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Natural Analog Study of Engineered Protective Barriers at the Hanford Site

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Summary

The objective of natural analog studies is to evaluate the long-term performance of engineered protective barriers, based on surficial deposits that have formed within the Pasco Basin during the recent geologic past and are analogous to the protective barrier. There is the possibility that, over the 1,000-year design life, layers within an engineered protective barrier might become intermixed, thereby compromising the integrity of the barrier. The long-term performance of the barrier depends, in part, on maintaining an adequate thickness of layers as well as integrity of layer interfaces. Over time, geologic processes could mix layers or reduce the effective thickness enough to allow moisture or organisms to come into contact with the buried wastes.

Possible natural physical, chemical, and/or biological processes that could adversely affect an engineered barrier over the next 1,000 years include deflation by wind, soil compaction, soil eluviation/illuviation, bioturbation, and cryoturbation. Based on the present barrier design and the types of alteration that have taken place in Holocene soils observed throughout the Pasco Basin, none of these processes alone appears to be a significant threat to the engineered protective barriers over the next 1,000 years. However, a combination of these processes acting together (e.g., deflation in combination with compaction or bioturbation) could conceivably reduce the effective thickness of protective layers although the likelihood of this combination of events occurring is small.

Because of the complexity of the engineered barrier design, none of the natural analogs found within the Pasco Basin are totally representative of the entire proposed engineered barrier design. Natural analogs, however, provide useful information on the rates and effects of various geologic, pedologic, and biologic processes on geologic strata, which can be applied to predict the long-term performance of engineered protective barriers (Winograd 1986).

Acknowledgments

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1.0 Introduction

The purpose of this study is to evaluate surficial sedimentary deposits formed in the Pasco Basin over the geologic past as analogs for engineered protective barriers. Evidence for likely changes to be expected in an engineered barrier are preserved in geologically recent deposits (Winograd 1986). Although the design life of the *engineered barrier* is only 1,000 years (Buckmaster 1993), soils and sediments of this age are uncommon in the Pasco Basin. The majority of the uppermost deposits in the Pasco Basin are much older than 1,000 years; they were laid down during or soon after a series of giant cataclysmic floods that ended about 13,000 years B.P. (Baker et al. 1991). Since that time, very little alteration of the land surface has taken place so that surficial soils represent periods of relatively uninterrupted soil development that began forming as early as 13,000 years B.P. Therefore, a study was undertaken of these older soils because they provide "built-in" conservatism in the evaluation of the long-term geologic effects on engineered barriers. Thus, natural analog sites in the Pasco Basin contain soils that are an order of magnitude older than the design life of the engineered protective barriers.

The evidence of and probability for the following natural processes that could adversely affect the long-term stability of an engineered protective barrier reviewed in this report are

- deflation by wind
- soil compaction
- soil eluviation/illuviation
- bioturbation
- cryoturbation.

Another purpose of this report is to document natural analogs sites identified in the Pasco Basin. The search for analog sites began in the early 1980s with a regional reconnaissance that identified 44 sites. These sites were re-evaluated for comparability to the engineered protective barrier. The list of sites was narrowed to three favored natural analog sites that have the best exposures and comparability to engineered barrier design. Originally, the analog sites were evaluated based on their similarity to two types of barrier design, either a simplified two-layer barrier or a graded (multilayer) barrier. During the spring and summer of 1990, the authors revisited these sites and identified several new analog sites. Since that time, the prototype barrier design has changed to a more complex configuration (Buckmaster 1993). The three favored sites are described in more detail in this report and recommendations for additional characterization are provided.

A glossary of terms that might be unfamiliar to the general reader is presented in the Appendix; these terms are italicized the first time they appear in the body of the report.

2.0 Engineered Protective Barrier Design

The prototype engineered barrier, proposed to be built over the 216-B-57 Crib within the 200 East Area of the Hanford Site, is 5 m thick and consists of multiple layers (Buckmaster 1993). The purpose of the barrier is to minimize the amount of natural recharge and biointrusion over areas of contamination (Figure 2.1). This will be accomplished by placing 2 m of fine-grained sediment over a 1.5-m coarse substrate. In between, a layer of gravel will be placed over the coarse substrate, followed by a layer of sand. The gradation in grain size between fine- and coarse-grained layers is designed to act as a filter to prevent the downward movement of fine-grained layers into the void spaces of the gravel below. The uppermost fine-grained layer will contain up to 15% gravel to facilitate evapotranspiration and minimize *deflation* (i.e., erosion) of the barrier by wind. The purpose of the fine-grained soil cap is to form a capillary barrier against the downward movement of moisture by creating a reservoir for precipitation and a host for plants to encourage evapotranspiration of moisture back to the atmosphere. Present designs propose using McGee Ranch soil (Last et al. 1987) from the western Hanford Site for the uppermost fine-grained soil layers capping the engineered barrier. A natural vegetative cover will be encouraged to grow atop these fine-grained layers. The purpose of the thick underlying gravel layer is to discourage biointrusion. At depth within the barrier, a composite asphalt layer will serve as a redundant moisture barrier. The base of the barrier will consist of a sandy soil layer to provide a foundation for the barrier and to protect the underlying in situ soil from disturbance during construction of the barrier.

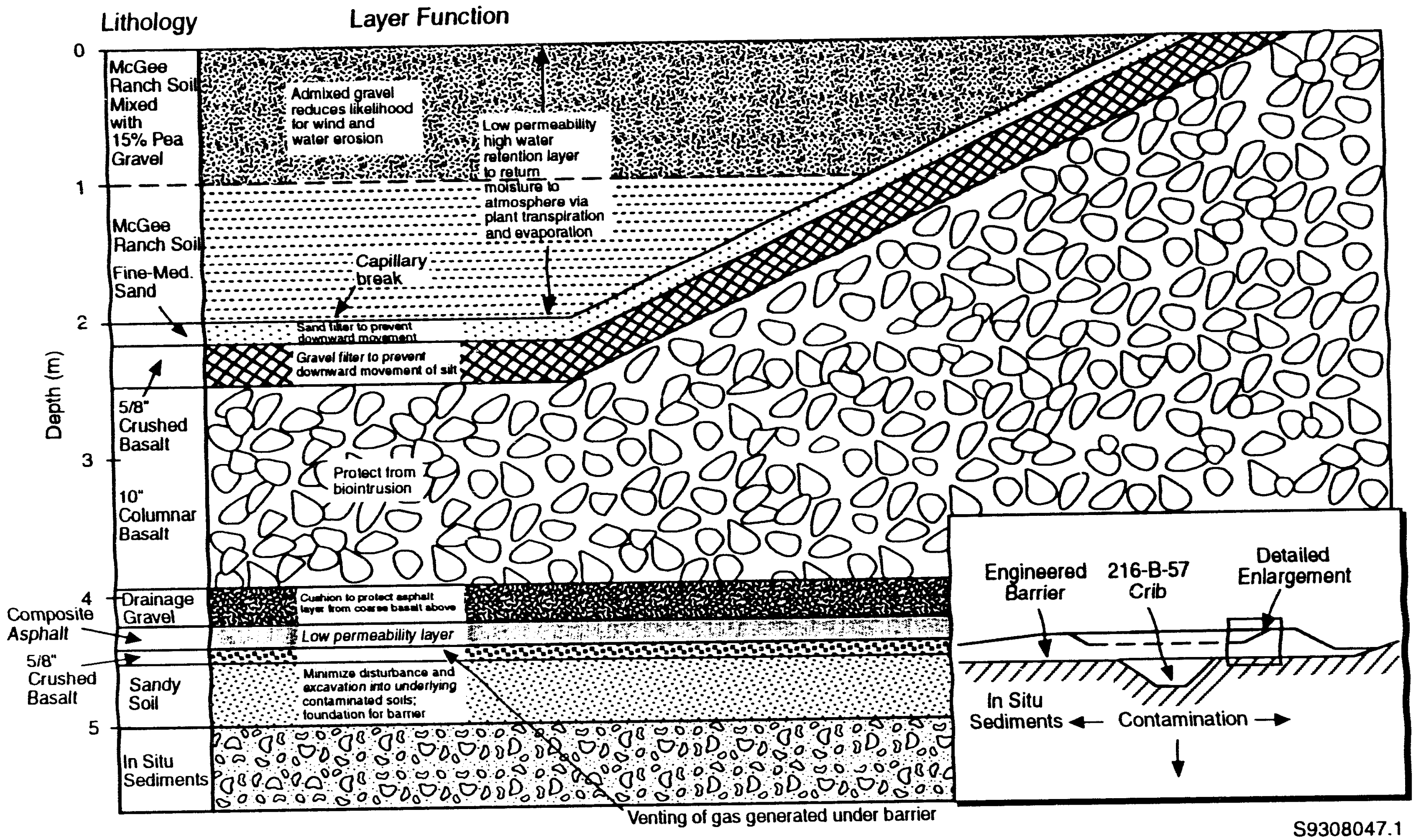

Figure 2.1. Prototype Barrier Design for the 216-B-57 Crib (Modified after Buckmaster 1993)

3.0 Natural Processes that Affect Long-Term Stability

Naturally occurring physical, chemical, and biological processes at the surface could potentially have an adverse affect the long-term performance of engineered barriers. Long-term stability depends, in part, on maintaining an adequate thickness of fine-grained topsoil and maintaining layer interfaces. Over time, there is the possibility for the fine-grained topsoil atop the barrier to become deflated by wind. Changes during *diagenesis* can occur through compaction, *eluviation*, *illuviation*, *bioturbation*, and/or *cryoturbation* processes. These processes potentially could lead to mixing of the layers or could reduce the effective thickness of the fine-grained layer enough to allow moisture or organisms to come into contact with the buried wastes. In summary, the following natural processes have the potential to adversely affect an engineered barrier over the next 1,000 years:

- deflation by wind
- soil compaction
- soil eluviation/illuviation
- bioturbation
- cryoturbation.

3.1 Deflation by Wind

Eolian processes, including the transport and deposition of particles by wind, are active at the Hanford Site, and wind-derived deposits mantle much of its surface (DOE 1988). Wind erosion, or deflation, is presently occurring on the exposed, windward (southwest) sides of ridges in the Pasco Basin and within the center of the basin as blowouts within dunefields, especially in areas where the vegetation has been disturbed. The transport and accumulation of eolian materials are a function of wind speed, atmospheric turbulence, surface roughness, ground cover, ground temperature, soil moisture content and soil structure, and particle size distribution (Glantz et al. 1990). Based on historical records collected at the Hanford Site since the 1940s, winds in the southern half of the site experience more directional variability, with high-speed winds predominantly from the southwest in the cool-season months. Winds in the northern portion of the site where the 200 Area waste sites lie, are predominantly from the northwest, with higher-speed northwest winds occurring in the warm-season months. The southern half of the Hanford Site, where the 300 Area waste sites lie, has a higher sand-drift potential than the northern portion of the site (Glantz et al. 1990).

To protect the engineered barrier from deflation, gravel (up to 15%) will be mixed with the uppermost layer of McGee Ranch soil (Figure 2.1). The gravel admix will aid in evapotranspiration and help to stabilize the surface soil. If deflation should occur, only the fine-grained sand would blow away leaving the gravel behind; the gravel would quickly armor the surface and protect it from the wind, eliminating further deflation.

3.2 Soil Compaction

Post-construction settling could have the following effects on an engineered barrier: 1) it would decrease the volume and effective thickness, 2) it would decrease the porosity, and 3) it would increase the density of layers within the barrier.

While mechanical compaction of the barrier may occur during construction of the barrier (i.e., during bulldozing, grading, etc.), little additional compaction is expected due to natural settling over time during the design life of the engineered barrier. Porosity of in situ McGee Ranch soil is estimated at about 0.48 based on a bulk density of 1.4 g/cc and a particle density of 2.72 g/cc.[a] Furthermore, silt loam packs in such a way that the final density and porosity will be invariant over time. An exception might be the uppermost 50 cm which could actually become less dense because of the effects of bioturbation and freeze-thaw activity. The performance of the engineered barrier would not be in jeopardy because the original thickness of the McGee Ranch soil layers (2 m) appears to be enough to allow for the expected few centimeters of post-construction expansion and/or compaction while maintaining an adequate thickness for plant growth and moisture retention.

3.3 Soil Eluviation/Illuviation

Given enough time and moisture, the processes of eluviation and illuviation will cause soil constituents (e.g., colloids, clays, oxides, and soluble salts) to migrate and concentrate into discrete horizons with differing geochemical and structural properties. These pedogenic processes and their byproducts usually occur within a meter or two of the surface. The depth and degree of soil horizon development depends on soil type, which in turn depends on climatic variables such as temperature and moisture, as well as the parent material.

Very little eluviation appears to have taken place in the Pasco Basin, based on macroscopic inspections of soil development that has occurred during the Holocene Epoch ($\leq$10,000 yrs B.P.). During advanced stages of *pedogenesis* subvertical prismatic to columnar fractures may develop, which can create preferential pathways for the movement of water and/or biological activity. While vertical fracturing has been observed in paleosols of the Ringold Formation (Figure 3.1), these secondary pedogenic structures are only weakly developed or nonexistent in late-*Quaternary* soils within the Pasco Basin. Some eluviation is apparent in late-Quaternary deposits described by McDonald (1987), where slightly higher color chroma, weak prismatic, and moderate subangular blocky soil structure are more developed compared to adjacent horizons. Below this zone of eluviation, calcic soil development begins at a depth of ~40 cm. Other forms of illuviation, including clay-rich argillic horizons, are not present in the region in post-flood sediments or paleosols dating to about 50,000 yrs B.P. (McDonald 1987).

(a) Gee, G. W., Senior Staff Scientist, Pacific Northwest Laboratory, personal communication.

Figure 3.1. Columnar to Prismatic Soil Structure Developed Within a Paleosol of the Ringold Formation. Fractures could provide preferential pathways for the movement of moisture and/or organisms. Notebook is 12 cm wide.

3.3.1 Calcium Carbonate Horizons

Accumulations of $CaCO_3$ are common in modern arid to semiarid soil environments (Gile et al. 1966, Machette 1985). Calcic soils develop from the process of illuviation in progressive stages (Table 3.1), starting with powdery and filamentous $CaCO_3$ (Stage I) for the most immature calcic soils. At the other end of the spectrum is a Stage VI carbonate accumulation, characterized by thick (meters), lamellar and/or brecciated calcic zones that are completely plugged or replaced with $CaCO_3$. Evidently, the source for Ca^{++} is through airborne dust delivered to the surface via rainwater (Machette 1985). Soluble salts, including $CaCO_3$, precipitate out of solution as the wetting front moves downward within the soil. In immature soils, $CaCO_3$ precipitation is often along root traces, suggesting that biogeochemical interactions along root traces, perhaps induced by microbial activity, play a part in $CaCO_3$ precipitation (Hunter et al. 1990).

Relative ages of soils may be estimated using the degree of calcic soil development (Machette 1985). Soils developed since the last cataclysmic flood (~ 13,000 yrs B.P.) display Stage I-II calcic development. Within the Pasco Basin, Stage III-IV buried calcic soils are developed atop 125,000-year-old middle-*Pleistocene* cataclysmic flood deposits (Baker et al. 1991). The more advanced stages of calcic soil development (Stage V-VI) may require from hundreds of thousands to millions of years to form (Machette 1985) but require a stable, nonaggrading ground surface for development and preservation. Multiple cycles of less well-developed calcic soil occur where soils aggrade over time.

Table 3.1. Stages of Carbonate Accumulation in Paleosols (after Rettalack 1988)

Stage	Paleosols Developed in Gravel	Paleosols Developed in Sand, Silt, or Clay
I	Thin, discontinuous coatings of carbonate on underside of clasts	Dispersed powdery and filamentous carbonate
II	Continuous coating all around, and in some cases between clasts: additional discontinuous carbonate outside main horizons	Few to common carbonate nodules and veinlets, with powdery and filamentous carbonate in places between nodules
III	Carbonate forming a continuous layer enveloping clasts; less pervasive carbonate outside main horizon	Carbonate forming a continuous layer formed by coalescing nodules; isolated nodules and powdery carbonate outside main horizon
IV	Upper part of solid carbonate layer with a weakly developed platy or lamellar structure, capping less pervasively calcareous parts of the profile	
V	Platy or lamellar cap to the carbonate layer strongly expressed; in places brecciated and with pisoliths of carbonate	
VI	Brecciation and recementation, as well as pisoliths common in association with the lamellar upper layer	

Considering that calcic soils, which are characteristic of a dry climate, are present in deposits up to 10.5 million years B.P. within the Pasco Basin, arid to semiarid conditions are expected to continue indefinitely. Based on soil development within the last 10,000 years, expected illuviation over the next 1,000 yrs within the engineered barrier will probably not develop beyond Stage I-II $CaCO_3$ accumulations. The net effect of secondary carbonate will likely be positive with respect to an engineered barrier, in that calcic horizons will act to inhibit the downward movement of groundwater and reduce the potential for deflation beneath the calcic horizon.

3.4 Bioturbation

Bioturbation, the churning and stirring of sediment by organisms including plant roots and burrowing animals, is common in the uppermost 1 m of the soil column. While bioturbation may extend beyond this depth, biologic activity drops off significantly beyond the 1 m depth. Large mammals generally do not burrow beyond a 25-cm depth at the Hanford Site (Cadwell et al. 1989). Over time, plants and animals tend to thoroughly mix the soil, creating a homogeneous layer near the surface. Animal burrows that remain open may create preferential pathways for the movement of moisture downward within the soil (Cadwell et al. 1989). An example of bioturbation, in the form of backfilled animal burrows, is presented in Figure 3.2.

In a study of rooting depths on the Hanford site, Klepper et al. (1985) found that maximum root penetration occurred with native antelope bitterbrush (10-20 year old) to depths of about 300 cm. Eight out of 14 plant species studied had roots that penetrated to 150 cm or more. In general, root density was greatest in the upper meter.

3.5 Cryoturbation

Cryoturbation (disturbance of soil resulting from freeze-thaw activity) is another potential mechanism for disturbance of layers within an engineered barrier. Cryoturbation can occur in the presence of moisture and *frost-susceptible* materials containing as little as 3% to 10% silt or clay (Washburn 1980). Generally, the more moisture that is present, the more intense the cryoturbation. Silt and clay expand rapidly in volume upon freezing, with the expansion of ice crystals. Soils containing silt (particle sizes of 4-62 microns) are especially susceptible to heaving (Embleton and King 1968). Repeated expansion and contraction can lead to preferential sorting by grains-size and/or bedding *involution*. Sand and coarser-grained materials normally do not form *segregation ice* in the *active layer*.

Because of cool winters, freeze-thaw cycles occur between November to March on the Hanford Site. Between 1912 through 1980, the total number of freeze-thaw cycles occurring at the ground surface averaged 93/year (with a range of 25-168 years) (Stone et al. 1983). However, due to the insulating effects of the soil, relatively few freeze-thaw cycles occur below 10 cm of the surface. During the last 5 years, maximum depths of freezing and seasonal *permafrost* have been less than 1 m (Figure 3.3). Based on the history of climatic change over the geologic past, climate is expected to change to some degree over the next 1000 years (Smiley et al. 1991). A decrease in temperature or

Figure 3.2. Bioturbation, in the Form of Relict Animal Burrows, in Pleistocene-Age Loess of the Palouse Formation

increase in moisture could alter the number, depth, and intensity of freeze-thaw cycles, which could adversely affect an engineered barrier by causing mixing and sorting of soil components via cryoturbation.

The Pasco Basin may have been influenced by much greater *cryogenic* activity as recently as 12,000 years B.P. when the Cordilleran Ice Sheet covered a large portion of northern Washington (Figure 3.4), approaching to within 100 km of the Pasco Basin (DOE 1988). During the Wisconsinan glaciation 15,000-22,000 yrs B.P., the Pasco Basin and eastern Washington may have been under a periglacial *tundra*-like environment (Figure 3.4) similar to present-day conditions that exist adjacent to active glaciation in northern Canada and Alaska. By 10,000 yrs B.P., the glacial border had retreated significantly into northern Canada. Currently, the only permafrost present in the contiguous United States is sporadic in nature and restricted to higher alpine regions within the Rocky Mountains.

Distinctive surficial landforms associated with periglacial environments include

- thermal contraction features (*ice wedges*, sand wedges, frost cracks)
- *frost mounds* (hummocks, *pingos*, *palsas*)
- topographic depressions (*thermokarst*)
- *patterned ground* (polygons, circles, stripes).

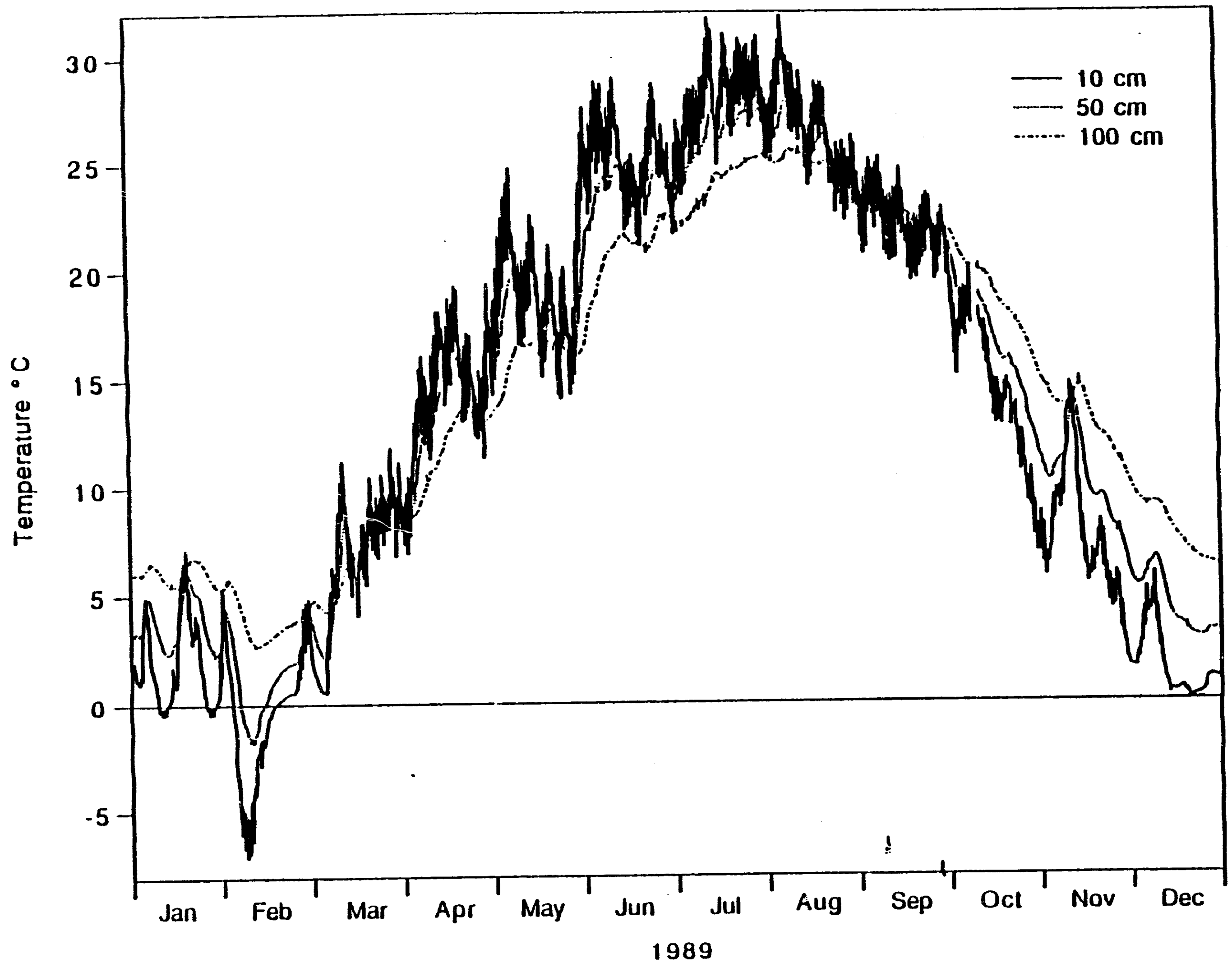

Figure 3.3. Soil Temperature and Depth Versus Time Plot for 1989 from the Hanford Meteorological Station Lysimeter Site. Frozen ground extended to a depth of 50-100 cm and lasted for approximately 10 days in early 1989. Only one freeze-thaw cycle occurred below 50 cm, while three freeze-thaw cycles occurred at the 10 cm depth.

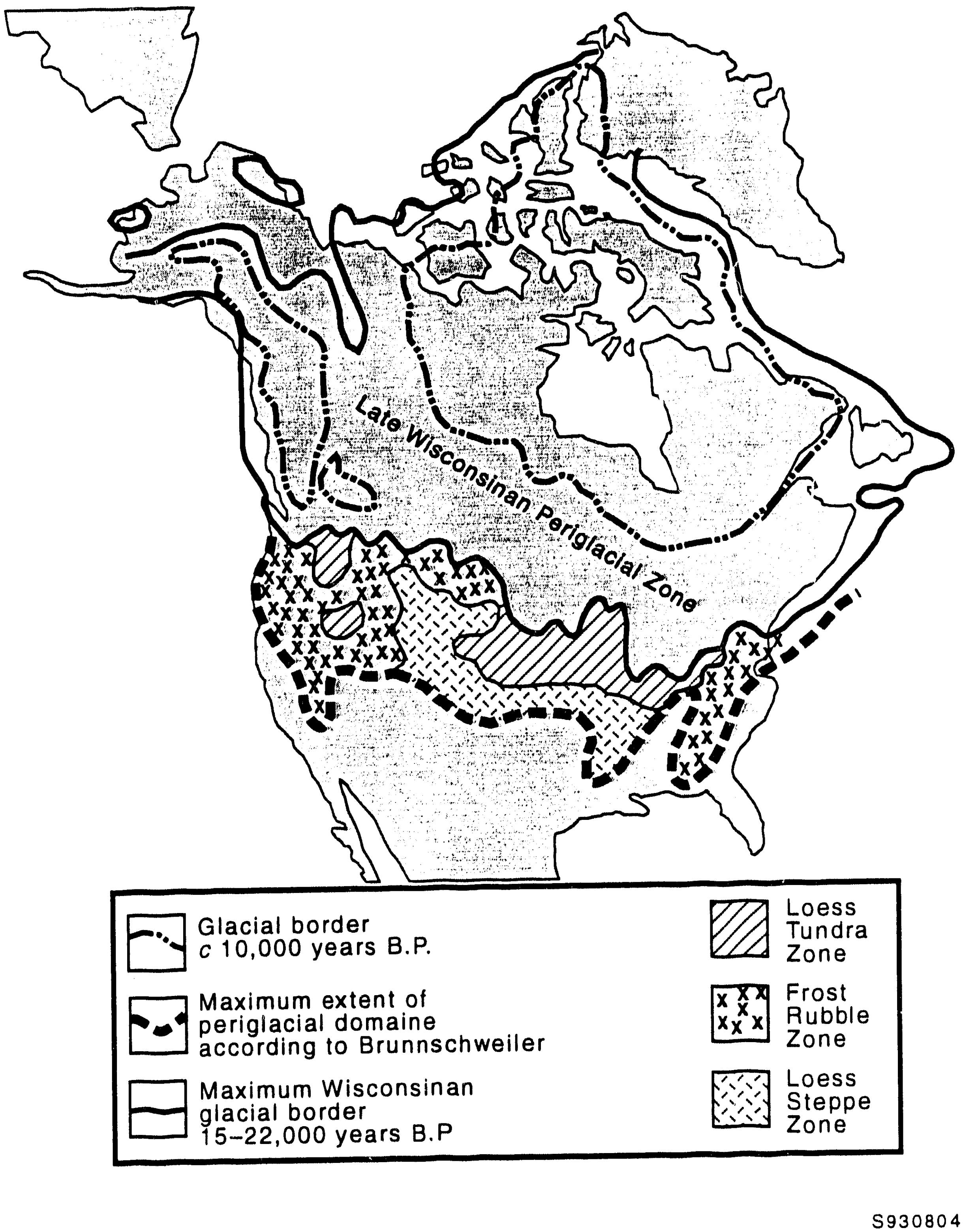

Figure 3.4. Tentative Reconstruction of Glacial and Periglacial Zones in North America During the Wisconsinan Glaciation. After French (1976).

These landforms are the result of cryoturbation, associated with permafrost and/or freeze-thaw activity within the active layer, which include *frost heaving* and cracking. Some of these features, such as ice wedges, are restricted to areas of continuous permafrost, while others, like thermokarst, occur over a wider range of permafrost conditions (Figure 3.5). Soils in cold environments are often disturbed by freeze-thaw activity, (e.g., stirring, churning, and/or sorting) frost cracking, and frost heaving (Karte 1983, Retallack 1990). When water freezes at 0°, it expands by 9% of its volume (Williams and Smith 1989). Thus, during the freeze-thaw process, frost heaving can result in the progressive elevation of the ground surface from 10 to 30 cm during a single winter (Anderson 1981). Ground displacement depends on soil type, stratification, grain-size distribution, groundwater conditions, rates of freezing, and other factors (Williams and Smith 1989). Heaving is absent when pores between sedimentary particles are large (i.e., coarse-grained sediments). Cryoturbation tends to take heterogeneous materials and sort them according to grain size. Accordingly, coarse particles tend to move to the top and the fine-grained particles move downward to the bottom of the freeze-thaw layer (Embleton and King 1968). Other evidence for cryogenesis include sand wedges (Retallack 1990) and bedding involutions (French 1976).

3.5.1 Potential for Cryogenic Alteration within the Pasco Basin

While there is the possibility that ice-age conditions, similar to those that occurred during and soon after the Pleistocene, could resume as early as 15,000 years from now (Craig et al. 1983), there is a very low probability that glaciation will advance significantly nearer the Pasco Basin over the next 1,000 years.

The many types of periglacial features and their relative distribution with respect to the different types of permafrost are illustrated in Figure 3.5. With the exception of mima mounds, no permafrost indicators (polygons, circles, hummocks at the surface or sediment-filled cracks, or involutions in the subsurface) have been observed within the Pasco Basin that could be attributed to a periglacial environment. Clusters of mima mounds, a type of patterned ground, are locally present in upland areas surrounding the Pasco Basin. Generally, they are developed in thin soils (1 m or less) overlying basalt bedrock at higher elevations. The formation of mima mounds is probably multigenetic depending on location, climate, substrate, etc. Other possible mechanisms for their formation, besides freeze-thaw activity, include 1) biological (pocket gopher) activity, 2) runoff or wind erosion combined with vegetation anchoring, or 3) runoff erosion combined with desiccation cracking (Washburn 1988). Another type of patterned ground present in the Pasco Basin are polygons (Lillie et al. 1978), but these represent the surface expression of vertical *clastic dikes*, which are probably not related to cryogenic activity, as discussed later in this report.

Because most surficial deposits in the Pasco Basin are late-glacial to post-glacial in age, all *periglacial* evidence may have been stripped away or modified by the last cataclysmic flood(s) that occurred at the end of the last ice age. However, if this is the case, then permafrost indicators should be preserved at higher elevations around the margins of the Pasco Basin, which were relatively unaffected by floodwaters. To date, no such features, with the possible exception of mima mounds, have been observed or reported around the margins of the Pasco Basin.

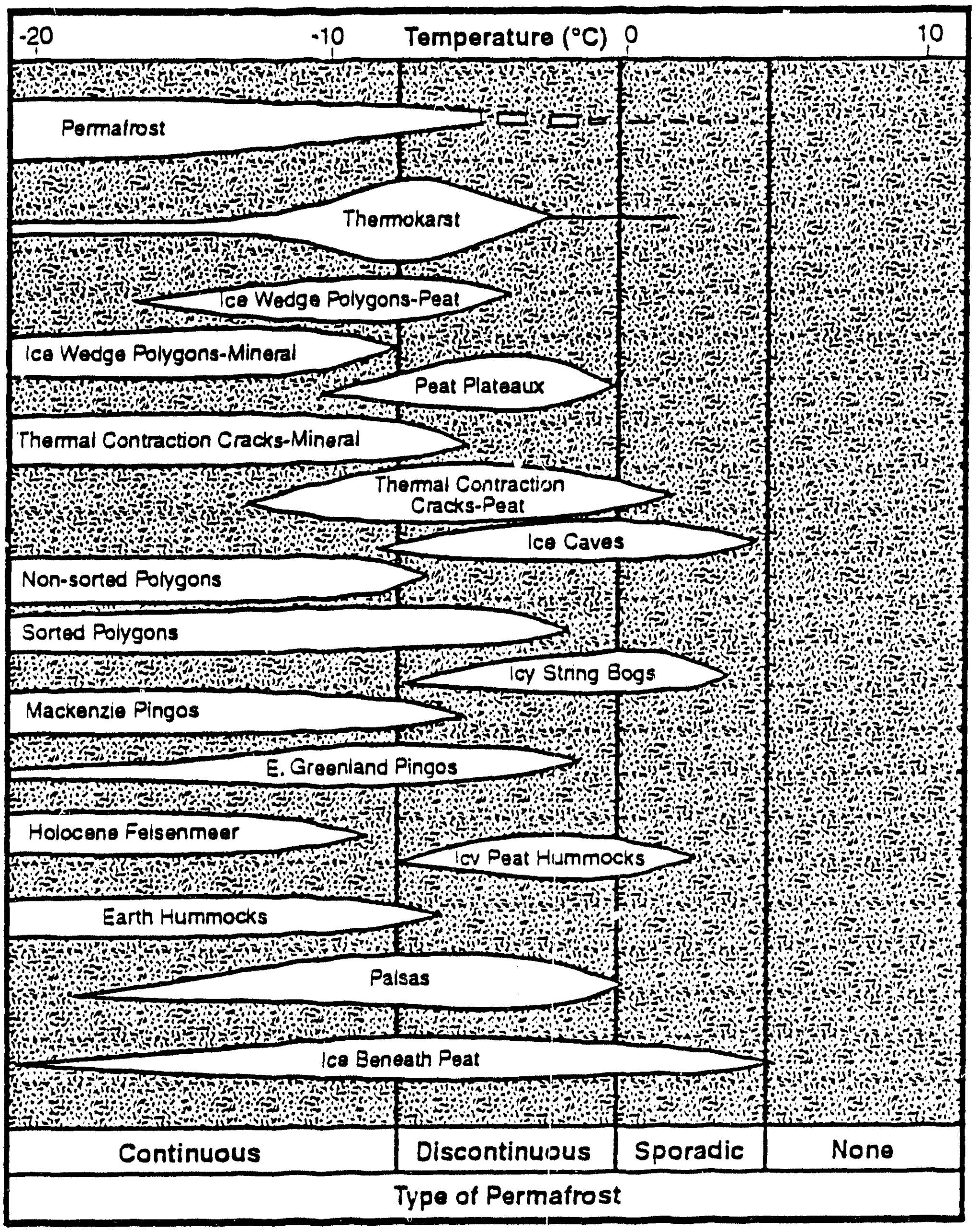

Figure 3.5. Relationship and Distribution of Landforms Associated with Permafrost. After Harris (1981).

It may be argued that the relatively even distribution of matrix-supported pebbles and cobbles frequently seen "floating" within the uppermost fine-grained eolian sediments in outcrops within the Pasco Basin is due to frost heaving via "uplift" during cryoturbation (Washburn 1980). An example of coarse-grained clasts floating in a fine-grained matrix is shown in Figure 3.6. The floating clasts in Figure 3.6, however, are due to bioturbation, not cryoturbation, which tends to sort heterogeneous materials by grain size (Corte 1963). In Figure 3.6, surficial (mostly eolian) material is randomly mixed with underlying coarser-textured glaciofluvial sediments.

Another argument against cryogenesis is the lack of cryogenic structures within the late-Pleistocene-age Touchet Beds, which are slackwater flood deposits within and adjacent to the Pasco Basin containing abundant silt (Bjornstad 1980). If cryoturbation were an active process during or soon after the last glaciation, there should be relict evidence for cryogenic structures, such as *thermal contraction cracks* and/or involuted bedding, in these deposits. While some contorted bedding of Touchet Beds is reported (Bjornstad 1980), it is related to soft-sediment deformation, which occurred contemporaneously with deposition. Wedge-shaped features in slack-water flood deposits called clastic dikes, are common but originate from dewatering and/or desiccation unrelated to frost cracking (Black 1979). Because of the Touchet Bed's fine-grained nature, evidence for frost cracking or cryoturbation

Figure 3.6. Mixing of Fine-Grained Eolian Material (above) with Coarse-Textured Cataclysmic Flood Gravels (below) Exposed in a Borrow Pit at Wahluke Slope. Mixing of coarse material with the fine is probably the result of bioturbation.

should be preserved in these deposits if crygenesis was an active process. The lack of evidence for cryogenic structures in the Touchet Beds suggests that cryoturbation did not occur during, or since, the late-Pleistocene (i.e., during the last 30,000 years). While periglacial conditions may have existed during this time, other factors, such as moisture content of the soil or soil texture, may have precluded the development of any cryogenic features.

Over the next 1,000 years, sporadic permafrost or seasonally to diurnally *frozen ground* will most likely continue to develop during the winter months. However, based on soils formed over thousands of years and historical records, the effects of cryofurbation do not appear to extend below 5-10 cm of the surface. For these reasons the probability for cryogenic alteration to adversely affect an engineered barrier over the next 1,000 years appears very low.

4.0 Regional Reconnaissance for Potential Analog Sites

A regional reconnaissance survey of potential analog sites was initiated in the early 1980s when a total of 44 sites were identified (Figure 4.1). During the spring and summer of 1990, these sites were revisited and several new analog sites were identified. Many of the original analog sites, particularly those near the 200 East and 200 West Areas, have since been graded and/or revegetated and no longer provide useful exposures.

Originally, analog sites were evaluated based on their similarity to two types of barrier design: a simplified two-layer barrier and a graded (multilayer) barrier. Most natural analog sites within the Pasco Basin consist of mixtures of fine-grained, eolian (windblown) sand and silt overlying coarse-grained, Pleistocene-age cataclysmic flood gravels (Baker et al. 1992). Fine-grained eolian deposits

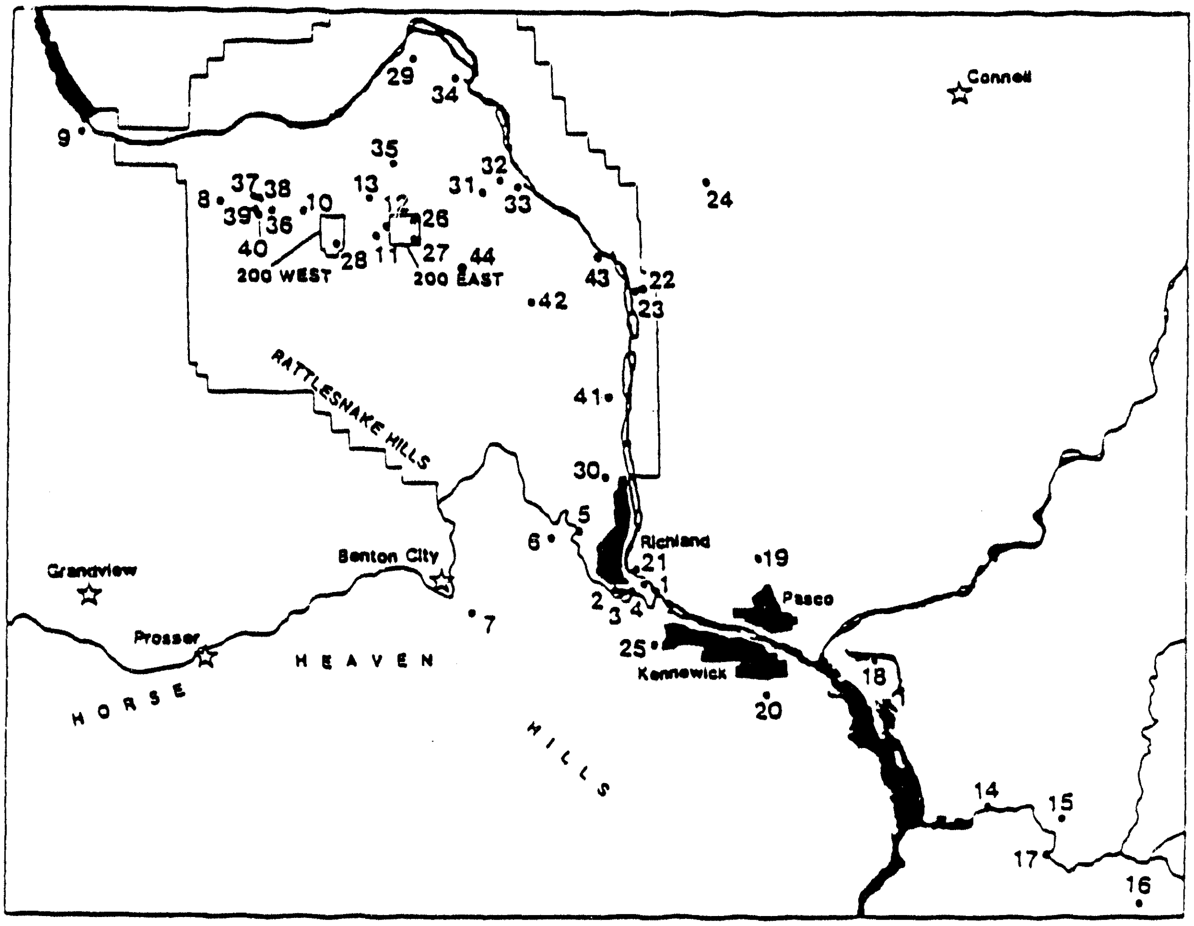

Figure 4.1. Location of the Original 44 Natural Barrier Analog Sites Identified in the early 1980s

are analogous to the McGee Ranch soil, and coarse-grained flood deposits are analogous to some of the coarser-grained layers in the prototype barrier design (Figure 2.1). The eolian materials were deposited sometime after the last cataclysmic flood, which occurred approximately 13,000 years ago (Mullineaux et al. 1978). Matrices within the Pasco Gravels, however, often are filled with poorly sorted mixtures of sand and silt. Most likely, the poorly sorted matrix represented in the Pasco Gravels is a result of transient flow dynamics and rapid deposition during cataclysmic flooding. However, illuviation is also a possibility. Surficial soils, which have developed atop the most recent flood deposits, are relatively immature and display evidence for illuviation in the form of powdery and filamentous $CaCO_3$ (Stage 1 carbonate accumulation, Table 3.1) and evidence for bioturbation within the uppermost 2 m.

Geologic descriptions documented at analog sites include sediment lithology, approximate thickness, mineralogy, interpretation of depositional history, contact relations, calcic soil development, sedimentary structures, depth of root penetration and/or burrowing, size sorting, roundness of gravels, evidence for bioturbation/cryoturbation, maximum size of gravels, presence/absence of open-work framework in gravels, and a description of the gravel matrix. These data, summarized in Table 4.1, were used to compare analog sites and evaluate long-term stability of engineered protective barriers.

4.1 Representative Natural Analog Sites

Criteria were developed to narrow the list of potential natural analog sites to the three best sites for possible further characterization. The criteria, listed in generally decreasing order of importance, are

1. a total of 0.3-2.0 m of fine-grained soil overlying gravels
2. exposure of existing ground surface exposed to surficial processes for thousands of years (indicated by presence of calcic soil development)
3. proximity to waste-management operations
4. dominant particle size in fine-grained soils is silt
5. low-relief, geomorphically stable surface
6. coarse-grained layer consists of poorly graded, open-work, cobble-sized, angular gravels
7. evidence for bioturbation and/or cryoturbation
8. presence of calcic soil development
9. presence of multiple layers
10. accessibility.

Table 4.1. Comparison of Sites Recommended for Further Characterization

Analog Site	Fine-Grained Layers			Coarse-Grained Layers			Multiple Layers	Pedogenic Carbonate Devel.	Illuviation of Clay/Silt	Root Penetration (cm)
	Thickness (cm)	Lithology	Bioturbation	Open-Work Fabric	Dominant Gravel Size	Roundness of Gravel Clasts				
Wahluke Slope Pit	Upper 60-150 Lower 15	Upper gS Lower (g)mS	Upper Yes Lower ?	Rare	Pebble	Subrounded to Well-Rounded	Yes	*Stage I-III*	*Yes*	*90-170*
Pit 9	Upper 30-60 Lower 30-60	Upper gS Lower (g)mS	Upper No Lower Yes	Upper Common Lower Rare	Pebble-Cobble	Subangular to Well-Rounded	Yes	Stage I-III	?	60-150
Pit 29	Upper 90 Lower 60	Upper gmS Lower S	Upper ? Lower No	Upper Some Lower Some	Pebble-Cobble	Subangular to Rounded	Yes	Stage I?	?	?

S - Sand
gS - gravelly sand
gmS - gravelly silty sand
(g)mS - slightly gravelly silty sand

Many of the sites satisfy some of the criteria yet none satisfy all the criteria. Sites that best satisfy the criteria, which we recommend for detailed characterization of long-term performance, include

- Wahluke Slope Pit
- Pit 9 (Premix Pit)
- Pit 29.

These three sites (Figure 4.2) satisfy all the above criteria except for 4 and 6. Criteria 4 and 6, however, were not found to coexist anywhere within the Pasco Basin. For example, instead of a silt loam (comparable to the McGee Ranch soil) overlying open-work gravels, there exists a sandy loam overlying well-graded, matrix-filled, subangular-to-rounded, pebble-cobble gravel. This is significant because the McGee Ranch soil has a relatively high water-retention capacity (Last et al. 1987) compared to the sandier soils at natural analog sites. Specifically, differences in silt content may affect the amount and depth of water penetration, which in turn influences illuviation of clay, carbonate, and other soluble salts. However, even though the properties of the geologic materials at analog sites are not totally representative of the proposed engineered barrier design, analog studies provide information on the effects of various geologic, pedologic, and biologic processes on interface stability and long-term performance (Winograd 1986).

4.1.1 Wahluke Slope Pit

This recently discovered locality (not studied in the 1983 reconnaissance) consists of clast-supported flood gravels underlying 60-150 cm of eolian sand. Locally, up to a meter of recent backfill material overlies the eolian sand. Two pits are present. In the western pit, the surficial soil is composed of dominantly fine ecolian sand with 10% to 15% matrix-supported pebbles (Figure 4.3). The pebbles within the sand contain no carbonate coatings and are oriented randomly. This random orientation of the long axis of the pebbles suggests that their presence is not due to eolian processes; bioturbation is the most likely explanation. In the eastern pit, the fine-grained (slightly pebbly, silty sand) surficial soil is discontinuous and, based on its interstratification with flood gravels, appears to be of glaciofluvial origin.

Gravel clasts in both pits consist of mostly Ringold Formation pebbles transported and redeposited during Pleistocene cataclysmic flooding. Stage I-III carbonate development is present in the gravels at both pits. The matrices between the well-rounded, clast-supported pebbles are filled with medium-to-coarse sand. Matrix-free, open-work gravels are rare. Locally, near the contact with the overlying fine-grained soil, gravel matrices are filled with compact silt and clay, which may be the result of illuviation (Figure 4.4). Multiple layers are present in the western pit, where the gravels contain a lens of slightly gravelly silty sand about 6 m long and 15 cm thick. This lens has Stage I-II carbonate accumulations. The fact that the flood gravels and the fine-grained lens are relatively compacted and consolidated suggests that they were deposited during a middle Wisconsinan or older flood event (perhaps $\geq$30,000 years ago). Large-scale foreset bedding, a distinguishing characteristic of flood deposits, is well-preserved toward the top of the gravel sequence (Figure 4.3).

In the western pit, a well-developed 15- to 30-cm-thick calcic soil horizon is present. The base of this horizon is generally just below the silty sand/gravel contact. It generally has Stage II carbonate development, with some discontinuous Stage III calcium carbonate accumulation (Figure 4.5). This stage of calcic soil development further indicates the gravels were deposited during a middle Wisconsinan or older flood.

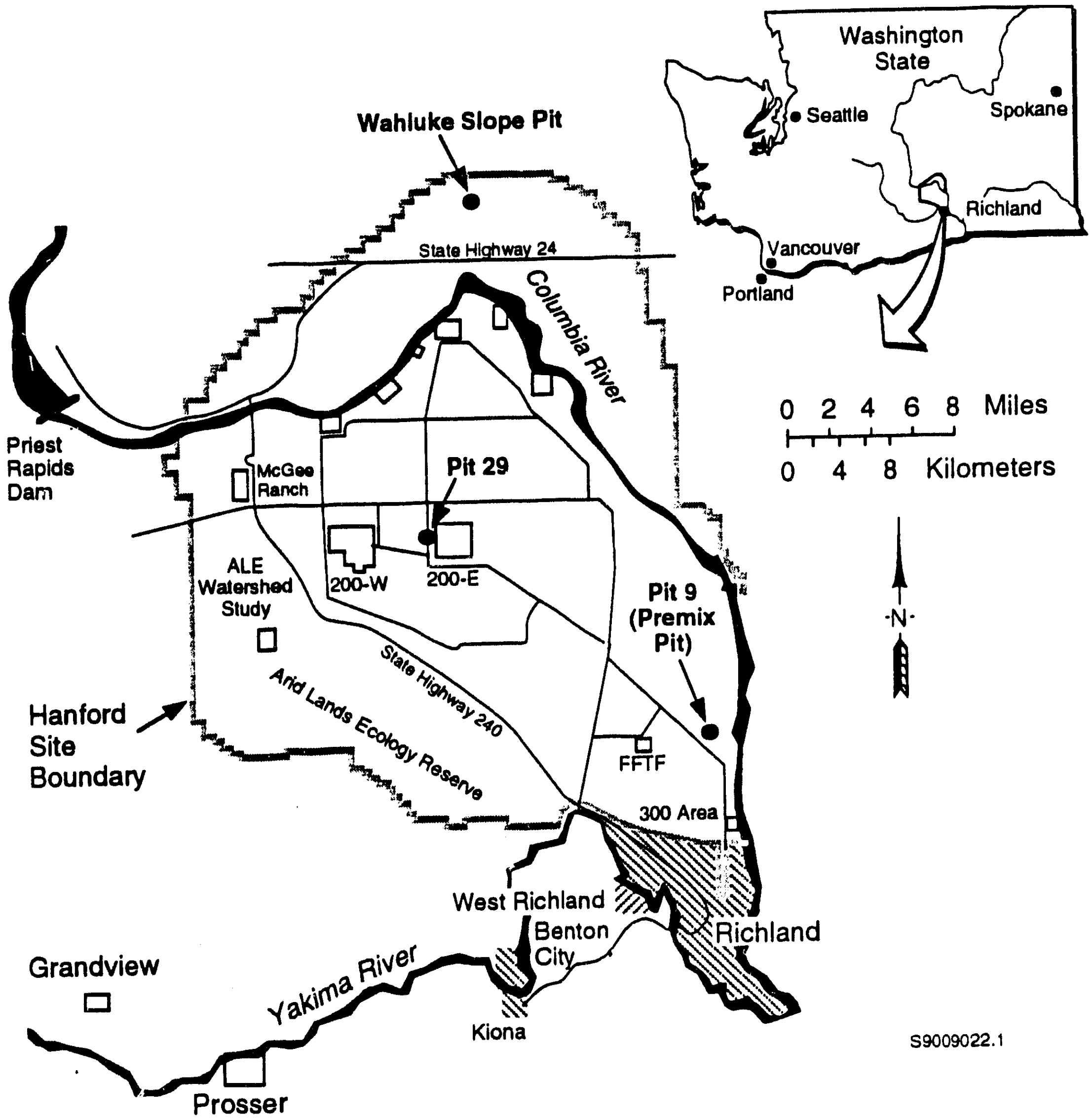

Figure 4.2. Locations of Three Sites Recommended for Further Characterization

4.1.2 Pit 9 (Premix Pit)

This large, active pit contains several good exposures, the best of which occur along the east wall (Figure 4.6). Strata exposed at this site (illustrated by their respective letters in Figure 4.6) and their interpreted origin include A) bulldozed backfill material, B) pebbly sand (recent soil), C) upper silty sandy gravel (younger flood gravel), D) a silty sand lens (buried paleosol), and E) a lower silty sandy gravel (older flood gravel). Following is a detailed description of these layers.

A. *Backfill material.* This chaotic mixture of silt, sand, and gravel is locally foreset bedded but lacks any evidence for soil development. It is therefore interpreted to represent a layer of backfill material probably pushed into its present position with a bulldozer during formation of the pit.

Figure 4.3. The Wahluke Slope Pit. Fine-grained soil overlying foreset-bedded flood gravels infilled with Stage I-II carbonate development.

B. Pebbly sand. This unit may be up to about a meter thick and is relatively continuous across the outcrop. Primarily eolian sand contains 10 to 15% matrix-supported gravel, most of which is pebble-size; however, some cobbles are present. No direct evidence for bioturbation (burrowing) was observed in this unit yet its relatively dark color and massive structure suggests recent soil development.

C. Upper silty sandy gravel. This gravelly flood deposit is mostly unconsolidated and matrix-supported but may also show a clast-supported, open-work fabric. It has an average thickness of about 1 m. Gravels are subangular to well-rounded and appear to be slightly coarser than the lower silty sandy gravel sequence. Stage I carbonate development is common.

D. Silty sand lens. This unit, up to 60 cm thick, extends laterally for a distance of approximately 9 m. The compact nature and abundance of fossilized root traces indicate the lens represents a buried soil horizon that developed atop an older flood sequence. The discontinuous nature of the lens (Figure 4.6) is probably due to erosion associated with a younger flood that deposited the overlying flood gravel. The lens is largely barren of gravel except near the contact with the underlying gravel unit where burrowing activity incorporated pebbles from below (Figure 4.7).

Figure 4.4. The Wahluke Slope Pit. Fine-grained silt and clay filling gravel matrices may be the result of illuviation of fines from above. Stage II carbonate development is also present.

E. Lower silty sandy gravel. This unit consists of dominantly clast-supported gravels in a silty sandy matrix. It is generally semiconsolidated and shows well-developed foreset beds (e.g., see the middle of the right side of Figure 4.6). Gravels may be up to cobble-size but are more commonly in the range of coarse pebbles or smaller, and they are generally subangular to well-rounded. Stage I carbonate is common on the undersides of gravel clasts. This unit is in sharp contact with the silty sand lens, although locally there is evidence for some illuviation across this textural boundary.

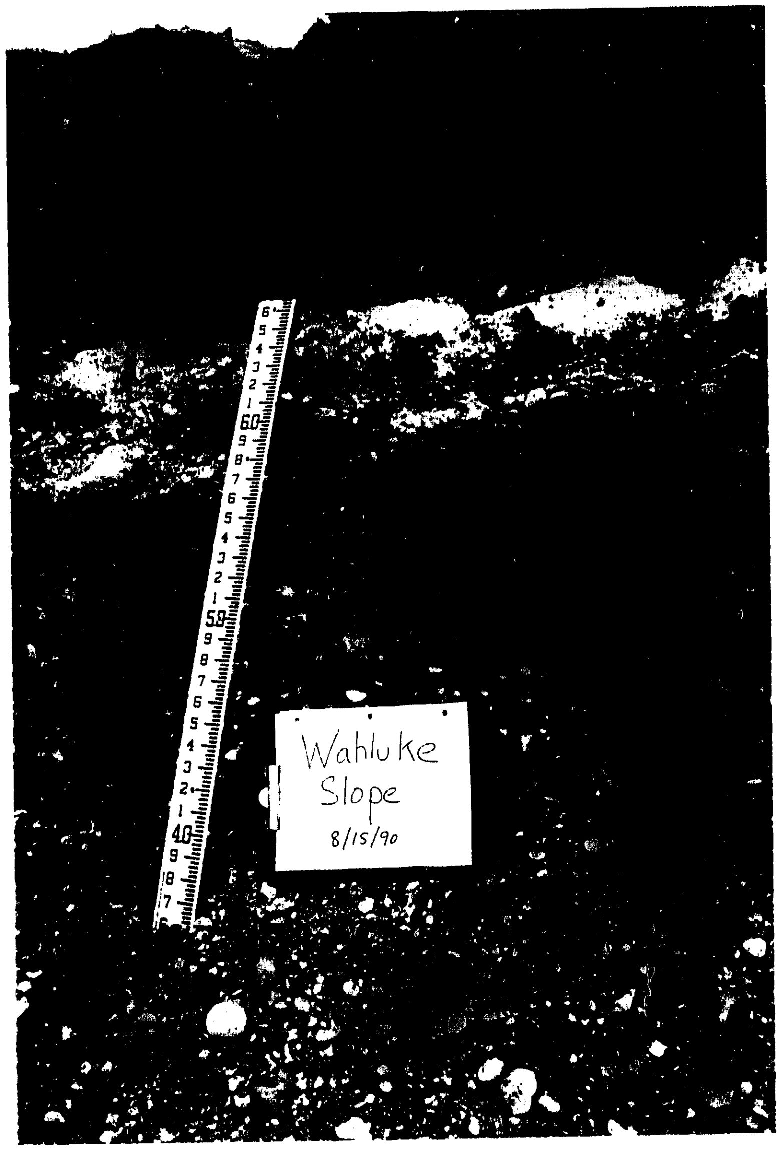

Figure 4.5. The Wahluke Slope Pit. Close-up of Stage II to III carbonate development toward top of glaciofluvial gravel sequence. The lack of a well-defined interface between fine-grained eolian and coarse-grained glaciofluvial units is probably due to bioturbation.

4.1.3 Pit 29

The observed sequence at this site (Figure 4.8) consists of (in descending order) A) pebbly silty sand, B) sandy gravel, C) sand, and D) sandy gravel to silty sandy gravel.

A. Pebbly silty sand. This pale brown, eolian sand is approximately a meter thick. It contains approximately 15% matrix-supported pebbles; these appear to be derived from the underlying gravel, probably via bioturbation.

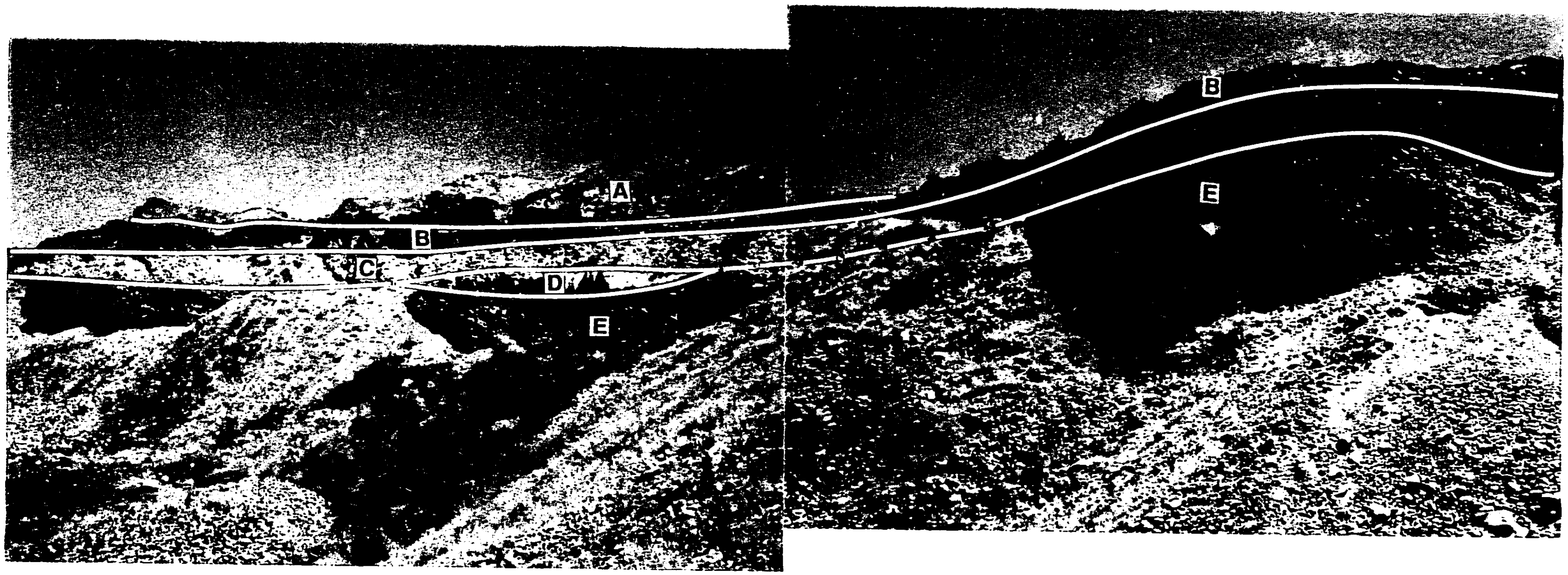

Figure 4.6. East Side of Pit 9 Exposure. Layers (described in text) include A) bulldozed backfill material, B) pebbly sand (recent soil), C) upper silty sandy gravel (younger flood gravel), D) a silty sand lens (buried paleosol), and E) a lower silty sandy gravel (older flood gravel).

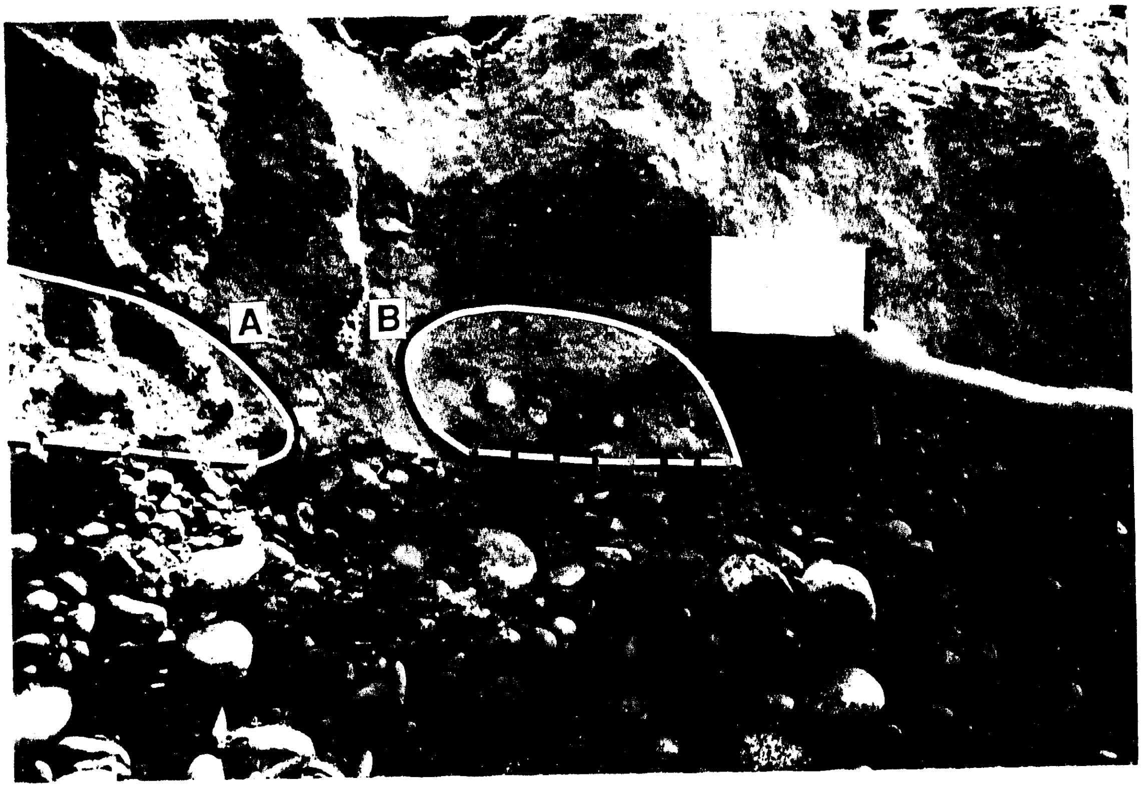

Figure 4.7. Two Animal Burrows (A and B) Within a Buried Soil Horizon at Pit 9, Located Along the Contact Between Layers D and E in Figure 4.6. Animals have burrowed down into the underlying gravel layer as indicated by the gravels present in the burrows, demonstrating that burrowing animals do not necessarily stop at the fine-grained/coarse-grained soil interface.

B. Sandy gravel. This gravel contains pebble-to-cobble sized, angular-to-rounded clasts composed predominantly of basalt (60% to 90%). The sandy gravel is poorly sorted, generally unconsolidated, and contains some localized open-work fabric. Pebbles and cobbles near the top of the unit commonly show Stage I carbonate development.

C. Sand. This unit shows planar (base) to foreset lamination (Figure 4.8). It contains no floating gravel clasts or other evidence for bioturbation. The contact with the overlying gravel is planar and sharp.

D. Sandy gravel to silty sandy gravel. This unit consists of dominantly sandy gravel mixed with fine-grained silt at the top (Figure 4.8). The silt may represent a paleosol because it appears weathered and contains rootlets. An alternative explanation is that the silt is derived from leaching and illuviation from the overlying sand unit. Gravels are up to cobble-size, and are generally semiconsolidated; however, some open-work fabric is also present. The contact with the overlying unit is relatively sharp.

Figure 4.8. Multiple Layers at Pit 29. Two layers of predominantly sand and two layers of predominantly gravel are represented. Silt is locally concentrated along the top of layer D.

4.2 Comparison of Site Characteristics

Table 4.1 compares some of the geologic, pedologic, and biologic characteristics of the three sites recommended for detailed characterization. As shown on this table, the main differences are 1) the relative amounts of silt and gravel in the sandy surficial eolian units, 2) the degree of bioturbation, 3) the amount of open-work fabric in gravels, 4) the relative amount of cobble-size gravels, 5) the degree of roundness, 6) the stages of calcium carbonate soil development, and 7) the multiple layer configuration and depth.

At two of the three sites, bioturbation is considered the most likely mechanism for mixing of the surficial fine-grained soils with underlying gravels; no significant mixing is represented at the third site. Stages of carbonate accumulation at the three sites ranged from Stage I to III. Secondary calcium carbonate development is related to water movement and precipitation within the soil; therefore, a comparison of carbonate development with respect to grain size, other heterogeneities, and depth will provide information on likely long-term carbonate development within an engineered barrier.

Multiple depositional cycles are present at all three sites. Multiple cycles allow for a greater variability in texture, etc., than would be present if only a single cycle was present and also allow for the interactions between multiple layers and interface stability.

5.0 Recommendations for Further Study

The next phase of work to evaluate interface stability is to complete detailed field and laboratory analyses of the three recommended analog sites. In addition, we propose that reconnaissance studies continue to look for additional natural analog sites with characteristics more similar to actual barrier design (i.e., silt loam overlying coarse, angular gravels). It is probable that these types of deposits are present northeast of the Pasco Basin within the Palouse Hills/Channeled Scabland provinces where silt-dominated, eolian loess is ubiquitous and often overlies coarse-grained, angular, basaltic flood gravels within anastamosing Missoula flood channels that dissect the loess hills of the Palouse region. While the Palouse region is somewhat removed from the Hanford Site, the climate and vegetation are similar to that of the Pasco Basin. The Palouse region receives slightly more precipitation and therefore may provide an even more conservative record of soil-forming processes.

A possible mechanism that has the most potential to adversely affect interface stability is bioturbation. Burrowing animals that mix materials across textural interface boundaries could compromise long-term barrier performance (i.e., dysfunction of the capillary boundary). While the effects of burrowing animals on water infiltration have been evaluated (Cadwell et al. 1989), the effects of burrowing animals on interface stability have yet to be considered. One of the purposes of the coarse-grained layer in barrier design is to deter burrowing animals. Yet examination of natural analogs in the field indicates that animals have burrowed downward from the fine-grained soil into the coarse-grained material, mixing these layers in the process. Examples of this are represented in the Wahluke Slope pit (Figures 3.6) and at Pit 9 (Figure 4.7) where flood gravel clasts are incorporated into the overlying fine-grained materials, apparently as a result of bioturbation.

6.0 Conclusions

A total of 44 analog sites were narrowed down to three sites with characteristics that most closely resemble engineered protective barriers and warrant further investigation. While no analog was found that exactly matches the complexities built into the engineered barrier design, valuable information was obtained on the long-term effects of natural processes (e.g., illuviation, bioturbation, cryoturbation) on the interface stability of layers within the proposed engineered barrier. Illuviation that can be expected over the next 1,000 years would be in the form of thin filaments and stringers of calcium carbonate accumulating within a meter of the barrier surface. Calcic accumulation will probably have a net positive affect on an engineered barrier because long-term calcic accumulations will act to decrease the permeability of the soil, as well as the rate of downward water percolation and the potential for wind deflation. Furthermore, the graded nature of the barrier beneath the fine-grained McGee Ranch soil should be effective at preventing any significant downward movement of fine-grained soil into the underlying matrix-free fractured basalt layer. Due to compaction, the overall thickness of the barrier is not expected to vary by more than a few centimeters; furthermore over the long term; the original thickness of the layers appears to be adequate to avoid any adverse affects associated with layer reduction. The present engineered barrier design (Figure 2.1), with its 1.5-m-thick layer of coarse fractured basalt several meters below the surface, appears adequate to preclude biointrusion of underlying contamination by plants or animals. Significant disturbance of the engineered barrier via cryoturbation does not appear likely over the design life of the barrier because there is no evidence for significant cryoturbation in analogous sediments deposited over the last 30,000 years.

Based on the present barrier design and the types of alteration that have taken place in Holocene soils within the Pasco Basin, none of the above natural processes alone appears to be a significant threat to the engineered protective barriers over the next 1,000 years. However, a combination of these processes acting together (e.g., deflation in combination with compaction or bioturbation) could conceivably reduce the effective thickness of layers although the likelihood of this combination of events occurring is small.

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Appendix

Glossary

Appendix

Glossary

active layer - Seasonally frozen ground overlying *permafrost*. A surface layer of ground that is alternately frozen each winter and thawed each summer. The active layer lies above permafrost, which stays frozen year round. Thickness of the active layer ranges from several centimeters to a few meters.

bioturbation - The churning and stirring of a sediment by organisms.

clastic dike - A sedimentary dike consisting of a variety of clastic materials derived from underlying or overlying beds. In the Pasco Basin, clastic dikes are believed to be dewatering structures associated with lake draining following cataclysmic floods.

compaction - Reduction in bulk volume or thickness of, or the pore space within, a body of fine-grained sediments in response to the increasing weight of overlying material or to the pressures resulting from earth movements within the crust.

cryogenic - The science of low-temperature phenomena.

cryoturbation - A synonym of congeliturbation, which is a collective term to describe the stirring, churning, modification, and all other disturbances of soil resulting from frost action which involves *frost heaving*, solifluction, and differential and mass movements, producing patterned ground.

deflation - The sorting out, lifting, and removal of loose, dry, fine-grained particles by turbulent eddy action of the wind; a form of wind erosion.

diagenesis - The sum of physical, inorganic chemical, or biochemical changes in a sedimentary deposit after its initial accumulation, and excluding metamorphism.

eluviation - The downward movement of soluble or suspended material in a soil, from the A horizon (zone of leaching) to the B horizon (zone of accumulation), by surface water percolation (see *illuviation*).

engineered barrier - An addition to the geological environment which has been designed, fabricated, and emplaced to minimize or preclude transport of hazardous and/or radioactive constituents.

frost heave - The process whereby *segregation ice* forms in *frost susceptible*, fine-grained materials and groundwater is drawn in to feed growing ice crystals at the frost line. Given slow freezing of water-saturated, frost-susceptible materials, lenses or layers of segregation ice form parallel to the surface reaching several meters in thickness and resulting in localized heaving of the ground surface. Over time, the frost heave process leads to *cryoturbation* and sorting in the *active layer* and *patterned ground* at the surface.

frost mound - A general term for a knoll, hummock, or conical mound in a *permafrost* region, containing a core of ice, and representing a generally seasonal and localized upwarp of the land surface, caused by *frost heaving* and/or hydrostatic pressure of groundwater.

frost susceptible - Applied to a material of particular grain-size composition that is subject to *frost heaving* (i.e., silt and clay). Conversely, nonfrost-susceptible materials include those consisting of mostly sand and/or gravel.

frozen ground - Ground that has a temperature below freezing and generally contains a variable amount of water in the form of ice. Seasonally frozen ground remains frozen only through winter; perennially frozen ground is referred to as *permafrost*.

Holocene - An epoch of the *Quaternary* period, from the end of the Pleistocene from approximately 10,000 years to the present time.

ice wedges - Wedge-shaped, foliated ground ice produced in *permafrost*, occurring as a vertical or inclined sheet, dike, or vein tapering downward, and measuring from a few millimeters to as much as 6 m wide and from 1 m to as much as 30 m deep. It originates by the growth of hoar frost or by the freezing of water in a narrow crack or fissure produced by thermal contraction of the permafrost in extreme cold. Where ice wedges are connected in polygonal networks they may form *patterned ground*.

illuviation - The accumulation, in a lower soil horizon, of soluble or suspended material that was transported from an upper horizon by the process of *eluviation*.

involution - A highly irregular, aimlessly contorted sedimentary structure consisting of local folds and interpenetrations of fine-grained material in clayey strata, and developed by the formation, growth, and melting of ground ice (i.e., *cryoturbation*).

mima mound - A type of *patterned ground*. The term is used in the Northwestern U.S. for one of numerous low, circular, or oval domes composed of loose, unstratified, gravelly silt and soil material. They are present both on glacial outwash (e.g., Puget Lowland) as well as on thin soils overlying basalt (e.g., Channeled Scabland). The basal diameter varies from 3 m to more than 30 m, and the height varies from 30 cm to about 2 m. The formation of mima mounds is probably multigenetic depending on location, climate, substrate, etc. Possible mechanisms for formation include 1) biological (pocket gopher) activity, 2) runoff or wind erosion combined with vegetation anchoring, or 3) runoff erosion combined with desiccation or *permafrost* cracking (Washburn 1988).

paleosol - A buried soil horizon of the geologic past.

palsa - An elliptical dome-like *frost mound* containing ice lenses of peat, commonly 3 to 6 m high and 2 to 25 m long, occurring in subarctic bogs of the *tundra* and often surrounded by shallow open water.

patterned ground - A group term for certain well-defined, more or less symmetrical forms such as circles, polygons, nets, steps, and stripes that are characteristic of, but not necessarily confined to, surficial material subject to intensive frost action. It is classified according to type of pattern and presence or absence of sorting. Patterned ground occurs principally in polar, subpolar, and arctic regions, but also includes features in tropical and subtropical areas.

pedogenesis - The mode of origin of the soil with special reference to the processes of soil-forming factors responsible for the development of the solum from parent material.

periglacial - (a) Said of the processes, conditions, area, climates, and topographic features at the immediate margins of former and existing glaciers and ice sheets, and influenced by the cold temperature of the ice. (b) By extension, said of an environment in which frost action is an important factor, or of phenomena induced by a periglacial climate beyond the periphery of the ice.

permafrost - Perennially *frozen ground*. Any soil, subsoil, or other surficial deposit, or even bedrock, occurring in arctic, subarctic, and alpine regions at a variable depth beneath the Earth's surface in which a temperature below freezing has existed continuously for a long time (from two years to tens of thousands of years). Permafrost forms when the depth of winter freezing exceeds the depth of summer thaw. Permafrost is overlain by an *active layer*, which undergoes seasonally freezing and thawing. The definition of permafrost is based exclusively on temperature, and disregards the texture, degree of *compaction*, water content, and lithologic character of the material. The thickness of permafrost ranges from over 1000 m in the north to 30 cm in the south; it underlies about one-fifth of the world's land area. The distribution of permafrost is controlled by climatic, geologic, hydrologic, topographic, and botanic factors.

pingos - A large *frost mound*, esp. a relatively large, conical mound of soil-covered ice (commonly 30 to 50 m high and up to 400 m in diameter), raised in part by the hydrostatic pressure of water within or below the *permafrost* in Arctic regions (esp. Canada), and of more than one year's duration; an intra-permafrost ice-covered hill or mound. Its crest is sometimes ruptured or collapsed due to melting of the ice, thus forming a star-shaped crater. The mound itself often resembles a small volcano.

Pleistocene - An epoch of the *Quaternary* Period, extending from approximately 1.8 million years B.P. to 10,000 years B.P.

Quaternary - A geologic period between 1.8 million years B.P. and the present, which includes the *Pleistocene* and *Holocene* Epochs.

segregation ice - Ice films, seams, lenses, pods, or layers, generally 1-150 mm thick, that grow in the ground by drawing in water as the ground freezes. Also referred to as Taber ice.

thermal contraction crack - A nearly vertical fracture developed by thermal contraction in rock or *frozen ground* with appreciable ice content. Thermal contraction cracks commonly intersect to form *patterned ground* in plan view. Also referred to as frost cracks.

thermokarst - Karst-like subsidence features produced in a *permafrost* region by local melting of ground ice and the subsequent settling of the ground.

tundra - A treeless, level, or gently undulating plain characteristic of arctic and subarctic regions. It usually has a marshy surface, which supports a growth of mosses, lichens, and numerous low shrubs and is underlain by a dark, mucky soil and *permafrost*.

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