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Barrier Analogs: Long-Term Performance Issues, Preliminary Studies, and Recommendations

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Summary

The U.S. Department of Energy's Hanford Protective Barrier Development Program is funding studies of natural analogs of the long-term performance of waste site covers. Natural-analog studies examine past environments as evidence for projecting the future performance of engineered structures. The information generated by analog studies is needed to 1) evaluate the designs and results of short-term experiments and demonstrations, 2) formulate performance-modeling problems that bound expected changes in waste site environments, and 3) understand emergent system attributes that cannot be evaluated with short-term experiments or computer models. Waste site covers will be part of dynamic environmental systems with attributes that transcend the traits of engineered components.

Long-term performance issues that might be addressed with analog studies include climate change, soil development, vegetation change, mound stability, and human intrusion. Climate change will influence all components of a waste cover system. Analogs of localized responses to future global climate change exist as evidence remaining from similar past climates. Soil development, the chemical reactions and physical rearrangements that naturally occur in all soils, can alter the structure and hydrologic properties of materials used to construct waste covers. Future influences of soil development can be inferred from measurements of key soil properties in old soil profiles that are (or were) similar to waste covers. Many waste cover designs are dependent on water extraction by plants. The effects of vegetation change can be inferred from plant measurements at sites having soils similar to waste covers, but differing with respect to climate and disturbance histories. Studies of ancient manmade mounds may provide evidence of the future stability of waste covers and of mound characteristics that may discourage human intrusion.

This report discusses results of the previously unreported preliminary studies conducted in 1983 and 1984. These results indicate that analogs could play an important role in predicting the long-term behavior of engineered waste covers. Layered exposures of glacial-flood-deposited gravels mantled with silt or sand that resemble contemporary barrier designs were examined. Bergmounds, another anomaly left by cataclysmic glacial floods, were also examined as analogs of surface gravel. The following design considerations emerged from a moderate characterization of these deposits:

- A capillary moisture barrier design consisting of a fine-textured topsoil overlying a mixed layer of gravel and coarse sand (pitrun gravel) may be more stable than designs featuring graded, well-sorted soil, sand, and gravel layers.

- Soil development processes that can alter soil hydraulic properties, such as particle aggregation and illuviation of soluble salts and colloids, will likely take place on waste covers.

- The depth and dispersion of carbonate accumulation may provide an indication of past soil water movement in layered soils.

- Disturbances causing deep-rooted perennial vegetation to be replaced by shallow-rooted, short-lived species could reduce plant water extraction and trigger drainage.

- Spatial patterns in surface water infiltration, water retention, and evapotranspiration may evolve on waste covers in response to soil formation processes and clumped plant distribution patterns.

We recommend the continuation of analog studies of the effects of soil development and vegetation change on soil water. Soil development studies should address the effects of carbonate accumulation, soil illuviation, pedoturbation (soil mixing processes), and soil structure (particle aggregation). The emergence of spatial patterns in soil-plant-water relations on engineered covers should also be considered. Because vegetation change can be difficult to predict, analog studies of vegetation change should be undertaken only after a conceptual model of plant community dynamics on engineered covers has been developed. In general, new analog studies should be initiated only after research has clearly defined: 1) the application of the analog to performance assessment; and 2) the characteristics of the analog relative to initial and eventual states of the engineered cover.

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1.0 Introduction

Pacific Northwest Laboratory (PNL)[a] and Westinghouse Hanford Company (WHC) are working jointly on the Hanford Protective Barrier Development Program, funded by the U.S. Department of Energy (DOE) to engineer earthen "protective barriers" that will inhibit plants, animals, and water from contacting radioactive waste lying underground; the barriers would impede the migration of contaminants to the groundwater and to the land surface. The work is justified by a Record of Decision issued by the DOE on the *Final Environmental Impact Statement Disposal of Hanford Defense High-Level, Transuranic, and Tank Wastes* (DOE 1987) for application to the Hanford Site in south-central Washington. The Record of Decision defers decisions on the disposal of many waste classes until additional research on near-surface disposal methods has been completed and reviewed by the public. This policy reflects the uncertainty associated with evaluating the long-term behavior of engineered structures. Defensible predictions of the performance of engineered barriers for up to 1,000 years may be required (40 CFR 191).

The Hanford Protective Barrier Development Program consists of three distinct yet interactive research approaches for assessing the long-term performance of possible barriers (Figure 1.1). One approach is to conduct field and laboratory experiments on a limited number of designs, under controlled environmental conditions. The second is to evaluate, using computer models, the long-term behavior of many barrier designs under many environmental scenarios. The third approach, adopted by this report, involves the identification and evaluation of analogs of long-term barrier behavior. An

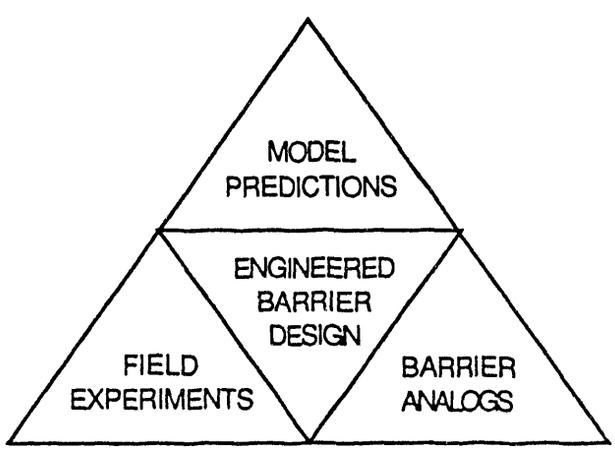

Figure 1.1. The Hanford Barrier Development Triad, Contributing to an Engineered Barrier Design

(a) Pacific Northwest Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

analog provides evidence of changes in past environments that can be applied to evaluate the future performance of engineered barriers. The purposes of this report are to review the long-term performance issues and the rationale for analog studies, to summarize previously unpublished barrier analog work, and to provide recommendations for future work.

2.0 Reasons For Analog Studies

Barrier analog studies address the limitations and uncertainties inherent in evaluating the long-term behavior of engineered structures exclusively from manipulative experiments and computer models. In the Hanford Protective Barrier Development Program, barrier analog studies have three purposes:

- to help guide the selection and to judge the accuracy of treatments imposed in field and laboratory experiments that are intended to represent long-term changes in the barrier environment,

- to support the conception of computer model problems that deal with long-term changes in the climate, vegetation, and barrier construction materials, and

- to examine anthropogenic, geomorphic, pedologic, and ecological indicators of emergent long-term changes in the barrier system that may not be understood from short-term experiments or computer model simulations.

Several field and laboratory experiments have measured how barriers will respond to imposed changes in processes that control water movement, erosion, and biointrusion. However, how representative the treatments in these experiments are of future barrier states is uncertain. Thus, barrier analog studies are needed to tailor new experiments to the long-term conditions to be encountered at the Hanford Site and to evaluate how closely experiments already underway simulate such conditions.

It would be impractical to attempt to test with manipulative experiments the many combinations of barrier designs and environmental scenarios of interest. If properly designed, however, manipulative experiments can generate data needed to validate computer models of barrier behavior. With computer models, it may be possible to simulate many combinations of barrier designs and environmental scenarios. The usefulness of models is limited, however, by the quantity and quality of input data and validation data, and in particular by a lack of knowledge concerning how climate, vegetation, and the construction materials may change over time. Field and laboratory experiments inadequately depict long-term changes in some key parameters. Thus, analog studies are needed to better understand future variation in key performance parameters and to use this knowledge to design modeling problems that bound future change.

The final role of analog studies is to uncover emergent clues as to the long-term behavior of barriers that already exist and are recorded in the Hanford Site geomorphology, pedology, and ecology. The engineered cover will be part of a dynamic environment with attributes that transcend the traits of individual components. System attributes that may emerge over the long-term can only be poorly understood from short-term experiments and computer models. For example, computer models

of plant water extraction rely on parameters for individual species such as root and stomatal conductance. In contrast, species interactions cause plant communities to exhibit patterns in water extraction, and in other processes, that are beyond the traits of component species (Barbour et al. 1987).

3.0 Long-Term Performance Issues and Analogs

Analog studies may be appropriate to help resolve five issues of long-term barrier performance: 1) climate change, 2) vegetation change, 3) soil development, 4) cover stability, 5) human intrusion, and 6) asphalt durability.

3.1 Climate Change

Field experiments and models of water movement, erosion, and biointrusion in engineered covers all include meteorological parameters that are functions of climate. These parameters are known for the present climate, but not for any future changes in climate. Future climate variation at the Hanford Site may exceed variation in the meteorological record. The global climate system may have been thrown off balance by a rise in atmospheric concentrations of carbon dioxide, methane, and other greenhouse gases. According to the greenhouse theory, the climate system will be restored to equilibrium by a warming of the lower atmosphere. Surface warming of the magnitude predicted by some models would be unprecedented in the present interglacial period (Ramanathan 1988). Furthermore, models that correlate past climatic variability with periodicity in the earth's orbital parameters suggest that the earth's climate may be moving into another ice age during the next 10,000 years (Imbrie 1985).

The influence of global climate change on the local Hanford climate is poorly understood. In an attempt to predict the magnitude and impact of global warming, government agencies such as the DOE, the U.S. Environmental Protection Agency, and the National Science Foundation are funding extensive efforts to model global circulation. However, these general circulation models (GCMs) lack the precision needed to predict the impacts of warming at regional and local scales. The GCMs do agree, however, that the mean annual temperature of western regions will rise between 1.5 and 5°C.

Paleoecological and paleoclimatic records of analogous periods of climatic change can provide more precise information on climate change impacts than that provided by GCMs. During the mid-Holocene (an interval from approximately 9000 to 5000 years B.P.), global temperatures were between to 1 and 2°C warmer than at present (Kutzbach 1987). Evidence of the regional and sometimes local ecological, hydrological, and climatic conditions that characterized portions of that period is available from pollens, fossil tree lines, fluvial sediments, lake basin deposits, eolian landforms, and archaeological sites. These sources can provide proxy evidence for a wide variety of environmental conditions expected to result from higher global temperatures, including changes in such variables as dominant patterns of atmospheric circulation (Nielson 1986), seasonal variation in temperature and precipitation (Fritts 1976), runoff characteristics of trunk streams (Kochel and Baker 1982), and the distribution and content of plant and animal communities (Ruddiman and Wright 1987).

Climate analogs could be used in two ways: to select input data for model simulations and to confirm climate treatments imposed in field experiments. The Hanford Protective Barrier Development Program has initiated a project to identify past extreme-climate states that could reasonably be expected in the future and then to either statistically generate weather sequences for those states or measure performance parameters at analogs of those states. Because of the all-pervading influence of climate change on long-term performance, a separate task that goes beyond the scope of this report has been developed (Petersen et al. 1993).

3.2 Soil Development

Long-term predictions of water movement in protective barriers require an understanding of potential changes in soil hydraulic properties resulting from soil-development processes. Soil development involves both complicated reactions and relatively simple rearrangements of soil materials. Soil development processes act either to differentiate a uniform soil mass into distinctive layers (horizonation) or conversely to inhibit soil horizonation by mixing layers formed previously (haploidization). Processes that could alter water movement and storage in engineered covers include both internal processes, such as the illuviation of fine-textured, soluble, and colloidal material from higher to lower horizons in a profile, and external processes, such as the erosion, deposition or redistribution of surface sediments.

The long-term performance of a layered cover design will depend in part on maintaining discontinuity at interfaces of fine-textured and coarse-textured layers. Over time, the possibility exists for the fine-textured soil and soluble salts to migrate downward, filling the matrices of underlying soil and gravel layers. Theoretically, fine-grained and colloidal material could move downward either during the construction of the cover or via eluviation/illuviation processes during soil development. The movement of fines from topsoil layers and their accumulation in sand and gravel layers could compromise the capillary break and reduce the water storage capacity of the topsoil. These processes also cause the development of soil structure, which can influence rates and patterns of water movement.

Another soil-forming process that could affect soil hydraulic properties, and cap stability, is pedoturbation. Pedoturbation is a process of mixing that takes place, to some degree, in all soils. Some types of pedoturbation act to mix surface layers (Boul et al. 1980). Examples include mixing by burrowing animals such as ants and rodents, by plant root growth, and by seismic activity. Other processes could cause admixed gravel layers to move toward the surface or cause a mixing of textural interfaces within a barrier. Examples of these processes include the formation of lag layers by winnowing, frost heaving (cryoturbation), movement of gas in soils during and after rain (Evenari et al. 1974), and shrink-swell action of expansive clays. In contrast to winnowing, loess (wind-deposited silts) slowly deposited on a graveled surface can be transported below the gravel in cracks formed in underlying vesicular soil, thus elevating the gravel above the former land surface (McFadden et al. 1987).

Naturally occurring, layered sediment profiles of alluvial and eolian origin occur on the Hanford Site. These deposits often resemble proposed barrier designs closely enough that their careful study could be used to refute or support field-plot studies and performance assessment models. The influences of soil-development processes could be inferred from measurements of key performance parameters at these analog sites. The analog sites could constitute soil development chronosequences, which are groups of several sites having similar soil parent material, stratigraphy, and climate but differing in age. As such, the studies would encompass a range of conditions including recently disturbed soils and soils that have developed for thousands of years.

3.3 Vegetation Change

Plant transpiration (extraction of water from the soil by plants) is an important component of models of water movement in protective barriers (Nyhan and Barnes 1988, Fayer 1987). Model simulations have shown that the performance of some designs in preventing drainage depends largely on evapotranspiration (ET), a combination of evaporation from the soil surface and plant transpiration (Fayer et al. 1985). Water not lost by ET and runoff is stored in the soil or is lost as subsurface drainage below the root zone. For long-term barrier performance predictions, it will be important to know how changes in the plant community inhabiting a barrier may influence evapotranspiration.

The vegetation on engineered covers will likely change significantly. The plant community may change in response to climate or to disturbances such as fire or inadvertent cultivation. Climate change and disturbances can alter the numbers, types, and diversity of species, and may be accompanied by changes in water extraction rates. Even under the present climate and without disturbances, species abundance, biomass production, and transpiration rates vary seasonally and from year to year in response to precipitation and temperature.

In the arid west of North America, succession may follow no inherent order or schedule in the context of species associations replacing each other over time. The arrival of alien species further confounds predictability. For example, the dominance gained by alien species such as *Bromus tectorum* (cheatgrass) and *Salsola kali* (Russian thistle) in southeastern Washington over the past 150 years is unprecedented. These species dominate not only cultivated and overgrazed lands at and adjacent to the Hanford Site, but they are supplanting native species on undisturbed sites as well (Mack 1986). New aliens continue to appear, and in some cases their potential ranges are quite large.

Alien species such as *B. tectorum* tend to foster their own persistence. Fire was important in presettlement ecology, but these relatively infrequent, low-temperature fires probably altered species composition little (Daubenmire 1975). In contrast, increased incidence and intensity of fire resulting from the several-fold greater litter production of *B. tectorum* (Rickard et al. 1977) may be having the long-term effect of eradicating native shrubs such as *Artemisia tridentata* (sagebrush). Who could have predicted this in 1850? Knowing that over the past 150 years dramatic unprecedented changes in the

vegetation of Hanford unrelated to climate have taken place and that these changes are continuing today, with what degree of certainty can we expect to predict how the vegetation will change over the next 10,000 years?

The only unequivocal way to document the influence of plant succession on evapotranspiration would be to take repeated measurements. However, because we don't have decades to track plant succession, we need an alternative. Plant community chronosequences offer a reasonable, albeit less certain, alternative. For our purposes, a chronosequence can be defined as a suite of sites having soils similar to an engineered cover but differing with respect to the history of disturbance and climate. Future climate states and types of disturbances would be conjectured, the plant communities that might be present during these states would be inferred, present-day analogs of these states would be located, and evapotranspiration (and other key parameters) would be measured at those sites.

No standard methods for measuring evapotranspiration in the field exist for arid landscapes. Meteorological methods have been used to estimate ET over large relatively uniform landscapes such as field crops, but the standard calculations (Penman, Thornthwaite, or Priestly-Taylor) give biased estimates for the non-wetted condition. When these estimators are used at arid sites, actual water loss from soils is overestimated, except during and immediately following rainfall events (Gee et al. 1989). Leaf and whole-plant methods are more precise, but data extrapolation to a landscape scale is difficult. Lysimetry is precise but expensive. Micrometeorological techniques and remote sensing may provide community-and landscape-scale data, but they lack precision. A combination of methods may provide both precision and scale.

3.4 Cover Stability

The conceptual Hanford barrier is an above-grade mound. The effectiveness of the design in isolating the waste medium will depend in part on the long-term stability of the mounded structure, which could be inferred from the survival of similar ancient manmade earthen mounds that exist today in a variety of settings. Manmade mounds as old as 2500 years are found in the eastern and southwestern United States. Similar, often much older, features exist throughout the world in environmental conditions resembling those that now, or in the future, may exist at Hanford. Age and design characteristics of these mounds vary. Manmade deposits often resemble proposed waste cover structures closely enough that careful study of their design, soil physical properties, and erosion could be useful for assessing long-term performance.

A mound study was initiated in support of cover design research for uranium mill tailings impoundments (Lindsey et al. 1983; Walters 1987). Although an in-depth analysis of information collected by that study remains to be undertaken, results of the preliminary work show that such an analysis is warranted. Mound structures exist in China, Korea, Europe, North Africa, the eastern United States, and Central and South America. As the most visible residues of ancient human habitation, mounds attract intensive research attention, and many have been excavated. Information would therefore be

available from the literature or could be obtained through collaboration with excavators. The artifacts contained in many mounds provide an accurate means for chronological control (Sharer and Ashmore 1978). The value of these analogs may be limited by the imprecision of dating methods and the unlikelihood that rapidly built, layered series of deposits will be identical to proposed cover designs in their absolute thickness, textural characteristics, and construction history. Nevertheless, information obtained from mound studies could provide insights as to which kinds of designs would be most durable.

3.5 Human Intrusion

Four intruder scenarios can be addressed by analog studies: exploration for resources, discovery of resources (which can include those in the waste deposit), recovery of materials in the waste medium, and recycling of waste materials. Combined, these scenarios address the possibility that people may rediscover usable, locally scarce raw materials beneath the barriers and then mine the waste for those materials. Facilities should be designed to minimize the possibility of this kind of exposure.

As currently designed, barriers would be readily distinguishable as manmade structures. Once future residents discover that usable materials lie beneath their surfaces, and if the knowledge that the contents are dangerous is lost, these obviously manmade covers are likely to be intruded into regularly. This would not only result in exposure to the intruders, processors, and users of the materials, but would also eliminate the covers as barriers to water infiltration, raising the risk of exposure from contaminated groundwater.

The Hanford Protective Barrier Development Program has funded a study of archaeological analogs that was oriented toward developing a system for marking waste sites (Kaplan and Adams 1986). The research focused on markers and the characteristics that promoted long survival of marker objects and marker texts. It did not, however, consider the relationship between the recognizability of a monument as manmade and the likelihood of intrusion. To provide such information, studies of archaeological mounds could be expanded to include consideration of rates of intrusion and of the time elapsed between construction and first intrusion. Other types of archaeological deposits, such as village sites, could also be investigated to determine the relationship between intrusion rates and the presence of obviously manmade structures.

3.6 Studies of Ancient Asphalt

The protective barrier designs that are currently being considered for the Hanford Site include an asphalt membrane placed beneath the layered capillary barrier of loam, sand, and gravel. This membrane will serve as a secondary means for preventing water from infiltrating into an underlying waste form if the capillary barrier fails. Because asphalt exposed at the ground surface is subject to attack by microorganisms and is degraded by exposure to sun and weather, its suitability as a moisture barrier

has come into question. The study of ancient asphalts, used as floors in ancient mounds and as moisture barriers in a variety of contexts, could provide data needed for answering the question of asphalt's suitability in barrier designs.

Tar is found in natural seeps in many parts of the world and, mixed with sand and other aggregates, has been used as a mastic or sealant for thousands of years (Meyer and Schenk 1985). Within the United States, asphalt from tar seeps was used by Native American peoples of California and of the southeast to seal baskets and canoes, attach tools to handles, and serve as a general glue for many purposes (Hudson et al. 1978; Gutman 1979). Archaeological assemblages from these areas often contain asphalt artifacts. This is especially true of California, where asphaltum, as it is locally called, is a common component of graves dating back more than 5000 years (Gutman 1979; Priestaf 1979).

Asphalt artifacts from grave contexts are analogous to asphalt membranes proposed for use in the protective barrier environment because their burial was intentional rather than being the result of natural soil accretion. Asphalt placed in such contexts is subject to a chemical, physical, and microbial environment similar to that of protective barriers. Analysis of the chemical and physical properties of an age-series of asphalts from the same source could, therefore, provide important data on the durability and probable performance of this material on the time scale of millennia.

4.0 Preliminary Hanford Barrier Analog Studies

In 1983, Rockwell Hanford Operations initiated a study to assess the feasibility of locating and examining geologic exposures and ecological settings at Hanford as analogs of the long-term performance of protective barriers. The results have not been reported previously. The study progressed through three phases: 1) reconnaissance, 2) a study of soil water storage and root growth in layered and massive barrier design analogs, and 3) a study of the effects of surface gravel on soil water and plant cover.

4.1 Analog Site Reconnaissance

The initial reconnaissance focused on locating gravel pits, roadcuts, old manmade earthen structures, and other sediment exposures with features similar to the conceptual barrier designs of the time. The designs included massive-rock, massive-soil, and layered-soil-and-gravel cover designs (Phillips et al. 1985; DOE 1987). This initial search was limited primarily to the Hanford formation and to local alluvium, colluvium, and eolian veneers within the Pasco Basin. The age, depositional environment, and location of the Hanford formation made it a desirable and convenient candidate for finding sediment stratigraphies similar to massive-soil and, especially, layered-soil-and-gravel cover designs.

4.1.1 Hanford Formation Geology and Hydrology

The Hanford formation is one of six major stratigraphic sequences underlying the Pasco Basin (Tallman et al. 1979). The sequences, in ascending order, are 1) "basement rocks" of undetermined origin, 2) the Columbia River Basalt Group and interstratified sediments of the Ellensburg Formation, 3) the Ringold Formation, 4) early Palouse soil, 5) the Hanford formation, and 6) local veneers of alluvium, colluvium, and eolian sediments.

The Hanford formation consists of a sequence of cataclysmic flood sediments deposited when ice dams, formed in western Montana and eastern Idaho during Quaternary periods of glacial maxima, were breached, causing massive volumes of water to spill abruptly across eastern and central Washington (Baker 1973). The floods scoured the land surface, locally eroding the Ringold Formation, the basalts, and the sedimentary interbeds, and leaving a network of buried channels crossing the Pasco Basin (Tallman et al. 1979). Thick sequences of sediments were deposited by several episodes of Pleistocene flooding, the last major flood sequence being dated at about 13,000 years before present (Mullineaux 1986).

The Hanford formation has been divided locally into two facies: Pasco gravels and Touchet beds. The Pasco gravels, deposited extensively throughout the channel floors and depositional basins, consist of relatively poorly sorted coarse sands and gravels that commonly display foreset bedding. This morphology indicates a high-energy depositional environment. In contrast, the Touchet beds, found along

the margins of the Pasco Basin and in adjoining valleys, consist of rhythmically bedded sequences of graded silt, sand, and gravel units. This morphology indicates a relatively low-energy depositional environment where slackwater conditions occurred during the impoundment of flood waters behind Wallula Gap. Both facies were examined during the reconnaissance for barrier analogs.

The unsaturated zone in the Pasco Basin varies in thickness from 0 m at the Columbia River to over 135 m on the 200 Area Plateau and generally occurs in surficial eolian sediments, the Hanford formation, and the early Palouse soil. An unconfined aquifer lies within partially consolidated sands and gravels of the Ringold Formation and the unconsolidated sands and gravels of the Hanford formation. Recharge is thought to occur primarily from higher elevations bordering the Pasco Basin, from influent reaches of the Columbia and Yakima rivers, and from ephemeral streams along the flanks of surrounding hills. Recharge through the Hanford formation sediments and overlying deposits within the central part of the Basin may range locally from near zero to a large fraction of the annual precipitation (16 cm/yr), depending on the soil texture and the abundance and type of vegetation. Morphological indicators of past water movement through layered surficial sediments were sought during the reconnaissance for barrier analogs.

4.1.2 Methods and Observations

Forty-four sites within the Pasco Basin were examined as stratigraphic analogs of massive-soil, massive-rock, and layered barrier designs and for clues as to the long-term performance of these designs (Figure 4.1 and Table 4.1). Observations at each site were recorded in field notes and on a formatted checklist. The checklist consisted of five parts: 1) site description, 2) structural analogs represented, 3) hydrogeological observations, 4) ecological observations, and 5) barrier performance indicators.

Location, land use history, topography, and climate were included in the site description. In addition to the type of barrier represented by the exposure, if any, the site was subjectively scored (Table 4.1) for possible additional study, based on the following geological and ecological observations:

Geological Features

1. Physical dimensions and depositional environment
2. Stratigraphy, matrix, grain sizes, bedding forms, sorting, and roundness
3. Lithology
4. Secondary mineralization
5. Proximity to the water table
6. Estimation of age based on occurrence of datable horizons
7. Occurrence and description of geofilters
8. Occurrence and description of surface gravel
9. Sediment weathering
10. Moisture distribution

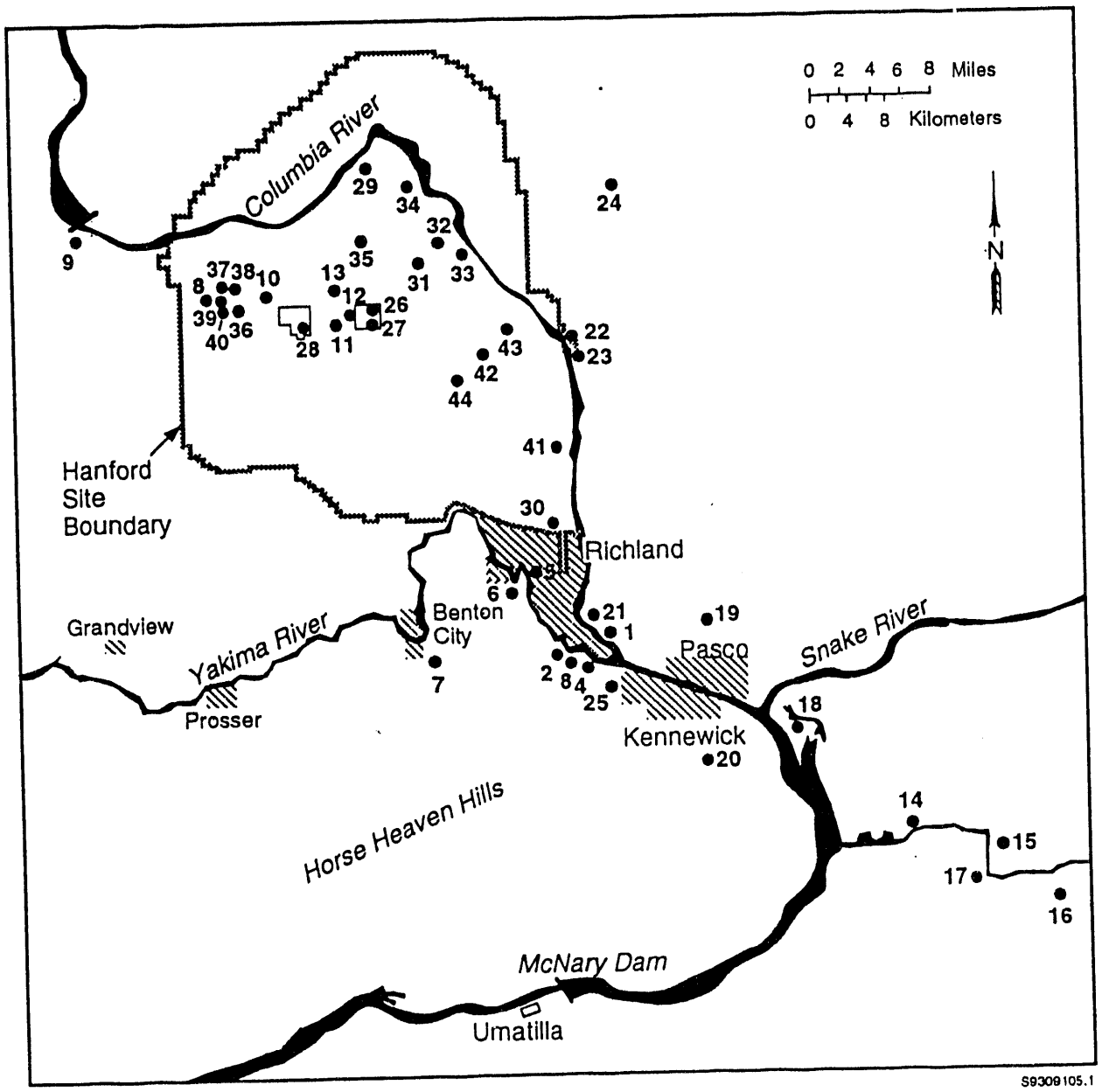

Figure 4.1. Barrier Analog Reconnaissance Sites Visited in 1983 (See Table 4.1 for site names)

Table 4.1. Names and Suitability Scores for Sites Visited During the Reconnaissance for Barrier Analogs

Number[a]	Site Name	Score[b]
1	New Columbia River Bridge Pit	3
2	ACME Pit Alluvium	2
3	ACME Pit East	2
4	ACME Water Station	3
5	Old Richland Landfill	2
6	Flat Top Mountain	2
7	Weber Canyon	2
8	Cold Creek Bergmounds	1
9	Umtanum Ridge Talus	3
10	DC-4 and 5 Gravel Pits	1
11	200 Area Batch Plant	3
12	Pit 29	1
13	Ethel Substation Pit	1
14	Reese Junction	3
15	Divide Anticline	3
16	Gardenia Cliffs	2
17	Cummins Bridge	2
18	McNary Pit	2
19	Oregon Street Gravel Pit	2
20	45th Street Pit, Kennewick	3
21	Upper River Road Gravel Pit	2
22	Spring Gravel Pit	3
23	Ringold Gravel Pit	1
24	Shelfield Road Gravel Pit	3
25	Amon Wasteway Railroad Cuts	2
26	200 East Area Ash Pit	2
27	PUREX Sand Pit	1
28	200 West Area Ash Pit	1
29	Pit 21	2
30	Pit 6	2
31	Pit 13	2
32	Pit 3 (Gable Mountain Sand Pit)	2

Table 4.1. (contd)

Number[a]	Site Name	Score[b]
33	Pits 16 and 17	2
34	Pits 15, 19, and 20	1
35	NSTF Sand Pit	1
36	Bergmound 1	1
37	Bergmound 2	2
38	Bergmound 3	2
39	Bergmound 4	2
40	Bergmound 5	2
41	Premix Pit	2
42	May Junction Pit	1
43	Hanford Town Site School Grounds	3
44	Route 4 Backslope	1

(a) Numbers correspond to site locations shown on Figure 4.1.
(b) Relative scores of suitability for continued study; the highest rating is 1 and lowest is 3.

Ecological Features

1. Plant species composition and relative abundance
2. Magnitude and probable source of plant community disturbances
3. Estimation of the pre-disturbance, natural vegetation
4. Evidence of environmental gradients or mosaics
5. Soil morphology (horizonation, texture, structure)
6. Evidence of burrowing animal activity
7. Distribution of exposed plant roots, root casts, and animal burrows relative to geologic and edaphic features

Sites given a score of 1 were considered good candidates for additional study, those scoring a 2 were considered fair candidates, and sites receiving a 3 were excluded from consideration. Finally, the investigators noted specific indicators of barrier performance, such as moisture distribution, plant root distribution, animal burrows, and the presence of geofilters. All of this information, plus several photographs of each exposure, has been compiled in a barrier analog site catalog as a reference for future studies.

4.1.3 Reconnaissance Summary

Findings of the reconnaissance are summarized below:

1. Many sediment exposures resembled the layered barrier design. These profiles consisted of fluvial or eolian silts and fine-grained sands overlying fluvial gravels and sands. However, layered sediment profiles with features closely resembling conceptual layered-barrier designs, with continuous geofilters and "open-work" (well-sorted) fluvial gravels, were uncommon. Pockets of open-work fluvial gravels were observed, but not as continuous horizons. The lack of continuous layers of open-work gravel indicates either that the depositional environment for such a stratigraphy was uncommon or that it was unstable. If graded sediments are unstable in nature, and if over time fine-grain material gradually fills in the interstitial voids in underlying gravel layers, then designs that incorporate fine soils over well-sorted gravels and larger materials should be re-evaluated.

2. The prevalent stratigraphy observed during the survey consisted of fluvial and eolian sands and ailts overlying mixed (not graded) horizons of fluvial cobble, gravel, and coarse-grained sand. Similar two-layer configurations may be preferable to layered designs with graded geofilters if they can be demonstrated to provide a suitable capillary moisture barrier.

3. As is common in desert soils, horizons of calcium carbonate accumulation (caliche) were observed in many of the sediment exposures. The formation of $CaCO_3$ horizons in desert soils is linked to patterns of soil water movement (Arkley 1963). The distribution of carbonates at these sites appeared to be related to the depth of the fine-textured topsoil layer, and to the diffuseness of the boundary between the fines and the underlying fluvial gravels. Where the topsoil was thick and the boundary abrupt, distinct and narrow calcic horizons often occurred at the layer interface, suggesting that deeper carbonate illuviation has been limited by low moisture content. Where the topsoil was coarse or thin, carbonate deposits were observed on the underside of fluvial cobbles and gravels, possibly indicating past water movement below the boundary. These observations have since led to studies of pedogenic carbonate as an indicator of long-term water movement in layered profiles, and of carbonate influences on soil hydraulic properties and water movement (Hunter et al. 1990).

4. The depth of exposed plant roots varied among sites. Where soils were relatively uniform and without underlying coarse-textured sediments, roots of rabbitbrush (*Chrysothamnus nauseosus*), sagebrush (*Artemisia tridentate*), bitterbrush (*Purshia tridentate*), and hopsage (*Grayia spinosa*) penetrated to depths greater than 250 cm. In contrast, in layered profiles, plant roots often spread laterally in fine soils above coarse-textured layer boundaries.

5. Bergmounds, formed by the melting of debris-laden icebergs following the last Missoula flood (Fecht and Tallman 1978), were considered potential analogs of gravel armoring on barriers. Gravel mulch or admix may be used in the barrier design to control erosion by wind and water. However, the incorporation of gravel into the barrier topsoil may also influence water infiltration, water retention, and the water extraction behavior of vegetation. Bergmounds near the Yakima Barricade displayed fairly uniform veneers of gravel-size basalt diamicton (glacial rock).

6. Four of the sites that scored high during the reconnaissance (Pit 29, PUREX Sand Pit, Bergmound 1, and Route 4 Backslope) were selected for detailed characterization following a subjective ranking of candidate sites. Physical similarity to a proposed barrier design, presence of barrier performance indicators, proximity to waste management operations, ease of sampling, and other logistical factors were considered in this subjective ranking.

4.2 Comparison of Layered and Massive-Soil Barrier Analogs

Layered and massive-soil barrier designs had been proposed for demonstration when the analog studies commenced in 1983 (Phillips et al. 1985). Research on landfill disposal alternatives for radioactive and hazardous waste in arid and semiarid lands has consistently favored the use of layered systems. The massive-soil design was included to satisfy criteria and standards proposed at that time for land disposal of radioactive waste (10 CFR 61). Deposits analogous to the layered and massive-soil designs were selected for further characterization from a ranking of the 44 sites visited in 1983. Pit 29 and PUREX Sand Pit, site numbers 12 and 27 in Figure 4.1, were examined as analogs of layered and massive-soil designs, respectively.

4.2.1 Objectives

The objectives of this study were to

1. quantify the physical properties of analog site soil profiles for comparison with engineered designs,
2. compare soil water storage in layered and massive-soil barrier analogs,
3. compare soil water storage in disturbed and undisturbed vegetation growing at the soil analog sites,
4. measure carbonate distribution as a possible indicator of past water movement patterns, and
5. measure the depths and distributions of plant roots relative to edaphic features.

4.2.2 Sampling Methods

Locations were chosen at each of the two sites (Pit 29 and the PUREX Sand Pit) for the three components of the preliminary characterization: 1) a disturbed surface immediately back from the pit face, 2) an adjacent undisturbed area for a second excavation (trench), and 3) a location for the installation of hydroprobe access ports. Pit faces were cut back to obtain water content samples not influenced by lateral drying. Neighboring trenches were excavated with a backhoe to depths of approximately 2.5 m alongside mature sagebrush and bitterbrush in the undisturbed locations.

Soil Descriptions

Descriptions of the pit and trench faces, including the dimensions, approximate grain sizes, color, lithology, and reaction to 10% HCl of each sediment bed, were recorded in geologist's logs. Each profile was also subdivided into genetic horizons and described using standard soil nomenclature (Soil Survey Staff 1975).

Gravimetric Water Content

Soil and sediment samples at depth increments roughly corresponding to genetic horizons were extracted, sealed in corrosion-resistant containers with tight-fitting lids and plastic tape, and then transported to the laboratory by day's end. Samples were then weighed (balance precision = ± 0.1 g), oven-dried for at least 20 h with the lid removed, and reweighed with the lid replaced to determine the soil water content (ASTM 1980).

Particle-size Analysis

Particle-size distributions were analyzed by sieving. A desegregated, oven-dried aliquot of 150 g was taken from composites of three samples for each depth and placed in the top of a nest of 20.3-cm U.S. Standard brass sieves having the coarsest mesh screen on the top, descending to the finest mesh screen on the bottom (Table 4.2). The nest was shaken on a Rotap® mechanical shaker for at least 15 min. Soil separates were then transferred from each sieve to a balance, using a brush to make a transfer, and weighed to $\pm$ 0.1 g. Aggregates were broken up in a soil grinder. Sieves were cleaned between aliquots with a stream of compressed air. If the sum of recorded weights exceeded 2% of the original sample weight, the analysis was repeated.

Carbonate Analysis

Carbonate was determined using a CO_2-displacement procedure (Appendix A). All soil fractions that passed through U.S. Standard sieve no.18 in the particle-size analysis were used for the analysis.

Sediment and Soil Classification

Two classification schemes were used: a quantitative classification based on particle-size distributions, and a taxonomic classification using standard soil science nomenclature (Soil Survey Staff 1975). The particle-size classes were determined by the weight percent of gravel and the sand:silt ratio using a scheme modified by Tallman et al. (1979) (Figure 4.2). The sand, silt/clay, and gravel portions of each sample were determined from the particle-size analysis shown in Table 4.2. Table 4.3 lists the classification symbols used to report the data.

Plant Cover, Root Depths, Stature, and Age

Percent cover of the plant canopy was estimated on the disturbed surface along pit faces and in undisturbed communities adjacent to the trench excavations at both sites. The soil surface adjacent to the face of Pit 29 had recently been denuded by heavy equipment. Canopy cover is considered a better index of the importance of a specie in a community than is density (number/ unit area) because it permits less biased comparisons of different growth forms (Mueller-Dombois and Ellenberg 1974). A

Table 4.2. Sieve Sizes, Corresponding Particle Sizes, and Particle-size Classes for Granulometric Analysis of Desegregated Sediment Samples[a]

U.S. Standard Sieve Number	Retained Particle Size (mm)	Particle-Size Nomenclature
		Gravel
5	>4.0	Fine pebbles (FP) and larger
10	2.0-4.0	Very fine pebbles (VFP)
		Sand
18	1.0-2.0	Very coarse sand
35	0.5-1.0	Coarse sand (CS)
60	0.26-0.5	Medium sand (MS)
120	0.125-0.25	Fine sand (FS)
230	0.063-0.125	Very fine sand (VFS)
		Silt and Clay
325	0.043-0.063	Very coarse silt
pan[b]	<0.043	Clay to coarse silt

(a) Modifiers often used to denote second-order fractions of gravel and sand classes are shown in parentheses.
(b) The pan was the sediment fraction that passed through U.S. Standard Sieve number 325.

modified Daubenmire (1959) cover class method was employed. We used the prescribed 0.1-m^2 quadrat to estimate *Bromus tectorum* (cheatgrass) cover, but used 1.0-m^2 quadrates for *Artemisia tridentate* (sagebrush) cover estimates. Both quadrates were placed at 1.0-m intervals along 50-m transects.

The trenches at both sites were carefully excavated to expose the roots of as many *Artemisia tridentate* (sagebrush) and *Purshia tridentate* (bitterbrush) as practical. The roots of two *Purshia* and four *Artemisia* were excavated in the trench adjacent to the PUREX Sand Pit (a massive-soil barrier analog) and seven *Artemisia* were uprooted in the trench adjacent to Pit 29 (a layered soil barrier analog). Plant height and canopy area were measured for each specimen, and stem cross-sections were cut for cross-dating with a master chronology of *Artemisia* growth rings at Hanford.

4.2.3 Comparison with Engineered Designs

Differences between the stratigraphy of engineered designs and the sites examined as natural analogs of these designs can be attributed either to the initial depositional morphology of the flood deposits or to pedogenic processes that have since altered their morphology. This genetic separation is

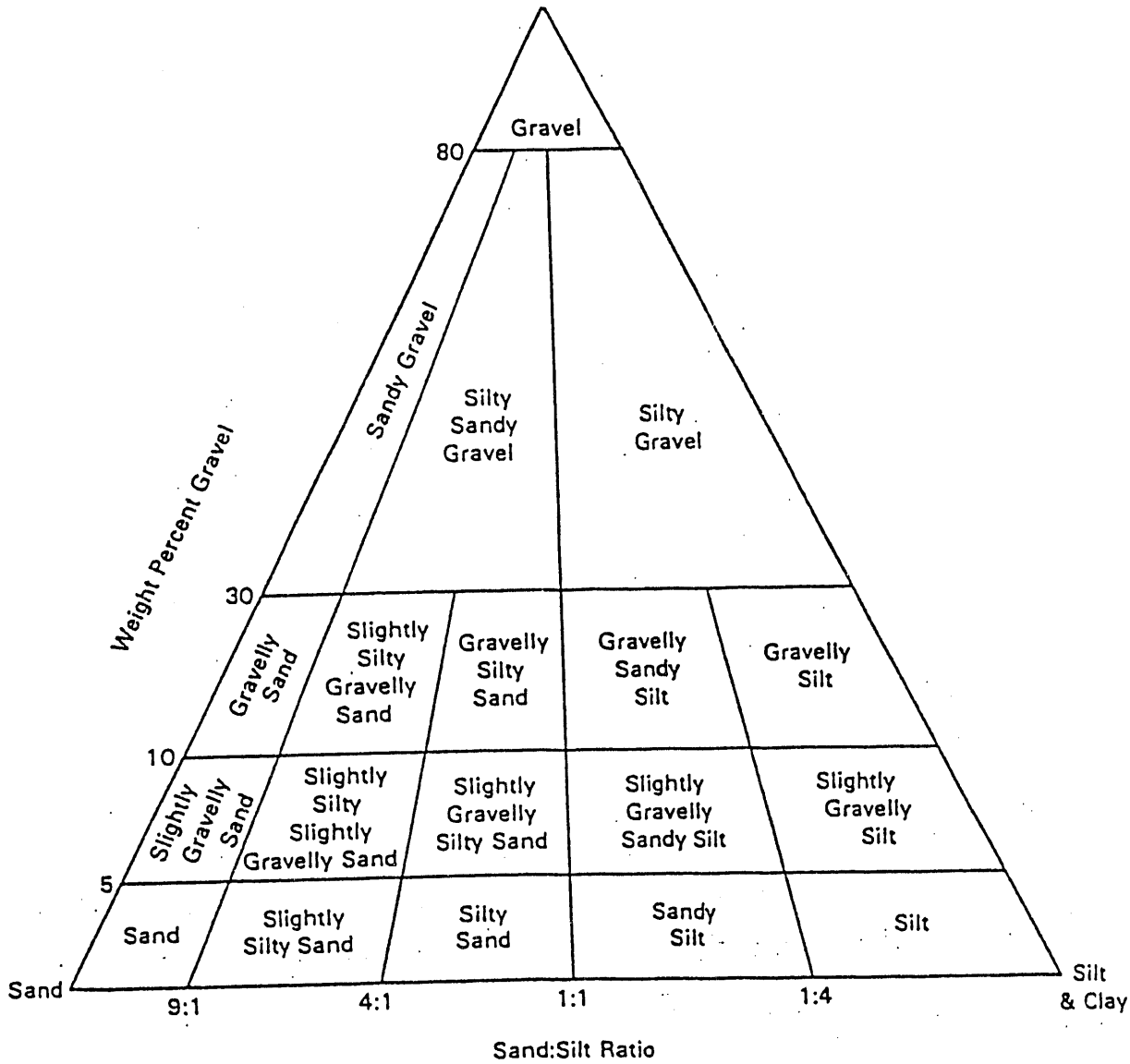

Figure 4.2. Sediment Classification Scheme (Tallman et al. 1979)

Table 4.3. Sediment Classification Symbols

Symbol[a]	Classification Nomenclature	Symbol[a]	Classification Nomenclature
G	Gravel	(MG)S	Slightly silty slightly gravelly sand
SG	Sandy gravel	(G)MS	Slightly gravelly silty sand
MSG	Silty sandy gravel	(G)SM	Slightly gravelly sandy silt
MG	Silty gravel	(G)M	Slightly gravelly silt
GS	Gravelly sand	S	Sand
(M)GS	Slightly silty gravelly sand	(M)S	Slightly silty sand
GMS	Gravelly silty sand	MS	Silty sand
GSM	Gravelly sandy silt	SM	Sandy silt
GM	Gravelly silt	M	Silt
(G)S	Slightly gravelly sand		

(a) The symbol "M" and the terms "silty" or "silt" are defined here to include both silt- and clay-size particles (<0.063 mm).

critical to forming inferences about the long-term stability and behavior of the designs from analogs—initial conditions must be understood. Particle-size distributions of both the engineered designs and the analog profiles were examined as a physical measure of their present likeness. The geomorphology and pedology of the analog sites displayed evidence of their depositional morphology and subsequent pedogenic changes.

Particle-size Distributions

The functional performance of engineered waste covers, as barriers to unsaturated flow, will depend on the depth, water retention, and in situ hydraulic conductivity of the soil and gravel layers (Fayer et al. 1986). Particle-size distribution can be used as an index of the potential water storage capacity of a soil, but it cannot be viewed as the only test of material suitability. For our purposes, however, particle-size distribution was considered to be the single most appropriate parameter.

Tables 4.4 and 4.5 show the gravel, sand, and combined silt/clay fractions for layered and massive-soil designs and for analog profiles. To construct these tables, data from Appendix B and from an engineering study of barrier materials at the Hanford Protective Barrier Test Facility (Phillips et al. 1985) were reduced. The analog-site data were summarized using the Wentworth classification scheme (Wentworth 1922) with divisions between gravel, and sand, and between sand and silt-size particles at 2 mm and 63 μm, respectively. In Phillips et al. (1985), 20 μm was used as the break between sand and silt.

Table 4.4 shows the particle-size distributions in the PUREX Sand Pit and the massive-soil design. The only noteworthy difference between the two was the lower silt content in the PUREX trench profile. As shown in Table 4.5, other than their differences in dimensions, Pit 29 profiles and the layered

Table 4.4. Particle-size Distributions and Classes for the Massive-Soil Barrier Design and for Analog Profiles at PUREX Sand Pit (Particle Size as wt%)[a]

Depth	Massive-Soil Design				Purex Sand Pit							
					Face				Trench			
(cm)	Gr	Sa	Si&Cl	Class	Gr	Sa	Si&Cl	Class	Gr	Sa	Si&Cl	Class
0					0	85	15		0	80	20	(M)S
30					0	85	15		0	91	9	
60					0	82	18		0	97	3	
90					0	86	14		0	98	2	
20					0	90	10	(M)S	1	97	2	
150					0	94	6		1	97	2	
180					0	97	3		0	99	1	
210					0	97	3		0	99	1	S
300	0	85	15	(M)S								
315					0	99	1					
415					0	98	2					
515					0	97	3	S				

(a) Modified after Folk (1974). Design specifications from Phillips et al. (1985). Particle size breaks between gravel, sand, and silt/clay fractions are 2 mm and 63 μm for the analog profiles and 2 mm and 20 μm for the layered design.

design differ primarily in silt/clay content in the top 60 to 80 cm, in sand content below 100 cm, and in the diffuseness of layer boundaries. Pit 29 "topsoil" had close to twice the silt/clay content as the layered design. Therefore, we would expect it to have a higher water storage capacity. Unlike the layered design, however, 10 to 44% of the mass of the lower gravel layers at Pit 29 was sand, and the boundary between topsoil and gravel was more diffuse than was intended in the engineered design. These data support the reconnaissance observations that continuous, well-sorted (open-work) gravel layers underlying graded layers of silt and sand may be difficult to find in Hanford formation sediments.

Geomorphology of Pit 29 and the PUREX Sand Pit

Pit 29 sediments are of the Pasco gravel facies of the Hanford formation, with a surface layer of eolian sediment. The Pasco gravels were deposited by proglacial flood waters as these waters spread out and lost energy after entering the Pasco Basin from the northwest. The southeasterly flowing

Table 4.5. Particle-size Distributions and Classes for the Graded Barrier Design and for Analog Profiles at Pit 29 (Particle Size as wt%)[a]

Depth	Graded Design				Pit 29 Face				Pit 29 Trench 1				Pit 29 Trench 2			
(cm)	Gr	Sa	Si&Cl	Class	Gr	Sa	Si&Cl	Class	Gr	Sa	Si&Cl	Class	Gr	Sa	Si&Cl	Class
25					24	53	23	GMS								
30									2	75	23					
60									2	63	35	MS				
70													1	76	23	MS
80					5	59	36	MS								
90	0	85	15	(M)S												
100									6	48	46	(G)SM				
110	121	76	3	GS	80	14	6	MSG					6	55	39	(G)SM
120									68	24	8					
140													68	25	7	
150					54	44	2	SG	92	8	0					
165													64	34	2	
180					90	10	0		72	27	1					
195													86	12	2	G
210	100			G	93	6	1		89	10	1					
240					87	13	0	G	80	19	1	G				

(a) Modified after Folk (1974). Design specifications from Phillips et al. (1985). Particle size breaks between gravel, sand and silt/clay fractions are 2 mm and 63 μm for the analog profiles, and 2 mm and 20 μm for the layered design.

waters formed a large expansion bar known informally as the 200 Areas Bar. Although several episodes of flooding have been postulated, the gravels at this site were likely deposited by the last event. Based on an apparent correlation of these sediments with those containing the Mount St. Helens set "S" ash (Mullineaux 1986), these gravels appear to be about 13,000 years old.

The gravels in Pit 29 display southward-dipping foreset beds of clast-supported and partially open-work gravel up to 5 cm in diameter. The coarse materials grade upward into lenses of clean, well-sorted pea gravel and poorly sorted, slightly gravelly sandy silt. These flood deposits were blanketed by a silty fine to very fine eolian sand. The contact between the Pasco gravels and the eolian sand was gradational, indicating some reworking and redepositing of the finer-grained Hanford formation sediments by wind and by soil-forming processes.

PUREX Sand Pit sediments were interpreted to be reworked and redeposited eolian sediments derived from the glacio-fluvial Hanford formation. A layer of volcanic ash, correlated to Mount St. Helens set "S" and dated at approximately 13,000 years ago, was encountered at a depth of about 5 m. The structures of the deposits depict a long period of repeated eolian deposition followed by a more

recent period of stability and soil development. The deposits are part of a longitudinal dune now stabilized by vegetation. Long, eastward-dipping foreset laminations were observed below 1.5 m, with some evidence of bioturbation (mixing by burrowing animals and plant root growth). Above 1.5 m, bioturbation and pedogenic processes had disrupted the primary sediment structure.

Soil Morphology

Soil profiles in the trenches excavated adjacent to Pit 29 and the PUREX Sand Pit were examined for evidence of possible long-term pedologic changes that could influence engineered-barrier performance. Tables 4.6 and 4.7 are pedon descriptions of these profiles using Soil Conservation Service nomenclature (Soil Survey Staff 1975). Carbonate contents, which may reflect long-term water movement patterns, are summarized in Appendix B.

Both pedons were classified taxonomically as *typic torripsamments*, which means that they resemble many other recent sandy soils that have evolved in a dry climate. Although as *entisols* they exhibit limited profile development, soil-forming processes evidenced as horizons (layers) unrelated to depositional stratification have transformed these soils to be quite different from a newly constructed, relatively uniform soil mass such as the barrier topsoil. Distinct "A" horizons, layers forming adjacent to the surface and consisting of humified organic matter mixed with mineral constituents, were readily apparent in both pedons by their darker color. The A horizons displayed moderate to strong granular structure and contained many fine roots. The formation of soil structure, the aggregation of soil particles into larger units with planes of weakness between them, may influence soil permeability and water-holding capacity. These influences cannot be measured in the structureless soils of an engineered-barrier test plot.

Both pedons exhibited weak cambric "B" horizons with moderate, medium-to-coarse prismatic structure. Slightly higher silt and clay content in the B horizons portray the gradual illuviation (analogous to immigration) of fines by water and gravity. The B horizons are transitional between the overlying A horizons and the underlying C horizons of mineral soil. In general, C horizons lie below the zone of major biological activity and are little affected by pedogenic processes, other than the accumulation of soluble salts.

The C horizons in these pedons consisted of structureless, single-grain layers of coarse sand and, in Pit 29, gravel. Calcification, the eluviation (analogous to emigration) of calcium carbonate, is the salient pedogenic feature. Differences between the pedons in the depth and dispersion of carbonates may portend differences in water movement patterns between layered and massive-soil barriers. The depth of $CaCO_3$ eluviation in desert soils is largely dependent on soil water flow, and increases with increasing mean annual precipitation (Arkley 1963, Jenny 1980). Temperature and evapotranspiration also strongly influence water movement and thus carbonate accumulation patterns (Ahmad 1978, McFadden and Tinsley 1985). However, since climate and vegetation at the two sites are nearly identical, the sharp contrast in $CaCO_3$ accumulation between the sites (Figure 4.3) is not attributable to precipitation and evapotranspiration. The difference in stratigraphy is a more plausible cause. The textural break in the Pit 29 profile may retard drainage, whereas the lack of major textural breaks and the general lack of carbonate deposits in the PUREX Sand Pit may suggest deeper drainage.

Table 4.6. Pedon Description for the Massive Soil Barrier Analog Profile Adjacent to the PUREX Sand Pit (Site #27 in Figure 4.1)

Horizon	Description
A11	0 to 3 cm; very dark brown (10 YR 3/1) sandy loam, dark grayish brown (10 YR 4/2) when dry; strong fine granular-structure, loose (dry), very friable (moist), nonsticky and slightly plastic (wet); many fine and very fine roots; clear smooth boundary.
A12	3 to 11 cm; dark brown (10 YR 3/3) sandy loam, brown (10 YR 5/3) when dry; moderate medium granular structure; soft (dry), very friable (moist), nonsticky and slightly plastic (wet); many fine and very fine roots; clear smooth boundary.
B2	11 to 32 cm; dark brown (10 YR 4/3) sandy loam, yellowish brown (10 YR 5/4) when dry; moderate medium prismatic structure; slightly hard (dry), very friable (moist), nonsticky and slightly plastic (wet); many very fine roots; clear smooth boundary.
C1	32 to 58 cm; dark grayish brown (10 YR 4/2) coarse loamy sand, light brownish gray (10 YR 6/2) when dry; weak medium prismatic structure; soft (dry), loose (moist), nonsticky and nonplastic (wet); very few coarse and few very fine roots; gradual smooth boundary.
C2	58 to 80 cm; dark grayish brown (10 YR 4/2) coarse sand, gray (10 YR 6/1) when dry; structureless single grain; loose (dry and moist), nonsticky and nonplastic (wet), very few coarse roots, abrupt wavy boundary.
C3ca	80 to 95 cm; dark grayish brown (10 YR 4/2) coarse sand, gray (10 YR 6/1) when drv; structureless single grain; loose (dry and moist), nonsticky and nonplastic (wet); violently effervescent; clear wavy boundary.
C4	95 cm plus; dark grayish brown (10 YR 4/2) coarse sand, gray (10 YR 6/1) when dry; structureless single grain, loose (dry and moist), nonsticky and nonplastic (wet); slightly effervescent.

Table 4.7. Pedon Description for the Layered Barrier Analog Profile Adjacent to Pit 29 (Site #12 in Figure 4.1)

Horizon	Description
A1	0 to 15 cm; dark brown (10 YR 4/3) sandy loam, brown (10 YR 5/3) when dry; very coarse granular structure; slightly hard (dry), very friable (moist), nonsticky and slightly plastic (wet); many very fine roots; clear wavy boundary.
B2	5 to 50 cm; brown (10 YR 4/3) sandy loam, pale brown (10 YR 6/3) when dry; coarse prismatic structure; slightly hard (dry), very friable (moist), nonsticky and slightly plastic (wet); common medium and few fine roots; clear smooth boundary.
C1	50 to 81 cm; dark grayish brown (2.5 Y 4/2) sandy loam, light brownish gray (2.5 Y 6/2) when dry; coarse prismatic structure; slightly hard (dry), very friable (moist), nonsticky and slightly plastic (wet); common medium and few fine roots; abrupt smooth boundary.
IIC2ca	81 to 110 cm; yellowish brown (10 YR 5/4) loam, light brownish gray (2.5 Y 6/2) when dry; coarse prismatic structure; hard (dry), friable (moist), slightly sticky and plastic (wet); violently effervescent; 10% gravels, calcium carbonate buildup on pad faces; clear smooth boundary.
IIC3ca	110 to 240 cm; dark grayish brown (2.5 Y 4/2) gravelly coarse sand, light brownish gray (2.5 Y 6/2) when dry; structureless single grain with same medium subangular block; hard (dry), loose (moist), nonsticky and nonplastic (wet); violently effervescent; calcium carbonate buildup on lower side of gravels; 70% gravels.

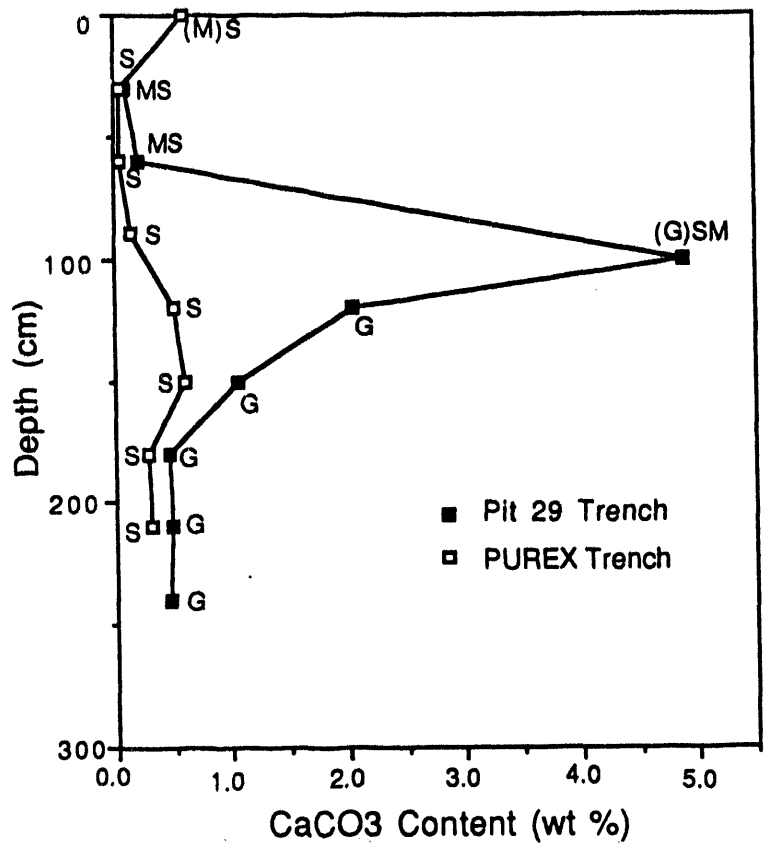

Figure 4.3. Comparison of Calcium Carbonate in the Massive-Soil Barrier of the PUREX Trench and the Layered Barrier of Pit 29 Trench. Particle-size Classes for Each Horizon are Indicated (see Table 4.2 for class definitions).

The spike of carbonate accumulation in the Pit 29 profile coincides with the textural boundary between silty-sand and gravel layers. A task to explore the relationship between carbonate deposition and water movement in layered sediments has since been published (Hunter et al. 1990).

4.2.4 Plant Cover and Root Penetration

Negligible differences in sagebrush and cheatgrass cover were detected in plant stands sampled adjacent to Pit 29 and the PUREX Sand Pit (Table 4.8). The slight differences in the data could very well be artifacts of sampling error or the bias associated with the method used. Therefore, inferred dissimilarities based on these data would be unfounded. Table 4.9 lists all species observed.

Plant root penetration is of interest for two reasons. First, water movement below the root zone may drain through the lower layers of a barrier and contact underlying waste. Second, plant roots that

Table 4.8. Canopy Coverage of Sagebrush and Cheatgrass in Stands Adjacent to Pit 29 and the PUREX Sand Pit (% cover)

Species	Pit 29	PUREX Sand Pit
Sagebrush (*Artemisia tridentate*)	7.9	6.0
Cheatgrass (*Bromus tectorum*)	17.4	19.8

Table 4.9. Higher-Plant Species Observed at Pit 29 and the PUREX Sand Pit

Scientific Name	Common Name	Pit 29	PUREX Sand Pit
Ambrosia acanthicarpa (Hook.)	Bur ragweed	x	x
Amsinckia tessellata Gray	Tessellate fiddleneck		x
Artemisia tridentate Nutt.	Big sagebrush	x	x
Balsamorhiza careyana Gray	Carey's balsamroot	x	x
Bromus tectorum L.	Cheatgrass	x	x
Chaenactis douglasii (Hook.) H. & A.	Hoary false-yarrow	x	
Comandra pallida (DC.) Jones	Pale bastard toadflax	x	x
Chrysothamnus viscidiflorus (Hook.) Nutt.	Green rabbitbrush		x
Cryptantha circumscissa (H. & A.) Johnst.	Matted cryptantha	x	
Cryptantha pterocarya (Torr.) Greene	Winged cryptantha	x	
Cymopteris terebinthinus (Hook.) T.& G.	Turpentine cymopteris	x	
Descurainia pinnata (Walt.) Britt.	Western tansymustard	x	x
Erysimum asperum (Nutt.) DC.	Rough wallflower		x
Lactuca serriola L.	Prickly lettuce	x	
Machaeranthera canescens (Pursh) Gray	Hoary aster	x	
Oenothera pallida Lindl.	Pale evening primrose		x
Phlox longifolia Nutt.	Longleaf phlox	x	
Poa sandbergii Vasey	Sandberg's bluegrass	x	x
Psoralea lanceolata Pursh	Scurf pea	x	
Purshia tridentate (Pursh) DC. L	Bitterbrush	x	
Salsola kali L.	Russian thistle	x	x
Sisymbrium altissimum L.	Tumblemustard	x	x
Sitanion hystrix (Nutt.) Smith	Squirreltail grass	x	
Sphaeralcea munroana (Dougl.) Spach	Munro's globe-mallow	x	x
Stipa comata Trin. & Rupr.	Needle-and-thread		x
Tragopogon dubius Scop.	Yellow salsify	x	x

contact the waste zone may move certain radionuclides to above-ground tissues, which may subsequently be disseminated by wind or herbivory. Root depths in these analog profiles also provided a general index of soil water content. Root-depth, height, and canopy-area data for several plants excavated at Pit 29 and the PUREX Sand Pit are summarized in Table 4.10. The roots of bitterbrush (*Purshia tridentate*), a woody rose that thrives on inactive dunes in the Columbia Basin, penetrated deeper than 250 cm in undisturbed soils at the PUREX trench. The roots of one bitterbrush appeared to go much deeper than 250 cm, but sloughing sand from the drying walls of the trench inhibited further digging. The mean root depth for bitterbrush and sagebrush (*Artemisia tridentate*) growing in the trench was 190 cm. In contrast, the mean root depth for annual forbs growing in disturbed soil near

Table 4.10. Root-Depth, Plant-Height, and Canopy-Area Measurements for Shrubs and Forbs Excavated in the Massive-Soil and Layered Barrier Analog Profiles

Site	Species	Root Depth (cm)	Height (cm)	Canopy Area (m^2)
Pit 29	*Artemisia tridentate*	>180	210	3.8
Trench	*A. tridentate*	170	90	1.3
	A. tridentate	230	180	3.6
	A. tridentate	>210	150	1.7
	A. tridentate	190	120	0.9
	A. tridentate	170	140	0.7
	A. tridentate	190	100	0.8
PUREX	*Artemisia tridentate*	150	90	1.4
Trench	*A. tridentate*	160	80	1.4
	A. tridentate	140	90	0.4
	A. tridentate	170	130	2.0
	Purshia tridentate	>250	210	6.4
	P. tridentate	260	220	5.5
PUREX	*A. acanthicarpa*	132	17	-
Pit Face	*A. acanthicarpa*	107	25	-
	A. acanthicarpa	107	15	-
	A. acanthicarpa	109	23	-
	A. acanthicarpa	112	23	-
	Salsola kali	130	18	-
	S. kali	137	18	-
	S. kali	102	15	-
	Sisymbrium altisimum	97	48	-
	Ambrosia acanthicarpa	81	23	-

the PUREX Pit face was 111 cm. Sagebrush roots at Pit 29 penetrated the topsoil-gravel boundary by more than 100 cm, an indication that water also frequently percolates past the boundary. This percolation can be attributed to inadequate moisture retention in the shallow, relatively coarse topsoil layer. We can conjecture that an engineered barrier with similar topsoil depth and texture would drain, and may fail to prevent plant roots from contacting the waste.

Root depth and above-ground plant dimensions were poorly correlated. A multiple-regression analysis suggested that only weak linear relationships existed between sagebrush root depth and a combination of height and canopy area (Table 4.11). Less than 25% of the total variation in root depths for seven sagebrush excavated in the PUREX trench and for four in the Pit 29 trench could be attributed to a linear relationship with height and canopy area. With height in the model, canopy area contributed nothing significant to the regression relationship. This suggests that root penetration was related more to layering in the soil profile and associated water storage patterns than to above-ground dimensions.

4.2.5 Soil Water Profile Comparisons

The water extraction behavior of plant communities growing on barriers will largely control drainage and groundwater recharge. However, the dynamics and heterogeneity of arid-land plant communities make water extraction behavior difficult to quantify. Furthermore, vegetation disturbances can alter species composition, growth, and root activity and thus cause a step intervention in water extraction rates.

Comparisons of profiles of soil water content measured in September 1983 at Pit 29 and the PUREX Sand Pit demonstrate the impacts of vegetation disturbance (Figures 4.4 and 4.5). Higher water content in disturbed soil profiles bordering the pit faces than in undisturbed trench profiles

Table 4.11. Multiple-Regression Statistics for the Relationship Between Root Depth, Plant Height, and Canopy Area of Sagebrush Excavated at the Massive-Soil (PUREX Sand Pit) and Layered (Pit 29) Barrier Analog Profiles

Coefficient of Multiple Determination
$r^2 = 0.38$; $R_a^2 = 0.23$

Analysis of Variance

Source	Sum Squares	d f	Mean Square	F-test
Regression	2594.5	2	1297.3	2.489
Error	4169.1	8	521.1	p = .1444
Total	6763.3	10		

Beta Coefficients

Parameter	Value	Standard Error	t-value	Probability
β_0	132.3			
β_{height}	0.339	0.295	1.148	0.284
$\beta_{canopy\ area}$	2.072	11.023	0.188	0.856

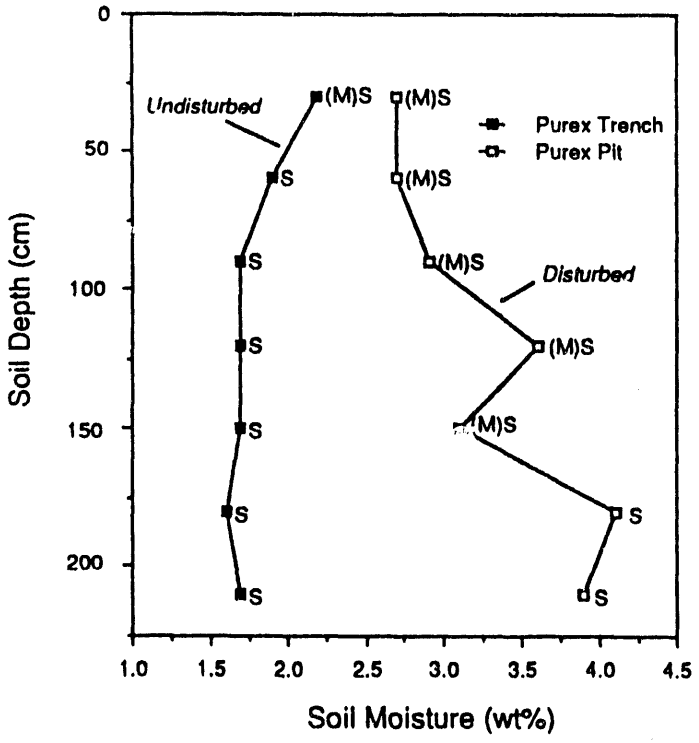

Figure 4.4. September 1983 Profiles of Soil Water Content Below Disturbed and Undisturbed Vegetation at the Massive-Soil Barrier Analog Site, the PUREX Sand Pit

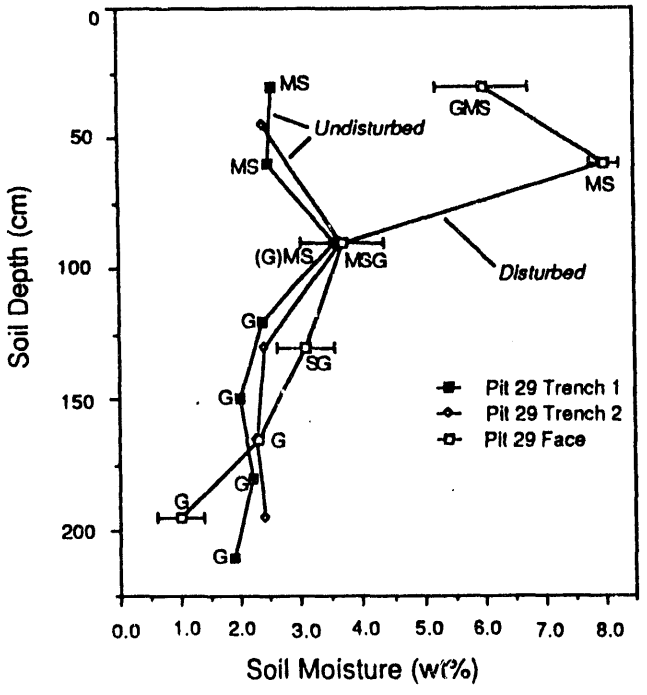

Figure 4.5. September 1983 Profiles of Soil Water Content Below Disturbed and Undisturbed Vegetation at the Layered Barrier, Pit 29

adjacent to the pits can be attributed to differences in the vegetation. Sparse stands of relatively shallow-rooted annual grasses and forbs grew in the pit profiles. The trench profiles supported stands of mature sagebrush. Although these are one-time measurements, the low water contents in the PUREX trench profile (Figure 4.4), the undisturbed massive-soil barrier analog site, indicate that little water is draining from the root zone. In contrast, a relatively high water content below the root zone in the PUREX Pit, the disturbed-site profile, may be evidence of drainage. Contrasting moisture contents were also observed between disturbed and undisturbed vegetation in the fine-soil layer of the layered-barrier analog at Pit 29 (Figure 4.5). Soil moisture content at the disturbed site was more than twice that at the undisturbed site.

4.3 Surface Gravel Analogs

A surface gravel mulch or gravel admix may be included in the barrier design to control wind and runoff erosion. Several barrier program tasks are devoted to determining the optimum design for controlling erosion (Ligotke 1988) and for measuring the influence of gravel on soil water balance within a barrier (Fayer et al. 1985; Gee et al. 1989; Waugh 1989). In general, depending on its thickness, a surface gravel mulch can increase surface water infiltration, decrease surface evaporation, and change the composition, abundance, and water extraction behavior of vegetation (Beedlow 1984; Nichols et al. 1984). Also, because the thermal conductivity and thermal capacity would likely be lower in a surface gravel layer than in a fine-textured surface (Rosenberg et al. 1983), gravel could impede plant community recovery following disturbances such as fire. Well-designed lysimeter and field-plot experiments may depict the water relations of a newly constructed barrier, but they may not depict inevitable changes in gravel, vegetation, and soil water interactions over time.

The purpose of this investigation was to measure the influence of gravel mulch on soil water content and vegetation abundance at sites potentially analogous to barrier surfaces tens to hundreds of years after construction. Two sites visited during the 1983 reconnaissance (Section 4.1) were selected for study. Bergmound 1, located in the Cold Creek Valley about 400 m southeast of the Yakima Barricade, was examined as representing a thin gravel mulch. Bergmound 1 has a relatively even veneer of gravel-sized basalt diamicton. The Route 4 Backslope site, located at the southwest corner of the intersection of Route 4 and the Central Landfill turnoff, was considered an analog of a thick gravel mulch. Mature *Purshia tridentate* (bitterbrush) growing out of a 15- to 20-cm-thick layer of round gravel and cobble covering the Route 4 Backslope site indicate that the gravel has been in place for many years. In Figure 4.1, Bergmound and Route 4 Backslope are site numbers 36 and 44, respectively.

4.3.1 Bergmound Geomorphology

The bergmounds or iceberg mounds of the Cold Creek Valley are artifacts of the last of many cataclysmic floods that scoured much of eastern Washington during periods of Pleistocene glaciation. The last cataclysmic flood occurred about 13,000 years ago (Mullineaux 1986). Debris-laden icebergs, fragments of a lobe of the continental ice sheet that had formed immense Glacial Lake Missoula (Waitt and Thorson 1983), were carried on flood waters into the Pasco Basin after the ice dam failed. As the flood waters drained out of the Pasco Basin through Wallula Gap, after being hydraulically impounded behind the Gap, many icebergs were apparently caught up in back-water eddies in the Cold Creek

Valley, and came to rest on the newly deposited slackwater sediments (Touchet Beds). The berg-mounds melted, leaving their load of glacial rock (diamicton) as a surface veneer. The mounds probably formed by erosion of surrounding unprotected sediments, most likely as the flood waters receded (Fecht and Tallman 1978). Subsequent wind and runoff erosion of surrounding non-graveled sediments over the past 13,000 years may have enhanced the relief of the mounds.

4.3.2 Methods

Paired 30-m-square field plots (one with a gravel cover and the other with no gravel cover) were marked at both the Bergmound 1 and Route 4 Backslope sites. Similar field plots without gravel were marked adjacent to the gravel plots in areas with otherwise similar soils and vegetation. The sites were sampled in May and June of 1984.

A combination of line-intercept (Canfield 1941) and point-intercept method (Goodall 1957) were used to measure cover. Eleven transects, 30 m long, were placed east to west every 3 m to attain a uniform coverage. The cover of grasses, forbs, cryptogams, litter, soil, and gravel was sampled using a 10-pin point-intercept frame. Percent cover for a species was estimated simply as the proportion of hits. The percent canopy coverage of shrub species was estimated by dividing the total length of a transect (tape measure) intercepted by a species by the length of the transect. Five sediment cores were extracted from each field plot in a stratified random manner, one from the plot center and the other four from random points within each plot quarter. Samples were retrieved from incremental depths and analyzed for gravimetric water content and particle-size distribution using the procedures described in Section 4.2.

4.3.3 Particle-size Distribution

Particle-size distribution was sampled as an index of soil water retention. The Route 4 Backslope soils were much coarser textured than Bergmound 1 soils, being a sand compared with a loam or silt loam. As a rough comparison, using the Bodman and Mahmud (1932) equation for moisture equivalent, the approximate field capacities were $< 10\%$ for Route 4 Backslope soils and between 20% and 30% for Bergmound 1 soils. Therefore, inferences relating gravel-layer thickness and soil water content based on a comparison of the two sites would be unfounded. In contrast, the sand and silt/clay fractions in graveled and nongraveled plots at each site were not significantly different (Table 4.12), lending credence to inferences from plot pairs. Soil particle-size distribution data for these sites are contained in Appendix C.

4.3.4 Plant Community Comparisons

Plant species composition and abundance depend, in part, on the season of observation. Therefore, the list of species observed at Bergmound 1 and Route 4 Backslope in June and May (Table 4.13) is most likely incomplete. Many summer-active plants identifiable later in the year are probably missing. Nonetheless, several patterns are evident from the lists. Species richness, the total number of species observed, was greater in the sandy Route 4 Backslope soil than in the Bergmound 1 silt loam (40 versus 19). Species composition varied little between the graveled and non-gravel plots at Bergmound 1, the thin-gravel-mulch analog. Only five species, 26%, were observed on one and

Table 4.12. Particle-size Distribution and Sediment Classes for Profiles of Surface Gravel Analog Sites

Study Site	Depth	Gravel, >2.0 mm (%)		Sand, 0.063-2.0 mm (%)		Silt + Clay, 0.063 mm (%)		Sediment Class[a]
		x	SE(x)	x	SE(x)	x	SE(x)	
Bergmound	0-5	5.45	2.74	60.40	4.58	34.15	5.33	(G)MS
Gravel	40-50	0.97	0.36	36.49	1.97	62.54	2.06	SM
	100-110	0.58	0.41	32.70	5.64	66.72	6.01	SM
Bergmound	0-5	0.44	0.27	50.82	8.91	48.74	9.04	MS-SM
Control	40-50	1.23	0.45	36.59	8.82	62.17	8.90	SM
	100-110	1.34	1.07	40.04	4.56	58.62	4.32	SM
Backslope	0-20	56.84	6.93	41.34	6.83	1.83	0.15	SG
Gravel	40-50	0.07	0.03	98.45	0.56	1.47	0.54	S
	120-130	0.14	0.10	97.56	1.22	2.31	1.23	S
	200-210	0.23	0.13	95.41	2.70	4.36	2.75	S
Backslope	0-10	0.01	0.01	94.70	0.83	5.29	0.83	S
Control	80-90	0.00	0.00	95.27	0.91	4.73	0.91	S
	160-170	0.03	0.03	95.66	1.57	4.31	1.58	S
	240-250	0.13	0.11	93.35	2.47	6.52	2.38	S

(a) Symbols defined in Tables 4.2 and 4.3

Table 4.13. Vascular Plant Species Observed at the Surface Gravel Analog Sites

Scientific Name	Common Name	Bergmound Gravel	Bergmound Control	Backslope Gravel	Backslope Control
Shrubs					
Artemisia tridentate Nutt.	Big sagebrush	X	X	X	X
Chrysothamnus nauseosus (Pall.) Britt.	Gray rabbitbrush	X			
Chrysothamnus viscidiflorus (Hook.) Nutt.	Green rabbitbrush		X	X	
Grayia spinosa (Hook.) Moq.	Spiny hopsage	X	X		X
Purshia tridentate (Pursh) DC. L	Bitterbrush			X	X
Grasses					
Bromus tectorum L.	Cheatgrass	X	X	X	X
Oryzopsis hymenoides (R. & S.) Ricker	Indian ricegrass		X	X	X
Poa sandbergii Vasey	Sandberg's bluegrass	X	X	X	X
Sitanion hystrix (Nutt.) Smith	Squirreltail grass	X	X		
Vulpia octoflora Walt.	Slender six-weeks				X
Forbs					
Achillea millifolium L.	Common yarrow				X

Table 4.13. (contd)

Scientific Name	Common Name	Bergmound Gravel	Bergmound Control	Backslope Gravel	Backslope Control
Ambrosia acanthicarpa Hook.	Bur ragweed				X
Amsinckia tessellata Gray	Tessellate fiddleneck	X		X	
Astragalus caricinus (Jones) Barneby	Buckwheat milkvetch	X	X		
Astragalus sclerocarpus Gray	Stalked-pod milkvetch			X	X
Astragalus succumbens Dougl.	Crouching milkvetch		X		
Balsamorhiza careyana Gray	Carey's balsamroot			X	X
Chaenactis douglasii (Hook.) H. & A.	Hoary false-yarrow			X	
Cryptantha circumscissa (H. & A.) Johnst.	Matted cryptantha				X
Cryptantha fendleri (Gray) Greene	Fendler's cryptantha				X
Cryptantha pterocarya (Torr.) Greene	Winged cryptantha				X
Cymopteris terebinthinus (Hook.) T.& G.	Turpentine cymopteris			X	X
Descurainia pinnata (Walt.) Britt.	Western tansy mustard			X	X
Draba verna L.	Spring whitow-grass		X		
Epilobium paniculatum Nutt.	Tall willow-herb	X	X	X	X
Erigeron filifolius Nutt.	Thread-leaf fleabane	X			
Erigeron poliospermus Gray	Cushion fleabane			X	
Erigeron pumilus Nutt.	Shaggy fleabane	X	X		
Erysimum asperum (Nutt.) DC.	Rough wallflower			X	X
Fritillaria pudica (Pursh) Spreng.	Yellow bell				X
Gilia leptomeria Gray	Great Basin gilia				X
Holosteum umbellatum L.	Jagged chickweed			X	X
Hymenopappus filifolius Hook.	Columbia cut-leaf			X	
Lactuca serriola L.	Prickly lettuce				X
Layia glandulosa (Hook.) H. & A.	White daisy tidytips	X	X		
Machaeranthera canescens (Pursh) Gray	Hoary aster		X	X	X
Medicago sativa L.	Alfalfa			X	
Mentzelia albicaulis Dougl.	White stem mentzelia			X	
Oenothera pallida Lindl.	Pale evening primrose			X	X
Penstemon acuminatus Dougl.	Sharp leaf penstemon			X	X
Phacelia hastata Dougl.	Whiteleaf phacelia			X	
Phacelia linearis (Pursh) Holz.	Threadleaf phacelia				X
Phlox longifolia Nutt.	Longleaf phlox	X	X		X
Psoralea lanceolata Pursh	Scurf pea			X	
Salsola kali L.	Russian thistle			X	X
Sisymbrium altissimum L.	Tumblemustard			X	X
Sphaeralcea munroana (Dougl.) Spach	Munro's globe-mallow	X	X		
Townsendia florifer (Hook.) Gray	Showy townsendia	X			
Tragopogon dubius Scop.	Yellow salsify			X	X
Species richness		15	16	27	31

not the other. At the Route 4 Backslope site, the thick-gravel-mulch analog, 55% of the species observed, or 22 species, grew on only one of the plots. Except for *Chrysothamnus nauseosus* (gray rabbitbrush) and *Grayia spinosa* (spiny hopsage), however, all were only minor components of these communities.

At both sites, estimates of total plant cover were nearly 50% greater on non-gravel soil than on graveled soil (Table 4.14). At Bergmound 1, the increase was nearly proportional among the more abundant species. In contrast, marked differences were measured in the relative dominance of the

Table 4.14. Percent Cover of Gravel, Soil, Litter, Cryptogams, and Higher Plants on Surface Gravel Analog Plots, Bergmound 1 and the Route 4 Backslope

Surface Component	Bergmound 1				Route 4 Backslope			
	Gravel		No Gravel		Gravel		No Gravel	
	mean	2SE	mean	2SE	mean	2SE	mean	2SE
Gravel	10.9	3.8	0.2	0.4	44.4	7.2		
Soil	38.9	7.4	24.4	7.2	20.6	5.5	40.4	8.8
Litter	36.7	7.2	52.5	7.0	11.2	5.2	32.4	6.4
Cryptogams	1.5	6.2	3.1	1.9	12.0	3.7	3.8	2.5
Grasses and Forbs								
Achillea millifolium					0.2	0.4		
Astragalus sclerocarpus					0.4	0.8		
Bromus tectorum	10.2	3.7	18.9	4.7	9.6	3.6	20.4	5.2
Cryptantha pterocarya							0.2	0.4
Cymopteris terebinthinus					3.2	2.2	0.8	1.0
Festuca ovina							0.1	0.1
Machaeranthera canescens	0.2	0.4			0.1	0.1		
Oenothera pallida							0.2	0.4
Oryzopsis hymenoides					0.4	0.6		
Penstemon acuminatus					0.1	0.1		
Poa sandbergii	0.2	0.4	0.4	0.5	0.8	1.0	0.4	0.6
Sphaeralcea munroana	0.6	0.8						
Shrubs								
Artemisia tridentate	11.6	1.8	16.2	1.3	0.3	0.3	6.2	1.7
Chrysothamnus nauseosus					0.9	0.4		
Chrysothamnus viscidiflorus					2.1	0.6	4.3	1.2
Grayia spinosa	7.7	1.3	10.2	1.3			1.1	0.5
Purshia tridentate					14.2	2.2	12.0	2.7
	30.5							
Total plant cover			45.7		31.8		45.7	

more abundant species in the graveled and non-gravel plots at the Route 4 Backslope site. The non-gravel plot had more than twice the *Bromus tectorum* (cheatgrass) cover than the same soil with a thick-gravel mulch, twice as much *Chrysothamnus viscidiflorus* (green rabbitbrush), 20 times as much *Artemisia tridentate* (sagebrush), slightly less *Purshia tridentate* (bitterbrush), and only a third as much cryptogam cover.

4.3.5 Soil Water Comparisons

No conspicuous differences in soil water content with and without a surface gravel layer were evident (Figures 4.6 and 4.7; Appendix D). However, contrary to what might be expected, the water content in the no-gravel plot adjacent to Bergmound 1 was slightly higher (Figure 4.6). Given little difference in soil texture, 50% less plant cover, and a lag layer of gravel that has been shown elsewhere to enhance infiltration and to suppress evaporation (Rosenberg et al.1983; Nichols et al. 1984), one might expect higher soil water content in the bergmound. Three possible explanations are that 1) the vegetation extracts any excess infiltration, 2) runoff reduces infiltration on the slope of the bergmound, and 3) the relatively dark-colored basalt veneer may increase net radiation at the ground surface, enhancing evaporation.

Standard-error statistics are perhaps more informative than mean values in this analysis. If the sampling were repeated many times, the mean would probably be within the bounds of the error bars about 95% of the time. The high variance suggests that no real differences exist in the mean moisture content of graveled and no-gravel plots. The source of this high variance may be most important in assessing the long-term performance of barriers. The coefficients of variation (Table 4.15) suggest that the high variance in water content may reflect, in part, variation in soil texture. Other factors that might cause the development of spatial patterns on barriers in soil water infiltration, drainage, and evapotranspiration include soil development, mixing of surface gravels by burrowing animals, and plant distribution patterns.

4.4 Summary of Observations

Observations and conclusions from these preliminary studies of barrier analogs include the following:

1. Pasco Basin sediments consisting of Pleistocene-age silts and sands overlying proglacial flood gravels differ from layered engineered-barrier designs in two ways: layer interfaces are relatively diffuse, and gravel-layer matrices are commonly filled with silt and/or sand. By comparison, the engineered designs specify abrupt layer interfaces and well-sorted gravel layers. A two-layer design, with the gravel-layer matrices filled in with sand at construction (pit-run gravel), may be more stable than a graded-layer design. Studies of the depositional morphology of analog profiles and of subsequent soil formation processes that disrupt the interface, or move fines into the gravel layer, may provide an indication of long-term barrier stability.

2. Evidence of a gradual downward movement of fines in analog site profiles and the formation of soil structure, both of which can influence soil water retention and movement, may reflect future soil formation processes on barriers.

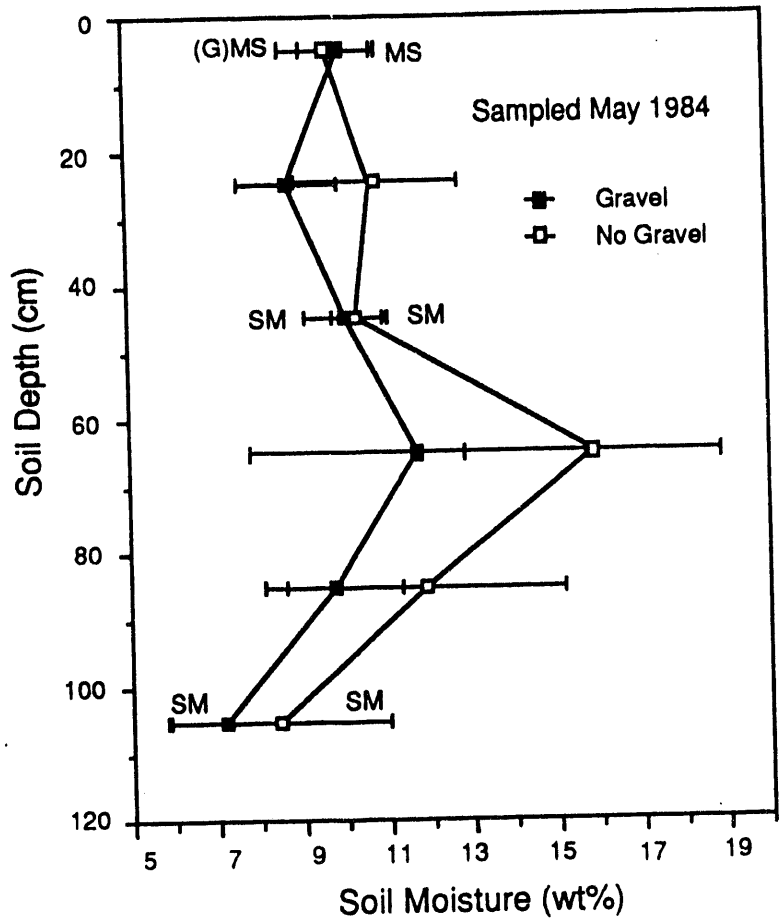

Figure 4.6. Mean Soil Water Content (n=5) at Bergmound 1 Surface Gravel Analog and an Adjacent No-gravel Plot. Error Bars are 2SE (mean). Letters designate sediment classes.

3. Contrasts in the depth and diffuseness of $CaCO_3$ accumulation in massive-soil and layered barrier analogs were attributed to the occurrence of a zone of drying at the textural boundary between loamy sand and underlying gravel horizons in layered profiles. The effects of carbonate accumulation on soil hydraulic properties could be studied at these sites. The carbonate accumulation patterns also support the capillary barrier concept. In contrast, the occurrence of $CaCO_3$ deposits on gravels underlying relatively thin fine-soil layers at some sites may suggest frequent drainage. The presence of sagebrush roots in the gravel layers at these sites was additional evidence of water movement past the coarse-fine boundary. Therefore, the depth of fines is a critical design issue.

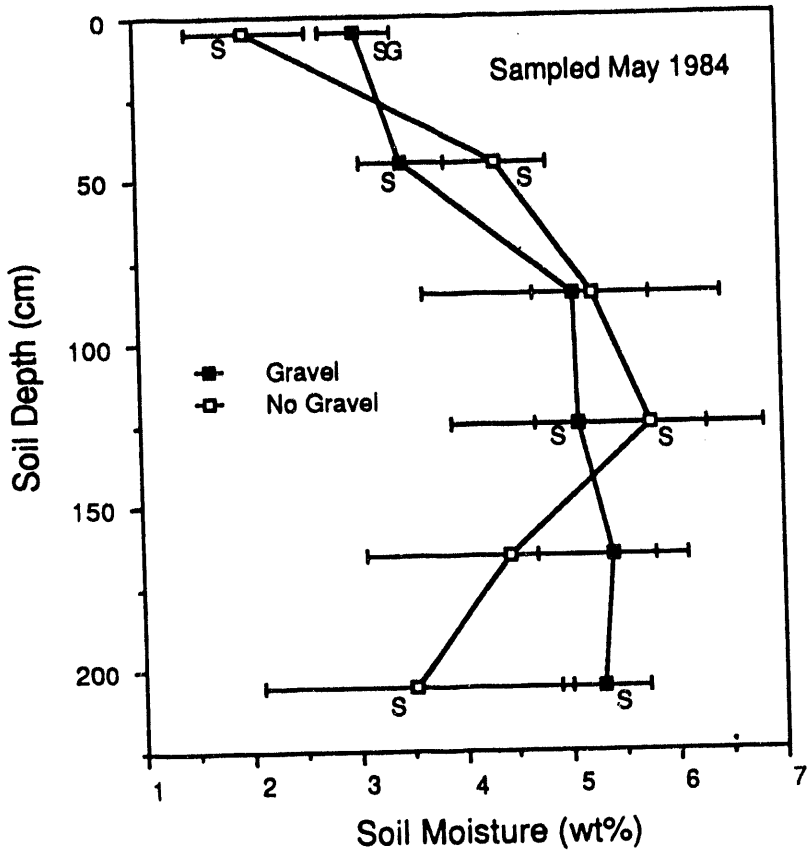

Figure 4.7. Mean Soil Water Content (n=5) at the Route 4 Backslope Gravel Mulch Analog and an Adjacent No-gravel Plot. Error Bars are 2SE (mean). Letters designate sediment classes.

4. Prior surface disturbances at some analog sites, which replaced deep-rooted perennial species with shallow-rooted annual species, apparently resulted in lower plant water extraction, greater soil water content, and an increased probability of drainage.

5. Comparisons of paired plots with and without gravel at a Bergmound (a thin surface-gravel analog) and on an old roadside backslope (a thick surface gravel analog) suggested that 1) a heavy gravel mulch could significantly alter species composition and 2) relatively sparse gravel surfaces can reduce plant cover in this environment. Variation in soil water data, possibly caused by mosaics in the surface environment, masked any salient differences in mean water content of graveled and non gravel plots. Time series data on soil water storage are needed. Future analog studies should investigate the evolution of spatial patterns and the influences of these patterns on the hydrologic performance of barriers.

Table 4.15. Coefficients of Variation for Percent Sand, Percent Silt and Clay, and Percent Water Content in Soil Profiles of Surface Gravel Analogs

Study Site	Depth	Sand	Silt and Clay	Water Content (wt%)
Bergmound Gravel	0-5	17.0	34.9	9.8
	20-30			14.8
	40-50	12.0	7.4	10.8
	60-70			37.5
	80-90			30.8
	100-110	38.5	20.1	21.2
Bergmound Control	0-5	39.2	41.5	12.2
	20-30			20.2
	40-50	53.8	32.0	6.3
	60-70			21.3
	80-90			30.8
	100-110	25.5	16.5	33.9
Backslope Gravel	0-5	36.9	18.3	12.4
	40-50	1.2	81.3	12.9
	80-90			30.9
	120-130	2.8	119.5	26.3
	160-170			14.5
	200-210	6.3	140.7	8.9
Backslope	0-5	2.0	35.1	30.7
	40-50	2.1	42.9	12.3
	80-90			11.5
	120-130	3.7	81.7	20.6
	160-170			34.2
	200-210	5.9	81.5	45.5

5.0 Recommendations For Future Barrier Analog Studies

To support evaluations of long-term barrier performance, we recommend four areas for future study: 1) soil development, 2) vegetation dynamics, 3) durability and performance of anthropogenic materials and structures analogous to those used in barrier designs, and 4) analog site selection standards. These tasks would support the selection of treatments for field experiments, the acquisition of model input and validation data, and an understanding of emergent long-term processes that may be difficult to evaluate otherwise. Studies of paleoclimatic analogs of future climate extremes are funded under a separate task (Petersen 1993). Two additional issues of importance to the Hanford Protective Barrier Development Program, barrier mound stability and human intrusion (Sections 3.4 and 3.5), will be investigated using archaeological analogs as part of the National Low-Level Waste Management Program (Chatters et al. 1990).

5.1 Soil Development Studies

Analog studies of the effects of soil development on barrier performance (Section 3.3) should focus on four issues: 1) carbonate accumulation, 2) soil mixing, 3) soil structure, and 4) spatial patterns in soil-plant-water relations.

5.1.1 Carbonate Accumulation

A study conducted for PNL by Washington State University in 1989 (Hunter et. al 1990) addressed two barrier performance issues: 1) whether the distribution of carbonates in layered sediments is related to Holocene water movement and whether it can be used as an analog of future water movement in protective barriers, and 2) what feedback effect carbonate accumulation would have on soil hydraulic properties in protective-barrier designs.

The most significant pedogenic indicators of soil water movement in arid and semi-arid environments are clay, silt, and soluble salts, including $CaCO_3$. The accumulation of $CaCO_3$ was considered to be the most likely pedogenic indicator of water movement at the Hanford Site. The geochemistry of $CaCO_3$ is relatively simple, and depends on the availability of Ca^{2+}, the pCO_2, and water. Two mechanisms were identified as being primarily responsible for carbonate precipitation in soils: evapotranspiration and degassing of CO_2. Thus, there likely is both a biotic and an abiotic component involved in the precipitation of carbonate in soil. The amount and morphology of carbonates in soils is a function of the progressive accumulation of carbonate over time. Two models (CALDEP and CALSOIL) that simulate the accumulation of $CaCO_3$ were examined. Both use saturated flow as the mechanism for water and solute transport. Although one was determined to be more sensitive to soil and climate parameters that influence water movement, it was concluded that neither model simulates in an effective manner the conditions expected in the protective barriers.

Based on the study, we recommend the following:

1. Although carbonate accumulation is related to patterns of soil water movement over many years, the concept that the depth at which carbonates precipitate is the depth below which no unsaturated recharge occurs should be abandoned. The presence of a calcic horizon indicates that the soil solution became supersaturated with respect to carbonate, not that water flow stopped completely.

2. Natural analogs should be used to measure hydraulic properties of calcic horizons and to compare them with noncalcic soils to determine the likely influence of carbonate accumulations on water movement in the protective barriers.

Therefore, natural analogs do not directly answer the drainage question, but they do indicate that calcic horizons will form in the protective barriers. The questions remain, however, of how much, when, and where in the barrier carbonate will accumulate. Enough uncertainty about the effect of carbonate accumulations on the hydraulic properties exists that the study should continue with this focus.

5.1.2 Soil Illuviation and Pedoturbation

The long-term performance of the barrier depends in part on maintaining an adequate thickness of fine-textured topsoil, and on maintaining discontinuity at layer interfaces. Over time, there is the possibility for soil fines to settle or migrate downward, filling either completely or partially the matrices of the underlying gravel layer. Upward movement of gravel into the fine-grained layer could occur as well, through the freeze-thaw process (i.e., frost heaving). Either of these scenarios could reduce the effective thickness of the fine-grained layer enough to allow moisture or organisms to come into contact with the buried wastes. It is possible, however, that the time required for these processes to significantly affect barrier performance exceeds the planned use life of the barrier.

Many of the sites visited in the initial reconnaissance (Section 4.1) are candidates for analog studies of layer discontinuity. Most of these sites consist of either Pleistocene-age slackwater silt and sand (Touchet Bed facies) overlying coarse-grained Missoula flood gravels (Pasco gravels facies) or Holocene loess (windblown silt) overlying Pasco gravels. The Pasco gravels sometimes display an openwork (i.e., matrix-free) fabric comparable to the coarse layer in present barrier designs. Matrices within the Pasco gravels, however, more often are filled with poorly sorted mixtures of sand and silt. While it is most likely that the wide range in grain sizes in the Pasco gravels is a result of transient-flow dynamics and rapid deposition during cataclysmic flooding, filling in of voids by fine-grained material from above is still a possibility.

Two issues should be addressed in a study of the stability of layer interfaces in analogs of both the two-layer design (fines over gravels infilled with sand) and the graded barrier design. One would focus on the downward movement of fine-grained sediment and colloidal material. The other would examine the potential for upward movement of gravel via freeze-thaw processes. Several approaches could be taken to determine the extent to which fine-grained sediment is translocated downward. These include

detailed descriptions of the parent material and soil horizons and analyses of particle-size distributions, clay and petrographic mineralogy, and geochemistry. The study should focus on field and laboratory analyses of soil horizons, specifically on the amount of eluviation/illuviation that has taken place. Rates and timing of sedimentation and soil formation could be analyzed using age-dating techniques such as tephra (volcanic ash) markers, thermoluminescence methods, and organic carbon (^{14}C) methods.

The upward movement of gravel, against the force of gravity, is well documented in periglacial and other environments that undergo frequent alternate freezing and thawing. Mixing of soil layers through the freeze-thaw process, or cryoturbation, is most pronounced in soils having a predominance of silt-sized particles in proglacial arctic environments (Embleton and King 1968). The Hanford Site experienced periglacial conditions as recently as 13,000 years ago, when the Cordilleran Ice Sheet covered northeastern Washington (Waitt and Thorson 1983). The potential for a return to periglacial conditions within the next 10,000 years (Craig and Hanson 1985) makes cryoturbation a possibility over the proposed design life of the barrier. This study should begin with a literature search to determine the controlling factors (e.g., temperature regime, moisture regime, grain-size distribution, etc.) that lead to cryoturbation. Once the phenomenon is understood, a field reconnaissance should be performed. Potential analog sites are those where fine-grained soils, developed in eolian loess, overlie gravels or basalt bedrock rubble in areas of low relief. In these environments, any coarse-grained clasts found in a loess matrix may have been lifted upward by cryoturbation. This work should be performed in conjunction with the climate change task to determine likely changes in temperature and precipitation that might lead to cryoturbation over the next 10,000 years.

Because erosion would lower the water storage capacity of the topsoil layer of the barrier, a design option to mulch or admix the surface soil with gravel has been proposed. Studies are under way to test and model the resistance of various gravel-armor designs to wind erosion (Ligotke 1989) and overland flow and to measure the influence of gravel on soil water balance and vegetation (Waugh 1989). Much of this work would be superfluous if gravel surfaces were shown to be unstable over time. Regardless of how the surface gravel is initially put down, as a mulch or as an admixture, its morphology may change in response to the balance of several factors, some of which would tend to mix the gravel, whereas others would tend to move the gravel to the surface (Section 3.3).

Analogs of surface gravel exist at the Hanford Site (Section 4.3). The origin and morphology of gravels at these sites, and evidence of pedoturbation, should be further characterized. This should include characterization of soil micromorphology for vesicular structures and other pedologic evidence of soil mixing. Analysis of the mineralogy, geochemistry, and relative ages of gravels and silt deposits may also be needed to sort out soil formation sequences. Before intensive studies of such analogs are conducted, it is necessary to determine whether pedoturbation appears to significantly affect layer-interface stability on the time scale for which barriers are designed.

5.1.3 Soil Structure

Soil structure is the aggregation of soil particles, or clusters of particles, that are separated from adjoining aggregates by planes of weakness (Soil Survey Staff 1975). Some of these aggregates, called peds, have thin surface films that act to keep them apart. Other peds are held together wholly by internal forces. Soil structure can greatly influence water movement and plant growth. Soils with weak spheroidal peds are often more permeable and have a greater water storage capacity than soils with massive or blocky structure. In contrast, some soils with very well-developed spheroidal peds have a low water storage capacity, and drain rapidly, much like a coarse, gravely soil. In these soils, water moves rapidly along the planes of weakness and does not readily penetrate the peds.

Soil structure should be described at soil development and vegetation analog sites using standard soil characterization methods and nomenclature (Soil Survey Staff 1975). A suite of sites should be selected that are of the same soil type (Ritzville or Warden silt loam) but that differ with respect to climate and disturbance histories. If secondary soil aggregation is evident, the hydraulic properties of these soils (e.g., hydraulic conductivity) should be measured in situ and compared with the properties of the structureless soil of a newly constructed barrier.

5.1.4 Spatial Patterns in Soil-Plant-Water Relations

In arid ecosystems, plant species are typically distributed neither randomly nor uniformly, but in clumps. This occurs for three reasons: 1) seeds and fruits fall close to the parent, 2) rhizomes and stolens produce offspring near the parent plant, and 3) the habitat, at finer scales, consists of microsites within which species establish with varying degrees of success. Of importance to barrier performance, plant distribution patterns can influence soil water balance, either directly or by causing patterns to emerge in soil development processes.

Spatial patterns in plant distribution and soil development exist at McGee Ranch, which is the source area at Hanford for fine sediment that will be used in the construction of barriers. A study of the likelihood that this morphology will reform on barriers, and its influence on the soil water balance, was initiated in 1990. The study was funded in part by the National Low-Level Waste Management Program (Chatters et al. 1990). The distribution of hummocks (small mounds) at McGee Ranch appears to be associated with the distribution of hopsage and sagebrush. Soil mounds found in close association with clumped vegetation were called "coppice dunes" by Melton (1949). At McGee Ranch, coppice dunes are circular to oblong with diameters of 1 to 3 m, and range in height from 20 to 70 cm. Sagebrush were found growing on the mounds and in depressions between mounds. In contrast, hopsage was found growing only on the mounds.

Preliminary results of the McGee coppice-dune study suggest that soil formation in dune and interdune units has not been continuous through time. The soils of both interdune and dune consist of a loamy sand layer (or sandy loam) overlying silt loam. The upper part of the silt loam contains large numbers of vesicular pores below which is a zone of laminated silts and sands. Although the genesis of

vesicular pores is not fully understood, they most commonly form in surface horizons that are subjected to extreme wetting and drying (crusts form as the wet surface dries, trapping and "casting" gas bubbles). Thus, the silt may have been the land surface at one time, subsequently having been overlain by wind-blown loam. In fact, many interdunes lack the loam overlay. The laminar soils are probably slackwater sediments attributed to late Pleistocene catastrophic floods. The primary difference between dune and interdune units is the thickness of the sandy strata. The thickness is ascribed to the trapping of blowing sand by the shrubs.

The secondary phase of the study, a comparison of soil water storage in dune and interdune units, began in 1990. The monitoring of soil moisture should be continued to establish the seasonality of water storage changes. Plant distribution patterns should also be quantified. Distance methods (Podani 1984) could be used to detect distribution patterns of larger shrubs (sagebrush and hopsage). A Poisson analysis of cover quadrate data (Barbour et al. 1987) could be used to detect patterns in grass and forb distribution. Spatial patterns in water content at depth associated with surface spatial patterns could be measured using gravimetric methods or neutron moisture probes in a stratified random-sampling scheme.

5.2 Vegetation Dynamics Studies

Changes in vegetation will influence the performance of engineered covers as infiltration, erosion, and biointrusion barriers (Section 3.2). Vegetation will change seasonally, yearly, and over the long-term. Change will be driven by propagule accessibility, soil development, climatic variability, disturbances such as fire, and species interactions (competition, microorganism associations, allelochemic reactions, herbivory). Change is manifested by shifts in the abundance, composition, and diversity of species, and may be accompanied by changes in biogeochemical cycling, in energy exchange at the land surface, and (of importance in assessing barrier performance) in rates of evapotranspiration. Consequently, vegetation change is complicated and its effects are difficult to model and predict. The following phased research study is recommended for an evaluation of possible future vegetation changes on barriers.

5.2.1 Parameter Identification

Protective barrier program tasks should be reviewed, and important vegetation parameters identified. This review will determine what field data to collect at analog sites. The review should include vegetation input parameters for water balance and erosion models and treatments used, or planned, for laboratory and field-plot studies of wind erosion, water erosion, water balance lysimetry, and biointrusion. The parameters should then be prioritized based on regulatory standards and the results of model sensitivity analyses and prior field-study results.

5.2.2 Conceptual Model

A conceptual model should be used as a tool for gaining a better understanding of processes influencing vegetation development on protective barriers and thus for guiding the development of field studies. The model should be based on the following balances and tradeoffs: 1) balances between species and habitat factors (climate, soils, topography, allelopaths, herbivory, natural and human disturbance) and physiological tolerance of species to these factors, 2) balances between propagule accessibility (dispersal mechanisms) and landscape accommodation, 3) balances between allogenic and autogenic factors, and 4) tradeoffs in plant partitioning of a limited energy budget among contrasting physiological, morphological, and reproductive characteristics. Figure 5.1 is a simple conceptual model.

5.2.3 Site Selection

Criteria should be defined and candidate study sites selected based on predicted changes in the barrier environment. The selection should emphasize habitat factors that influence vegetation change (e.g., climate, fire, grazing, etc.) and that are unique to engineered barriers (e.g., soil compaction and topographic position). Selection criteria should also be based on a range of possible changes in barrier habitat factors as determined from other long-term barrier performance tasks (climate change, soil

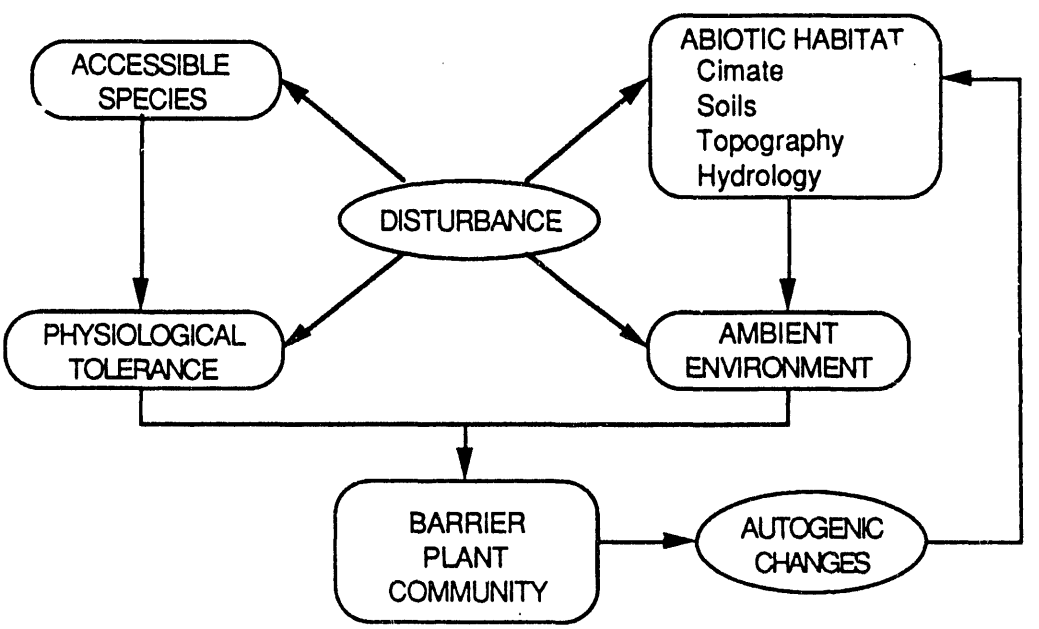

Figure 5.1. Simple Conceptual Model of Plant Community Development and Change on Barriers

development, erosion, and biointrusion). From this information, a set of extreme conditions or states should be defined that would test the performance of the barrier. A reconnaissance for analog sites of these extreme conditions (climate, soils, disturbance histories) should be conducted using tools such as remote imagery and geographical information systems (GISs) where appropriate (see Section 5.4).

5.2.4 Experimental Design

The last step, which should be undertaken only after the previous steps have been completed, is to design and conduct comparative experiments at selected analog sites. The studies should be designed to compare analogs of different environmental states with each other, and with initial barrier conditions as defined by engineering specifications. Site conditions (e.g., soils, climate) must be quantified as part of these studies, as must vegetation parameters associated with barrier performance.

5.3 Durability and Performance of Anthropogenic Materials and Structures

The two anthropogenic components of the proposed barrier design for which analogs can be found are the barrier mound itself and the asphalt moisture membrane to be buried within it. Both these components have analogs in the archaeological record in the United States and elsewhere.

Studies of ancient temple and burial mounds, which were initiated in support of research for uranium mill tailings impoundments and carried further under the National Low-Level Waste Management Program (Chatters et al. 1990) should be continued as part of analog research for protective barrier development. Study of data on these mounds, obtained by archaeologists over the past century, indicates that certain mound designs have a better chance for long-term survival. Additional study should analyze data on manmade mounds that were assembled for the low-level waste program and estimate survival probabilities of different mound designs. Extant mounds that share design characteristics with proposed barriers and/or that are located in arid or semiarid environments should be identified and studies conducted to determine the relationship between mound design characteristics and water distributions beneath the mound surface. Fieldwork would entail coring or trenching of the mound, characterizing mound stratigraphy and soil physical characteristics, and measuring soil water content of each mound stratum. Work would be conducted in conjunction with ongoing archaeological projects in Arizona and the American Midwest. Results would support assessments of barrier performance after long-term exposure to natural modification processes.

Ancient asphalt will provide a source of analog data on how the chemical and physical properties of this material change through time. Materials suitable for sampling and chemical analyses are available in museum collections from archaeological sites on the south-central coast of California. Selected specimens would be dated and analyzed to determine their source. A sample of items from the same source would be analyzed by petrochemical experts and compared to material collected for this study

from the same source, to ascertain how they have changed in the centuries since they were last heated and buried. The result would be a trajectory of change in the asphalt's properties with time, from which the performance of the moisture membranes to be used in barriers could be estimated.

5.4 Analog Site Selection With Geographical Information Systems

Site selection should involve 1) defining analog site criteria for the study, 2) retrieving landscape data to identify candidate sites, 3) conducting field reconnaissance to corroborate site characteristics, and 4) selecting study areas. Geographical information systems would enable one to retrieve, store, manipulate, and make readily and rapidly available a vast amount and variety of landscape-scale environmental data. With a GIS, landscape characteristics such as geology, soils, vegetation, climate, and land use could be acquired, analyzed, and integrated in the site-selection process.

A GIS enables a user to input, modify, overlay, search, analyze, display, and output maps and aerial or satellite image data. Geographic data can consist of line data, such as property boundaries and roads; text data, such as tables or written descriptions; points, such as well locations or study sites; and grid-cell data, such as soil and vegetation maps. Data can be input to a GIS directly as with digital satellite imagery, it can be digitized using desk-top scanners as when entering soils and vegetation maps, or it can be entered manually with a digitizing tablet as with point and line information.

Once in the GIS system, a wide range of operations can be performed, including image analysis, coordinate conversions, overlays, statistical calculations, database operations, three-dimensional representations, distance measurement, and many others. The critical step in using a GIS is geo-referencing the data, or locating the data points with respect to a map grid. Once geo-referencing is completed, data analysis and modeling can be performed quickly and accurately.

Criteria defining parameters such as soils, geology, vegetation, climate, landform, and geographic position for analogs of various barrier components and environmental states could be compiled for each analog task. The types and forms of needed landscape data could be determined from these criteria. Numerous sources of landscape data, including Landsat and SPOT satellite imagery, vegetation maps, soil surveys, geological surveys, and meteorological databases, could be compiled to identify candidate analog sites in the Columbia Basin and, if needed, throughout the Northwest and Intermountain West. Imagery could be obtained and classified using supervised and unsupervised classification techniques to identify areas with desirable land-cover features. Pacific Northwest Laboratory's Geographic Resource Analysis Support System (GRASS) could be used for data integration, manipulation, and the initial selection of candidate sites. Field data obtained during reconnaissance of candidate sites could be entered into the GRASS database and used in conjunction with imagery and map data for the final selection of study locations.

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Appendix A

Carbonate Content Analysis Procedure

Appendix A

Carbonate Content Analysis Procedure

A.1 Reagents

1. Hydrochloric acid, 4 M - Add 340 mL of concentrated reagent grade HCl to about 500 mL of deionized water. Dilute to 1 L and mix thoroughly.

2. Calibration standard - Dry a quantity of reagent- grade (or primary standard) sodium carbonate for 2 h at 120 to 125°C. Weigh 31.80 ≥ 0.01g, dissolve it in deionized water, and dilute to 1.00 L. Store in a polyethylene bottle. This solution should be protected from evaporation and contamination and replaced each month. One milliliter is equivalent to 30.0 mg of $CaC0_3$.

3. Quality assurance standard - Use reagent-grade calcium carbonate with a minimum assay of 99%. Dry overnight in an oven at a minimum temperature of 120°C and store in a desiccator.

4. Displacement solution - Dissolve 100 g of sodium sulfate decahydrate ($Na_2SO_4,10H_2$) in 500 mL of deionized water. Add about 1 g of sodium bicarbonate, $NaHCO_3$, and 2 mL of a 0.5% methyl orange solution. Add HCl (4-5 M) to make slightly acid (a definite pink color). Stir until CO_2 bubbles are no longer visible. This solution will be saturated with CO_2 and will not have a tendency to absorb CO_2 from the sample.

A.2 Equipment

1. Balance - Single pan, sensitive to a minimum of 0.01 g or less.

2. Gasometer - Shop-made, consisting of gas tube, graduated gas buret, compensating tube, and leveling bulb.

3. Flasks - Pyrex, 150 mL with 34/28 standard taper neck fitted with special acid buret.

4. Magnetic stirrer and stir bars.

5. Buret (for dispensing calibration standard) - Twenty-five or fifty milliliter, graduated in 0.1-mL increments, fitted with a loose cap to exclude dust. This buret must be kept clean. If it does

not drain smoothly (drops retained on walls), it should be cleaned with a warm solution of detergent or trisodium phosphate (5 g/L) and rinsed thoroughly.

6. Interval timer

A.3 Method

1. Weigh approximately 5 g to ≥ 0.01 g of sample and transfer to a reaction flask. Add a stir bar to the flask (for quality assurance standard, use 0.10 to 0.15 g weighed to 0.0001 g).

2. Fit the acid buret to the top of the flask and place flask on magnetic stirrer.

3. Close top of acid buret with a rubber stopper.

4. Turn three-way stopcock to vent gas tube and compensating tube to the air.

5. Adjust height of leveling bulb until liquid level in gas buret is at 0.

6. Turn three-way stopcock to connect gas tube to gas buret with outside vent tube closed.

7. Set timer for three minutes and open stopcock on acid buret. Turn magnetic stirrer on.

8. When the timer alarms, lower the leveling bulb until the liquid levels in the compensating tube and gas buret are the same. Record the volume reading on the gas buret (adjusting the levels in this way ensures that the gas in the buret is at atmospheric pressure).

9. Rerun the sample if a) a leak is suspected in the apparatus or, b) if the volume of gas measured is greater than the greatest gas volume used in the calibration. In such case, rerun using a smaller sample.

10. Percent calcium carbonate is determined using the method of Horowitz (Nelson 1982).

11. Return the unused portion of sample to original container in the Hanford Geotechnical Sample Library.

12. Results of the analysis are to be forwarded to the cognizant geoscientist who transfers the information onto the Sediment Analysis form.

A.4 Calcium Carbonate Analysis Quality Assurance

1. Run calcium carbonate standard every four hours. If the recovery is outside of 100 percent by $\geq$ 15 percent, run a new calibration curve. Rerun the calcium carbonate standard to verify the new calibration curve.

2. At the completion of every ten sample analyses, select one of the samples at random and rerun.

A.5 Reference

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Appendix B

Particle-Size-Distribution, Sediment Classes, $CaCO_3$ Content, and Soil Moisture Content for Pit 29 and the PUREX Sand Pit (Sampled September 1983)

Appendix B

Particle-Size-Distribution, Sediment Classes, $CaCO_3$ Content, and Soil Moisture Content for Pit 29 and the PUREX Sand Pit (Sampled September 1983)

Pit 29, Pit Face

Depth (cm)	Particle sizes (mm) >2.0	1.0-2.0	0.5-1.0	0.25-0.50	0.125-0.25	0.063-0.125	<0.063	Sediment Glass	$CaCO_3$ (%)	SMC (wt%)
0-25	24.0	1.4	4.9	6.8	12.5	27.3	23.2	GMS	0.05	6.03
50-80	5.4	1.9	5.1	6.9	13.6	31.1	36.1	MS	0.37	8.03
80-110	79.9	2.5	4.3	0.9	4.1	1.9	6.3	MSG	0.38	3.73
110-150	54.1	10.1	18.9	11.6	2.7	1.0	1.6	SG	0.28	3.07
150-180	90.2	3.7	3.8	1.3	0.4	0.2	0.3	G	0.79	2.30
185-205	93.0	2.0	2.5	1.0	0.4	0.3	0.8	G	3.79	0.97
205-235	87.3	5.1	5.3	1.5	0.3	0.1	0.4	G	0.26	2.40

Pit 29, Trench Face 1

Depth (cm)	Particle sizes (mm) >2.0	1.0-2.0	0.5-1.0	0.25-0.50	0.125-0.25	0.063-0.125	<0.063	Sediment Glass	$CaCO_3$ (%)	SMC (wt%)
30	1.5	1.2	5.4	11.1	20.1	37.5	23.0	MS	0.10	2.57
60	1.7	1.0	4.5	8.1	15.1	33.7	35.4	MS	0.20	2.49
90	6.1	15.7	14.8	5.7	8.3	12.6	46.5	(G)SM	4.89	3.56
120	67.9	5.7	6.9	5.9	3.2	2.5	7.8	G	2.05	2.38
150	92.0	3.2	2.5	1.3	0.3	0.1	0.4	G	1.07	2.00
180	72.0	10.7	10.5	5.1	0.8	0.3	0.7	G	0.47	2.20
210	88.6	4.0	3.5	2.4	0.5	0.3	0.5	G	0.48	1.90
240	80.2	5.7	5.3	6.2	1.2	0.4	0.8	G	0.47	2.50

Pit 29, Trench Face 2

Depth (cm)	Particle sizes (mm) >2.0	1.0-2.0	0.5-1.0	0.25-0.50	0.125-0.25	0.063-0.125	<0.063	Sediment Glass	$CaCO_3$ (%)	SMC (wt%)
45	1.2	1.0	4.8	10.6	20.2	38.7	23.3	MS	0.3	2.42
90	6.2	2.1	5.3	7.1	13.8	26.4	38.8	(G)SM	5.17	3.65
130	68.1	3.4	5.0	6.3	4.5	4.6	7.2	G	5.95	2.43
165	64.3	8.9	10.9	9.3	3.2	1.4	1.8	G	0.66	2.27
195	85.8	5.0	2.7	2.7	1.0	0.5	2.0	G	0.95	2.42

Purex Sand Pit, Trench Face

Depth (cm)	Particle sizes (mm) >2.0	1.0-2.0	0.5-1.0	0.25-0.50	0.125-0.25	0.063-0.125	<0.063	Sediment Glass	$CaCO_3$ (%)	SMC (wt%)
0	0.1	2.7	17.4	12.0	19.6	28.1	19.7	(M)S	0.60	0.9
30	0.3	10.3	31.5	11.5	16.4	20.6	9.4	S	0.00	2.2
60	0.1	7.7	49.6	12.6	14.6	13.1	2.7	S		1.9
90	0.1	7.8	43.6	16.3	15.4	14.8	1.9	S	0.13	1.7
120	0.5	12.9	43.5	11.6	13.9	15.5	2.2	S	0.50	1.7
150	0.8	10.9	37.9	15.0	17.7	15.9	2.1	S	0.60	1.7
180	0.0	2.1	45.1	22.1	17.3	12.0	1.4	S	0.27	1.6
210	0.0	1.6	36.6	24.7	20.9	14.7	1.4	S	0.29	1.7

Purex Sand Pit, Pit Face

Depth (cm)	Particle sizes (mm) >2.0	1.0-2.0	0.5-1.0	0.25-0.50	0.125-0.25	0.063-0.125	<0.063	Sediment Glass	$CaCO_3$ (%)	SMC (wt%)
0	0.1	1.5	10.2	9.5	27.9	35.3	15.2	(M)S	0.00	0.7
30	0.1	2.4	17.5	12.2	21.6	31.6	14.6	(M)S	0.03	2.7
60	0.1	2.3	17.4	12.6	19.2	30.6	17.7	(M)S	0.02	2.7
90	0.1	3.6	20.7	13.0	20.0	28.2	14.3	(M)S	0.72	2.9
120	0.1	5.3	24.0	12.8	21.7	25.7	10.0	(M)S	0.14	3.6
150	0.1	4.0	27.9	17.4	22.8	22.1	5.9	S	0.43	3.1
180	0.1	6.8	46.2	14.1	15.4	15.0	2.6	S	0.07	4.1
210	0.1	3.4	36.7	22.4	19.2	15.6	2.5	S	0.30	3.9
315	0.1	3.5	33.1	31.8	20.1	10.4	0.9	S	0.24	3.3
415	0.0	1.0	24.1	31.2	26.0	15.8	1.8	S	0.18	3.3
515	0.0	0.8	17.6	27.2	28.7	23.0	2.9	S	0.65	3.9

Appendix C

Particle-Size-Distribution Data for Bergmound 1 Gravel, Bergmound 1 No-gravel, Route 4 Gravel, and Route 4 No-gravel Analog Sites

Appendix C

Particle-Size-Distribution Data for Bergmound 1 Gravel, Bergmound 1 No-gravel, Route 4 Gravel, and Route 4 No-gravel Analog Sites

Bergmound 1 Gravel Site

Depth (cm)	Particle Sizes (mm)								
	>4.0	2.0-4.0	1.0-2.0	.5-1.0	.25-0.5	0.125-.25	.063-.125	.043-.063	<.043
0-5	0.2	0.8	0.5	1.0	4.6	16.4	28.9	24.8	22.9
0-5	0.1	0.4	0.5	1.3	2.8	25.0	43.3	16.6	10.0
0-5	14.8	0.7	0.3	0.9	2.6	22.7	33.1	15.6	9.2
0-5	5.9	0.7	0.4	1.0	4.9	21.3	40.8	17.7	7.4
0-5	2.5	1.2	1.1	1.8	4.2	13.7	28.7	23.3	23.4
40-50	0.0	0.4	0.1	0.4	1.9	6.6	24.6	29.7	36.4
40-50	0.6	1.3	1.2	2.2	1.9	8.8	17.9	24.7	41.4
40-50	1.2	0.5	0.5	0.9	3.4	10.0	28.2	27.0	28.5
40-50	0.5	0.3	0.3	0.5	0.7	3.8	33.7	35.7	24.6
40-50	0.0	0.1	0.2	0.5	1.7	4.6	28.2	33.2	31.6
100-110	0.0	0.0	0.1	0.1	0.1	1.9	23.6	36.1	38.1
100-110	1.2	1.0	0.7	1.0	3.3	14.8	33.7	21.2	23.2
100-110	0.0	0.1	0.3	0.5	1.4	5.5	24.8	27.0	40.4
100-110	0.1	0.3	0.4	0.8	3.0	8.0	19.4	23.7	44.3
100-110	0.0	0.2	0.8	1.6	1.4	3.1	13.1	27.3	52.4

Bergmound 1 No-Gravel Site

Depth (cm)	Particle Sizes (mm)								
	>4.0	2.0-4.0	1.0-2.0	.5-1.0	.25-0.5	0.125-.25	.063-.125	.043-.063	<.043
0-5	0.0	0.0	0.2	0.4	1.1	10.0	40.9	30.8	16.7
0-5	0.1	0.2	0.4	1.2	2.9	14.2	40.8	27.8	12.3
0-5	1.3	0.1	0.4	1.3	4.0	18.1	37.5	22.7	14.6
0-5	0.3	0.1	0.1	0.9	2.6	19.6	41.5	24.0	10.9
0-5	0.0	0.0	0.1	0.2	0.4	1.6	13.9	37.2	46.7
40-50	0.0	0.0	0.1	0.3	0.5	2.3	17.4	35.6	43.9
40-50	0.5	0.6	0.8	1.9	3.8	5.9	20.7	31.3	34.5

Depth (cm)	>4.0	2.0-4.0	1.0-2.0	.5-1.0	.25-0.5	0.125-.25	.063-.125	.043-.063	<.043
40-50	0.7	2.1	1.0	1.3	0.9	4.8	23.6	33.1	32.5
40-50	0.0	1.0	1.4	1.7	1.8	4.4	17.7	34.3	37.7
40-50	0.3	0.9	1.4	4.4	7.5	23.2	34.2	22.8	5.2
100-110	0.0	0.1	0.4	0.9	0.9	14.0	35.7	22.8	25.2
100-110	0.0	0.5	0.3	0.5	0.5	2.6	23.3	31.7	40.6
100-110	0.0	0.3	0.5	1.6	2.3	6.8	26.1	25.9	36.6
100-110	3.9	1.8	1.2	1.8	2.1	7.2	22.7	22.8	36.7
100-110	0.1	0.1	0.4	1.4	3.1	11.7	32.4	24.2	26.7

Route 4 Backslope Gravel Site

Depth (cm)	Particle Sizes (mm)								
	>4.0	2.0-4.0	1.0-2.0	.5-1.0	.25-0.5	0.125-.25	.063-.125	.043-.063	<.043
0-20	60.5	7.7	4.9	17.8	4.5	2.2	0.9	0.3	1.2
0-20	63.0	4.7	4.2	20.8	3.3	1.9	0.1	1.0	1.0
0-20	56.3	8.3	4.4	20.7	4.4	3.1	1.3	0.3	1.1
0-20	18.8	13.1	8.7	38.5	8.1	7.9	2.9	0.9	1.3
0-20	40.2	11.5	7.9	26.5	4.3	5.8	1.8	0.6	1.4
40-50	0.0	0.0	0.1	11.1	44.7	38.1	5.9	0.1	0.1
40-50	0.0	0.1	0.7	9.3	23.2	40.9	22.5	2.3	1.0
40-50	0.0	0.1	3.6	18.4	27.8	31.0	17.1	1.4	0.5
40-50	0.0	0.0	2.7	17.4	32.0	36.6	10.3	0.5	0.4
40-50	0.0	0.1	1.5	12.4	22.9	47.5	14.5	0.8	0.3
120-130	0.0	0.0	0.3	7.9	18.5	37.2	28.8	4.5	2.6
120-130	0.0	0.1	0.4	15.0	31.6	37.7	14.0	0.9	0.3
120-130	0.0	0.5	2.3	12.9	20.9	44.3	17.4	1.1	0.6
120-130	0.0	0.0	0.0	4.9	31.1	57.6	6.2	0.2	0.1
120-130	0.0	0.0	0.7	5.7	17.7	52.2	22.5	0.9	0.3
200-210	0.0	0.1	2.1	7.7	19.9	43.7	25.0	1.3	0.1
200-210	0.0	0.3	1.4	9.0	28.3	37.7	21.0	2.0	0.3
200-210	0.0	0.7	1.8	9.7	23.6	39.1	23.3	1.8	0.1
200-210	0.0	0.0	1.3	5.0	13.3	36.7	28.4	12.3	3.0
200-210	0.0	0.0	2.0	4.2	17.8	57.7	17.4	0.7	0.2

Route 4 Backslope No-Gravel Site

Depth (cm)	Particle Sizes (mm)								
	>4.0	2.0-4.0	1.0-2.0	.5-1.0	.25-0.5	0.125-.25	.063-.125	.043-.063	<.043
0-10	0.0	0.0	0.0	3.7	23.4	44.5	24.6	2.7	1.1
0-10	0.0	0.0	0.5	12.5	25.0	34.2	22.8	3.5	1.6
0-10	0.0	0.1	0.3	5.7	22.3	39.8	27.5	3.0	1.4
0-10	0.0	0.0	0.1	6.1	22.5	41.8	25.0	3.0	1.6
0-10	0.0	0.0	0.1	5.3	18.3	36.4	31.3	5.0	3.5
80-90	0.0	0.0	0.2	8.9	21.2	37.4	28.2	2.7	1.5
80-90	0.0	0.0	0.1	2.2	9.9	36.7	46.4	4.3	0.3
80-90	0.0	0.0	0.1	3.6	17.3	40.3	35.1	3.1	0.6
80-90	0.0	0.0	0.2	4.9	19.4	41.2	31.4	2.9	0.1
80-90	0.0	0.0	0.6	2.7	11.7	27.2	49.6	6.3	1.9
160-170	0.0	0.0	0.1	3.1	25.0	47.5	21.9	1.8	0.6
160-170	0.0	0.0	0.1	7.1	14.9	36.4	38.5	2.8	0.3
160-170	0.0	0.1	0.1	4.3	30.3	39.0	23.1	2.7	0.4
160-170	0.0	0.0	0.2	3.0	10.8	25.6	49.8	7.9	2.7
160-170	0.0	0.0	0.0	0.7	17.1	51.8	28.0	2.2	0.2
240-250	0.0	0.0	0.2	3.6	13.5	49.9	29.8	2.7	0.3
240-250	0.0	0.0	0.3	16.2	18.8	36.0	25.3	2.8	0.6
240-250	0.0	0.6	1.2	7.8	7.5	20.2	47.4	12.3	3.1
240-250	0.0	0.1	0.2	2.8	7.9	38.5	47.4	2.8	0.2
240-250	0.0	0.0	0.0	5.1	2.6	25.9	58.7	6.9	0.9

Appendix D

Soil-Water-Content Data for Bergmound 1 Gravel, Bergmound 1 No-gravel, Route 4 Gravel, and Route 4 No-gravel Analog Sites (Sampled May 1984)

Appendix D

Soil-Water-Content Data for Bergmound 1 Gravel, Bergmound 1 No-gravel, Route 4 Gravel, and Route 4 No-gravel Analog Sites (Sampled May 1984)

		Soil Moisture Content (wt%)		
Site	Depth (cm)	Value	Mean	SE (mean)
Bergmound 1 Gravel	0-10	9.9	10.0	0.44
	0-10	10.1		
	0-10	8.4		
	0-10	10.9		
	0-10	10.7		
	20-30	7.6	8.8	0.58
	20-30	8.2		
	20-30	7.8		
	20-30	9.8		
	20-30	10.5		
	40-50	9.2	10.1	0.49
	40-50	10.5		
	40-50	8.7		
	40-50	10.8		
	40-50	11.3		
	60-70	9.6	11.7	1.97
	60-70	10.2		
	60-70	9.3		
	60-70	10.0		
	60-70	19.6		
	80-90	8.4	9.8	0.80
	80-90	10.1		
	80-90	11.8		
	80-90	7.5		
	80-90	11.0		

Site	Depth (cm)	Soil Moisture Content (wt%) Value	Mean	SE (mean)
	100-110	6.1	7.2	0.68
	100-110	5.6		
	100-110	8.0		
	100-110	7.4		
	100-110	8.8		
Bergmound 1 No-Gravel	0-10	9.8	9.7	0.53
	0-10	9.5		
	0-10	11.2		
	0-10	7.9		
	0-10	10.1		
	20-30	10.0	10.7	0.97
	20-30	9.1		
	20-30	14.3		
	20-30	9.1		
	20-30	11.2		
	40-50	9.3	10.4	0.29
	40-50	10.3		
	40-50	10.5		
	40-50	10.8		
	40-50	10.9		
	60-70	20.3	15.9	1.51
	60-70	15.9		
	60-70	10.8		
	60-70	16.1		
	60-70	16.2		
	80-90	10.9	11.9	1.64
	80-90	11.6		
	80-90	9.9		
	80-90	10.4		
	80-90	17.7		
	100-110	5.9	8.4	1.28
	100-110	10.4		
	100-110	6.5		
	100-110	12.5		
	100-110	6.9		

Site	Depth (cm)	Soil Moisture Content (wt%) Value	Mean	SE (mean)
Route 4 Gravel - 25 cm surface gravel layer	0-10	2.3	2.5	0.23
	1-10	2.4		
	0-10	2.7		
	0-10	2.8		
	0-10	2.3		
	15-20	2.0	2.2	0.40
	15-20	2.6		
	15-20	2.0		
	15-20	2.7		
	15-20	1.8		
Soil Surface	0-10	3.5	3.1	0.17
	0-10	2.8		
	0-10	3.4		
	0-10	3.0		
	0-10	2.6		
	40-50	3.7	3.5	0.20
	40-50	3.5		
	40-50	3.7		
	40-50	2.7		
	40-50	3.8		
	80-90	7.8	5.1	0.70
	80-90	4.2		
	80-90	4.7		
	80-90	3.9		
	80-90	4.7		
	120-130	7.5	5.1	0.60
	120-130	4.3		
	120-130	4.6		
	120-130	4.5		
	120-130	4.6		
	160-170	5.7	5.4	0.35
	160-170	5.6		
	160-170	5.0		
	160-170	6.4		

Site	Depth (cm)	Soil Moisture Content (wt%) Value	Mean	SE (mean)
	160-170	4.3		
	200-210	5.3	5.3	0.21
	200-210	5.5		
	200-210	5.5		
	200-210	4.5		
	200-210	5.7		
Route 4 No-Gravel	0-10	2.9	2.0	0.28
	0-10	1.6		
	0-10	1.3		
	0-10	2.2		
	0-10	2.2		
	40-50	4.3	4.4	0.24
	40-50	4.5		
	40-50	4.9		
	40-50	3.5		
	40-50	4.6		
	80-90	4.9	5.2	0.27
	80-90	5.9		
	80-90	5.3		
	80-90	4.4		
	80-90	5.7		
	120-130	5.1	5.8	0.53
	120-130	7.3		
	120-130	4.6		
	120-130	5.8		
	120-130	6.0		
	160-170	5.4	4.4	0.68
	160-170	3.4		
	160-170	2.3		
	160-170	5.8		
	160-170	5.3		
	200-210	6.4	3.5	0.72
	200-210	3.1		
	200-210	2.6		
	200-210	3.0		
	200-210	2.6		

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