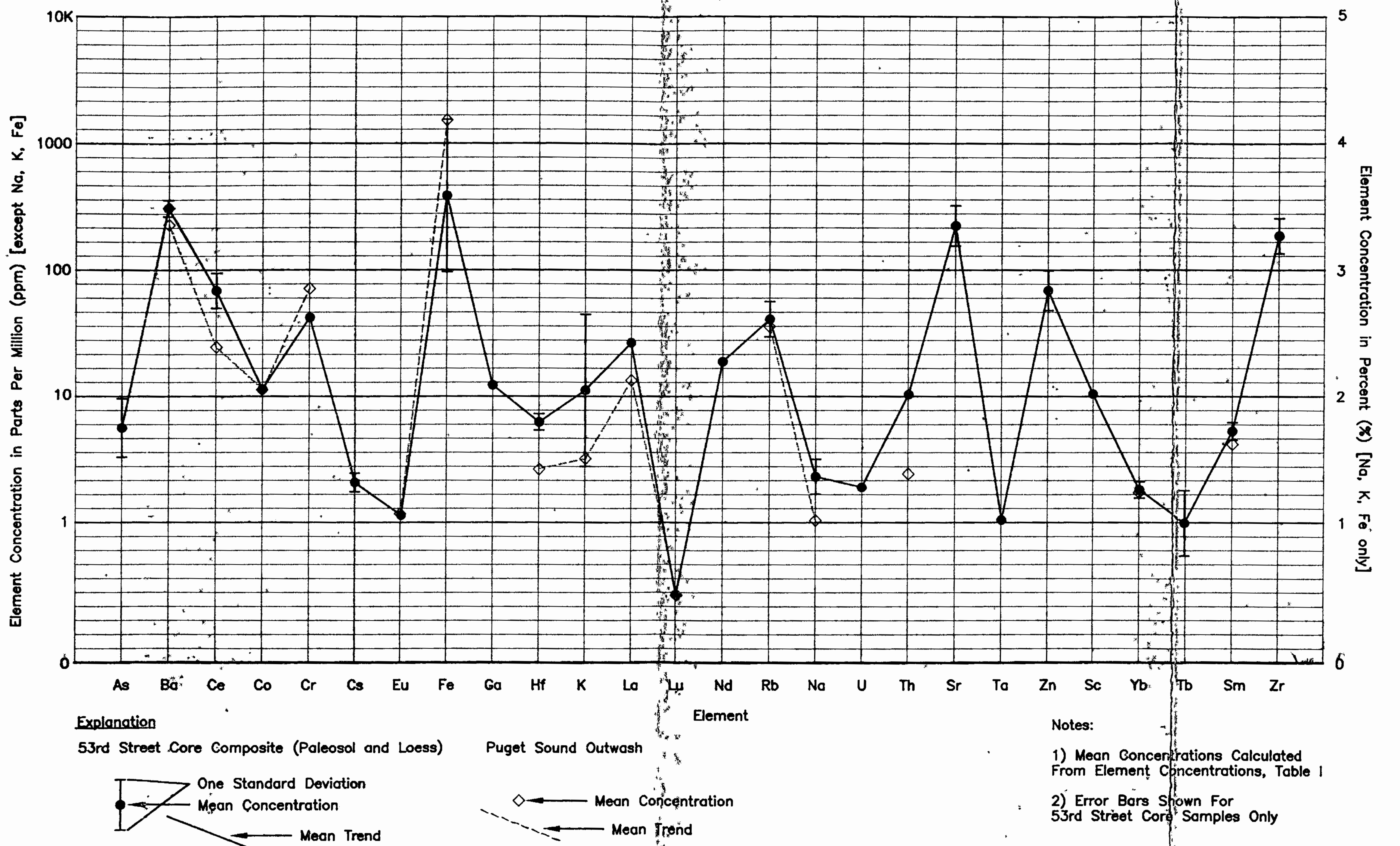


Figure 23: Average Element Concentration, 53rd Street Composite vs. Puget Sound Outwash

in any of the three samples, or if encountered, these data were lost in the retrieval error mentioned previously. This is the case for the elements arsenic, cesium, gallium, neodymium, uranium, tantalum, zinc, scandium, terbium and zirconium. Only the elements chromium and iron have a concentration recorded for all three PS samples.

The reduced data field from the Puget Sound region also increases the difficulty of speculating about relationships between the PHS and this potential source of glacial sediment. In the iron vs. hafnium study (Figure 24), only two samples are shown, reduced from the initial three because hafnium could not be detected in sample PS-2. Even less information is forthcoming from the scatterplot of the thorium/scandium ratio (Figure 12) - a single point! Given this quite small group to draw conclusions from, however, the pair of samples in Figure 24 plot lower in hafnium (avg. 4.8 ppm) than the 53rd Street "type" PHS average. As they appear on the iron vs. hafnium scatterplot (Figure 24), these samples appear to have more in common with the younger, andesite- or Cascadian-volcanic sediments of the HCS/YRCS or the Boring Lavas of Barnes (1996). The contrast is well shown by observing the PHS as typified by the 53rd Street sample average shown in Figure 23. The single datum point plotted on the thorium-scandium ratio scatterplot (Figure 12) falls close to the

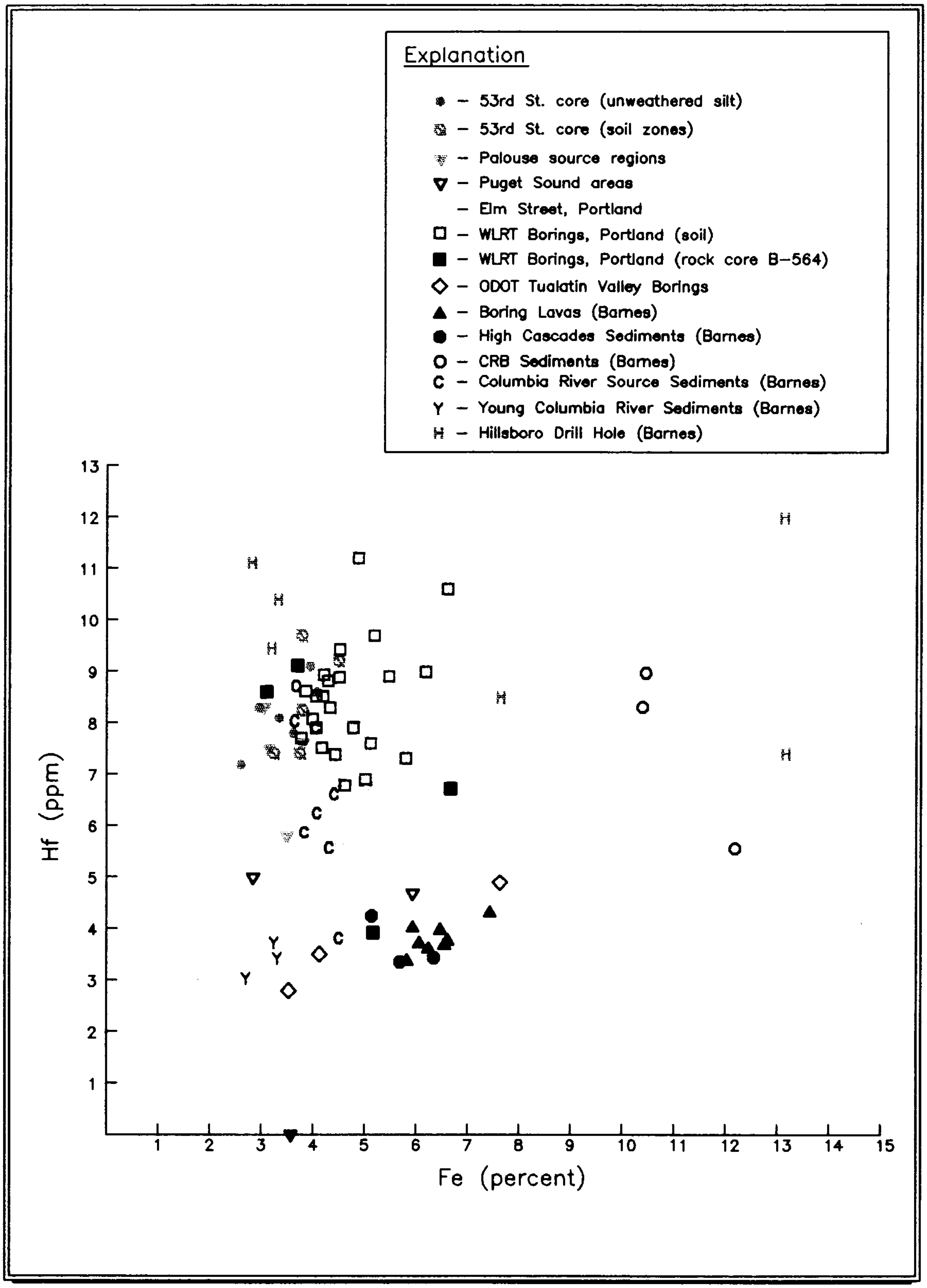


Figure 24

Scatter Plot: Iron v. Hafnium (All Samples) geochemical ratio of the Cascadian volcanics of the HCS, as well as the basalts of the CRBs and the Boring Lavas (0.2Th/1Sc). When this ratio is plotted against overall scandium abundance, this single Puget Sound sample displays a geochemistry most similar to the andesitic sediments of the HCS. Taken altogether, this suggests that the glacial outwash sediments in the Puget Sound/Chehalis River drainage area sampled in this study make relatively poor candidates for Portland Hills Silt source areas.

CONCLUSIONS

What, then, can we conclude from this look at the soil morphology and geochemistry of the Portland Hills Silt, nearby silty sediments, and two of the potential source areas for glacial and glaciofluvial sediments? Based on the work of this study, and the related geochemistry of Barnes (1996), it appears that the following areas can be addressed.

1. Provenance of the PHS

The Portland Hills Silt sampled at NW 53rd Street, in all of the WLRT borings, at the garage excavation on Elm Street on Vista Heights, and in the sediments derived from the Columbia River (CRSS) identified by Barnes (1996) such as the SRM and the Willamette "Blue Clay" appear similar geochemically. In addition, the Palouse soils of eastern Washington and Oregon are geochemically broadly alike, even indistinguishable, from these PHS soils.

It would also appear that the Puget Sound sediments appear geochemically dissimilar to the Portland Hills Silt and related sediments.

It would follow, then, that the parent-product relationship between continental glacial rock flour and the Portland Hills Silt posited by Lentz (1977) is supported by geochemistry. The working hypothesis I recommend is to see the continental silts of the Northwest region as part of a larger system created by the seaward flow of water. The continental ice sheets provide a source of rock flour that is the ultimate source for all of these silty and loessal sediments. Glacial silts are carried down the Columbia River and it's tributaries. A portion of these silts are deposited in the Portland Basin and floodplains of the Columbia River. A portion of this portion is blown onto the surrounding hillslopes. At intervals, great outburst floods deposit a thick blanket of silty sediment across the Palouse region and along the Columbia Valley to Portland and beyond. Derived from the same source areas, I believe that this sediment is geochemically quite similar to the silty alluvium and alluvially-derived loess of the Portland area. It is likewise blown from the basin onto the hills above, forming part of the uppermost segment of this loess sequence. Thus the main conclusion of the Lentz (1977) investigation, that continental glacial material, including that of the Palouse region of eastern Oregon and Washington provided the source of an eolian Portland Hills Silt, is confirmed by this study.

2. PHS and Soil Chronology

This question is really two related questions: how old are the paleosols formed in the PHS (absolute age), and how mature are the soils, i.e., the degree of soil development (relative age). The first question cannot be addressed by this study, while the geochemical data may help shed some light on the latter.

Absolute Age of the Paleosols

Nothing in the geochemistry of the paleosols observed in this study allows us to speculate on the chronological age of these soil horizons. Soil morphology, and stratigraphic data provided by the WLRT construction, provide better age constraints on the PHS. Based on this information, I believe that we can extend the minimum age of the PHS from 34,000 years to the 10,000 to 15,000 YBP age of the youngest modern soil. Based on the volcanic stratigraphy of WLRT Boring 564, the maximum age can be extended to at least as far back as 0.96 Ma (Conrey and others, 1996; Ken Walsh, Parsons Brinckerhof, personal communication, 1996). Based on this information, I recommend that the original soil chronology of Lentz (1977) be revised.

The geochemical homogeneity of the PHS, combined with an increasingly more complex paleopedologic record and the absence of soil horizon dating, leave us at a standstill with regard to dating of the internal paleosols. Even the paleoclimatic implications of these deposits are at issue. Lentz (1977) assumed that the paleosol horizons represented warmer, interglacial periods that would provide increased vegetation growth. He believed that resulting increase in biomass accumulation in the "A" horizon, in chelation and in translocation of clay particles would result in increased soil formation. This is in direct contrast with the ideas of Foley (1982) which suggest that glacial maxima occasion lowered sediment supply and resultant depositional hiatus and soil formation.

Soil stratigraphy is complicated by locations such as Elm Street and the well-developed, highly variable PHS paleosols in the Highland/East Sylvan district (Scott Burns, PSU, personal communication, 1996). This suggests that the chronology and extent of soil development in the PHS probably owes more to local microclimatic conditions and topography than to the regional glaciations.

Relative Age of the Paleosols

A low level of soil development within PHS parent materials is suggested by the geochemical "transparency" of the soil horizons - that is, the overall absence of major soil-formation related patterns of geochemical enrichment or depletion. There appears to be some good indication of soil processes in the leaching of large mobile cations such as sodium and to a lesser extent, potassium. Other element concentrations that we might expect to typify soil formation, such as the eluviation/illuviation of iron or magnesium and the buildup of relatively immobile or insoluble species such as zirconium, are not seen in the soil zones analyzed in this investigation. The lack of a geochemical "soil signature" may be suggestive, along with the lack of other signs of pedological maturity such as the low Harden indices, of poorly developed Inceptisols formed in cool, brief periods between rapid pulses of eolian sedimentation. These pulses are variable, as evidenced by the thickness of the uppermost, Missoula Flood-derived loess which varies from about one meter at the Elm Street site to as much as five meters at 53rd Street, less than five kilometers away.

Paleosols: Conclusions

Based on the above observations, this study believes that a complex, multivariate soil-formation history is contained within the Portland Hills Silt. At least four major episodes of loess deposition can be observed. These are almost certainly tied to Quaternary glacial activity, although whether glacial maxima or minima produce loess deposition relative to soil formation can be debated. Soil development on these loesses ranges from the immature, Inceptisol soils of 53rd Street to the well-developed Alfisol at Elm Street. Certainly it seems likely that the ages and degree of maturity of paleosol formation in the PHS is more intricate than the four, area-wide intervals of soil formation proposed by Lentz (1977). Soil formation will have been affected by such elements as sediment supply, slope angle; microclimate factors such as vegetation, rainfall, snowmelt and insolation; and catena position.

3. The "Sandy River Mudstone - equivalent"

Geochemistry does appear to strongly support a revision in the stratigraphy of West Hills proposed by Squier (1993).

The four samples in the rock core B-564, as well as the samples from the other four WLRT borings, identified as "Sandy River Mudstone-equivalent" by that investigation appear very similar to the bulk of the PHS geochemistry performed for this study. A small number of these samples would appear to have been reworked by alluvial or colluvial processes and contain some allocthonous material. The high degree of geochemical similarity, petrologic and, in many cases, depositional similarities gives reason for this study to conclude that this "SRM-equivalent" material is part of the Portland Hills Silt.

Having thus concluded, this assertion is somewhat compromised by my failure to perform geochemistry for known Sandy River Mudstone in this study. While the geochemical affinities of the "SRM-equivalent" and PHS can be confirmed, the larger possibility that PHS and SRM may be indistinguishable geochemically cannot be ruled out. In all likelihood they are quite similar.

Physical evidence from the "SRM-equivalent" may be more helpful in providing support for this conclusion. Observations of this material, both from the WLRT borings as well as in-situ exposures in the tunnel shaft walls, can be summarized as follows:

- The "SRM-equivalent" contains rip-up clasts of recognizable PHS along with traces of mica and much lithic clasts including subrounded to angular basaltic sand to gravel.
- Portions of the "SRM-equivalent" sediments have been best observed during construction of the WLRT. Here, several exposures have been identified by a project geologist (Ken Walsh, Parsons Brinckerhoff, personal communication, 1996) as high-energy, first-order stream alluvium and slopewash deposits.
- In some locations, the "SRM-equivalent" contact is in angular unconformity with the underlying CRB: note the apparent onlap onto the Frenchman Springs basalt near B-564 in Figure 16.
- The Tualatin Mountains are known to have been a topographic high by as early as 15 Mya, where they diverted the Frenchman Springs Basalt (Beeson and others, 1991)

All of the above suggests that the Tualatin Mountains were a topographic highland at the time of the late Miocene. From this it may be proposed that a thick deposit of silty to sandy silt sediment encountered on such an upland is more likely to be a loess than a fluvial or lacustrine deposits such as the Sandy River Mudstone.

To convert all of the WLRT "SRM-equivalent" to Portland Hills Silt cannot be considered a major stratigraphic revision. Even L.R. Squier's WLRT project manager admitted that the initial stratigraphic identification of these sediments as SRM was more a conjecture than anything else (Gary Peterson, L. R. Squier, personal communication, 1994), and the corrected stratigraphy will be contained in the WLRT as-built report to be released in the near future (Ken Walsh, Parsons Brinckerhof, personal communication, 1996).

Based on the inclusion of the "SRM" portions of the B-564 core discussed above, overall age of the Portland Hills Silt can now be plausibly extended to at least the 0.97 Ma-age of the stratigraphically superposed Boring Lava reverse polarity flow. I proposed that this sediment be called "Ancient Portland Hills Silt (APHS)"

4. Elm Street and the NETV

The Elm Street soil does appear to fall within the PHS-geochemistry field, with some interesting anomalies which are likely the product of soil development, with a possibility of local Boring Lava-ash contamination.

The small sample group in the NETV samples, and the missing records in the data set of the Tualatin Valley sediments, discourages any definitive statement. The obtuse chemical behavior of the NETV samples is confusing, but in general these samples do not appear particularly akin to any of the other geochemical groups in this study. This geochemical behavior may be the effect of Coast Range-derived sediments (Michelle Barnes, Agra Earth & Environmental, personal communication, 1996) being deposited in the Tualatin Valley during Pleistocene times. The poor quality of the NETV samples provides this study with an excuse to defer the geochemical analysis of the Tualatin Valley. This basin will be better addressed in the studies of Wilson (1997).

RECOMMENDATIONS FOR FUTURE WORK

The most perplexing question that remains is the problem of the "other" fine-grained sediments of the Tualatin and Portland Basins. Generally, the silts of the Portland Heights appear to share a similar chemistry. The chemical relations of the Portland Hills Silt to the silt and clay sediments that fill the surrounding basins are more troublesome. This relationship might be elucidated by additional work on these sediments to produce a database to contrast with that contained in this study. The geochemistry from this study is admittedly sparse, incomplete, and in places such as the chemical behavior of the NETV sediments, more apt to raise questions than settle them.

Ideally, the funding and interest would exist for a further inquiry into the geochemistry of the fine-grained sediments of the Portland area, in which a broader data field incorporating multiple samples of Willamette Silt, Tualatin Silt and Sandy River Mudstone would be analyzed and the results carefully compared with studies such as this one, Barnes (1996) and the valuable work of other Portland State geochemistry students.

Having made this suggestion, however, the unpleasant suspicion is raised by what has been observed of fine-grained sediment geochemistry in the above-mentioned studies; that INAA may not be particularly useful in separating these sedimentary units from one another. Any investigator wishing to continue this method of inquiry would be well advised to pause and consider that the geochemical differences between these units may be small, subtle, and quite difficult to recognize.

The question of soil development in the PHS is another matter and might be well addressed using other methods such as palynological analysis or thermoluminescent age-dating. As more development and, therefore, more roadcut and boring data become available, soil stratigraphy within the PHS across the West Hills should come closer to becoming a reality. A patient researcher might be capable of refining the ages, soil stratigraphy and development of paleosols in the Portland region. This is not merely an idle speculation, based on the reported incidence of landsliding that appears to develop along paleosol horizons in the Portland Hills Silt.

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APPENDIX A

FIELD LOGS

PRELIMINARY Subject to revision

SOILS AND GEOLOGICAL EXPLORATION LOG
HIGHWAY DIVISION

TB-810

Project Earthquake Study		Hole No. ~~FB-50~~
Highway Corvell Rd / 63rd	County Multnomah	Prefix
Purpose of Work		Bridge No.
Equipment B-53 83-894		Tube Elev.
Geologist	Driller J. Lee	Recorder Dermot O'Keefe
Hole Location Line, Sta. Lt.	C.L. Rt.	Ground Elev.

Tests	No.	Drilling Method		Groundwater Level Date	Depth
"N" — Standard Penetration,	No.	Auger Depth			
"M" — Oregon Miniature Pile,	No.	Casing Depth			
"C" — Core, Barrel Type HQ3	No.	Open Depth			
"U" — Undisturbed Sample, Size	No.	Total Depth			

Date Started 4-2-92 | Date Completed | Sample Data Sheet No.

Depth, ft.	Test Type No.	Driving Resistance	Measured Recovery	% Recovery	Hardness / R.Q.D.	Graphic Log	% Natural Moisture	Material Description: Color, Consistency, Plasticity, Organic Content, Wet-Dry, Jointed-Broken, Angular-Rounded, Drill Remarks etc.
0	C-1		4.6					Clayey SILT, Brown, Stiff, moist, low plasticity (CL)
5	N-1	5-7-7	1.3					N-1 (Same As Above)
6.5	C-2							Same As Above
10	N-2	4-3-3	1.5					Same As Above
11.5	C-3							Lost 1.5 feet upon recovery description Same As Above
15	N-3	3-1-0	.7					Same As Above
15.7	C-4							Same As Above
20.0	N-4	6-6-9	1.3					Same As Above

734-3976 (REV. 12-82)

Cornell / 53rd Hole No. TB-810 Page 2 of 7

PRELIMINARY subject to revision

Depth, ft.	Test Type No.	Driving Resistance	Measured Recovery,	Recovery	Hardness R.Q.D.	Graphic Log	% Natural Moisture	Material Description (Color, Consistency, Plasticity, Organic Content, Wet-Dry, Jointed-Broken, Angular-Rounded, Drill Remarks etc.)
21.3	C-5							Same as Above, but sediment is more compact
25.0	C-6							Same as above
30.0	U-1	200 lbs						Small amount of Drive pressure about 200 lbs.
32.0	U-2							200# to 33.5 then 4000#
34.3	N-5	4-5-18	1.5					Brown, Clayey Silt w/ Tr. Sand, stiff, med to high plasticity.
	C-7		1.5					Same as N-5.
35.0	C-8		3.4					Red/Brown Clayey silts w/ Trace Sand. Stiff, Med plasticity.
40	C-9		4.0					Same as above.
45	C-10		5.1					Brown Clayey silt. Stiff med. plasticity. Dry.
50	N-6	9-12-14	Ø					No Recovery
	C-11		4.7					Same as C-10.
55	C-12		5.0					Same as above
60	N-7	5-9-14	Ø					No Recovery
	C-13		4.0					Same as C-12
65	C-14		5.1					Same as above

Cornell/53rd

SOILS AND GEOLOGICAL EXPLORATION LOG

HIGHWAY DIVISION

TB-810

Project			Hole No. ~~TB-509~~
Highway		County	Prefix
Purpose of Work	PRELIMINARY subject to revision		Bridge No.
Equipment			Tube Elev.
Geologist		Driller	Recorder
Hole Location	Line, Sta.	Lt. C.L. Rt.	Ground Elev.

Tests		Drilling Method	Groundwater Level
"N" — Standard Penetration,	No.	Auger Depth	Date / Depth
"M" — Oregon Miniature Pile,	No.	Casing Depth	
"C" — Core, Barrel Type	No.	Open Depth	
"U" — Undisturbed Sample, Size	No.	Total Depth	

Date Started	Date Completed	Sample Data Sheet No.

Depth, ft.	Test Type No.	Driving Resistance	Measured Recovery	% Recovery	Hardness / R.Q.D.	Graphic Log	% Natural Moisture	Material Description (Color, Consistency, Plasticity, Organic Content; Wet-Dry, Jointed-Broken, Angular-Rounded, Drill Remarks etc.)
70	N-8	7-10-12	1.5			Silts & Clay		Brown Clayey Silts, Stiff dry, Med Plasticity
	C-15		4.7					Same as N-8.
75	C-16		5.2					Same as above.
80	N-9	12-16-26	1.0					Same as above. More Stiff.
	C-17		3.8					Brown Silt w/ Clay, Sand. Stiff, Dry, Med to high plasticity. (Possible decayed rock).
85	C-18		3.2			26.3 / 86.2		Red/Brown silty Sand to 86.2. Decomposed Basalt w/ Fero-mag Inclusions. Some vessicles intact.
90	C-19		5.0			Basalt		Green/Grey + Brown Decayed Basalt. Some silts near top of sample.
95	C-20		5.2					Grey/Brown Basalt, vessicular and jointed. Highly decomposed in areas.
100	C-21		5.0					Grey/Brown Basalt, vessicular and jointed.

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Cornell/53rd Hole No. TB-810 Page 4 of 7

PRELIMINARY subject to revision

Depth, ft.	Test Type No.	Driving Resistance	Measured Recovery	% Recovery	Hardness / R.Q.D.	Log	Natural Moisture	Material Description (Color, Consistency, Plasticity, Organic Content, Wet-Dry, Jointed-Broken, Angular-Rounded, Drill Remarks etc.)
105	C-22		5.0					Grey/Brown Basalt, fractured + Jointed, decomposed in areas.
110	C-23		5.0					Brown/Grey Basalt, fractured, Jointed + Vesicular, decomposed in areas w/ Ferro-mag inclusions.
115	C-24		5.1					Same as above.
120	C-25							SAME AS ABOVE
125	C-26		5.0					SAME AS ABOVE
130	C-27		5.0					Fresh to Decomposed Basalt Jointed + vesicular, Grey to Brown.
135	C-28		5.1					Same as above
140	C-29		5.1					Same as above.
145	C-30		5.1					Same as above
150	C-31		5.1					Same as above
155	C-32		5.1					Same as above
160	C-33		5.0					Brown to tan Decomposed Basalt, Highly Fractured + Jointed w/ some vessicles.
165	C-34		5.1					Grey Basalt, Highly vesicular + Jointed, slightly decomposed.
170	C-35		5.0					Same as above.

SOILS AND GEOLOGICAL EXPLORATION LOG

HIGHWAY DIVISION

TB-810

PRELIMINARY subject to revision

Project			Hole No. ~~TB-509~~
Highway		County	Prefix
Purpose of Work			Bridge No.
Equipment			Tube Elev.
Geologist		Driller	Recorder
Hole Location	Line, Sta. Lt.	C.L. Rt.	Ground Elev.

Tests		Drilling Method	Groundwater Level	
"N" — Standard Penetration,	No.	Auger Depth	Date	Depth
"M" — Oregon Miniature Pile,	No.	Casing Depth		
"C" — Core, Barrel Type	No.	Open Depth		
"U" — Undisturbed Sample, Size	No.	Total Depth		

Date Started	Date Completed	Sample Data Sheet No.

Depth, ft.	Test Type No.	Driving Resistance	Measured Recovery,	% Recovery	Hardness / R.Q.D.	Graphic Log	% Natural Moisture	Material Description -- Color, Consistency, Plasticity, Organic Content; Wet-Dry, Jointed-Broken, Angular-Rounded, Drill Remarks etc.
175	C-36		5.0					Same as above.
180	C-37		5.0					Same as above
185	C-38		5.0					Same as above
190	C-39		5.0					Fresh to Slightly decompos Basalt. Highly vesicular + Fractured.
195	C-40		5.0					Grey fresh Basalt. less fractured + vessicular.
200	C-41		5.0					Same as above.
205	C-42		5.0					Grey fractured Basalt. Some vessicles + Clay in joints.
210	C-43		5.0					Same as above
215	C-44		5.0					Same as above
220	C-45		5.0					Same as above

PRELIMINARY subject to revision

Depth, ft.	Test Type No.	Driving Resistance	Measured Recovery	Recovery	Hardness R.Q.D.	Graphic Log	Natural Moisture	Material Description (Color, Consistency, Plasticity, Organic Content; Wet-Dry, Jointed-Broken, Angular-Rounded, Drill Remarks etc.)
228	C-46		5.0					Grey fresh Basalt, Jointed w/ few vessicles. ~~moderate~~ light weathering along joint edges.
230	C-47		5.0					Same as above.
235	C-48		5.0	100	R4/33			C-48 BASALT, Medium Dark Gray, Fresh to slightly weathered, Hard, Close jointed with some clay and limonite alteration in tight joints. Aphanitic. Some Plagioclase visible 1mm
240	C-49		5.0	100	R4/1.6			C-49 Same as C-48 very close to close jointed.
245	C-50		5.0	100	R4/1.2			C-50 Same as C-49
250	C-51		5.0					Same as above
255	C-52		5.0					Fresh Basalt, Medium Grey, Jointed, Some small vessicles to, 257.7 Transition into Dark Brown moderately Decomposed Basalt w/ fewer vessicles + Joints. Some Ferro-Mag crystallization present.
260	C-53		3.6					Brown to ~~Red~~/Tan slightly to Highly decomposed Basalt. Ferro-Mag + silicate crystals present. .2' rounded gravel @ 265.4.
265	C-54		3.6		R-2 R0/0			C-54 Basalt. Red-Brown, Decomposed Soft to Extremely soft. Very close Jointed to rubble. Some vesicles. Flowtop Breccia. Weathered to Clay, Pelagonite.
270	C-55		5.0	100	R0-R2/15			C-55 Basalt. Red-Brown w/some Black. Soft to Extremely soft. Close to very close jointed. Some vesicles. Baked Zone. clay + pelagonite alteration

SOILS AND GEOLOGICAL EXPLORATION LOG

HIGHWAY DIVISION

TB 810

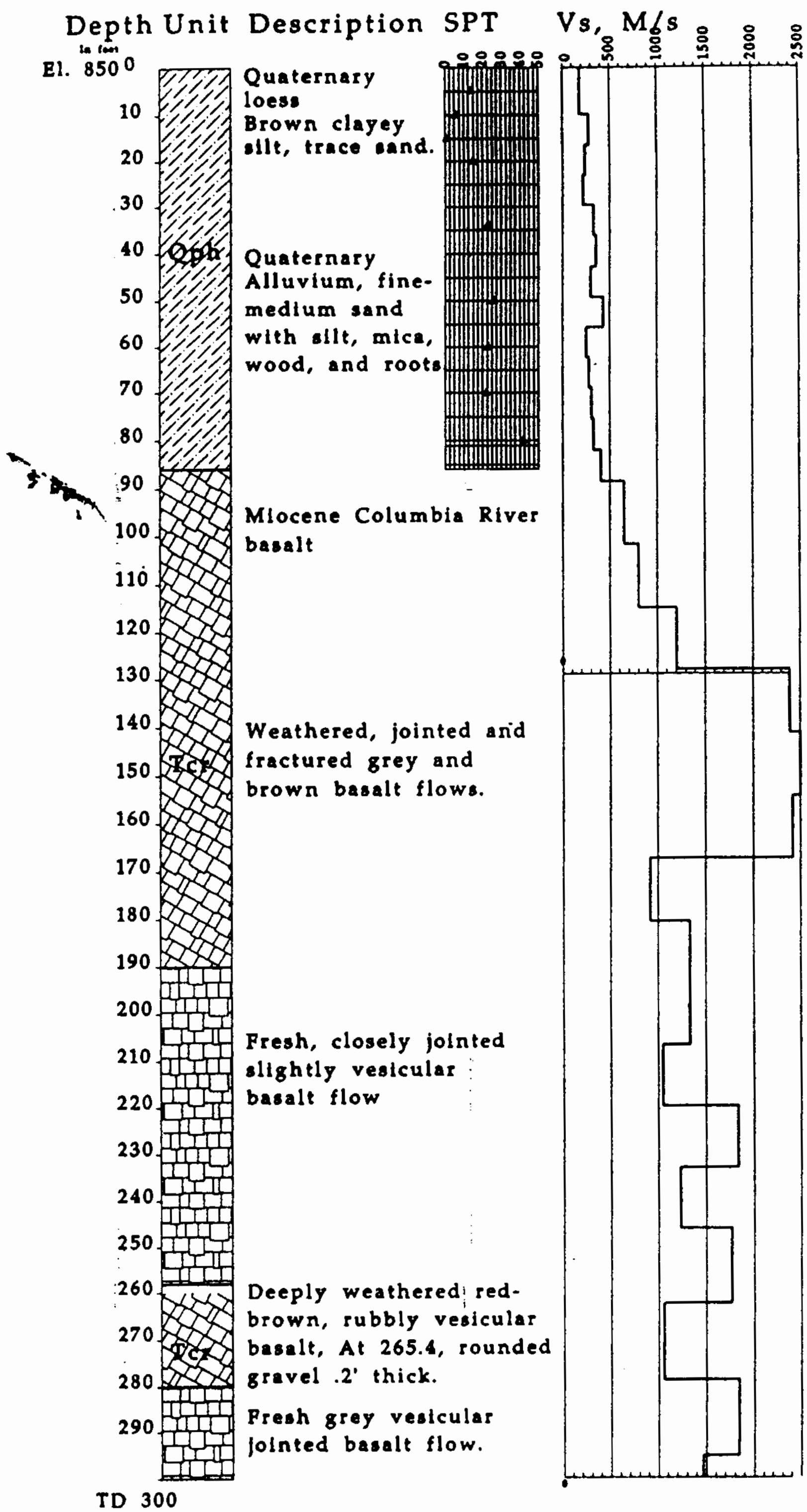
PRELIMINARY subject to revision

Project			Hole No. ~~TB-509~~
Highway		County	Prefix
Purpose of Work			Bridge No.
Equipment			Tube Elev.
Geologist		Driller	Recorder
Hole Location	Line, Sta. Lt.	C.L. Rt.	Ground Elev.

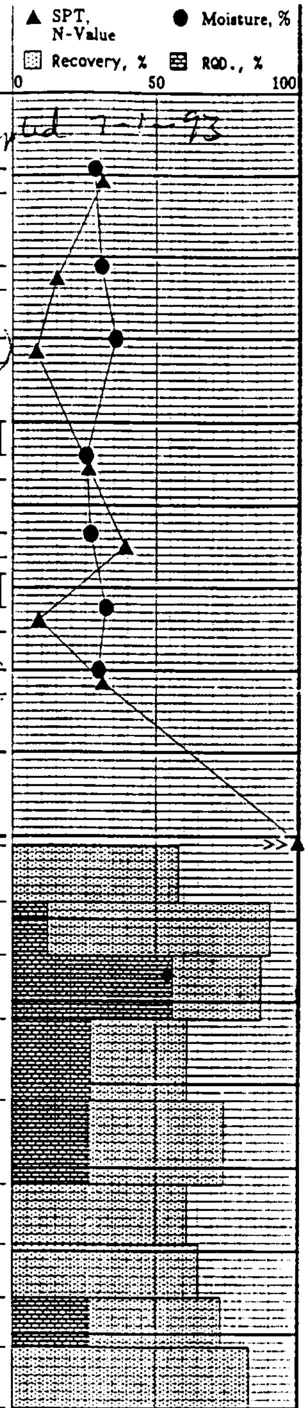
Tests		Drilling Method		Groundwater Level	
"N" — Standard Penetration,	No.	Auger Depth		Date	Depth
"M" — Oregon Miniature Pile,	No.	Casing Depth			
"C" — Core, Barrel Type	No.	Open Depth			
"U" — Undisturbed Sample, Size	No.	Total Depth			

Date Started	Date Completed	Sample Data Sheet No.

Depth, ft.	Test Type No.	Driving Resistance	Measured Recovery,	% Recovery	Hardness / R.Q.D.	Graphic Log	% Natural Moisture	Material Description (Color, Consistency, Plasticity, Organic Content; Wet-Dry, Jointed-Broken, Angular-Rounded, Drill Remarks etc.)
275	C-56		4.5					SAME AS C-55
280	C-57		5.0					Medium grey fresh BASALT large vessicles, fractured + Jointed w/ slight chemical weathering between joints.
285	C-58		5.0					Same as C-57.
290	C-59		5.0					Medium Grey to light Brown, Fresh BASALT w/ vessicles + Jointed. Clay filled joint @294.0.
295	C-60		5.0					Same as C-59.
								Bottom of Hole 300.0
300								


Depth Unit Description SPT
Vs, M/s
0 500 1000 1500 2000 2500
In feet
El. 850 0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
TD 300
Qph
Tcr
Tcr
Quaternary loess Brown clayey silt, trace sand.
Quaternary Alluvium, fine-medium sand with silt, mica, wood, and roots
Miocene Columbia River basalt
Weathered, jointed and fractured grey and brown basalt flows.
Fresh, closely jointed slightly vesicular basalt flow
Deeply weathered red-brown, rubbly vesicular basalt, At 265.4, rounded gravel .2' thick.
Fresh grey vesicular jointed basalt flow.

Back-Fill	Remarks	Elev. Depth 336.9	SURFACE ELEVATION IN FEET: 336.9 STATION: 927+81.2 OFFSET: -25 **Classification of Material**	Log	Depth, Feet	Samples
	Monument Cover				0	- Sampled 7-1-93
			Very stiff light brown SILT with trace fine sand and clay, moist PORTLAND HILLS SILT		5	S-1
			grades to stiff, wet		10	S-2
			grades to medium stiff SILT with some clay; moist to wet		15	S-3
		315.7 21.2	grades to very stiff red-brown mottled gray clayey SILT with trace fine sand, occasional organics		20	S-4 S-5
	Bentonite		grades to hard		25	S-6
			medium stiff orange-brown clayey SILT with trace fine sand;wet		30	S-7 S-8
		301.7 35.2	Very stiff dark red-brown silty CLAY to CLAY with some silt;moist to wet SANDY RIVER MUDSTONE		35 40	S-9 S-10*
		291.3 45.6	Very low to low strength (R1-R2) light green-gray/brown BASALT, very close to close joints, moderately severe weathering, moderately vesicular grades to moderate strength (R3), slightly weathered		45 50 55	S-11* S-12 R-1 R-2 R-3
	Sand	279.4 57.5	Very low strength (R1) red-brown BASALT, moderately vesicular, moderately weathered, close to very close joints grades to medium-high strength (R4), slightly weathered, slightly vesicular		60 65	R-4 R-5
			Low strength (R2) moderately weathered zone near 71 to 73 feet GRANDE RONDE BASALT Sentinel Bluffs		70	R-6 R-7
			grades to moderate strength (R3), locally bleached and altered (hydrothermally) BASALT, moderately weathered		75	R-8 R-9



Samples

I = 2.0" O.D. Split Spoon Sample

II = 3.0" O.D. Thin-Walled Sample

• = Sample Not Recovered

I = Rock Core Sample

⊕ = Geochemical Analysis Sample

NOTE:

= Tunnel Horizon (Horizontal Projection)

Lines representing the interface between soil/rock units of differing description are approximate only and may indicate gradual transition

Tests

Unconfined Compressive strength

Soil Laboratory Qu — Mod. Pocket Penetrometer

Torvane — Rock Laboratory Qu

Pocket Penetrometer — ◆ Point Load Test

ATTERBERG LIMITS

Liquid Limit

Natural Water Content

Plastic Limit

BORING LOG
B-574

Westside LRT Tunnel, LS-5A

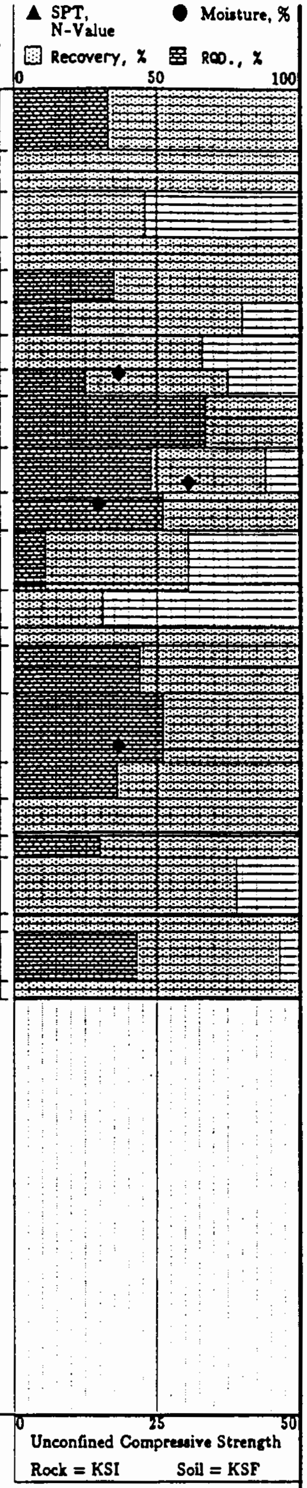
SQUIER ASSOCIATES

FEBRUARY 1993 91624

ROCKLOG4 2/6/93 05:00AM

Reviewed GP

Backfill	Remarks	Elev. Depth	Classification of Material	Depth, Feet	Samples
	Z-1 10/8/92 Z-1 10/23/92		Moderate strength (R3) gray-brown BASALT, very close joints, slightly vesicular, moderately weathered, locally drills to rubble	85	R-10 R-11 R-12
	Sand		grades to medium-high then high strength (R4-R5) light gray BASALT, very slightly weathered, dense, close to occasionally very close joints	90 95	R-13 R-14 R-15 R-16 R-17
		229.7	GRANDE RONDE BASALT Sentinel Bluffs Flow contact	100 105	R-18 R-19 R-20
	Z-1 Sensor	107.2	Low to very low strength (R1-R2) red-brown BASALT and FLOW BRECCIA, moderately vesicular, moderately weathered, very close slightly rough joints to rubbly with <.1" clay and silt fill recovery consists of sand and gravel size rock fragments with trace silt	110 115	R-21 R-22 R-23 R-24
		218.9 118.0	grades to medium-high strength (R4) light gray BASALT, slightly weathered, very close to close joints, dense	120 125	R-25 R-26 R-27 R-28 R-29
		207.9 129.0	Low strength (R2) dark brown BASALT, moderately vesicular with light clay fill, moderately severe weathering	130	R-30 R-31
		201.9 135.0	(Bottom of Boring) (9/12/92)	135	R-32



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Tests

Unconfined Compressive strength

- Soil Laboratory Qu
- Torvane
- Pocket Penetrometer
- Mod. Pocket Penetrometer
- Rock Laboratory Qu
- ◆ Point Load Test

ATTERBERG LIMITS
- Liquid Limit
- Natural Water Content
- Plastic Limit

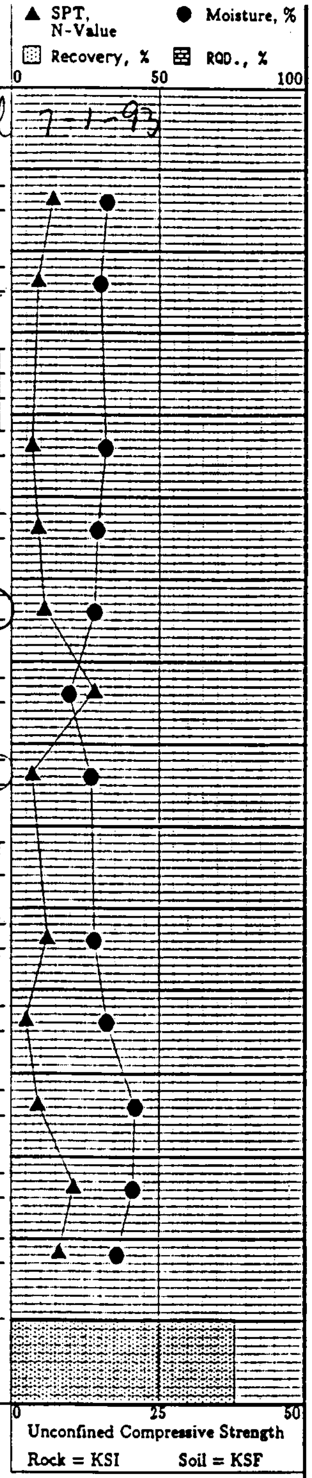
BORING LOG
B-574

Westside LRT Tunnel, LS-5A

SQUIER ASSOCIATES
FEBRUARY 1993 91624

ROCKLOG4

Back-Fill	Remarks	Elev. Depth 539.5	SURFACE ELEVATION IN FEET: 539.5 STATION: 911+26.3 OFFSET: -69.4 **Classification of Material**	Log	Depth, Feet	Samples
	Monument Cover	538.5 1.0	ASPHALT over BASE COURSE		0	
			Stiff brown mottled red-brown and gray SILT with trace fine sand and clay; moist to wet micaceous		5	
	Sand					S-1
			PORTLAND HILLS SILT		10	
			clay decreases, grades to brown			S-2
					15	• •
			grades to medium stiff SILT with trace to some clay and sand, and red-brown nodules		20	S-3 S-4
		515.5 24.0	Stiff mottled brown, red-brown and gray silty CLAY to clayey SILT with trace fine sand; moist to wet		25	S-5
			PORTLAND HILLS SILT			
		510.5 29.0	Stiff yellow-brown SILT with trace clay and fine sand; moist to wet		30	S-6
			grades to medium dense, decreasing clay; moist, micaceous		35	S-7
		500.5 39.0	Medium stiff mottled brown and red-brown silty CLAY to clayey SILT with trace fine sand; moist to wet		40	S-8
			SANDY RIVER MUDSTONE		45	S-9*
			grades to stiff brown mottled gray clayey SILT, micaceous; moist		50	S-10
			grades with trace fine sand		55	S-11
	Bentonite Seal				60	S-12
		473.5 66.0	Very stiff dark brown mottled sandy SILT with some clay and scattered to abundant very severely weathered vesicular basalt fragments; moist to wet		65	S-13
			RESIDUAL SOIL from BASALT		70	S-14
			Auger refusal @ 74.9 feet			
		464.6 74.9	Low strength (R2) light green-gray BASALT, moderately to very severely weathered with sandy to clayey zones to 1 inch, dense, very close joints to rubbly		75	R-1



Samples

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- **I** = Rock Core Sample
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Tests

Unconfined Compressive strength

- Soil Laboratory Qu
- Torvane
- Pocket Penetrometer
- Mod. Pocket Penetrometer
- Rock Laboratory Qu
- ◆ Point Load Test

ATTERBERG LIMITS
- Liquid Limit
- Natural Water Content
- Plastic Limit

NOTE:
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BORING LOG
B-525

Westside LRT Tunnel, LS-5A

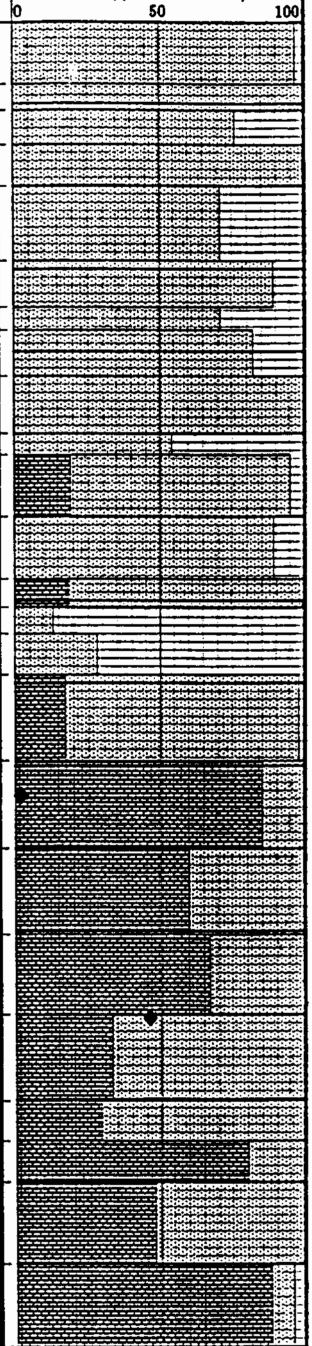
SQUIER ASSOCIATES
FEBRUARY 1993 91624

ROCKLOG4 2/8/93 09:03AM

Reviewed GLP

Back-Fill	Remarks	Elev. Depth	Classification of Material	Log	Depth, Feet	Samples
			grades to moderately weathered with soil zones			R-2
					85	R-3
						R-4
			grades to mixed ROCK fragments and SILT/CLAY matrix			R-5
					90	
						R-6
		445.5 94.0	Moderate to medium-high strength (R3-R4) brown gray BASALT, moderately severe to slightly weathered, slightly vesicular grading to dense, very close joints with locally 5 to 10mm thick sand/clay @ 98' grades to high strength (R5) gray brown BASALT		95	R-7
						R-8
					100	R-9
			GRANDE RONDE BASALT Sentinel Bluffs (M2)			R-10
		433.9 105.6	Very stiff to hard (soil) to very low strength (R1) yellow-gray altered BASALT, slightly vesicular, very severely weathered, altered and bleached with significant clay content		105	R-11
						R-12
		429.5 110.0	Medium-high to high strength (R4 to R5) gray BASALT, generally slightly weathered, with local severely weathered joints, very close grading to close joints Core loss in flow contact zone		110	R-13
					115	R-14
						R-15
	Bentonite Seal	421.5 118.0	Low strength (R2) variable gray, yellow and red brown slightly weathered FLOW BRECCIA, angular to rounded welded fragments in a matrix of soft CLAY FLOW TOP BRECCIA			R-16
					120	R-17
			grades to moderate strength (R3)		125	R-18
		409.7 129.8	High strength (R5) light gray BASALT, close to locally very close rough joints occasionally with fill to 2mm, close spaced incipient joints, very slightly weathered, very slightly vesicular to dense		130	R-19
					135	R-20
			grades to slightly vesicular with vugs to 20mm and joint fills 5 to 10 mm.		140	R-21
			GRANDE RONDE BASALT Winter Water grades to dense with very thin joint fill		145	R-22
						R-23
					150	R-24
		384.7 154.8	moderately vesicular @ FLOW CONTACT Low strength (R2) red-brown, purple and yellow FLOW BRECCIA, with welded BASALT fragments to several inches diameter in a clay mineral matrix, occasional clay filled planes of		155	R-25

▲ SPT, N-Value ● Moisture, % ▦ Recovery, % ▤ RQD., %



Unconfined Compressive Strength
Rock = KSI Soil = KSF

Samples

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Tests

Unconfined Compressive strength

- Soil Laboratory Qu
- Torvane
- Pocket Penetrometer
- Mod. Pocket Penetrometer
- Rock Laboratory Qu
- ◆ Point Load Test

ATTERBERG LIMITS
Liquid Limit
Natural Water Content
Plastic Limit

NOTE:
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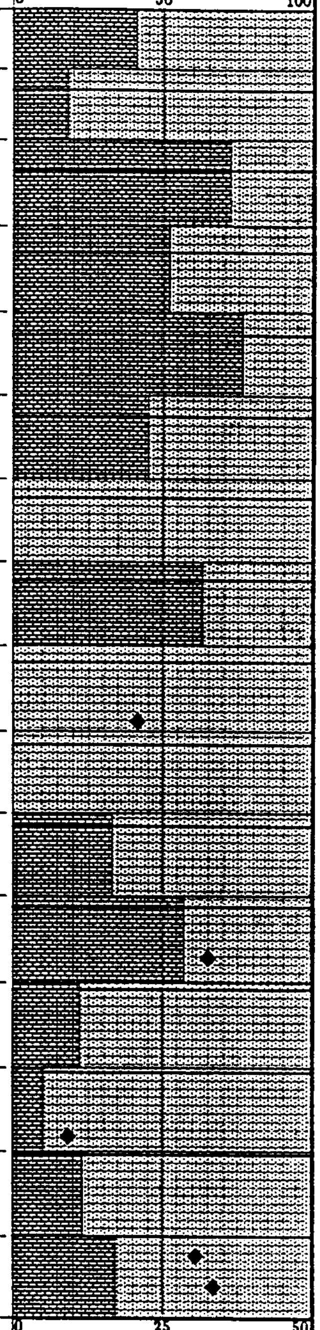
BORING LOG
B-525

Westside LRT Tunnel, LS-5A

SQUIER ASSOCIATES
FEBRUARY 1993 91624

ROCKLOG4

Back-Fill	Remarks	Elev. Depth	Classification of Material	Log	Depth, Feet	Samples
			weakness to 2"			R-26
			grades to very low strength (R1) yellow-brown broken/rubbly FLOW BRECCIA		165	R-27
			grades to low strength (R2), close joints with prominent 1 to 12" basalt fragments, vesicular to dense		170	R-28
	Bentonite Seal	367.5 172.0	Moderate strength (R3) dark gray BASALT, moderately vesicular, moderate weathering, close joints with substantial clay mineralization/healing to 25mm		175	R-29
			grades to high strength (R5) gray BASALT, close to locally very close joints generally with 1 to 2 mm clay fill, slightly weathered, slightly vesicular with large vugs		180	R-30
			green high plasticity clay filled zone 3" thick		185	R-31
					190	R-32
					195	R-33
			High to very high strength (R5 to R6) light gray BASALT, very slightly weathered, close to locally very close joints, rough fractures with light mineral coatings (some unbroken healed joints), with occassional high angle smooth joints with 2+ mm mineral fill, slightly vesicular with vugs to >1"		200	R-34
					205	R-35
					210	R-36
			GRANDE RONDE BASALT Winter Water		215	R-37
	Sand				220	R-38
	Z-1 10/23/92		grades to dark gray and slightly vesicular to dense		225	R-39
					230	R-40
			grades to light gray BASALT, slightly vesicular, very slightly weathered, close to locally very close joints with occassional subparallel high angle smooth joints with up to 4mm mineral fill		235	R-41



Samples

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Tests

Unconfined Compressive strength

- Soil Laboratory Qu
- Torvane
- Pocket Penetrometer
- Mod. Pocket Penetrometer
- Rock Laboratory Qu
- ◆ Point Load Test

ATTERBERG LIMITS
- Liquid Limit
- Natural Water Content
- Plastic Limit

NOTE:

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BORING LOG
B-525

Westside LRT Tunnel, LS-5A

SQUIER ASSOCIATES

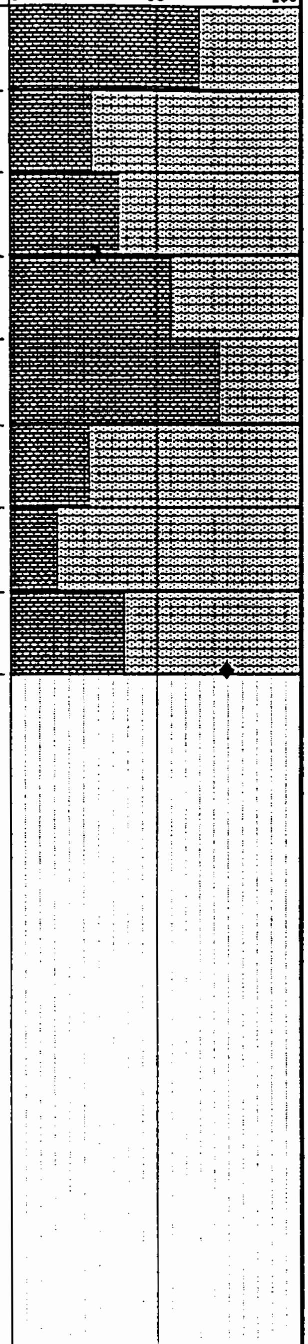
FEBRUARY 1993 91624

ROCKLOG4

Back-Fill	Remarks	Elev. Depth	Classification of Material	Log	Depth, Feet	Samples
∇	Z-1 5/26/92 Z-1 Sensor		GRANDE RONDE BASALT Winter Water		245	R-42
					250	R-43
					255	R-44
					260	R-45
			Columnar/colonnade jointing; mainly a large blocky texture with smooth interfaces, internally jointed with tight rough to stepped joints		265	R-46
					270	R-47
	Sand				275	R-48
		259.5 280.0	BOTTOM OF BORING (3/14/92)		280	R-49

▲ SPT, N-Value ● Moisture, % ▧ Recovery, % ▦ RQD., %

0 50 100



0 25 50

Unconfined Compressive Strength

Rock = KSI Soil = KSF

Samples

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Tests

Unconfined Compressive strength

- Soil Laboratory Qu
- Torvane
- Pocket Penetrometer
- Mod. Pocket Penetrometer
- Rock Laboratory Qu
- ◆ Point Load Test

ATTERBERG LIMITS

Liquid Limit
Natural Water Content
Plastic Limit

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BORING LOG

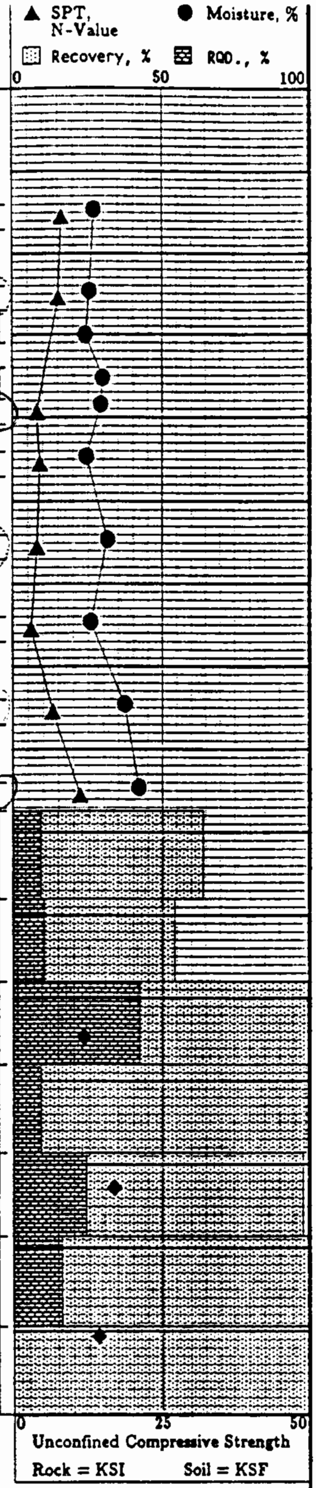
B-525

Westside LRT Tunnel, LS-5A

SQUIER ASSOCIATES

FEBRUARY 1993 91624

Back-Fill	Remarks	Elev. Depth 683.1	SURFACE ELEVATION IN FEET: 683.1 STATION: 893+44.5 OFFSET: 95.4 **Classification of Material**	Log	Depth, Feet	Samples
	Monument Cover Sand	680.5 2.6	FILL: GRAVEL (Road Base)		0	
			Very stiff light brown mottled gray SILT with trace fine sand and scattered organics; moist PORTLAND HILLS SILT grades to stiff		5 10 15	S-1 S-2 S-3
	Random Backfill		grades to medium stiff with trace to some clay; moist to wet		20 25	S-4 S-5 S-6
			grades to brown mottled gray and red-brown COBBLE at 29.5'		30	S-7 S-8
		648.1 35.0	Stiff orange-brown mottled gray silty CLAY to CLAY with some silt; moist to wet SANDY RIVER MUDSTONE		35 40	S-9
		639.3 43.8	grades to very stiff green-gray silty CLAY with some sand size severely weathered rock fragments; (Residual Soil)			S-10
			Very low strength (R1) gray mottled red-brown BASALT, slight to moderately vesicular, severely grading to moderately weathered, very close to close joints with clay mineral fill		45 50	R-1 R-2
		629.7 53.4	grades to low to moderate strength (R2-R3) brown-gray BASALT, slight to very slight weathering, dense to slightly vesicular, very close to close joints Medium-high to high strength (R4-R5), slightly to moderately vesicular		55 60	R-3 R-4
	Bentonite Seal		GRANDE RONDE BASALT Sentinel Bluffs (M1)		65 70 75	R-5 R-6 R-7



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Unconfined Compressive strength

- Soil Laboratory Qu
- Torvane
- Pocket Penetrometer
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ATTERBERG LIMITS
- Liquid Limit
- Natural Water Content
- Plastic Limit

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BORING LOG
B-527

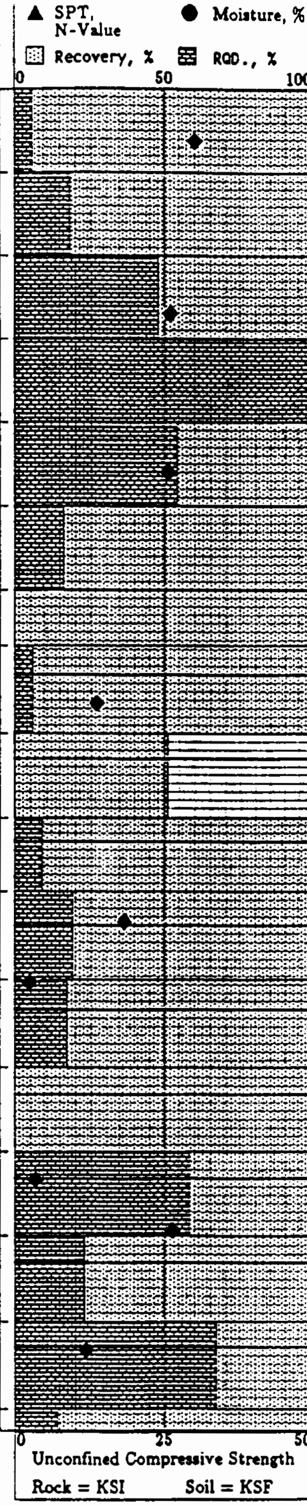
Westside LRT Tunnel, LS-5A

SQUIER ASSOCIATES
FEBRUARY 1993 91624

ROCKLOG4 2/5/93 07:30PM

Reviewed GLP

Back-Fill	Remarks	Elev. Depth	Classification of Material	Log	Depth, Feet	Samples
			Medium-high to high strength (R4-R5) dark gray BASALT, close joints with black mineral coat, very slight weathering, slightly vesicular			R-8
					85	R-9
			dense, close joints, common vertical fractures		90	R-10
					95	R-11
			Medium-high to high strength (R4-R5) dark gray BASALT, very slightly weathered to fresh with some brown clay on fractures below 103.5', close jointed, dense		100	R-12
			High to very high strength (R5-R6), fresh to slightly weathered, dense		105	R-13
			GRANDE RONDE BASALT Sentinel Bluffs (M1)		110	R-14
		565.1 118.0	grades to moderately vesicular FLOW CONTACT		115	R-15
	Bentonite Seal		Moderate strength (R3) purple-brown BASALT, moderately vesicular to locally dense, close joints, slight to very slightly weathered grades to purple-gray		120	R-16
			GRANDE RONDE BASALT Sentinel Bluffs (M2) grades to medium-high strength (R4)		125	R-17
		550.1 133.0	grades to high to very high strength (R5-R6) dark gray BASALT, slight to very slightly weathered, very close to close joints, dense FLOW CONTACT		130	R-18
			grades to low to moderate strength (R2-R3) BASALT, moderate to highly vesicular, very close joints, slight to very slightly weathered		135	R-19
			grades to moderate to medium-high strength (R3-R4), slightly vesicular, very close to close joints, very slight to slightly weathered		140	R-20
					145	R-21
		529.6 153.5	FLOW CONTACT		150	R-22
			Medium-high to high strength (R4-R5) dark gray BASALT, very slightly weathered, highly grading to slightly vesicular, very close to close joints		155	R-23



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Tests

Unconfined Compressive strength

- Soil Laboratory Qu
- Torvane
- Pocket Penetrometer
- Mod. Pocket Penetrometer
- Rock Laboratory Qu
- ◆ Point Load Test

ATTERBERG LIMITS
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- Natural Water Content
- Plastic Limit

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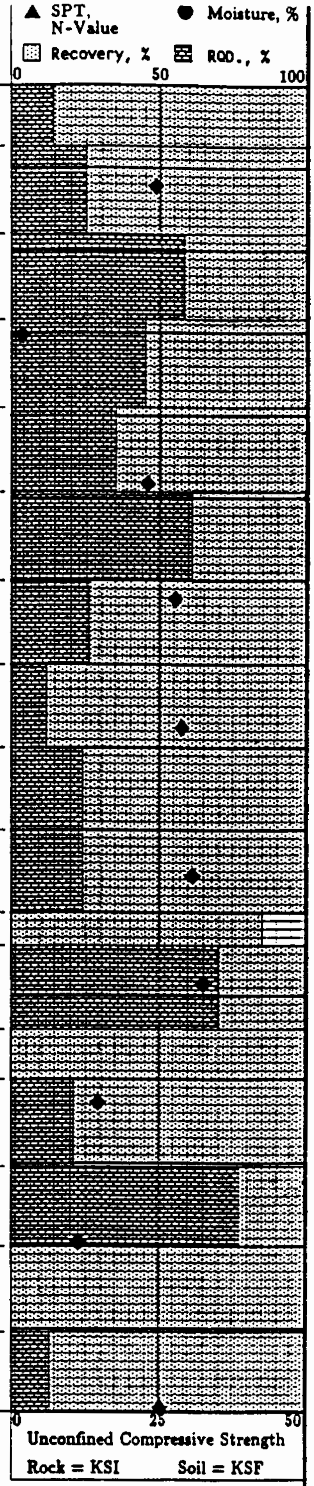
BORING LOG
B-527

Westside LRT Tunnel, LS-5A

SQUIER ASSOCIATES
FEBRUARY 1993 91624

ROCKLOG4

Back-Fill	Remarks	Elev. Depth	Classification of Material	Log	Depth, Feet	Samples
			Medium-high strength (R4) gray BASALT, very slight to slightly weathered, moderately vesicular grading to dense, very close to close joints with brown clay fill to 1 cm		165	R-24, R-25
			grades to high to very high strength (R5-R6) gray BASALT, very slightly weathered, dense, close joints, slightly to moderately vesicular		170, 175	R-26, R-27
			GRANDE RONDE BASALT Sentinel Bluffs (M2)		180, 185	R-28, R-29
	Bentonite Seal		grades to medium-high to high strength (R4-R5) gray BASALT, very slightly weathered to fresh, close joints, slightly vesicular grading to dense		190, 195, 200	R-30, R-31, R-32
			GRANDE RONDE BASALT Sentinel Bluffs (M2)		205, 210	R-33, R-34
		467.4 215.7	FLOW CONTACT		215	R-35
	Z-1 3/26/92 Z-1 10/23/92	463.1 220.0	Moderate to medium-high strength (R3-R4) red-brown FLOW BRECCIA, very close joints, very severe grading to very slight weathering, moderate to highly vesicular, local clay and brown soil zone to 5mm		220	R-36
			grades to moderate to medium-high strength (R3-R4) gray BASALT, very slight weathering, close to very close joints, slight to moderately vesicular		225, 230	R-37, R-38, R-39
	Sand		GRANDE RONDE BASALT Winter Water		235	R-40



Samples

I = 2.0" O.D. Split Spoon Sample
II = 3.0" O.D. Thin-Walled Sample
• = Sample Not Recovered
I = Rock Core Sample
⊕ = Geochemical Analysis Sample

NOTE:
= Tunnel Horizon (Horizontal Projection)

Lines representing the interface between soil/rock units of differing description are approximate only and may indicate gradual transition

Tests

Unconfined Compressive strength
- Soil Laboratory Qu
- Torvane
- Pocket Penetrometer
- Mod. Pocket Penetrometer
- Rock Laboratory Qu
- ◆ Point Load Test

ATTERBERG LIMITS
Liquid Limit
Natural Water Content
Plastic Limit

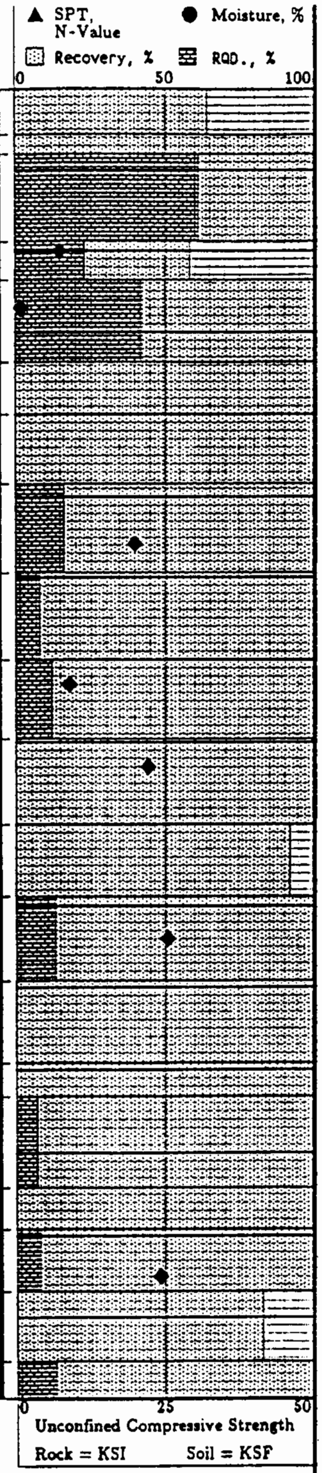
BORING LOG
B-527

Westside LRT Tunnel, LS-5A

SQUIER ASSOCIATES
FEBRUARY 1993 91624

ROCKLOG4

Fill	Remarks	Elev. Depth	Classification of Material	Log	Depth, Feet	Samples
			Moderate to medium-high strength (R3-R4) gray BASALT, very slight to fresh weathering, very close to close joints, slightly vesicular		245	R-41, R-42, R-43
		433.1 250.0	FLOW CONTACT Low to moderate strength (R2-R3) dark gray FLOW BRECCIA, very slight to fresh weathering, slight to moderately vesicular, close grading to very close joints		250	R-44
		428.1 255.0	Low to moderate strength (R2-R3) red/brown BASALT, very close joints, slight to very slightly weathered, slightly vesicular up to 5mm green clay joint fill locally GRANDE RONDE BASALT Winter Water		255, 260, 265, 270	R-45, R-46, R-47, R-48, R-49
	Sand	407.1 276.0	FLOW CONTACT Low to moderate strength (R2-R3) dark gray BASALT, very slightly weathered, very close joints, very slight weathering		275, 280, 285	R-50, R-51
		396.1 287.0	FLOW CONTACT Moderate strength (R3) BASALT, highly vesicular grading to dense, slight to very slight weathering, close grading to very close joints with red brown clay fill to 10mm		290, 295	R-52, R-53, R-54
			LOCAL SHEAR ZONE Abundant slickensided joints with green clay fill from 297' to 305' grades to low strength (R-2), moderate to moderately severe weathering, slightly to moderately vesicular, dense		300, 305	R-55, R-56
	Z-1 Sensor		local healed fractures with black clay mineral fill		310	R-57, R-58
			GRANDE RONDE BASALT Winter Water		315	R-59



Samples

= 2.0" O.D. Split Spoon Sample
= 3.0" O.D. Thin-Walled Sample
= Sample Not Recovered
= Rock Core Sample
= Geochemical Analysis Sample

Tests

Unconfined Compressive strength

- Soil Laboratory Qu
- Torvane
- Pocket Penetrometer
- Mod. Pocket Penetrometer
- Rock Laboratory Qu
- Point Load Test

ATTERBERG LIMITS
Liquid Limit
Natural Water Content
Plastic Limit

NOTE:
= Tunnel Horizon (Horizontal Projection)
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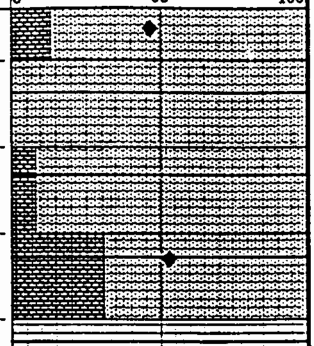
BORING LOG
B-527

Westside LRT Tunnel, LS-5A

SQUIER ASSOCIATES
FEBRUARY 1993 91624

LOG4

Back-Fill	Remarks	Elev. Depth	Classification of Material	Log	Depth, Feet	Samples	▲ SPT, N-Value ● Moisture, % ▤ Recovery, % ▦ RQD., % (0 – 50 – 100)
			grades to high strength (R5) gray BASALT, fresh to very slightly weathered close joints with green clay fill, dense		325	R-60	
	Sand				330	R-61	
			GRANDE RONDE BASALT Winter Water		335	R-62	
		343.1 340.0	BOTTOM OF BORING (2/18/92)		340	R-63	



0 25 50
Unconfined Compressive Strength
Rock = KSI Soil = KSF

Samples

- I = 2.0" O.D. Split Spoon Sample
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- • = Sample Not Recovered
- I = Rock Core Sample
- ⊕ = Geochemical Analysis Sample

Tests

Unconfined Compressive strength

- Soil Laboratory Qu
- Torvane
- Pocket Penetrometer
- Mod. Pocket Penetrometer
- Rock Laboratory Qu
- ◆ Point Load Test

ATTERBERG LIMITS
- Liquid Limit
- Natural Water Content
- Plastic Limit

NOTE:
▒ = Tunnel Horizon (Horizontal Projection)
Lines representing the interface between soil/rock units of differing description are approximate only and may indicate gradual transition

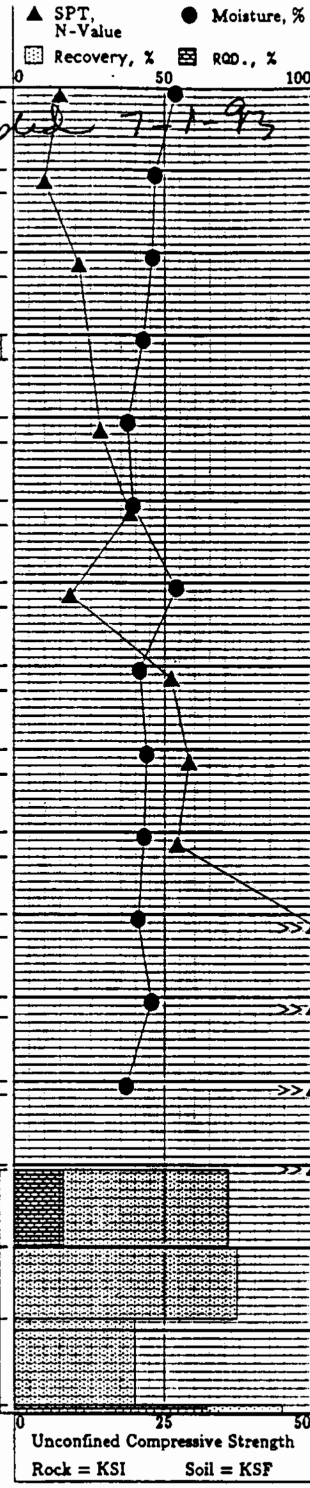
BORING LOG
B-527

Westside LRT Tunnel, LS-5A

SQUIER ASSOCIATES
FEBRUARY 1993 91624

ROCKLOG4

Back-Fill	Remarks	Elev. Depth	Classification of Material	Log	Depth, Feet	Samples
						S-17
		640.6 84.0	Medium dense dark orange to green-brown sandy SILT with some clay, sand and gravel size severely weathered rock fragments		85	S-18
					90	S-19
			grades to scattered organics		95	S-20*
					100	S-21
			grades to SILT with some sand, trace clay and severely weathered rock fragments		105	S-22
		616.4 108.2	Very stiff dark gray SILT with some clay and occasional layer of orange and yellow-green silty CLAY; moist to wet		110	S-23
	Bentonite Seal				115	S-24
		604.6 120.0	Medium dense gray-green to yellow-orange fine sandy SILT to silty SAND (sand size weathered rock fragments); moist to wet		120	S-25
					125	S-26
			RESIDUAL SOIL FROM BASALT		130	S-27
			grades to gravel size weathered rock fragments		135	S-28
					140	S-29
			grades to moist		145	S-30
		579.2 145.4	Medium-high strength (R4) gray BASALT, slightly to moderately weathered, dense, close joints with mineral coatings and trace clay			R-1
		574.6 150.0	Moderate strength (R3) gray/brown BASALT, moderate to moderately severe weathering, slightly vesicular, close to very close joints		150	R-2
		564.6	FRENCHMAN SPRINGS BASALT Ginkgo		155	R-3



Samples

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- [] = 3.0" O.D. Thin-Walled Sample
- * = Sample Not Recovered
- **I** = Rock Core Sample
- ⊕ = Geochemical Analysis Sample

Tests

Unconfined Compressive strength

- Soil Laboratory Qu
- Torvane
- Pocket Penetrometer
- Mod. Pocket Penetrometer
- Rock Laboratory Qu
- ◆ Point Load Test

ATTERBERG LIMITS
- Liquid Limit
- Natural Water Content
- Plastic Limit

NOTE:

= Tunnel Horizon (Horizontal Projection)

Lines representing the interface between soil/rock units of differing description are approximate only and may indicate gradual transition

BORING LOG
B-530

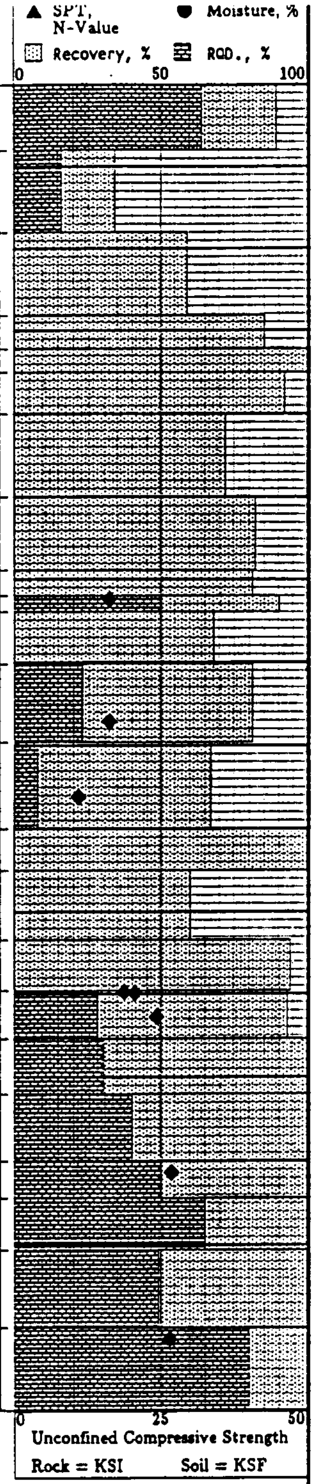
Westside LRT Tunnel, LS-5A

SQUIER ASSOCIATES

FEBRUARY 1993 91624

ROCKLOG4

Back-Fill	Remarks	Elev. Depth	Classification of Material	Log	Depth, Feet	Samples
		160.0	FLOW CONTACT			R-4
			Very low strength (R1), light gray to bleached white CLAYSTONE, soil paleosol, locally bleached and slickensided, smooth very close incipient joints,		165	
		559.2 165.4	VANTAGE HORIZON			R-5
			Moderate to medium-high strength (R3-R4) gray BASALT, slightly vesicular, slightly to moderately weathered, very close to close joints		170	R-6
	Z-1 3/26/92 Z-1 10/23/92				175	R-7 R-8 R-9
			GRANDE RONDE BASALT Sentinel Bluffs (M1)		180	R-10
			Moderate to medium-high strength (R3-R4) gray BASALT, variable dense to highly vesicular, very close joints, orange, green, brown and black staining and coatings on joint surfaces 1 to 2 mm thick		185	R-11
			grades to slightly vesicular, fine grained		190	R-12 R-13 R-14
	Bentonite Seal				195	R-15
					200	R-16
			grades to slightly weathered		205	R-17
					210	R-18
			High strength (R5) medium gray BASALT, dense, very slightly weathered, very close to grading to close joints			R-19
					215	R-20
					220	R-21 R-22
					225	R-23
			grades to close to moderately close joints		230	R-24 R-25
			1/2" calcite/clay mineral fill		235	R-26



Samples

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Ⅱ = 3.0" O.D. Thin-Walled Sample
• = Sample Not Recovered
I = Rock Core Sample
= Geochemical Analysis Sample

NOTE:
= Tunnel Horizon (Horizontal Projection)
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Tests

Unconfined Compressive strength
Soil Laboratory Qu
Torvane
Pocket Penetrometer
Mod. Pocket Penetrometer
Rock Laboratory Qu
◆ Point Load Test

ATTERBERG LIMITS
Liquid Limit
Natural Water Content
Plastic Limit

BORING LOG
B-530

Westside LRT Tunnel, LS-5A

SQUIER ASSOCIATES
FEBRUARY 1993 91624

ROCKLOG4

Back-Fill	Remarks	Elev. Depth	SURFACE ELEVATION IN FEET: 782.3 STATION: 821+4.9 OFFSET: -29.7 **Classification of Material**	Log	Depth, Feet	Samples	▲ SPT, N-Value ● Moisture, % Recovery, % RQD., % 0 50 100
		782.3					
	Monument cover		No samples taken in soils drilling		0		
	Bentonite				5		
			Auger cuttings Stiff gray-brown SILT with trace clay to silty CLAY		10		
					15		
					20		
					25		
					30		
	Drill cuttings				35		
		740.3 42.0	Hard (soil) to very low strength (R1) light gray BASALT, very severe weathering, very close to close joints, dense, reduced to soil like with intact rock structure evident, variable		40 45	R-1	
			grades to very low strength (R1) light gray BASALT at 48.4'-51.9' Very low to moderate strength (R1-R3) pink-gray BASALT, slight to very severe weathering, dense, very close to close joints		50 55	R-2 R-3	
			grades to hard (soil) to very low strength (R1) red-gray BASALT, very severely weathered, remolds to SILT with trace clay BORING LAVA FORMATION QTbn (Normal Polarity)		60 65 70	R-4 R-5 R-6	
	Bentonite	710.0 72.3	Very low strength (R1) brown gray FLOW BRECCIA, very severe weathering to clay		75	R-7	
		705.8 76.5	Moderate grading to high strength (R3-R5) light gray BASALT, very slightly weathered to fresh,			R-8	

0 25 50

Unconfined Compressive Strength
Rock = KSI Soil = KSF

Samples

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- • = Sample Not Recovered
- **I** = Rock Core Sample
- = Geochemical Analysis Sample

Tests

Unconfined Compressive strength

- Soil Laboratory Qu
- Mod. Pocket Penetrometer
- Torvane
- Rock Laboratory Qu
- Pocket Penetrometer
- ◆ Point Load Test

ATTERBERG LIMITS
- ← Liquid Limit
- ← Natural Water Content
- ← Plastic Limit

NOTE:

= Tunnel Horizon (Horizontal Projection)

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BORING LOG
B-564

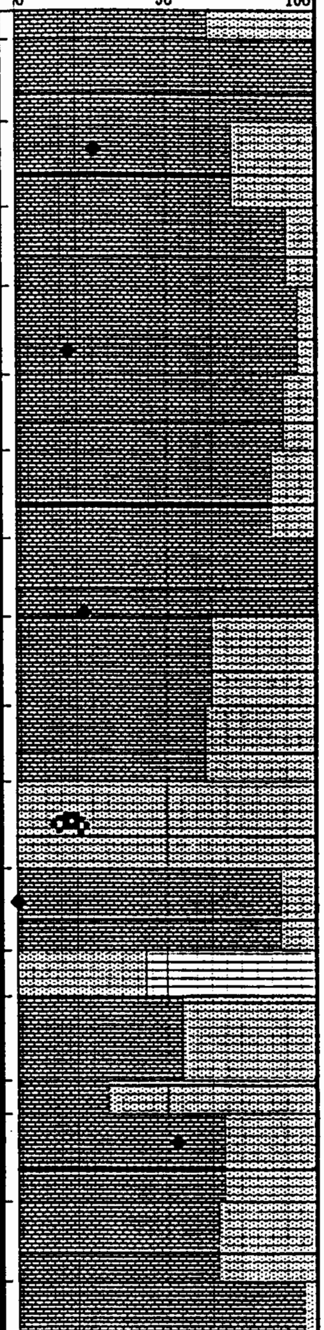
Westside LRT Tunnel, LS-5A

SQUIER ASSOCIATES
FEBRUARY 1993 91624

Reviewed GLP

Back-Fill	Remarks	Elev. Depth	Classification of Material	Depth, Feet	Samples
			dense to slightly vesicular, close to moderately close slightly rough joints with 0-10mm silt and clay fill		
			BORING LAVA FORMATION QTbn (Normal Polarity)	85	R-9
	Bentonite		near vertical red-brown clay joint fill to 10m, moderately close joints	90	R-10
				95	R-11
			BORING LAVA FORMATION QTbn (Normal Polarity)	100	R-12
				105	R-13
				110	R-14
			vesicle banding 112-113' at 5-10 degrees	115	R-15
			red oxidized zone 117-118'	120	R-16
	Open with some bentonite	656.7	increased occurance of SILT joint fill near flow base	125	R-17
		125.6 650.4	Hard (baked) brick red clayey SILT with some gravel sized angular basalt fragments near top, 4" of wet silt and sand at base SANDY RIVER MUDSTONE	130	R-18
		131.9 642.7	Very low to moderate strength (R1-R3) red gray FLOW BRECCIA, variable slight to moderately vesicular, close rough joints BORING LAVA FORMATION QTbn (Normal Polarity)	135	R-19 R-20
		139.6 640.2	Hard baked brick red sandy SILT with trace clay Sandy River Mudstone Equivalent	140	R-21
		142.1 632.8	Moderate to medium-high strength (R3-R4) gray BASALT, slight to very severe weathering, dense, very close to close rough joints, mixed with 30% brown silty SAND Intra-flow contact?	145	R-22 R-23
		149.5	Very low strength (R1) brown gray FLOW BRECCIA, close to moderately close joints, moderately weathered, dense, abundant brown SILT fill to 4cm BORING LAVA FORMATION QTbr (Reversed Polarity)	150 155	R-24

SPT, N-Value; Moisture, %; Recovery, %; RQD., % (0 – 50 – 100)



0 – 25 – 50
Unconfined Compressive Strength
Rock = KSI Soil = KSF

Samples

I = 2.0" O.D. Split Spoon Sample
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Tests

Unconfined Compressive strength
- Soil Laboratory Qu
- Torvane
- Pocket Penetrometer
- Mod. Pocket Penetrometer
- Rock Laboratory Qu
- ◆ Point Load Test

ATTERBERG LIMITS
Liquid Limit
Natural Water Content
Plastic Limit

NOTE:
= Tunnel Horizon (Horizontal Projection)
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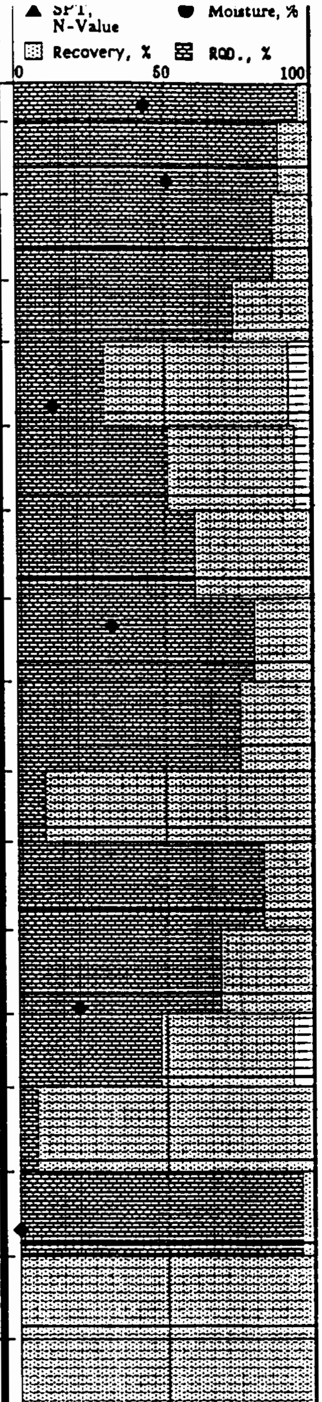
BORING LOG
B-564

Westside LRT Tunnel, LS-5A

SQUIER ASSOCIATES
FEBRUARY 1993 91624

ROCKLOG4

Back-Fill	Remarks	Elev. Depth	Classification of Material	Depth, Feet	Samples
		621.9 160.4	High strength (R5) light gray BASALT, fresh, dense, close to moderately close rough joints with 0-2mm brown silt and clay infill BORING LAVA FORMATION QTbr (Reversed Polarity)	165 170	R-25 R-26 R-27 R-28
	Open with some bentonite	607.2 175.1	Variable very low to moderate strength (R1-R3) FLOW BRECCIA, slight to very severe weathering, dense to highly vesicular, close to very close rough joints, zones up to 2' of SILT matrix, cobble and boulder sized basalt fragments, local slickensided surfaces BORING LAVA FORMATION QTbr (Reversed Polarity)	175 180 185	R-29 R-30 R-31
		592.3 190.0	Moderate strength (R3) gray BASALT, close rough to smooth joints, very slight weathering, highly vesicular, red SILT joint fill to <10mm locally BORING LAVA FORMATION QTbr (Reversed Polarity)	190 195	R-32
	Z-1 10/23/92	584.0 198.3	Very low strength (R1) brown gray FLOW BRECCIA, very close to close rough to smooth joints, moderately severe to severely weathered, dense, abundant brown sandy SILT matrix up to 50mm, abundant slickensides from 205-215	200 205 210	R-33 R-34 R-35 R-36
	Bentonite	567.7 214.6	Medium-high to high strength (R4-R5) gray BASALT, close joints, fresh, slight grading to moderately vesicular at base	215	R-37
		563.0 219.3	Very low to moderate strength (R1-R3) red-brown and gray FLOW BRECCIA, very close joints, abundant slickensides, moderately severe to severe weathering, dense, up to 6" of silty SAND and hard silty CLAY	220 225	R-38
		553.8 228.5	Very hard brown silty SAND with trace clay, baked	230	R-39
		551.5 230.8	Very hard dark green-gray clayey SILT grading to SILT with some clay	235	R-40
	Sand	545.3 237.0			R-41



Samples

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Tests

Unconfined Compressive strength
Soil Laboratory Qu
Torvane
Pocket Penetrometer
Mod. Pocket Penetrometer
Rock Laboratory Qu
◆ Point Load Test

ATTERBERG LIMITS
Liquid Limit
Natural Water Content
Plastic Limit

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= Tunnel Horizon (Horizontal Projection)
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BORING LOG
B-564

Westside LRT Tunnel, LS-5A

SQUIER ASSOCIATES
FEBRUARY 1993 91624

ROCKLOG4

Back-Fill	Remarks	Elev. Depth	Classification of Material	Log	Depth, Feet	Samples
			Very hard dark green gray SILT with trace clay, occassional very stiff zones			
					245	R-42
	Z-1 Sensor					
			SANDY RIVER MUDSTONE		250	R-43
			grades to light orange, nodules of FeO		255	R-44
						R-45
					260	R-46
					265	R-47
	Sand		grades to stiff to very stiff light tan to gray SILT with trace clay, micaceous, possible ash unit, local slickensided surfaces		270	R-48
					275	R-49
			SANDY RIVER MUDSTONE		280	R-50
					285	R-51
					290	R-52
					295	R-53
		485.5 296.8	(Bottom of Boring) (9/14/92)			

▲ SPT, N-Value ● Moisture, % ▦ Recovery, % ▦ RQD., % (0 – 50 – 100)

Unconfined Compressive Strength (0 – 25 – 50): Rock = KSI, Soil = KSF

Samples

- = 2.0" O.D. Split Spoon Sample
- = 3.0" O.D. Thin-Walled Sample
- = Sample Not Recovered
- = Rock Core Sample
- = Geochemical Analysis Sample

Tests

Unconfined Compressive strength

- Soil Laboratory Qu
- Torvane
- Pocket Penetrometer
- Mod. Pocket Penetrometer
- Rock Laboratory Qu
- ◆ Point Load Test

ATTERBERG LIMITS: Liquid Limit, Natural Water Content, Plastic Limit

NOTE:
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BORING LOG
B-564
Westside LRT Tunnel, LS-5A

SQUIER ASSOCIATES
FEBRUARY 1993 91624

ROCKLOG4

SOILS AND GEOLOGICAL EXPLORATION LOG

Highway Division, Region 1

Project Information	Crew/Equipment	Hole Information
Section Name: Westside Corridor	Equipment: PC Explorations CME 850	Hole Number: WC1-M102
Highway: Highway 217	Driller: Dave Johnson	X Coordinate: 641+55
County: Washington	Recorder: Jim Huss	Y Coordinate: Lt. 37
Bridge Name:	Geologist: B. VanVickle	Elevation: 233
Bridge Number:	Date Started: 3/17/92	Boring Depth: 320
EA Number: C0341405-010-926	Date Completed: 3/23/92	Tube Stick Up: 0

DRILL TESTS		DRILL METHOD		LEGEND
Number of SPT: 32	Core Type:	Type: 4" Hollow Stem Auger	Total Depth: 320'	SPT
Number of Shelby: 6	Number of Cores:	Type:	Total Depth:	Shelby
Other Tests:				Core

Depth	Elevation	Material Description	Graphic Log	Water Level	Driving Resistance	Sample Range	Test Number	Recovery (ft)	Recovery (%)	Moisture (%)	Hardness	R.Q.D.
	232	**FILL (0'-15')**										
5	227	**N-1** (5'-6.5') GRAVEL, GM. Dry to Damp.			2-4-11		N-1	0.4	27			
10	222	**U-1** (10'-12') Clayey GRAVEL, GC. Brown, Moist. Torvane=0.3 tsf.					U-1	1.3	87			
		N-2 (12'-13.5') Clayey SILT, with trace Basalt Gravel, ML. Gray-Brown, Low Plasticity, Damp, Stiff.			3-6-5		N-2	0.3	20			
15	217	**N-3** (15'-16.5') SILT, ML. Light Gray-Brown, Mottled, Nonplastic, Damp, Stiff. Micaceous.			4-6-7		N-3	0.7	47			
20	212	**U-2** (20'-22') Same as **N-3**.					U-2	2.0	100			
		N-4 (22'-23.5') Clayey SILT, ML. Brown, Mottled, Medium Plasticity, Damp to Moist, Medium Stiff. Micaceous.			3-3-5		N-4	1.5	100			
25	207	**N-5** (25'-26.5') SILT, ML. Brown, Low Plasticity, Moist, Soft, Micaceous.			4-3-2		N-5	1.5	100			

SOILS AND GEOLOGICAL EXPLORATION LOG

Highway Division, Region 1

Section Name: Westside Corridor | Test Hole Number: WCI-M102

Depth	Elevation	Material Description	Graphic Log	Water Level	Driving Resistance	Sample Range	Test Number	Recovery (ft)	Recovery (%)	Moisture (%)	Hardness	R.Q.D.
	202	**U-3** (30'-32') Clayey SILT, ML. Brown, Low Plasticity, Wet, Medium Stiff. Torvane=0.35 tsf.					U-3	2.0	100			
		N-6 (32'-33.5') Clayey SILT, ML. Brown, Medium Plasticity, Wet, Medium Stiff. Scattered Iron Oxide Concretions.			3-3-3		N-6	1.5	100			
35	197	**U-4** (35'-37') Same as **N-5**. Low Plasticity, Damp. Torvane=0.45 tsf.					U-4	2.0	100			
		N-7 (37'-38.5') Same as **U-4**. Mottled, Moist.			6-8-12		N-7	1.5	100			
40	192	**U-5** (40'-42') Same as **N-7**.					U-5	2.0	100			
		N-8 (42'-43.5') Silty CLAY, CL. Brown, Mottled, Medium Plasticity, Moist, Very Stiff.			7-10-13		N-8	1.5	100			
45	187	**N-9** (45'-46.5') Same as **N-8**. Scattered Iron Oxide Concretions.			6-8-10		N-9	1.5	100			
50	182	**N-10** (50'-51.5) Same as **N-9**.			9-10-15		N-10	1.5	100			
55	177	**N-11** (55'-56.5') Silty CLAY, ML. Gray-Brown, Mottled, Low to Medium Plasticity, Moist, Very Stiff. Micaceous with Scattered Iron Oxide Concretions.			7-11-16		N-11	1.5	100			
		U-6 (57'-59') Same as **N-11**. Torvane=0.35 tsf.					U-6	1.4	100			
60	172	**N-12** (60'-61.5') Silty CLAY, CL. Gray-Brown, Mottled, Medium Plasticity, Damp to Moist, Very Stiff. Micaceous.			6-8-13		N-12	1.5	100			
65	167											

SOILS AND GEOLOGICAL EXPLORATION LOG

Highway Division, Region 1

Section Name: Westside Corridor

Test Hole Number: WC1-M102

Depth	Elevation	Material Description	Graphic Log	Water Level	Driving Resistance	Sample Range	Test Number	Recovery (ft)	Recovery (%)	Moisture (%)	Hardness	R.Q.D.
	162	**N-13** (70'-71.5') Same as **N-12**. Scattered Iron Oxide Concretions.			8-10-13		N-13	1.5	100			
75	157											
80	152	**N-14** (80'-81.5') Clayey SILT, ML. Gray-Brown, Mottled, Low Plasticity, Damp to Moist, Very Stiff to Hard. Scattered Iron Oxide Concretions.			8-13-21		N-14	1.5	100			
85	147											
90	142	**N-15** (90'-91.5') Silty CLAY, CL. Gray-Brown, Mottled, Medium Plasticity, Moist, Hard. Micaceous with Scattered Iron Oxide Concretions.			7-13-22		N-15	1.5	100			
95	137											
100	132	**N-16** (100'-101.5') Same as **N-15**.			9-9-13		N-16	1.5	100			
105	127											

SOILS AND GEOLOGICAL EXPLORATION LOG

Highway Division, Region 1

Section Name: Westside Corridor

Test Hole Number: WC1-M102

Depth	Elevation	Material Description	Graphic Log	Water Level	Driving Resistance	Sample Range	Test Number	Recovery (ft)	Recovery (%)	Moisture (%)	Hardness	R.Q.D.
	122	**N-17** (110'-111.5') SILT, Gray-Brown, Mottled, Low to Nonplastic, Damp to Moist, Hard. Micaceous.			6-11-31		N-17	1.5	100			
115	117											
120	112	**N-18** (120'-121.5') Same as **N-17**.			6-9-11		N-18	1.5	100			
125	107											
130	102	**N-19** (130'-131.5') Clayey SILT, ML. Gray-Brown, Mottled, Low Plasticity, Damp, Hard. Micaceous with Scattered Iron Oxide Concretions.			11-15-25		N-19	1.5	100			
135	97											
140	92	**N-20** (140'-141.5') Same as **N-19**. Medium Plasticity, Wet.			11-16-22		N-20	1.5	100			
145	87											

SOILS AND GEOLOGICAL EXPLORATION LOG

Highway Division, Region 1

Section Name: Westside Corridor

Test Hole Number: WC1-M102

Depth	Elevation	Material Description	Graphic Log	Water Level	Driving Resistance	Sample Range	Test Number	Recovery (ft)	Recovery (%)	Moisture (%)	Hardness	R.Q.D.
	82	**N-21** (150'-151.5') Same as **N-19**. Gray, No Mottling. N21 150-151.5			10-14-18		N-21	1.5	100			
155	77											
160	72	**N-22** (160'-161.5') Same as **N-21**.			8-11-12		N-22	1.5	100			
165	67											
170	62	**N-23** (170'-171.5') No Recovery.			13-18-23		N-23	0.0	0			
175	57											
180	52	**N-24** (180'-181.5') SILT, ML. Gray-Green, Nonplastic, Damp, Very Stiff. Micaceous.			6-9-17		N-24	1.5	100			
185	47											

SOILS AND GEOLOGICAL EXPLORATION LOG

Highway Division, Region 1

Section Name: Westside Corridor

Test Hole Number: WC1-M102

Depth	Elevation	Material Description	Graphic Log	Water Level	Driving Resistance	Sample Range	Test Number	Recovery (ft)	Recovery (%)	Moisture (%)	Hardness	R.Q.D.
	42	**N-25** (190'-191.5') Same as **N-24**. Moist, Stiff to Very Stiff.			5-7-9		N-25	1.5	100			
195	37											
200	32	→ **N-26** (200'-201.5') Same as **N-24**. Dark Gray.			5-4-6		N-26	1.5	100			
205	27											
210	22	**N-27** (210'-211.5') Clayey SILT, ML. Dark Gray, Low Plasticity, Damp to Moist, Stiff. Micaceous.			4-6-7		N-27	1.5	100			
215	17											
220	12	**N-28** (220'-221.5') Same as **N-27**.			5-5-9		N-28	1.5	100			
225	7											

SOILS AND GEOLOGICAL EXPLORATION LOG

Highway Division, Region 1

Section Name: Westside Corridor

Test Hole Number: WCI-MI02I

Depth	Elevation	Material Description	Graphic Log	Water Level	Driving Resistance	Sample Range	Test Number	Recovery (ft)	Recovery (%)	Moisture (%)	Hardness	R.Q.D.
	2											
235	-3											
240	-8	**N-29** (240'-241.5') Silty CLAY, CL. Dark Gray-Green, Medium Plasticity, Damp to Moist, Very Stiff. Micaceous.			8-10-14		N-29	1.5	100			
245	-13											
250	-18											
255	-23											
260	-28	**N-30** (260'-261.5') Same as **N-29**. Gray-Brown, Mottled, Damp.			6-12-15		N-30	1.5	100			
265	-33											

SOILS AND GEOLOGICAL EXPLORATION LOG

Highway Division, Region 1

Section Name: Westside Corridor

Test Hole Number: WC1-M102

Depth	Elevation	Material Description	Graphic Log	Water Level	Driving Resistance	Sample Range	Test Number	Recovery (ft)	Recovery (%)	Moisture (%)	Hardness	R.Q.D.
	-38											
275	-43											
280	-48	**N-31** (280'-281.5') CLAY, CL. Gray, High Plasticity, Damp to Moist, Very Stiff. Micaceous.			4-8-11		N-31	1.5	100			
285	-53											
290	-58	Cutting sample taken at 290'										
295	-63											
300	-68	**N-32** (300'-301.5') Same as **N-29**. Dark Blue-Green, Damp.			8-12-13		N-32	1.5	100			
305	-73											

SOILS AND GEOLOGICAL EXPLORATION LOG

Highway Division, Region 1

Section Name: Westside Corridor

Test Hole Number: WCI-MI02!

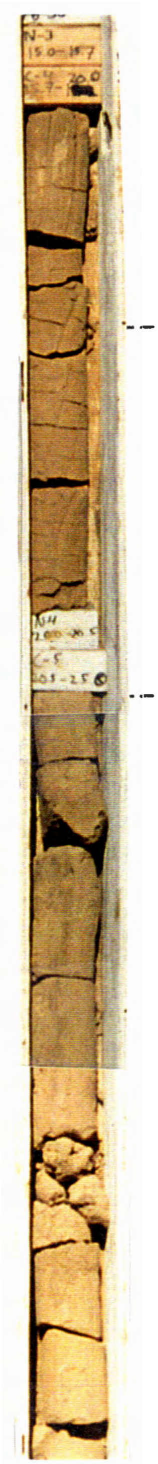
Depth	Elevation	Material Description	Graphic Log	Water Level	Driving Resistance	Sample Range	Test Number	Recovery (ft)	Recovery (%)	Moisture (%)	Hardness	R.Q.D.
	-78	Cutting samples taken at 310' and 320'.										
315	-83											
320	-88	Bottom of Hole at 320'										
325	-93											
330	-98											
335	-103											
340	-108											
345	-113											

APPENDIX B

DOGAMI CORE TB-810 (53rd STREET) PHOTOGRAPHS

Upper 15 feet of run not recovered: grab samples from surface to 15'0" (4.5m)

4.5m
15ft



Core description as follows: Soil/loess interval, description, texture, color (dry), color (remoistened), structure, clay films, dry consistency, moist consistency

15' to 20', bottom of Paleosol 4, vfSiL, 10YR 6/4d, 10YR 5/4m, m-gran, none, h-vh, fi

----Grain size distribution sample at 15 ft.

Bottom of Paleosol 4 at approx. 20 ft.

6m
20ft

----Grain size distribution sample at 20 ft.

20' to 36', Loess3, vfSiL w tr. Sand, 10YR 7/4d, 10YR 5.5/4m, sq-w gran, none, so-sh, lo

7.2m
24ft

7.5m
25ft

Loess3 (con't)

----INAA/Grain size distribution sample at 25 ft.

65mm dimension angular basalt fragment at 30' depth

---Grain size distribution sample at 30 ft.

10.2m
34ft

10.5m
35 ft

36' to 40', Paleosol 3, vfSiCL, 10YR
to 7.5YR 7/8d, 10YR 5/8 to 5YR 4/6m, 30% to
mottling, 1-2m pl, common thin br-po(w), vh-
vfr-fr

---INAA Sample at 37 ft.

---Grain size distribution sample at 37½ ft.

12m
40 ft

Approx. bottom of Paleosol 3, sq-w sbky, v_1 n
pf, h-vh, lo-vfr
---Grain size distribution sample at 40 ft.

12m
40ft

40' to 57', Loess2, vfSi,10YR 7/4d, 10YR 5/4m, massive, none to v_1 n pf, sh-h, lo-vfr

12.7m
42.5ft

13.5m
45ft

---INAA/Grain size distribution sample at 45 ft.

Loess2 (con't)

13.5m
45ft

14.3m
47.5ft

15m
50ft

15m
50ft

loess2 (con't)

----Grain size distribution sample at 50 ft.

----INAA/Grain size distribution sample at 52 ft.

15.75m
52.5ft

16.5m
55ft

---Grain size distribution sample at 55 ft.

16.5m
55ft

Loess2 (con't), vfSiL w/ tr. sand, 10YR 7/4d, 10YR 5/5m, m, none, h-vh, lo-fr

17.1m
57ft

57' to approx. 62', Paleosol 2, vfSiL, 10YR 6/6d, 10YR 5/7m, wsbky to wasbky, v_1 n-pf, h-vh, lo-vfr

18m
60ft

----INAA/Grain size distribution sample at 60 ft.

18m
60ft

Paleosol 2 (con't), vfSiCL, 10YR 5.5/6d, 10YR 4.5/8m, wabky, v_1-1 n pf, vh-eh, fr

gradual transition to Loess 1, vfSiCL, 10YR 6/6d, 10YR 4.5/8m, 2 pl to sabky, 1-2 n w, vh-eh, vfr-fr

----Grain size distribution sample at 62 ft.

19.5m
65ft

----INAA/Grain size distribution sample at 65 ft.

19.5m
65ft

Loess1 (con't)

20.25m
67.5ft

21m
70ft

---INAA/Grain size distribution sample at 70 ft.

21m
70ft

Loess1 (con't), vfSi, 10YR 6.5/6d, 10YR 5/8m, massive, none, h, lo-vfr

22.5m
75ft

---INAA/Grain size distribution sample at 75 ft.

22.5m
75ft Loess1 (con't)

becomes 10YR 7/6d, 10YR 4.5/6m

24m
80ft -----INAA/Grain size distribution sample at 80 ft.

24m
80ft

Loess1 (con't), 10YR 6.5/6d, 10YR 4/6m

24.9m
83ft

83' to 85', Paleosol 1, vfSiCL, 10YR 5/6d, 5YR 4/4m, 2sabky, 2 mk br-po, vh-eh, fr-fi

25.2
84ft

Bottom 30cm (1 ft) removed.

25.9
85'

----INAA/Grain size distribution sample at 85 ft.
Top of Columbia River basalt

APPENDIX C

2121 S.W. ELM STREET, PORTLAND, PHOTOGRAPHS

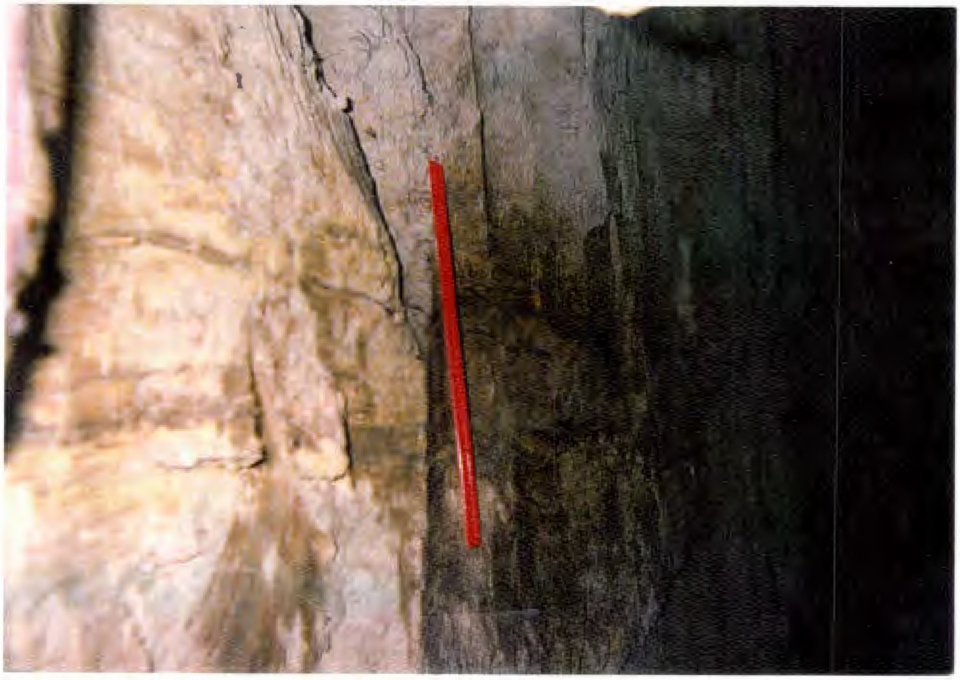
1. Looking northeast across S.W. Montgomery towards 2121 S.W. Elm Street

2. Northwest corner of garage excavation. Scale in meters from bottom of organic fill

3. Northwest corner of garage excavation. Note fine dark laminations below 1-foot ruler.

4. Details of dark laminations in 2Btb at 1.4 meters bgs

5. Detail of dark laminations at 1.4m bgs



6. lamination details, 1.4m bgs, .5m north of #4