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# Pedogenic Process in Engineered Soils for Radioactive Waste Containment

By

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# Abstract

## Pedogenic Process in Engineered Soils for Radioactive Waste Containment

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Doctor of Philosophy in Geography

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The emergence of soil morphology has long been under emphasized in the planning and maintenance of engineered soils for waste containment. Recent studies report that soil change induced alterations to waste cover engineering properties, including hydraulic conductivity, can occur in as little as five-years post construction. With mandated waste cover performance lifetimes of hundreds to thousands of years, an understanding of long-term change can directly increase human and environmental health at a reduced cost. This manuscript explores how engineered soils for waste containment change through space and time and documents how such natural changes impact as-built engineered performance. Special emphasis is placed on cover systems in the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA) portfolio managed by the United States Department of Energy, Office of Legacy Management (DOE-LM). Four sites were studied that represent engineering, climatic, and management conditions commonly found across the portfolio. Herein, we use 30-years of archived inspection reports to explore how setting, engineering design, and management influence rates and patterns of change; position engineered soils within a factorial framework of soil formation; discuss dominant pedogenic processes occurring in engineered soils over decadal time frames from field investigation and a literature review; and use a soil morphological development index to compare the soil morphology of in-service covers, and natural analogs, to measured hydraulic conductivity and radon diffusion coefficients to explore long-term rates of change.

*This work is dedicated to Henry Lin.*

*His passion for the landscape lives on.*

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Lastly, this work would not have been possible without the financial support of the University of California Chancellors Fellowship, the U.S. Department of Energy, Office of Legacy Management, and the University of California, Berkeley Department of Geography.

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## ABBREVIATIONS AND ACCRONYMS

BW – Bluewater, New Mexico UMTRCA site
CCB – Composite Capping Barrier
$cm^3$ – Cubic centimeters
CMB – Compressed Mineral Barrier
$D_{50}$ – Mean diameter of rock armor
DOE – United States Department of Energy
DOE-EM – United States Department of Energy Environmental Management
DOE-LM – United States Department of Energy, Office of Legacy Management
DRI – Desert Research Institute
EPA – United States Environmental Protection Agency
FC – Falls City, Texas UMTRCA site
INEL – Idaho National Engineering Laboratory
Kfs – Field saturated hydraulic conductivity
Ksat – Field saturated hydraulic conductivity
LANL – Los Alamos National Laboratory
LMS – Legacy Management Support
LV – Lakeview, Oregon UMTRCA site
$m^2$ – Meters squared
$m^2$/s – Meters squared per second
NRC – United States Nuclear Regulatory Commission
NUREG – United Stated Nuclear Regulatory Report
PMB – Planted Mineral Barrier
SB – Shirley Basin South, Wyoming UMTRCA site
SMDI – Soil Morphological Development Index
UMTRCA – Uranium Mill Tailings Radiation Control Act
UVA – University of Virginia
UW – University of Wisconsin

## DECLARATION OF CO-AUTHORED MATERIALS

This dissertation was completed as part of a joint U.S. Department of Energy (DOE) Office of Legacy Management (LM) and U.S. Nuclear Regulatory Commission (NRC) study "*Effects of Soil-Forming Processes on Cover Engineering Properties*". Scientists from DOE Legacy Management Support (LMS), NRC, the University of Wisconsin, Madison (UW), the University of Virginia (UVA), the Desert Research Institute (DRI) and the University of California, Berkeley collaborated on this study. Project collaborators from LMS focused on ecological and regulatory characterization, while researchers from UW, UVA and DRI focused on the characterization of engineering properties with emphasis on radon flux and saturated hydraulic conductivity, and NRC researchers focused on Pb210 and radon diffusion modeling. This dissertation focuses on the characterization of earth surface processes and soil morphology of waste disposal cells of the Uranium Mill Tailings Radiation Control Act (UMTRCA) portfolio. A list of published, in draft, and submitted works are provided in (Table A). Citations in this dissertation reference these working drafts.

| Table A. Published, submitted, and drafted publications from research group |
|---|
| Williams, M.M., Benson, C., Fuhrmann, M., Likos, W., Michaud, A., Stefani, N., Waugh W.J. (2019). Soil morphological development of in-service covers. In *Effects of Soil Forming Processes on Cover Engineering Properties*. NUREG/XX-XXX, ***in draft***.<br>Waugh, W.J., Benson, C., Fuhrmann, M., Likos, W., Michaud, A., Stefani, N., Williams, M.M. (2019). Overview and site selection. In *Effects of Soil Forming Processes on Cover Engineering Properties*. NUREG/XX-XXX, ***in draft***.<br>Likos, W., Benson, C., Fuhrmann, M., Michaud, A., Stefani, N., Waugh, W.J., Williams, M.M. (2019). Radon flux of in-service covers. In *Effects of Soil Forming Processes on Cover Engineering Properties*. NUREG/XX-XXX, ***in draft***.<br>Benson, C., Fuhrmann, M., Likos, W., Michaud, A., Stefani, N., Waugh, W.J., Williams, M.M. (2019). Hydraulic properties of in-service covers. In *Effects of Soil Forming Processes on Cover Engineering Properties*. NUREG/XX-XXX, ***in draft***.<br>Fuhrmann, M., Arlt, H., Benson, C., Waugh, W.J., Williams, M.M. (2019a). Proceedings of the Radon Barriers Workshop. U.S. Nuclear Regulatory Commission, Washington D.C. NUREG/CP-0312. https://www.nrc.gov/reading-rm/doc-collections/nuregs/conference/cp0312/<br>Fuhrmann, M., Michaud, A., Salay, M., Benson, C., Likos, W., Stefani, N., Waugh W.J., Williams, M.M. (2019b). Pb-210 Profiles in Radon Barriers, Indicators of Long-term Rn-222 Transport. *Applied Geochemistry*,104434. |

# 1. INTRODUCTION

Waste management has been of concern since humans began to settle in fixed geographic areas and represents one of the first human-soil interactions. Efficiencies have improved, yet the fundamental solution to waste management has not changed much in 10,000 years. While the toxicity of wastes that humans generate has become more concentrated and noxious, burial under the ground remains the safest of long-term management options. With the modern proliferation of highly toxic and environmentally mobile elements produced during the atomic age, the societal need to immobilize radioactive materials under the ground has given rise to the design and construction of engineered disposal cells for the long-term containment of wastes including uranium mill tailings (Figure 1.1). Given stakeholder concerns related to wastes generated from post World War II and Cold War efforts, the United States Congress passed the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978 (Public Law 95-604), providing a framework for the remediation and long-term stabilization of mill tailings at processing sites across the United States. This effort represents one of the world's largest coordinated land reclamation efforts (Diehl, 2013). The United States Department of Energy, Office of Legacy Management (DOE-LM) are the stewards of the UMTRCA portfolio, under license from the United States Nuclear Regulatory Commission (NRC).

Figure 1.1: Engineered disposal cells of the UMTRCA program

Durango, Colorado

Mexican Hat, Utah

Ambrosia Lake, New Mexico

L-Bar, New Mexico

Images courtesy of The Center For Land Use Interpretation

Soils, including engineered covers constructed for waste containment, are a heterogeneous mixture of reactive primary particles, secondary aggregates, pore space, liquids, gasses, and biota organized across scales at the Earth's surface. They are open and dynamic systems that are subject to recurring fluxes of energy and mass with impacts to both short-term function and long-term evolution. As living systems, soils evolve and change by taking freely available energy from the environment (in the form of sunlight, water, nutrients and other materials), transforming it, and moving towards higher order and more complex systems (Lin, 2011). As an energy consuming activity, soil evolution is a dissipative process that results in the self-organization of internal architecture as evident in the emergence of aggregates, pore space, soil horizons, and pedons in natural systems (Targulian and Goryachkin, 2004; Lin, 2010a; Lin, 2010b). The dynamic properties of soil change, and the self-organization of soil morphology through time, give rise to an abundance of natural soil diversity as seen in the many colors, textures, patterns and heterogeneities present across the worlds many soils. However, the inevitability of Earth surface process, and corresponding pedogenic processes that drive soil change, may run counter to conventional engineering efforts that rely on the rigid isolation of wastes through the structural maintenance of compressed clay barriers common to waste management systems across the planet, including those in the UMTRCA program.

Historically, the dynamic properties of soil change, and the emergence of novel soil morphology, have been under emphasized in the planning of engineered cover systems intended for the long-term containment of wastes. Disposal cells for the isolation of uranium mill tailings in the United States are expected to control radioactive, and other hazardous wastes, for up to 1,000 years, to the extent reasonably achievable, and, in any case, for at least 200 years (10 CFR Part 40). Conventional cover systems have largely been designed to resist natural processes, as opposed to working with them at considerable economic cost (Clarke et al., 2004). In as little as 5-years post construction, soil processes including bioturbation by plants and animals (Arthur and Markham, 1983; Burt and Cox, 1993; Link et al., 1995), freeze-thaw cycling (Kim and Daniel, 1992; Benson et al., 1995), and desiccation cracking (Montgomery and Parsons, 1989; Melchior, 1997) have led to the emergence of soil morphology and subsequent alterations to the as built hydraulic properties of compressed clay barriers in engineered covers (Taylor et al., 2003; Albright et al., 2004; Benson et al, 2011). Studies that connect cover performance and Earth surface processes are rare (Beedlow and Hartley, 1984; Burt and Cox, 1993; Link et al., 1994; Smith et al., 1997; Waugh et al., 1999; Taylor, et al., 2003; Albright et al., 2006a; Fourie and Tibbet, 2007), and systematic treatments that link soil process to engineering performance are sparse (DeJong et al., 2014).

### 1.1. STUDY QUESTIONS

This study addresses several scientific questions related to long-term change in engineered soils for waste containment:

A. Are changes to surface condition on engineered disposal cells systematic, and can trends be observed across space and time from annual inspection report archives?

B. Do changes to surface condition influence as-built soil morphology?

C. How can soil forming factors be used to describe soil and landscape morphology on engineered covers for waste containment?

D. How does the degree of soil morphological development influence soil engineering properties including radon diffusion and saturated hydraulic conductivity of compressed clay barriers?

E. Can natural analog environments be used to inform long-term trends in the development of soil morphology in engineered covers?

### 1.2. RESEARCH DESIGN

This study was conducted as part of a joint DOE-LM and NRC study "*Effects of Soil-Forming Processes on Cover Engineering Properties"*. Scientists and engineers from Legacy Management Support (LMS), NRC, the University of Wisconsin, Madison (UW), the University of Virginia (UVA), the Desert Research Institute (DRI) and the University of California, Berkeley collaborated on this study. Project collaborators from LMS focused on ecological and regulatory characterization, while researchers from UW, UVA and DRI focused on the characterization of engineering properties with emphasis on radon flux and soil hydraulic properties, while NRC researchers focused on Pb210 and radon diffusion modeling. This document focuses on the characterization of Earth surface processes and soil morphology of waste disposal cells in the UMTRCA portfolio.

Four sites that represent a wide range of cover types, climates, site conditions and vulnerabilities to change were selected for study. A combination of archival work, literature review, field surveys, and laboratory analysis were performed to address study questions. The development of surface features as a function of soil forming factors was performed through archival review of (LMS) annual inspection reports and field surveys. Relationships between surface condition, soil morphology and engineering properties were evaluated through the excavation of representative test pits on covers and natural analog sites to understand short term (in-service) condition and potential long-term effects of pedogenesis on soil engineering properties. In-field radon flux measurements were performed, and diffusion coefficients calculated as described by Likos et al., (2019). Laboratory based measurements were made to determine saturated hydraulic conductivity (*Ksat*) and soil water retention of large diameter block samples collected in the field as described by Benson et al., (2019). A morphological development index was modified from an existing model from high clay soils (Lin et al., 1999a) to compare the degree of development within compressed clay barriers against radon diffusion coefficients and Ksat measurements from collaborators. A literature review was performed to complement field survey observations and construct a conceptual discussion of dominant pedogenic processes in engineered soils for waste containment.

### 1.3. BACKGROUND: THE UMTRCA PORTFOLIO

The climatic distribution, well understood initial conditions, availability of consistent annual inspection reports, and shared regulatory structure, make the UMTRCA portfolio a valuable case study to document how natural processes impact the properties of engineered soils over time. The majority of UMTRCA sites occur in the western states (Figure 1.2). At the onset of the UMTRCA program in 1978, Congress designated 22 inactive uranium-ore processing sites for remediation under Title I and assumed financial responsibility for remediation, management, and maintenance. Many of these sites had been abandoned due to corporate bankruptcies. Remediation of the 22 sites resulted in the creation of 19 engineered disposal cells that contain uranium mill tailings and associated contaminated materials from milling operations. Sites designated as Title II had active milling licenses in 1978 or were issued a license after 1978 and the responsibility of remediation passed to corporate license holders. DOE-LM currently manages 19 Title I and 6 Title II disposal sites (as of March 2019). NRC anticipates licensing one additional Title I disposal site (Moab, UT) and another 24 Title II sites by 2050. In addition to the UMTRCA portfolio, hundreds of sites, of similar design and intention, exist across the United States under different regulatory authority including DOE-LM, Formerly Utilized Sites Remedial Action Program (FUSRAP), the U.S. Department of Energy, Office of Environmental Management (DOE-EM), and the U.S. Environmental Protection Agency (EPA), Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Findings from this study are applicable across sites of various regulatory authority.

Figure 1.2: Map of current and anticipated Title I and Title II UMTRCA sites managed by the Office of Legacy Management as of May 2019

## 1.4. FIELDWORK SITE SELECTION

The process for selecting individual sites and sampling locations on disposal cell covers incorporated a combination of as-built design data from archived site completion reports, radiological data, and observations of surface ecology. To achieve study objectives, the selection of individual sites, and test locations on disposal cell covers, was not random but intentionally biased. The selection process identified disposal sites and test locations on covers where researchers anticipated the greatest changes in cover performance—the worst-case conditions, not the average conditions. A points-based system was used to identify those sites that were most favorable to meeting study objectives. Complete site selection scoring methodology is described in Waugh et al., (2019).

### 1.4.1. STUDY SITES

The site selection process worked through two phases: (1) a ranking system of all Title I and Title II sites from attributes including design vulnerability, climate, vegetation, radiation source activity, and regulatory priority from NRC, and (2) a secondary selection emphasizing contrasting environments (climates and ecologies) and different cover designs. Bluewater, NM scored highest in the initial ranking (Phase 1) and had the greatest variety of cover designs (Phase 2). Three additional sites scored relatively high in the initial ranking and offered the greatest opportunity to compare sites with different designs and environments: Falls City, TX, Shirley Basin South, WY, and Lakeview, OR (Waugh et al., 2019).

#### 1.4.1.1. *FALLS CITY, TEXAS*

The Falls City disposal cell is located at a former uranium-ore processing facility in Karnes County, Texas, approximately 65 kilometers southeast of San Antonio at an elevation of 94 meters above sea level. The site is situated several kilometers west of the San Antonio River, in a sparsely populated mesquite and acacia dominated woodland, that is cleared for agriculture use. The region has an average annual temperature of 26.9 $^{o}$C (high) and 14.3 $^{o}$C (low) with average annual precipitation of 721 mm. The Koppen-Geiger climate is classified as Humid Subtropical, with an Udic-Ustic and Hyperthermic soil moisture and temperature regime. The disposal cell is 52 hectares in size and was completed in 1994. Grass on the cell is regularly cut and baled for cattle feed as part of the long-term surface reuse strategy.

#### 1.4.1.2. *BLUEWATER, NEW MEXICO*

The Bluewater disposal cell is in Cibola County, New Mexico approximately 15 kilometers northwest of Grants, at an elevation of 2,057 meters above sea level. The site once housed both acid-leach and carbonate-leach uranium-ore processing mills. The landscape is composed of basalt lava flows, sedimentary rock outcroppings, and a mix of alluvial and wind-deposited, unconsolidated, fine-grained sediments. Vegetation is dominated by Grama Galleta Steppe along with four-wing saltbush (*Atriplex canescens*) and rubber rabbitbrush (*Ericameria nauseosa*). The area around the disposal site is sparsely populated, and the main land use is livestock grazing. The region has an average annual temperature of 21.3 $^{o}$C (high) and 1.4 $^{o}$C (low) with average annual precipitation of 267 mm. The Koppen-Geiger climate is classified as Cold Semi-Arid with an Aridic-Ustic and Mesic soil moisture and temperature regime. The main tailings disposal cell on the site is 144 hectares in size and was completed in 1995. Emergent vegetation is present on the cell which includes Russian thistle (*Salsola spp*), fourwing saltbush, and squirrel tail (*Elymus elymoides*) grass. Deep rooting plants, including Siberian elm (*Ulmus pumila*) are regularly cut and sprayed with herbicide as part of the long-term surface management strategy.

#### 1.4.1.3. *LAKEVIEW, OREGON*

The Lakeview disposal cell is located roughly 12 kilometers northwest of the town of Lakeview Oregon in Lake County, Oregon at an elevation of 1,464 meters above sea level. The site is situated in a wide valley that is characterized by Quaternary lake sediments and well distributed alluvial cobbles. Vegetation consists of Ponderosa pine (*Pinus ponderosa*) forest in the surrounding higher mountain areas composed of predominantly coarse-grained sediments, and sagebrush-bitterbrush steppe in the fine-grained soils of the foothills and valley. The area is sparsely populated, and the predominant land use is cattle grazing. The region has an average annual temperature of 15.5 $^{o}$C (high) and 0.8 $^{o}$C (low) with average annual precipitation of 374 mm. The Koppen-Geiger climate is classified as Continental with dry summer and a Xeric and Frigid soil moisture and temperature regime. The disposal cell is 6.5 hectares and was completed in 1988. Vegetation can grow on the cell as part of the long-term management strategy.

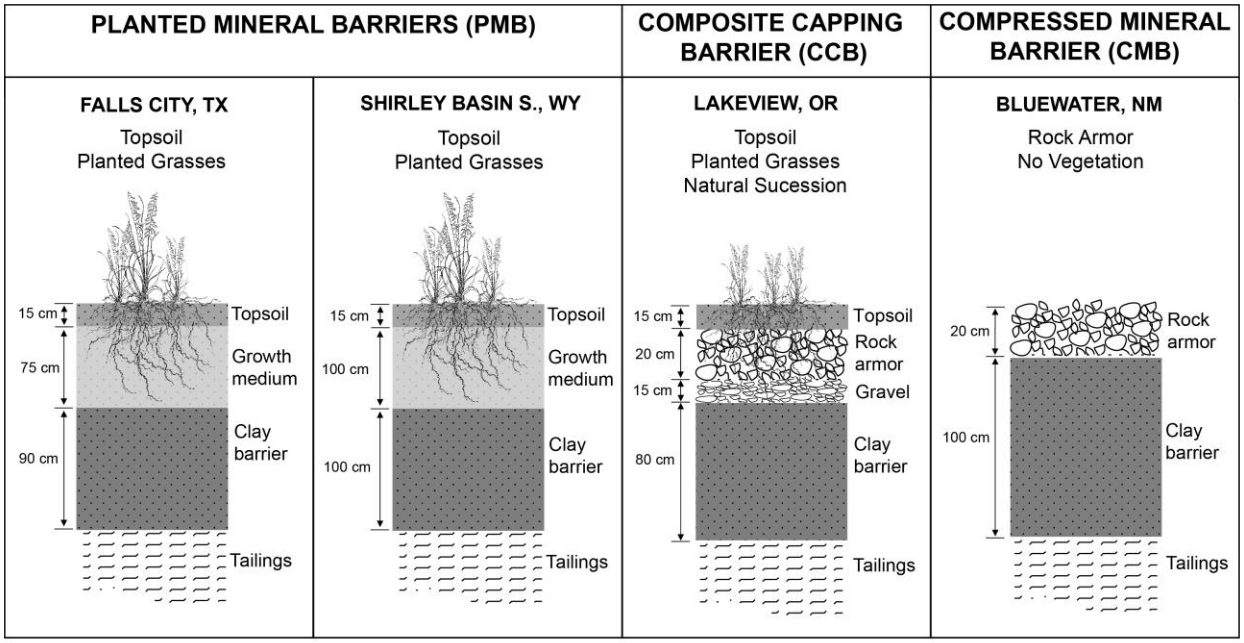
#### 1.4.1.4. *SHIRLEY BASIN, WYOMING*

The Shirley Basin disposal cell is located at a former acid-leach uranium mill site in rural Carbon County about 95 kilometers south of Casper, Wyoming at an elevation of 2,184 meters above sea level. The landscape consists of open rangelands composed of post glacial alluvial sediments formed into gently rolling hills covered by shortgrass prairie of Grama, Needlegrass, and Wheatgrass and occasional sagebrush (*Artemisia tridentata*). Agriculture is limited due to climate and available water. The region has an average annual temperature of 11.3 $^{o}$C (high) and -5.1 $^{o}$C (low) with average annual precipitation of 267 mm. The Koppen-Geiger climate is classified as Cold Semi-Arid with an Aridic-Ustic and Mesic soil moisture and temperature regime. The main tailings disposal cell on the site is 58 hectares in size and was completed in 2001. Vegetation on the cell is grazed by cattle as part of the long-term surface reuse strategy.

### 1.5. COVER DESIGNS

The long-term containment of wastes in the UMTRCA program is commonly accomplished through physical isolation by compressed clay barriers and overladen with either planted soils or rock armor, that are intended to limit liquid and radon gas flux. Three design stratagies were encountered in this study (Figure 1.3).

Figure 1.3: Stratigraphy of four UMTRCA covers at construction



Drawings modified from Waugh and Smith (1997)

### 1.5.1. PLANTED MINERAL BARRIERS

The Falls City, TX disposal cell has two different covers on the top-deck and side-slope. The top-deck cover consists of a 90 cm compacted clay layer; a 75 cm layer of soil considered to be suitable as a plant growth medium and protection layer; and a 15 cm layer of topsoil that was seeded with a mixture of native and introduced warm-season hay grasses. The side-slope cover has a 60 cm clay barrier; a 15 cm layer of gravel bedding material; and a 40 cm layer of limestone rock armor.

The Shirley Basin, WY disposal cell has a similar design as Falls City, TX. The top-deck cover has a 60-100 cm compacted clay barrier; a 60-100 cm silty sand overburden or protection layer, and a 15-25 cm topsoil layer. The topsoil was seeded with a mixture of cool-season native and introduced forage grasses. The interior side-slope cover has the same radon barrier and protection layer design, but with 12 cm of granite rock armor overlying a 10 cm filter (bedding) layer instead of topsoil and vegetation.

### 1.5.2. COMPOSITE CAPPING BARRIERS

The Lakeview, OR disposal cell top-deck and side-slope have a 45 cm compressed clay layer; a 15 cm sandy gravel bedding layer; and a 20-30 cm basalt riprap rock armor layer. After construction, DOE placed a 15 cm topsoil layer above the rock armor on the top deck and seeded it with a mixture of cool season grasses that support natural vegetation succession. The side-slopes did not receive the topsoil treatment or seeding.

### 1.5.3. COMPRESSED MINERAL BARRIERS

The main disposal cell at Bluewater, NM has a 50-100 cm compressed clay barrier; and 10-30 cm of basalt riprap rock armor. A variable thickness of mildly contaminated windblown fines from the surrounding environment was deposited on-top of mill wastes at the lower portion of the cell prior to the construction of the clay barrier. Additionally, the composition of mill tailings varies across the main disposal cell with sandy textured materials dominating the upper portion of the cell and finer textured (slime) tailings dominating the lower portion of the cell. The cell was unvegetated at construction.

## 1.6. DOCUMENT LAYOUT

This document provides a discussion on how engineered soils for waste containment change through space and time with impacts to long term performance. Special emphasis is placed on the clay barrier component of uranium mill tailings cover systems in the UMTRCA portfolio managed by the DOE-LM. Four sites were studied that represent engineering, climactic, and management conditions found commonly across sites in the broader UMTRCA portfolio. Chapter 2 presents results from a survey of Earth surface change across four UMTRCA sites from 30-years of archived inspection reports and discusses how engineering design and management influence rates and patterns of change. Chapter 3 provides a discussion that positions engineered soils within a factorial model of soil formation and uses soil morphological observations to explore how factorial combinations may be expressed through space and time. Chapter 4 provides a discussion on the dominant pedogenic processes occurring within engineered cover systems for waste containment over decadal time frames from soil survey results and a literature review.  Chapter 5 presents a soil morphological development index and explores how soil development impacts hydraulic conductivity and radon diffusion coefficients with impacts to long-term performance.

# 2. SURVEY OF EARTH SURFACE CHANGE ON ENGINEERED COVERS OVER DECADAL TIMEFRAMES

## 2.1. SUMMARY

This chapter compares the surface histories of four uranium mill tailings disposal cells distributed across the western United States. Through the analysis of written, pictorial, and numerical descriptions included in annual site inspection reports conducted between 1989 and 2017, we document the emergence of surface conditions on these waste disposal cells through space and time. A key-word ranking system informed the construction of qualitative delta graphs that capture the emergence of site-specific process and management histories. Across the four sites studied, the graphs show that variations in biological and geophysical surface features largely correspond with original cover design, climate, and ongoing surface management strategy. Deep, Planted Mineral Barriers (PMB's) designed with thick soil layers, an even stand of perennial grasses, and periodic vegetation management, display the least variation in surface features through time. Conversely, shallow, rock armored, Compacted Mineral Barriers (CMB's) that did not incorporate vegetation into original designs display the most variation in surface features through time. The intensity of vegetation development on rock side slopes generally correlated with total annual precipitation, with greater precipitation resulting in greater vegetation development. Precipitation also corresponded to the need for more active management of deep-rooted vegetation on rock slopes. The emergence of surface features is hypothesized to correspond to the development of soil morphology with impacts to long-term performance (explored further in Chapter 5). The documentation of surface histories from inspection reports, provides a non-invasive way to increase our understanding of long-term changes to cover systems across various climates and designs, thereby improving management effectiveness and reducing costs.

## 2.2. INTRODUCTION

Earth surface processes are those physical, chemical, biological, or human forcing's that directly cause, or are influenced by secondary feedbacks associated with, alterations to the form and function of Earth's surface (National Research Council, 2010). Conceptually, these forcing's can be organized into geophysical, biological, and human induced process categories. Several examples of the impacts that these forcing's have on landform development include: climatic impacts to rates of geomorphic processes (Bull, 1991); thermal cycling and rock breakdown (Hall, 1999); aeolian sculpting of landscapes (Seppälä and Seppälä, 2004); ecosystem responses to large scale soil erosion (Pimentel and Kounang, 1998); the development of plant roots and the conditioning of soils by organisms (Angers and Caron, 1998; Glinski, 2018); and the management of landscapes by humans (Hooke, 2000). The relatively new field of biogeomorphology has made great progress in improving our understanding of feedbacks between geomorphology and biota in controlling Earth surface processes and landform evolution (Reinhardt et al 2010; Corenblit et al, 2011). The field of geotechnical engineering has been incremental in its incorporation of long-term performance forecasting methodologies that account for future scenarios based on the emergence of biogeomorphic surface interactions over project design lifetimes. Given above-below ground linkages, secondary impacts to soil morphology, and soil morphological control on engineering properties including hydraulic isolation, the emergence of novel surface features on engineered disposal cells for waste containment are likely to influence performance over time. Annual site inspection reports offer a qualitative means to track the development of surface features on waste disposal cells through time. The documentation of surface histories from annual inspection reports, coupled with soil morphological characterization, provides a non-invasive way to increase our understanding of long-term changes to cover systems across various climates and designs, thereby improving management effectiveness and reducing costs.

### 2.2.1. ANNUAL INSPECTION OF SURFACE CONDITION ON UMTRCA SITES

Federal research groups have long considered how various surface processes may influence the performance of disposal cells over design lifetimes. One such report by Young et al., (1986), provided early guidance on processes that may lead to the emergence of future performance heterogeneity on disposal cells through pathways including: erosion by water, erosion by wind, settlement, human activity, growth of vegetation, burrowing by animals, desiccation and cracking of surface soil and clay radon barrier materials, freezing and thawing, landform movement from seismic activity, and the development of surface salt deposits. Young et al. (1986), anticipated that: 1) the conditions leading to the spread of toxic materials will develop differently from site to site; 2) the geological, hydrological, and meteorological characteristics of a site, the design of the tailings pile and its cover, and the human population density nearby will determine the rate at which conditions develop that could lead to the spread of tailings; and 3) the flux from the covered tailings pile could increase considerably with time as a result of processes such as drying out of the barrier and its cover, wind and water erosion, burrowing by animals, and the growth of vegetation. Testing these hypotheses is a central focus of the larger document for which this chapter is a part of.

In anticipation of long-term changes to engineering performance, and to ensure ongoing regulatory compliance, the mandate to perform annual site inspections was built into operational license agreements between the NRC and the DOE-LM. The annual inspection process is a largely qualitative observation method performed by walking several transects across the disposal cell and looking for the incidence of features on a standard check-list. If a feature of interest is present, a note is made, and a photograph generally taken. Inspections are scheduled to occur during the same month, each year, though deviations to such scheduling do occur for logistical or weather-related reasons. Site specific reports include: an observational narrative; a standardized site map with the location and corresponding photographs of any observed emergent features; results from any site-specific monitoring efforts requested by NRC or site stakeholders (i.e. rock armor breakdown measurements); and results from annual water quality monitoring. The inspection report for each UMTRCA site is made available each year to the public through a dedicated website, and a central archive is maintained by DOE-LM to house previous years site reports and other associated site information.

The observation of surface features during annual inspections that may indicate threats to cell performance have commonly prompted direct management action and in some instances, more detailed scientific investigations to better inform long-term stewardship. Connections between Earth surface condition, pedogenic process, soil morphology and engineering performance are discussed in later sections of this document.

## 2.3. OBJECTIVES

A. Can annual inspection reports from the DOE-LM archive be used to track changes in surface properties on UMTRCA disposal cells from construction to present?

B. How does the inclusion of vegetation at construction influence surface stability over time?

C. How does climate influence the need for human labor (management) at two contrasting planted sites of similar design?

D. How effective is the current UMTRCA annual inspection methodology at capturing surface condition when compared to an intentional walking survey?

## 2.4. METHODS

Archival research from site inspection reports dating back to the early 1980’s was used to construct site process histories and field surveys were conducted to verify records as follows.

### 2.4.1. ARCHIVAL RESEARCH AND DATA ANALYSIS

Access to the annual inspection report archive was made available through a records request with DOE-LM and Navarro Research and Engineering, Inc. The available records included annual inspection reports for 88% of the entire time series from construction to present with the following exceptions: Falls City, TX (years 2, 3, and 5 post construction); Bluewater, NM (years 1, 2, 3, and 4 post construction); Lakeview (year 1 post construction); and Shirley Basin, WY (years 1, 2, 3, and 4 post construction). A combination of factors led to the omission of early post construction annual inspection reports, most notably that annual inspections were not required for Title II sites (Bluewater, NM and Shirley Basin, WY) during the license transfer process into the DOE-LM portfolio.

Available annual inspection reports were reviewed for: 1) the direct inclusion of narratives or keywords associated with specific surface features that correspond to earth surface changes; 2) direct photographic representation of surface features observed during the inspection; or 3) the inclusion of observed features on sitemaps. A combination of the above information was used to determine the overall incidence of surface features at the site in any single year, and to construct a qualitative understanding of year-over-year trends in observed surface changes exerting the most influence on individual site development through time.

### 2.4.2. SURFACE PROCESS KEYWORD ANALYSIS AND SCORING

A keyword directory of surface features that correspond with Earth surface processes most relevant to long-term engineering performance was modified from those originally proposed by Young et al. 1986, (Table 2.1). As individual inspection reports were reviewed, the incidence of processes keywords was recorded. If explicitly stated in written form, the overall qualitative or quantitative incidence of each feature was considered when interpreting the overall year-to-year direction of change. While the annual inspection process is not focused on the collection of numerical data related to individual biological or geomorphic features, hand written notes did frequently indicate estimates for factors including: vegetation density, erosion feature counts, number of deep-rooted plants treated with herbicide, number of perimeter signs replaced, and number of animal burrows observed. In some instances, annual inspections coincided with separate scientific field investigations where quantitative data were collected. In the effort to normalize all observational data into simplified directional data, any quantitative information (i.e. there were 21 rills present on the site during inspection, or the ephemeral lake was estimated by LiDAR to be 4.1 hectares in size), were converted into year-over-year qualitative categories of more, less, same, or none observed. Written observations were cross referenced against visual information presented in site photographs and annotated maps to create a full understanding of annual observations.

Infrequently at individual sites, the seasonal timing of inspection surveys was changed for weather or logistical reasons. The month that each annual inspection was conducted, and the incidence of any alterations to site inspection timing, are provided in site process history tables found in Appendix A. Under such circumstances, or in the event of any ambiguity between photographic, written, and figure-based observations, the incidence and trajectory of any observed surface change (in relation to prior and future years) was determined on a case-by-case basis by the authors.

Surface features were consolidated into directional qualitative delta graphs from time of cell construction to present. The categories of more, less, same, or none observed resulted in +1, -1, 0 or n/a (data omitted) scores for each calendar year. Subsequent year-over-year scores were summed with the previous entry to result in the reporting of a directional delta graph for each surface feature.

| Table 2.1: Earth surface process and associated keywords | | |
|---|---|---|
| **PROCESS CATEGORY** | **SURFACE FEATURE** | **ASSOCIATED KEYWORDS** |
| **BIOLOGICAL** | Annual weeds | Weeds, explicit *name* of species, sprayed weeds. |
| | Grasses / perennial forbs | Grass, perennial, explicit *name* of species. |
| | Shrubs / bushes | Shrub, bush, woody plant, deep rooted plant, explicit *name* of species. |
| | Trees | Tree, explicit *name* of species. |
| | Animal burrowing | Burrow, mound, excavation, explicit *name* of species burrow. |
| **GEOPHYSICAL** | Surface subsidence | Settlement, subsidence, depressions, slumping |
| | Surface ponding | Ephemeral lake, lake ring (evidence of dried lake), ponding, pool, flooded, standing water, collecting water |
| | Shallow erosion | Flooding, river meandering, dislodgement of rock, transport of filter material, rain splash, surface overland flow, rills, gullies, channels, soil loss, accumulation of soil at downgradient. |
| | Rock breakdown | Degradation of rip rap, cracking, reduction in sieve size. |
| | Desiccation cracking | Tension cracks, surface cracks, desiccation. |
| | Freeze thaw cycling | Frozen, freeze/thaw. |
| | Aeolian deposition | Wind deposited fines, wind-blown, aeolian, dust in rock armor. |
| | Overland sediment transport | Sediment accumulation, soil movement, bedding movement. |
| | Precipitate formation and accumulation | Precipitate, salts, carbonate, crystals. |
| **SEISMIC** | Earthquakes | Earthquake, seismic activity, stated reading on the Richter scale. |
| **MANAGEMENT** | Cattle grazing | Livestock, grazing, cows. |
| | Mowing / haying | Mowing, grass cutting, haying, bailing. |
| | Cut / spray with herbicide | Explicit mention of cut and spray event. |
| | General site maintenance | Fence repair, sign repair, road repair, lock repair, gate repair, access repair. |

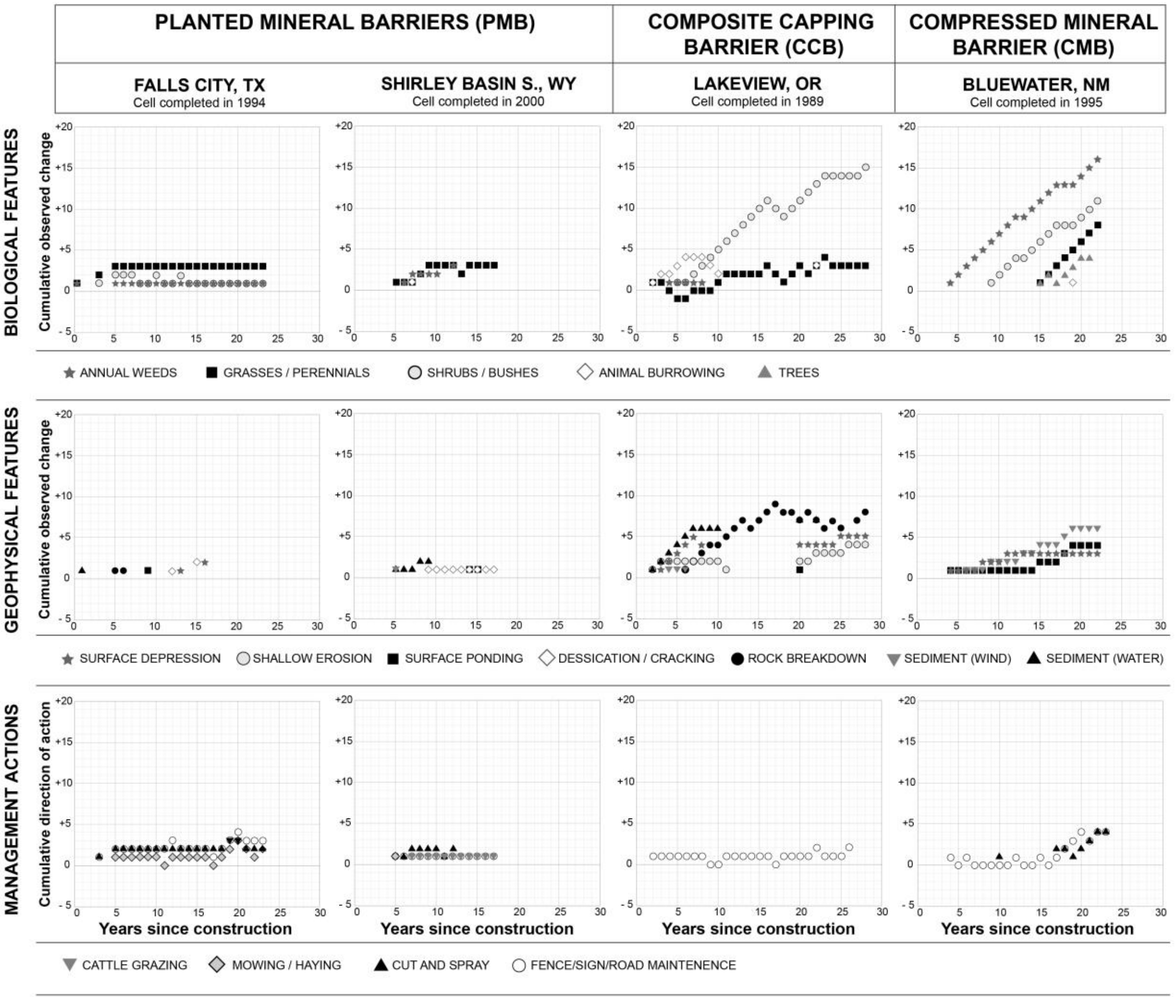
### 2.4.3. FIELD WALKING SURVEY AND COMPARISON TO INSPECTIONS

Since the inception of the UMTRCA program, annual inspections have largely emphasized performance rather than process characterization. Given that these inspections were not designed to exhaustively characterize the incidence of surface processes occurring at each site, we compared the most recent inspection reports to in-field observations seeking to explicitly identify evidence of such processes. Walking surveys were performed at Falls City, TX on April 23, 2016; Bluewater, NM on June 20, 2016; Lakeview, OR on October 28, 2017; and Shirley Basin, WY on June 22, 2018. During each survey, two transects were walked by MM. Williams. Transects were generally oriented from corner to corner and had an observational width of 20 meters. A checklist of surface features (Table 2.1) was used as reference, with the occurrence of any additional surface features annotated accordingly. Many photographs from these surveys are provided in Appendix A. The surface features observed during these walking transects were used to compare against the most recently performed inspection reports, in addition to a cumulative assessment of observed features across the entire time series of available annual inspection reports of that site to determine methodological similarity.

## 2.5. RESULTS AND DISCUSSION

The site-to-site variation in observed biological and geophysical surface features largely corresponds with original design and ongoing surface management strategy. Delta graphs that track the cumulative direction of biological and geophysical surface feature development (Figure 2.1) show that the deep Planted Mineral Barriers (PMB) at Falls City and Shirley Basin behaved most evenly over space and time with the fewest increases or decreases to observed surface condition. Conversely, the shallow Composite Capping Barrier (CCB) at Lakeview and the shallow Compressed Mineral Barrier (CMB) at Bluewater are characterized by the cumulative, and patchy, emergence of both biological and geophysical surface features through time. With exception to an increase in average daily minimum and maximum temperature at the Shirley Basin site, temperature and precipitation anomalies have remained largely consistent (with episodic seasonal variation), and any connection between surface feature occurrence and climate appear to be negligible at this time interval.  A time sequence of surface process and management events, for each site, can be found in Appendix A.

Figure 2.1: Delta graphs of biological and geophysical surface feature development and management actions



Annotated site histories are provided in Appendix A.

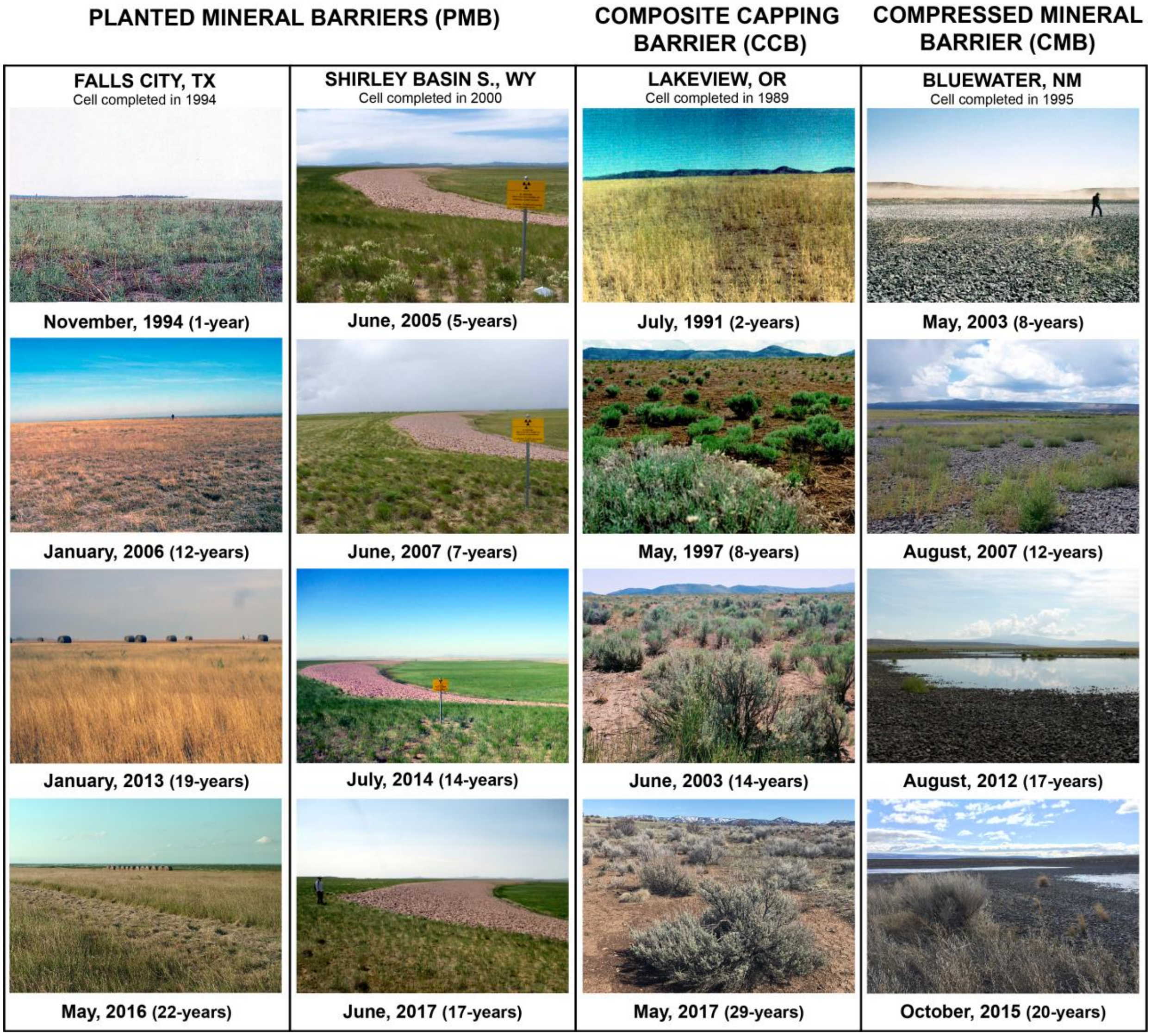
### 2.5.1. DEEP PLANTED MINERAL BARRIERS

The Falls City and Shirley Basin sites have deep clay barriers that are covered with overburden and rooting materials, that were designed to include an even stand of mixed grasses (Figure 1.3). The implementation of surface management strategies (haying and cattle grazing, respectively) correspond to observed stability in biological and geophysical surface condition, regardless of climate (Falls City being hot/humid, and Shirley Basin being cold/semi-arid). These sites largely mimic the ecology and management aesthetic of surrounding areas, with exception to rock side slopes. None of the features tracked during annual inspection reporting, at either site, deviate more than 4-steps since observations began. The delta graphs for both Falls City and Shirley Basin are characterized by relatively flat slopes with comparatively few irregularities. A total of 13 annual changes (8 increases, and 5 decreases) across all biological surface features, in addition to 6 annual changes (6 increases) across all geomorphic features were reported at the Falls City site between site construction in 1994 and 2017 (23 years). At the Shirley Basin site, a total of 8 annual changes (7 increases, and 1 decrease) across all biological surface features, in addition to 4 annual changes (4 increases) across all geomorphic features were observed since construction in 2000 and 2017 (17 years). At both sites, the majority of surface feature reporting was highly concentrated on observed changes occurring on rock armor slopes and included: vegetation encroachment, sediment capture, rock breakdown, and minor subsidence. The relative stability of landform features is also evident in time series photographs (Figure 2.2).

Most biological surface changes reported at the Falls City and Shirley Basin sites occurred during the first 7-years of inspection reporting and captured the incidental growth of weeds, and the establishment of perennial grasses dominated by yellow bluestem (*Bothriochloa ischaemum var. songarica)*, post construction. All ongoing observations of weeds or shrubs/bushes at these sites were localized along rock armor slopes. The incidence of deep-rooted plants, notably honey mesquite (*Prosopis glandulosa*), at the Falls City site is a periodic occurrence, and such plants are mowed annually on the top of the cell and cut and sprayed with herbicide on rock slopes. Despite management of mesquite, live mesquite roots are found in fracture planes in the top 15cm of the clay barrier (Chapter 4) suggesting long-term persistence in-lieu of cutting. The management of vegetation at the Falls City site is considerable, with up to 3 hay cuttings occurring annually, in addition to continued application of herbicide to control deep rooted vegetation growth on rock slopes. If such active management efforts were to be discontinued, deep-rooted vegetation (mesquite and potentially blackbrush) would spread across the cell with presently unknown impacts to clay barrier morphology or cover performance. Vegetation has been managed by cattle grazing at the Shirley Basin site since 2007 with great success. Cattle grazing often represents a lower cost alternative to cutting and bailing, through overgrazing can rapidly lead to the deterioration of soil quality leading to erosional risk. For some deep-rooted vegetation, including honey mesquite, grazing may not offer a viable solution to controlling root penetration into clay barriers given foraging preferences and vegetation durability.

The reporting of surface features that correspond to geophysical processes at the Falls City and Shirley Basin sites were sparse, with exception to several anomalies. Nominal overland flow driven sediment transport was observed during the early stages of vegetation establishment at Shirley Basin, in addition to the development of ephemeral standing water in wetlands, during high precipitation years, in a small zone along the toe of the rock armor slope (Appendix A). Subsequent desiccation cracking of topsoils along the toe-slope was commonly seen during drier years and hoof prints from livestock were evident suggesting that cattle are attracted to this location. Standing water was once observed along a downgradient bench at Falls City immediately following a heavy rain event, with notes indicating that the cell was actively shedding water from this location as designed. The breakdown of rock armor, and concerns over observed depressions in rock armor after rainfall events at Falls City were sparingly noted. In response, active monitoring efforts to track ongoing rock breakdown and slope stability were initiated, with all subsequent reports indicating that no further changes have occurred to date.

Figure 2.2: Time sequence of surface feature evolution across UMTRCA study sites



Photos were taken at roughly the same location, over many years of observation. With exception to Bluewater (2015) and Lakeview (2017) (photo credit: M.M. Williams), all photographs were sourced from annual site inspection reports cataloged by DOE-LM.

### 2.5.1.1. *FALLS CITY AND SHIRLEY BASIN SUMMARY*

Given the relative stability of surface condition at the Falls City and Shirley Basin sites, we would expect that the emergence of any subsurface conditions that could impact the performance of compressed clay barriers, such as the development of soil structure and the corresponding impacts to hydraulic properties, would do so relatively evenly across the cover. At these sites, location to location anomalies in cover system soil morphology or performance would therefore not be directly related to the incidence of the factors of Earth surface change characterized here. Observed performance variations would more likely be related to slight variations in material properties or installation method at construction and occur within ranges of intended performance criteria for engineering metrics including hydraulic conductivity.

### 2.5.2. SHALLOW CLAY BARRIERS

The Bluewater and Lakeview sites behaved most unevenly over space and time with the greatest increases and decreases to both biological and geophysical surface features. From the onset of annual monitoring at both sites, a change to at least one biological or geophysical surface feature occurred each year, and in most years, changes occurred across multiple features. This pattern of cumulative, and patchy, emergence of surface features, varies significantly from those observed at the Falls City and Shirley Basin sites, which are largely stable through time and space.

Delta graphs for both Bluewater and Lakeview show that cumulative change has occurred across almost all monitored categories. A total of 42 annual changes (41 increases, and 1 decreases) across all biological surface features, in addition to 12 annual changes (12 increases) across all geomorphic features were observed at the Bluewater site between construction in 1995 and 2017 (21 years). At the Lakeview site, a total of 41 annual changes (30 increases, and 11 decreases) across all biological surface features, in addition to 41 annual changes (32 increases, and 9 decreases) across all geomorphic features were observed between construction in 1989 and 2017 (28 years). The emergence of novel landform features is clear in the time series photographs for these sites (Figure 2.2).

These two sites were not originally designed to include native surface vegetation, though their construction strategy differs considerably. The Bluewater site is composed of a shallow clay barrier covered with rock. The Lakeview site was initially constructed as a shallow clay barrier covered with gravel and rock matrix (like Bluewater), however a decision by stakeholders was made in the latter stages of cell construction to cover the cell with a thin layer of topsoil and to allow natural vegetation to establish after seeding with cool season grasses. Given cell design, both sites are characterized by the emergence of vegetation along patterns of (largely un-managed) ecological succession common to adjacent natural areas.

#### 2.5.2.1. *SHALLOW COMPRESSED MINERAL BARRIER*

Considerable shifts in vegetation have occurred at the Bluewater site since monitoring began. Annual weeds were observed to increase in 16 of the 19 years monitored. Shrubs and bushes (notably fourwing saltbush) began establishing on the cover 9 years after construction, after which time observations of saltbush increased in 11 of the subsequent 14 years monitored. Perennial grasses began establishing on the cover 15 years post construction, with increases in spatial distribution observed during all subsequent annual inspections. Trees (i.e. Siberian elm) were also first seen on the cell 15 years after construction. While such trees were actively managed from that time onward (by cutting and herbicide application), they were observed to increase in distribution in 5 of the 8 years since first observed, requiring additional management.

The distribution of vegetation across the Bluewater site is patchy. Annual weeds, grasses, and Siberian elm trees tend to prefer the downslope section of the cell, which corresponds to higher seasonal average soil moisture levels in the radon barrier due to precipitation being shed to the collection basin on this section of the cell which has commonly been observed as an ephemeral lake during wet years (Appendix A. Figure 6: Ephemeral Lake). Vegetation at the upper section of the disposal cell is characterized by patchy zones of fourwing saltbush, which have deeper rooting systems and can outcompete grasses for moisture located deeper in the soil profile. To compound this natural moisture gradient due to differences in elevation, the lower part of the disposal cell was constructed with higher clay content materials directly underneath the radon barrier (from slime tailings remediation), while the upper sections of the cell were constructed with larger silt and sand size materials directly underneath the radon barrier (from sand tailings remediation).

Rates of cover subsidence on the lower portion of the cell at Bluewater correspond to the incidence of larger ephemeral lakes through time. Subsidence has been attributed to the gradual consolidation and dewatering of slime tailings underneath this area of the cell (DOE, 2014b). At the onset of annual monitoring in 1998, evaporite accumulation on rock armor in a depression zone on the lower portion of the cell suggested that a 1.8-hectare seasonal lake had developed. In 2014, that lake had expanded to 6.2 hectares in size, and corresponded to 1.4 meters of subsidence over the same time period as confirmed by aerial LiDAR. The maximum quantity of ponded water, observed through 2014, was equivalent to 15,500 metric tons of additional weight (DOE, 2014b). The formation of ephemeral lakes has also resulted in the observed deposition of transported fine sediment from upland cell locations (Appendix A. Figure 9: Sediment Transport). At present, the impacts of this feedback (if any) are unknown.

Along the side slopes of the Bluewater disposal cell, annual weeds and perennial grasses preferentially occur on the leeward slope, which directly corresponds to the deposition of aeolian dust, a feature that has gradually increased over time (Appendix B. Figure 5: Plants Establishing in Aeolian Dusts). Given slope orientation and prevailing wind direction, dusts are selectively deposited on the leeward slope. Areas of dusts in rock armor are thought to change the near surface water holding capacity (Groenevelt, 1989; Kemper et al, 1994) and provide optimal conditions for wind dispersed seed germination and long-term establishment. The deposition of aeolian dusts also represents a potential feedback that could drive ongoing cover evolution. As plants continue to emerge, surface friction will increase, which will result in a decrease to overland wind speed, and a selective deposition by dusts in vegetated areas (Appendix B. Figure 6: Aeolian Dust Deposition).

#### 2.5.2.2. *SHALLOW COMPOSITE CAPPING BARRIER*

The Lakeview site is characterized by considerable shifts in vegetation composition and percent cover over time (Figure 2.3). In the years that followed construction, grasses were slow to establish and the site experienced annual weed outbreaks in addition to notable surface erosion by both wind and water. From the onset of site monitoring, the density of grass cover has been sporadic through time, with the delta graph direction changing 13 of the 26 years observed. Observations of grass patchiness have also been shown to correspond with the settlement of topsoil into the rock armor below (Appendix A. Figure 9: Soil Settlement).

The most predominant observed feature has been woody shrub encroachment, with shrub density increasing in 16 of the 26 years observed. In 1994 (5 years post construction), the first rabbitbrush and big sagebrush plants began to establish on the cell, at which time it was predicted that deep rooted plants would begin to outcompete grasses given observed near surface top soil settlement into rock armor and factors of ecological succession in the area (Lakeview Annual Site Inspection Report, 1994). This prediction has proven correct for some, but not all, sections of the disposal cell. Across the northern section of the disposal cell, a patchwork of shrubs (which in addition to big sagebrush and rabbitbrush, also included bitterbrush by 1999), was interspersed with largely bare areas as is characteristic of the surrounding natural environment. Conversely, the southern section of the disposal cell remains characterized by greater grass density and fewer deep rooted shrubs. A mechanism for this observation is presently unknown, but it is hypothesized to be related to variable soil texture and top-soil settlement rates.

Figure 2.3: Comparison of vegetation patterning over 25-years at Lakeview, OR

**August, 1991** **October, 2016**

Photographs sourced from LMS annual site inspection reports cataloged by DOE-LM

In 1997 it was predicted that rabbitbrush populations would continue to increase followed by increases in sagebrush, bitterbrush, and eventually, serviceberry, chokecherry, and juniper (Lakeview Annual Site Inspection Report, 1997). In the event of continued nominal surface management, the likelihood of this natural succession pathway is high. While root conditioning and related soil developed processes have been shown to increase hydraulic conductivity from the original design target at 15-years post construction it has also been observed that plant succession may lead to an increase in evapotranspiration, keeping the clay barrier unsaturated and effectively offsetting the measured increase in permeability (Waugh, et al., 2007).

The emergence of various geophysical features including shallow erosion, rilling, wind scouring, and the transport of topsoil into side slope rock armor (Appendix A. Figure 9: Sediment Transport) have been observed, to varying degrees of significance, since monitoring began at Lakeview. With exception to the time period between 2000 and 2008 (a time that site inspection reporting contained far less language relevant to surface feature observations, generally), these erosional features were commonly tracked. In 1995 (six years after cell construction), rock armor on the side slope was observed to be deteriorating, with 10-15% of rocks crumbling in some areas (Lakeview Annual Site Inspection Report, 1995). A rigorous annual monitoring effort was then implemented. Between 1997 and 2017, rock armor monitoring indicated that mean diameter ($D_{50}$) was below the original design range in 14 of the 20 years sampled, however a trend analysis of $D_{50}$ values determined, at the 95% confidence level, that mean rock diameter has not significantly decreased since monitoring began (Lakeview Annual Site Inspection Report, 2017). Rock breakdown at Lakeview has been attributed to the presence of microfractures present in some of the basalt materials and physical processes including shrink/swell and freeze/thaw. In 2002, concerns about rock breakdown lead NRC to direct LMS and the U.S. Army Corp of Engineers to pursue additional Hydrologic Modeling. Based on these analyses, the minimum $D_{50}$ required to protect the disposal cell during probable maximum precipitation events were found to be 1.8 inches. This compares to the original $D_{50}$ of 2.7-inches and was substantially greater that the $D_{50}$ of 2.35-inches measured in 2002. The recalculation was included in a revised Long-Term Surveillance Plan for Lakeview later adopted by the NRC.

#### 2.5.2.3. *BLUEWATER AND LAKEVIEW SUMMARY*

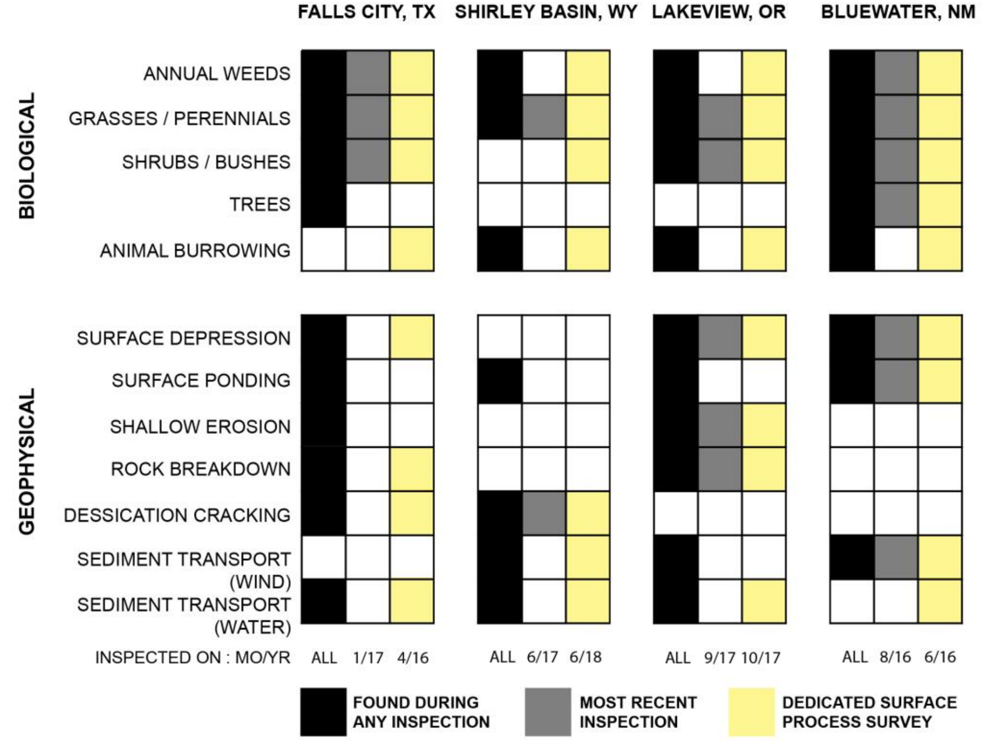
Due to the patchy distribution of surface condition at the Bluewater and Lakeview sites, we would expect an uneven emergence of subsurface soil conditions that could impact the performance of compressed clay barriers. At these sites, location to location differences in cover system soil morphology and hydrologic performance would conceivably be related to the surface features present at individual locations on the cell, and the greater unfolding of Earth surface process across the cell at large.

### 2.5.3. EVALUATION OF ANNUAL INSPECTION METHODOLOGY

The comparison of historical and most recent site inspection reports against an intentional walking survey, indicates that site inspections have successfully documented the presence of surface features occurring on each site, with few exceptions (Figure 2.4). Those features that are seasonal or weather dependent, including ephemeral lakes, desiccation cracking, or self-healing erosional features, in addition to management related anomalies (such as the removal of a tree) are the features most likely to be missed.

Of the 12 surface features tracked, and out of a total of 48 observational entries (12 features tracked across 4 sites), only 3 features found during the intentional walking survey were not also observed across all site inspection reporting. These were animal burrowing by ants at Falls City (Appendix A. Figure 2: Animal burrowing), the deposition of sediment by water at Bluewater (Appendix A. Figure 6: Sediment collection), and the incidence of a sporadically emergent shrub (saltbrush) at the Shirley Basin site. While animal burrowing was observed during annual inspections at Bluewater (Badgers in 2014), Lakeview (Badgers across several years; rodents in 2011), and Shirley Basin (Badgers in 2007), site inspections did not document the incidence of harvester ant mounds at Bluewater (Appendix A. Figure 5: Animal burrowing), the incidence of rodent burrowing at Bluewater (Appendix A. Figure 5: Rodent burrowing), ant mound burrowing at Lakeview (Appendix A. Figure 7: Animal burrowing) or rodent burrows at Shirley Basin (Appendix A. Figure 11: Animal excavation).

Figure 2.4: Comparison of site inspection methodologies



| | | FALLS CITY, TX | | | SHIRLEY BASIN, WY | | | LAKEVIEW, OR | | | BLUEWATER, NM | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BIOLOGICAL | ANNUAL WEEDS | ■ | ▨ | 🟨 | ■ | | 🟨 | ■ | | 🟨 | ■ | ▨ | 🟨 |
| | GRASSES / PERENNIALS | ■ | ▨ | 🟨 | ■ | ▨ | 🟨 | ■ | ▨ | 🟨 | ■ | ▨ | 🟨 |
| | SHRUBS / BUSHES | ■ | ▨ | 🟨 | | | 🟨 | ■ | ▨ | 🟨 | ■ | ▨ | 🟨 |
| | TREES | ■ | | | | | | | | | ■ | ▨ | 🟨 |
| | ANIMAL BURROWING | | | 🟨 | ■ | | 🟨 | ■ | | 🟨 | ■ | | 🟨 |
| GEOPHYSICAL | SURFACE DEPRESSION | ■ | | 🟨 | | | | ■ | ▨ | 🟨 | ■ | ▨ | 🟨 |
| | SURFACE PONDING | ■ | | | ■ | | | ■ | | | ■ | ▨ | 🟨 |
| | SHALLOW EROSION | ■ | | | | | | ■ | ▨ | 🟨 | | | |
| | ROCK BREAKDOWN | ■ | | 🟨 | | | | ■ | ▨ | 🟨 | | | |
| | DESSICATION CRACKING | ■ | | 🟨 | ■ | ▨ | 🟨 | | | | | | |
| | SEDIMENT TRANSPORT (WIND) | | | | ■ | | 🟨 | ■ | | | ■ | ▨ | 🟨 |
| | SEDIMENT TRANSPORT (WATER) | ■ | | 🟨 | ■ | | 🟨 | ■ | | 🟨 | | | 🟨 |
| | INSPECTED ON : MO/YR | ALL | 1/17 | 4/16 | ALL | 6/17 | 6/18 | ALL | 9/17 | 10/17 | ALL | 8/16 | 6/16 |

■ FOUND DURING ANY INSPECTION ▨ MOST RECENT INSPECTION 🟨 DEDICATED SURFACE PROCESS SURVEY

The comparison of inspection methodologies suggests that the Bluewater disposal cell is currently the most active site of those inspected with 7 of 12 features being tracked across all observation time periods (historically, recently, and intentionally). Conversely, the Shirley Basin site is the least active site with only 2 features being tracked across all time periods. While the overall number of surface features ever observed are highest for both the Falls City and Lakeview sites (10 of 12), all the geophysical features observed at Falls City were sporadically observed on no more than two occasions and can likely be attributed to the amount of precipitation present in the area.

While the presence of features may have been documented, the intensity of that feature's expression over time was not always well documented descriptively. If continued tracking of surface change is of value, it is suggested that a checklist of features be developed and that the categories of: same, more, less, or not present (year-over-year), be included as an explicit qualitative descriptor. Photographic evidence proved very informative in tracking site histories. Given the value of these photographs, it would be advantageous to select a series of single points (and orientations) on each site for photographs to be taken every year. Some sites have incorporated remote imaging stations to collect photographs from a fixed point daily. The Bluewater station was installed in 2016 in response to concerns about ephemeral ponding, with photos being used to inform managers of the need to siphon water off the disposal cell. Such photo sequences offer detailed resolution of surface changes and allow for highly informed management. Further exploration into technologies that will allow for the remote monitoring of disposal cells could provide detailed information on surface process that may result in long term impacts to performance before they result in cost increases.

### 2.6. SECTION REVIEW

Annual inspection reports from the DOE-LM archive can be used to track the incidence of surface features and inform long term surface evolution trends on UMTRCA waste disposal cells. Patterns of surface evolution likely contribute to subsurface alterations that may impact the engineering properties of compressed clay barriers for waste containment. Cover design, climate, and management influence patterns of surface evolution.

The deep and vegetated sites at Falls City and Shirley Basin behaved most evenly over space and time with the fewest increases or decreases to observed surface condition. Given the relative stability of surface condition at these sites, we would expect that the emergence of any subsurface conditions that could impact the performance of compressed clay barriers, such as the development of soil structure and the corresponding impacts to hydraulic properties, would do so relatively evenly across the cover. The cold and semi-arid site at Shirley Basin displayed more surface feature evenness over time as compared to the hot and humid site at Falls City. Such variation was largely attributed to deep rooted shrub development at the hot and humid Falls City site that requires recurring annual management that has increased over time.

The shallow sites with nominal active vegetation management at Bluewater and Lakeview are characterized by the cumulative emergence of both biological and geophysical surface features through time. Due to the patchy distribution of surface condition at these sites, we would expect and uneven emergence of subsurface soil conditions and a high likelihood that location to location differences in cover system soil morphology would be directly related to the surface features present.

Current inspection methodology captures most of the relevant surface features, if averaged over multiple years. In addition to animal burrows, seasonal or weather dependent features are most commonly missed. Photographs were most informative, and we recommend that fixed points be identified at cell construction, and directional photographs taken from these points during all subsequent annual inspections.

# 3. A FACTORAL FRAMEWORK OF MORPHOLOGICAL DEVELOPMENT IN ENGINEERED SOILS FOR WASTE CONTAINMENT

## 3.1. SUMMARY

To date, no systematic exploration between landform setting, soil process and engineered performance has been produced. Herein we propose a conceptual framework that describes morphological change in engineered soils as a function of design, environmental flux, management, and time. The framework can be used to describe combinations of factors that describe soil morphology in engineered soils across various conditions, with impacts to monitoring, maintenance, and hypothesis testing. Soil morphological investigations were performed across four UMTRCA sites, and examples of soil structure and root architecture under varying soil forming factors are used to explore factorial combinations that describe key soil morphological attributes in the portfolio. The investigation of soil morphology, under natural analog conditions, offers a means to predict clay barrier morphology under a combination of soil forming factors over regulatory time periods.

## 3.2. BACKGROUND

All soils, including those engineered for waste containment, are a heterogeneous mixture of reactive primary particles, secondary aggregates, pore space, liquids, gasses, and biota organized across scales at the Earth's surface. They are open and dynamic systems that are subject to recurring fluxes of energy and mass with impacts to both short term function and long-term evolution. As living systems, soils evolve and change by taking freely available energy from the environment (in the form of sunlight, water, nutrients and other materials), transforming it, and moving towards higher order (more complex) systems (Lin, 2011). As an energy consuming activity, soil evolution is a dissipative process that results in the self-organization of internal architecture as evident in the emergence of aggregates, pore space, soil horizons, and pedons in natural systems (Targulian and Goryachkin, 2004; Lin, 2010a; Lin, 2010b). The dynamic properties of soil change, and the self-organization of soil morphology through time, give rise to an abundance of natural soil diversity as seen in the many colors, textures, patterns and heterogeneities present across the worlds many soils. However, the inevitability of Earth surface process, and corresponding pedogenic processes that drive soil change, may run counter to conventional engineering efforts that rely on the rigid isolation of wastes through the structural maintenance of compressed clay barriers common to waste management systems across the planet, including those in the UMTRCA program.

Historically, the dynamic properties of soil change, and the emergence of novel soil morphology, have been under emphasized in the planning of engineered cover systems intended for the long-term containment of wastes. Disposal cells for the isolation of uranium mill tailings in the UMTRCA program are expected to control radioactive and other hazardous wastes for up to 1,000 years, to the extent reasonably achievable, and, in any case, for at least 200 years (10 CFR Part 40). Conventional cover systems have largely been designed to resist natural processes, as opposed to working with them, at considerable economic cost (Clarke et al., 2004). In as little as 5-years post construction, soil processes including bioturbation by plants and animals (Arthur and Markham, 1983; Burt and Cox, 1993; Link et al., 1995), freeze-thaw cycling (Kim and Daniel, 1992; Benson et al., 1995), and desiccation cracking (Montgomery and Parsons, 1989; Melchior, 1997) have led to the emergence of soil morphology and subsequent alterations to the as built hydraulic properties of compressed clay barriers in engineered covers (Taylor et al., 2003; Albright et al., 2004; Benson et al, 2011). Studies that indicate connections between cover performance and Earth surface processes and rare (Beedlow and Hartley, 1984; Burt and Cox, 1993; Link et al., 1994; Smith et al., 1997; Waugh et al., 1999; Taylor, et al., 2003; Albright et al., 2006a; Fourie and Tibbet, 2007), and systematic studies linking soil process to engineering performance sparse (DeJong et al., 2014).

Herein we propose a conceptual framework that describes morphological condition in engineered soils as a function of design, environmental flux, and management. Linkages to soil processes that influence the development of soil morphology are briefly summarized and are discussed in detail in Chapter 4. Examples of soil structure from field excavations across numerous surface conditions at four waste covers in the UMTRCA program are used to explore how cover design and biota correspond to emergent soil morphological condition. Such clarifications could aid in future research, long-term maintenance, and the design of new waste cover systems.

## 3.3. METHODS

A total of thirty-three soil profiles on four cover systems in the western United States were investigated. Six soil profiles were excavated at Falls City, TX, eleven soil profiles at Bluewater, NM, eight soil profiles at Shirley Basin, WY, eight soil profiles at Lakeview, OR. Soil profiles were selected to correspond to representative surface features present on each site and included a wide range of conditions. A detailed discussion of site selection and surface characteristics can be found in Waugh et al., 2019.

### 3.3.1. VEGETATION AND SURFACE FEATURE DESCRIPTION

A walking survey of surface features was performed at each site to characterize vegetation and cover condition (see Chapter 2). Surveys were coupled with historical observations to identify those locations at each site that were most representative of current and anticipated future surface condition given trends in vegetation succession from construction to present. The surface descriptions included microrelief features, vegetation description and taxonomy, presence of sediment and/or leaf litter, rock armor characteristics, presence of surface macropores/cracks, and evidence of active soil fauna. Full descriptions are included in the soil survey reported by Williams et al., (2019).

### 3.3.2. SOIL MORPHOLOGICAL CHARACTERIZATION

A backhoe was used to excavate trenches under soil forming factors of interest to allow for the collection of samples and the morphological description of cover profiles, with emphasis on the compressed clay barrier section, to within 50 mm of the depth of wastes.

Trenches were not less than 1500 mm in width, and in some instances reached depths in excess of 4000 mm. The same methods were used to excavate natural analog profiles. The locations of the excavations, at each site, are presented in full in Waugh et al., 2019. Care was taken to protect the surface of the profile face from being disturbed during excavation, and trench walls were excavated to within 150 mm from the intended plane of observation to protect in-field morphology from disruption caused from the excavator bucket, and to preserve the profile face from drying during flux measurements (Likos et al., 2019) and block sample excavation (Benson et al., 2019). After all instrumentation was removed, the trenches were thoroughly cleaned of debris and the intended plane of observation was cut back 15-200 mm with a spade (or other hand tools) to remove excavator smear marks or dried materials and expose representative cover and clay barrier morphology. Photographs of the profile were taken to provide pictorial representation of layer thickness, soil structure, root patterning, macropores, and other anomalous emergent and as-built features. The bottom of the clay barrier was differentiated from underlying source materials through observed color or textural shifts or the 2x increase in ionizing radiation (over background) by Scintillation counter.

For each horizon within the clay barrier profile, records were made for morphological properties including: profile thickness, horizon/material thickness, boundary, Munsell color, pedality/structure (size, shape and grade, consistent), root morphology per unit area (abundance, diameter, class), void structures or animal excavations, descriptions of inclusions and other anomalous morphology as per USDA, NRCS Field Guide to Soil Description v 3.0 (Soil Survey Division Staff, 2011). Soil moisture class was determined gravimetrically (GWC%), and a model that relates GWC% to suction used to group soils by water class state (Soil Survey Division Staff, 2011) in the following classes: saturated (>30%), wet (20-30%), moist (10-20%), dry (7-10%), very dry (<7%). The detailed characterization of (visible) interpedal, intrapedal, transpedal macropore space (size, type, and quantity) was adapted from Lin et al., (1999a). Pore size was based on radius (for cylindrical pores) or width (for planar pores) in six classes: very fine (<0.5 mm), fine (0.5–1 mm), medium (1–2.5 mm), coarse (2.5–5 mm), very coarse (5–10 mm), and extremely coarse (>10 mm). Type correspond to the general shape, continuity, and connectivity of pores across three classes: vughs (small spherical or elliptical cavities), channels (cylindrical and elongated), or planar fractures. Quantity was visually recorded across the soil surface to charts of pore areal percentages as modified from Soil Survey Division Staff, (2011) across five classes: very few (<0.25%), few (0.25–0.5%), common (0.5–2%), many (2–5%), and very many (>5%).

### 3.3.3. LABORAORY ANALYSIS

Soil samples were air dried, crushed, and passed through a 2 mm sieve prior to analysis. Plant-available nutrients were derived by modified Morgan extraction and inductively coupled plasma mass spectrometry (ICP-MS) (USDA Kellogg Soil Analysis Method, 4D2a2d1-22a-b1). Soil pH was measured as a 1:1 dilution with an electrode (USDA Kellogg Soil Analysis Method, 4C1a2a1). Total organic matter was derived by the wet oxidation method (Cornell Nutrient Analysis Laboratory, S2740). Total carbon, nitrogen, and hydrogen were measured by a LECO elemental analyzer (USDA Kellogg Soil

Analysis Method, 6A4a1a1-3). Nitrate, nitrite, and ammonia were measured colorimetrically by extraction (Cornell Nutrient Analysis Laboratory, S2506/S2503). Electrical conductivity was measured by a conductivity meter in 1:1 dilution (USDA Kellogg Soil Analysis Method, 4f1a1a). Calcite was measured by titration (Cornell Nutrient Analysis Laboratory, S2611). Particle size distribution was derived by hydrometer (Cornell Nutrient Analysis Laboratory, S1885). Gravimetric water content percent was derived by dry mass (ASTM D 2216). The determination of clay mineralogy was performed through XRD by Mineralogy, Inc. (Tulsa, Oklahoma) on soils sieved to <0.002 mm.

### 3.3.4. THE USE OF NATURAL ANALOGS

Studies of natural systems with shared attributes to engineered covers provide an understanding of emergent conditions that cannot be adequately evaluated from short-term experiments or computer modeling (Waugh, 1997). Given that the oldest engineered covers for waste containment in the UMTRCA program are less than 40-years old, and with service lives between 200-1000 years, lessons from natural analogs can provide great insight into how Earth surface and pedogenic processes influence long-term soil morphology, and engineered performance, under shared soil forming factors.

The ideal natural analog would contain shared parent material, biota, relief, and climate to the engineered cover system from the time that active soil formation began on that profile. Like conventional chronosequence studies in pedology, a space for time substitution would be made to isolate the impact that temporal change has on soil morphological properties responsible for regulating engineering performance (namely hydraulic conductivity, gas diffusivity, and erosivity). Other factors that can be studied through natural analog investigation include climate change, vegetation change, and changes to surface management. Soils formed in stable environments over the last 3,000 years provide the most informative analogs, however given challenges associated with identifying young soils with shared soil forming factors, soils formed in the Holocene are generally acceptable in understanding the trajectory of morphological change through time. Waugh et al., (1994), provides a detailed account of methodologies used for natural analog studies for engineered cover performance forecasting at the Hanford Site in Washington state. At present, the availability of natural analog studies for comparison to engineered covers is nominal and represents a significant knowledge gap.

## 3.4. SOIL FORMING FACTORS

The use of soil forming factors as a framework to describe soil and ecosystem condition is one of the most significant developments in the field of soil science. It allows for the general characterization of soils and ecosystems from interactions between a small number of master variables (state factors) with impacts to scaled resource monitoring and management (Buol et al., 2011). The framework describes soil (*s*) as a function of parent material (*p*), topographic setting (*r*), climatic variation (*cl*), biotic influence (*o*), and time (*t*) (Dokuchaev, 1886; Jenny, 1941). The expression of one factor in relation to the overall condition of a soil can be explored by isolating that single factor and keeping the others constant through the study of soil sequences. Spatial soil forming factors can be further grouped into flux factors (*cl* and *o*) and site factors (*p* and *r*). All spatial factors are dependent on time (*t*). Lin, 2011 expresses the cumulative effect of flux factors on soil development as conditioned by site factors as Eq. [3.1].

$$s = \int_{t_0}^{t_n} f[cl(t), o(t)]dt \mid_{p(t), r(t)}, \ldots \qquad [3.1]$$

Given that engineered soils for waste containment are expected to perform environmental control over time, an understanding of how both flux and site factors contribute to the alteration or maintenance of soil morphology may result in greater long-term sustainability at reduced cost. While traditional pedology has largely focused on soil formation in natural settings, human induced change through disturbance, cultivation, and secondary erosion have considerably accelerated rates of soil change to much shorter timeframes of years to decades (e.g. Richter and Markewitz, 2001). Efforts to incorporate man-made soil change into models of soil formation were initially proposed by Yaron (1966). Amundson and Jenny (1991) integrated humans as independent state factors through the inclusion of genotype and cultural inheritance. Dudal et al., (2002) suggested that human influence was so significant that it required an independent soil-forming factor all-together. Galbraith (2004) includes a well-developed discussion on how industrial and mine soils could be considered taxonomically, and how diagnostic horizons and epipedons in these soils can be approached. Such efforts have not only increased the awareness of anthropogenic impacts to ongoing soil processes, but also provided guidance on how to conceptually place these soils within existing pedological frameworks. However, adequate approaches to address the various nuances associated with the human construction of soils for long-term performance of engineering tasks remain underdeveloped.

## 3.5. FACTORS OF SOIL FORMATION IN ENGINEERED SOILS FOR WASTE CONTAINMENT

Engineered soils for waste containment are conceptually distinct from both natural soils and the majority of anthropogenically modified soils, in that traditional site factors (*p* and *r*) are of human design, sourcing, transport, and installation. Given that engineered soils in the UMTRCA program are entirely constructed, regulated by federal and state law, and actively managed to isolate wastes for up to 1,000 years, considerable forces, beyond nature, play a disproportionate role in defining soil morphology than existing models of soil formation include. As such, a conceptual framework of soil change in engineered soils must adequately incorporate the factors that define soil morphology at design, and through time, in order to have real impact across applied science and regulatory disciplines. Such clarifications could aid in future research, long-term maintenance, and the design of new waste cover systems.

Herein we refer to the initial design of an engineered soil for waste containment as (*de*). Engineering design (*de*) is influenced by a combination of: site factors (*sf*), natural material properties (*np*), and human cultural factors (*hc*). Site factors (*sf*) include historical climate (*cl*) and surrounding terrain features (tr) that influence overall disposal cell design and geometry, including slope and aspect (*r*). Natural material properties (*np*) include waste attributes (*wa*), cover stratigraphy (*st*), material texture (*tx*), material mineralogy (*mn*), construction defects (*cd*), and soil edaphic suitability for plant growth (*ed*). Human cultural factors (*hc*) include stakeholder engagement (*se*), political processes (*pp*), regulations (*rg*), and cost (*co*). The dots represent factors that are highly location or project specific such as risks associated with groundwater contamination, ownership disputes or bankruptcies, highly localized politics and regulations, executive orders, voluntary commitments, agreements with NGOs, contractual agreements, and risks associated with episodic natural events such as fires, floods or earthquakes. Collectively, the design of engineered soils for waste containment is expressed in Eq. [3.2].

$$de = f[sf_{f[cl,tr,r\ \ldots]}, np_{f[wa,st,tx,mn,cd,ed\ldots]}, hc_{f[se,pp,rg,co\ldots]}, \ldots] \qquad [3.2]$$

Ongoing human management (*m*) can be considered a recurring flux factor along with climate (*cl*) and organisms (*o*). Management is dependent on the soil condition at the time that an active management strategy was developed ($s_{t(n-1)}$) based on a similar set of human cultural factors as described above and is expressed in Eq. [3.3].

$$m = f[s_{t(n-1)}, hc_{f[se,pp,rg,co\ldots]}, \ldots] \qquad [3.3]$$

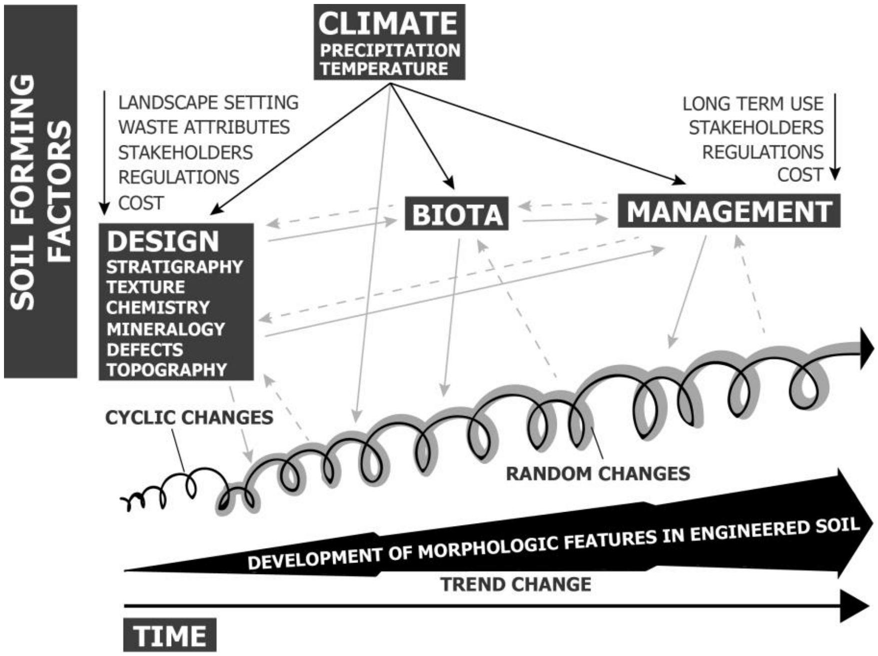
Collectively, a more representative model of soil formation in engineered soils for waste containment is presented in Eq. [3.4]. This model incorporates the cumulative effects of climate, organisms, and management on soil change as conditioned by design. Graphically, this model is presented in Figure 3.1. A more detailed discussion on how specific soil forming factors contribute to soil condition follows.

$$s = \int_{t_0}^{t_n} f[cl(t), o(t), m(t), \ldots]dt \mid_{de(t)} \qquad [3.4]$$

Table 3.1: Summary of factors of soil formation in engineered soils for waste containment

| Symbol | Factor | Example variables |
|---|---|---|
| s | Soil state | Soil morphology and ecosystem state |
| cl | Climate | Average temperature, average precipitation |
| o | Organisms | Flora and fauna |
| r | Slope and aspect | Degree of incline, length and geometry of slope |
| p | Parent material | Mineralogy, micro features, age of materials, natural source |
| t | Time | Time |
| de | Design | Variables included in site, material, and human cultural factors |
| sf | Site factors | Collectively: climate, terrain, slope and aspect |
| tr | Terrain | The geomorphology of the surrounding environment impacting flux |
| np | Natural material properties | Collectively: waste attributes, cover stratigraphy, material texture, material mineralogy, construction defects, and soil edaphics |
| wa | Waste attributes | The volume, mineralogy, toxicity, and reactivity of wastes. |
| st | Cover stratigraphy | The collective horizonation of cover layers from waste to surface |
| tx | Material texture | The clay, silt, sand and gravel fraction |
| mn | Material mineralogy | The clay mineralogy of barrier materials |
| cd | Construction defects | The inclusion of discontinuities in material properties in the barrier |
| ed | Soil edaphics | The suitability of the material to sustain plant growth |
| hc | Human cultural factors | Collectively: stakeholder engagement, political processes, regulation, and cost |
| se | Stakeholder engagement | The collection, and activity, of social groups (local to global) that have a vested interested in the site, and participate in expressing those interests during operation, remediation, closure, or maintenance |
| pp | Political processes | The development and enforcement of local, state, federal, and international laws by elected officials.  Often closely corresponds to stakeholder engagement |
| rg | Regulations | The specific laws (and amendments) that are the result of stakeholder engagement and political processes |
| co | Cost | The resources available for construction and maintenance of sites |

Figure 3.1: Soil forming factors in engineered soils for waste containment



Solid black arrows represent the dominant direction of influence. Solid gray arrows represent interactions. Dashed arrows represent a feedback between factors and cyclical, random and trend changes. Based on Lin, (2011).

### 3.5.1. CLIMATE

Climate influences two fundamental inputs to soil formation: precipitation and solar energy (Buol et al., 2011). Water dissolves and transports materials into, within, and out of soils, and directly contributes to plant and animal growth. As precipitation increases, vegetation diversity and abundance generally increase (Jenny, 1980). In areas with higher rainfall, plant rooting is more abundant at shallower depths in the soil profile, while plant rooting in arid zones is characterized by deeper rooting patterns given resource limitations and the need to collect enough water over greater lateral distances and depths (Fan et al., 2017).

While average climate conditions can provide guidance on expected vegetation patterning, extreme weather events, including large storms and flood events, can play considerable roles in shaping landscapes, particularly those in semi-arid and arid regions. On engineered disposal cells, such rainfall pulses can increase the risk of erosion and cells are commonly designed to withstand 10,000-year flood events. Maximum rainfall event calculations are used to determine surface erosion potential, mean rock diameter, and rock gradation as a function of slope and slope length (Maynord et al., 1989; Abt et al., 1991; Abt et al., 1998).

The majority of UMTRCA covers are in relatively dry environments, with 83% of the sites receiving between 200 and 400 mm of precipitation annually, impacting not only initial cover design, but also long-term performance (Voorhees et al., 1983). Periodicity and timing of precipitation during the year influences vegetation dynamics, soil water balance, and deep percolation. In semi-arid zones in the western United States, monsoonal rainfall during the summer will commonly result in shallow water storage in the root zone before being transpired by the fall. Under vegetated conditions, the duration of seasonal water deficit can also contribute to the formation and patterning of soil fractures from root induced desiccation and cracking (Kodikara and Costa, 2013).

Temperature plays a controlling role in regulating soil physical processes including freeze-thaw and shrink-swell cycling. Temperature also greatly influences the type and abundance of vegetation in an area. As temperatures increase, soil organic carbon and nitrogen tend to decrease resulting in edaphic feedbacks (Jenny, 1980). Air temperature is also a primary variable used in calculating potential evapotranspiration which greatly influences the rates and quantities of water movement through soils in semi-arid environments.

Rates of chemical reactions in the soil are impacted by temperature, and for every 10ºC increase in temperature, the speed of reactions generally increase by 2-3 times (Van't Hoff, 1884). Reactions including nitrogen mineralization, pH buffering, and respiration have profound impacts on plant growth. Under warmer climate conditions, rates of organic carbon decomposition and nitrogen mineralization increase with consequences to soil quality (Hungate, et al., 2003).

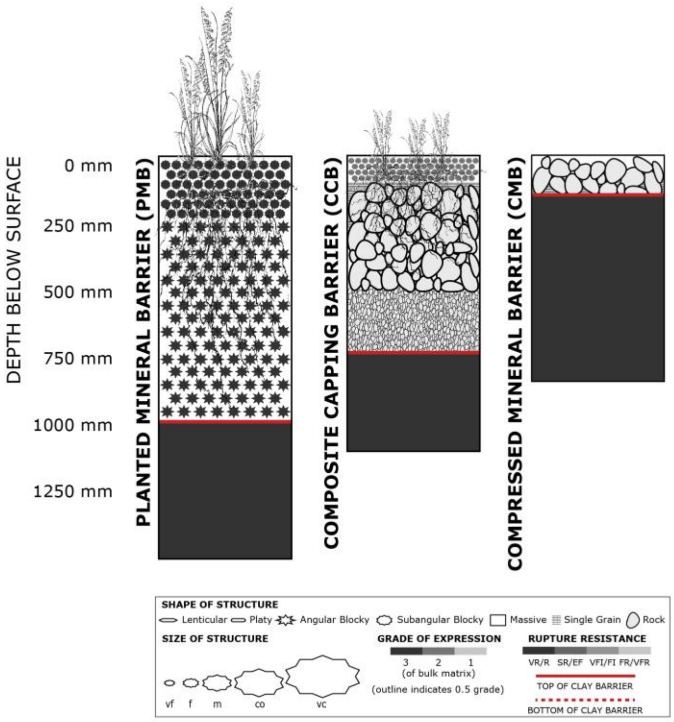
The absorption of thermal energy into soils is influenced by surface albedo through variables including vegetation, surface color, and aspect. The dark surfaces of basalt rock armor common to disposal cells in the UMTRCA program could absorb more heat than vegetated covers, while trees may provide the greatest insulation from solar gain. However, if rock armor is sufficiently deep, rocks (regaurdless of albedo) may thermally insulate barriers resulting in higher soil moisture at the clay barrier rock armor boundry. In the northern hemisphere, south facing slopes will also tend to be warmer and drier than north facing slopes, therefore the south facing slopes on shallow barrier systems may be more prone to desiccation and cracking and reduced vegetative cover.

### 3.5.2. CONSTRUCTION DESIGN AS PARENT MATERIAL AND RELIEF

The long-term containment of low-level radioactive wastes is commonly accomplished through physical isolation by compressed clay barriers that limit liquid and gas flux. These dense, compact, and low permeability layers are similar to claypans that slowly form through clay dispersion, downward particle sorting, and pore plugging over long time periods (Nikiforoff and Alexander, 1942; White et al., 1981). In contrast to sedimentary or fluvial processes that incrementally deposit sediments over long time-frames, the final stratigraphy of engineered covers is deposited in months, against the forces of gravity, to meet construction timelines and design goals. To maintain the engineering integrity of compressed clays under diverse environmental conditions, barriers are covered with materials that are intended to prohibit the likelihood of structural degradation from surface processes including freeze-thaw cycling, surface erosion, and plant and animal intrusion.

Cover designs can take many forms, and three designs were encountered during this study (Figure 3.2). Simple compacted mineral barriers (CMBs) are composed of a layer of compressed fine sediments (the clay barrier) placed directly over wastes and covered with a thin layer of gravel and topped by large aggregate rock armor for surface erosion control. In climates that can sustain surface vegetative cover, planted mineral barriers (PMBs) are commonly used and replace the rock armor of CMBs with a thick layer of planted fill soil to accomplish erosion control. Composite capping barriers (CCBs) are more sophisticated and employ additional layers above compressed clay barriers that serve as: capillary breaks to inhibit drying, lateral drainage layers to reduce infiltration, bio-intrusion layers to limit animal burrowing, and sufficiently thick layers of fill soil to isolate root growth to the zone above the compressed clay barrier. In addition to human cultural processes that influence overall site setting and cell design, natural material properties including waste attributes, along with the mineralogy, chemistry, and physical properties of construction materials, can influence both design and the rates and qualities of soil change through time.

Figure 3.2: Stratigraphy of several UMTRCA cover designs at construction



Drawings modified from (Waugh and Smith, 1997)

### 3.5.2.1. *HUMAN CULTURAL AND REGULATORY DRIVERS INVOLVED IN COVER PLACEMENT, DESIGN, AND MANAGEMENT*

The initial placement, design, and long-term management of waste disposal cells are dependent on many human cultural factors. Such factors occur at global-to-local scales and can have impacts to both static and dynamic site attributes. Static attributes can include geographic location, total volume of waste deposited, the characteristics of waste generated, and the year of construction. Dynamic attributes can include community engagement, political processes, and any amendments to the regulations through time.

For the UMTRCA program, the global geopolitical environment of World War II and the Cold War encouraged the domestic development of a uranium mining, milling, and processing economy, with the Atomic Energy Commission (AEC) purchasing most of the uranium that could be produced in the western United States until the 1970's. The location of uranium mills in the west (the primary location of waste disposal facilities in the UMTRCA program), was the product of a combination of economic factors including proximity to uranium mines, road and rail transport, labor, access to fresh water for processing, land ownership, permitting, local community engagement, federal policy, national security considerations, and profitability. An account of the political conditions that led to the drafting of UMTRCA can be found in Mogren, (2002). A detailed discussion of the regulatory background with respect to design, performance, and long-term monitoring of UMTRCA sites can be found in Waugh et al (2019). Decisions that were made during the initial development and operation of uranium mills ultimately continue to exert influence on how final cover designs perform through time given static site attributes.

#### 3.5.2.2. *THICKNESS, COMPACTION, AND DEPTH FROM SURFACE*

Clay barriers in the UMTRCA program were initially designed to control radon diffusion. Radium-226 (Ra-226) and Radon-222 (Rn-222) are progeny of Uranium-238 which is present in mill tailings (e.g. source materials). Rn-222 is a colorless, odorless, radioactive gas with a half-life of 3.8 days. Conceptually, the low gaseous diffusivity of the compressed clay barrier will attenuate Rn-222. With a low radon barrier diffusion coefficient, Rn-222 would decay several half-lives as it travels to the surface, thereby significantly reducing in concentration and mitigating risk to human health. For the control of radon gas, suitable barrier thickness is determined by modeling radon diffusion based on measurements of optimum density and moisture content and, in some cases, lab measurements of radon diffusion in columns (Nielson and Rogers, 1982, Rogers et al., 1984, NRC, 1989). Wastes with higher activity will require thicker barriers, therefore waste attributes (*wa*) exert control over final cover thickness and stratigraphy.

After EPA published draft groundwater quality standards in 1989, DOE refined the cover design process and placed greater emphasis on designing "low-permeability" radon barriers to maintain hydraulic isolation of subsurface wastes (DOE, 1989). At this time, DOE informally adopted a standard specified in the Resource Conservation and Recovery Act of 1976 (RCRA) for designing low-permeability caps for disposal of hazardous waste in shallow-land burial facilities. RCRA guidance requires a compacted soil layer with a saturated hydraulic conductivity less than $10^{-7}$ meters per second (m/s) (EPA, 1989). DOE design guidance indicated that this low conductivity could be achieved with either highly compacted native soil or bentonite-amended native soil (DOE, 1989). It is well accepted that the impacts of desiccation cracking (Montgomery and Parsons, 1989; Melchior, 1997), freeze thaw cycling (Kim and Daniel, 1992; Benson et al., 1995), and bioturbation by plants and animals (Burt and Cox, 1993; Link et al., 1995) are reduced with depth. The new guidance also provided a framework for selecting and designing cover components based on site-specific needs. This approach gave options for adding components to the original design such as a thick "protection layer" intended to isolate the clay barrier from surface processes including frost, plant rooting, and animal burrowing. Such barriers are commonly deep Planted Mineral Barriers (PMB) or deep Composite Capping Barriers (CCB).

#### 3.5.2.3. *PARTICLE SIZE DISTRIBUTION IN CLAY BARRIERS*

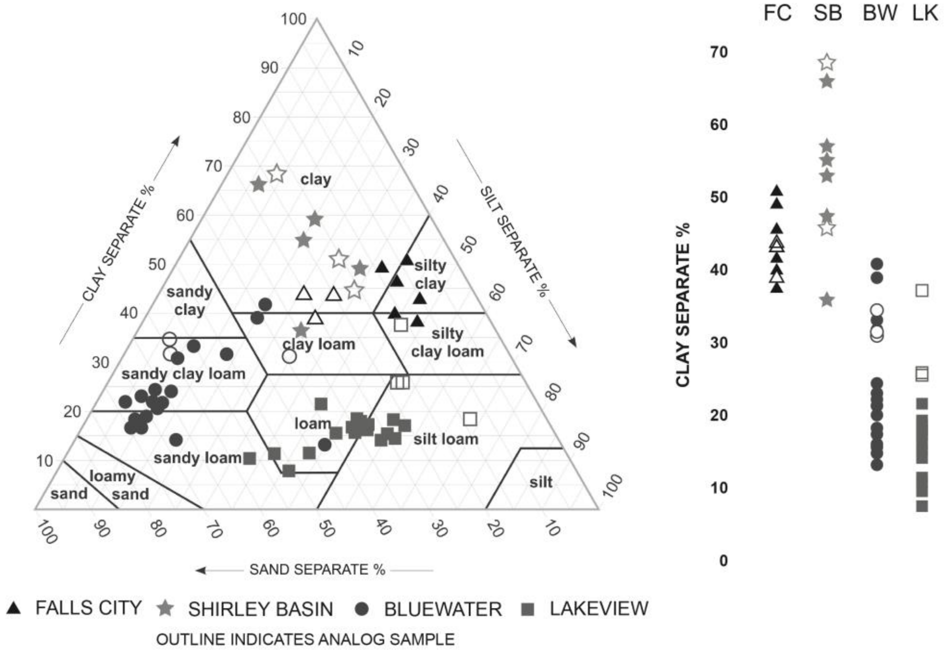
The distribution of pore space in parent materials influences the initial transport of liquids and gasses and subsequent patterns of soil change. The mechanisms of parent material deposition in natural landscapes significantly impact particle size distribution. Materials deposited by ice (glacial till) are poorly sorted and contain rock materials broadly scoured across landscapes, of sizes ranging from clay particles to boulders. Similarly, materials deposited by gravity at the base of mountains (colluvium) are also poorly sorted. Parent materials deposited by rivers and streams (alluvium) are sorted from larger to smaller particles with distance from water source. Those sediments deposited in lakes (lacustrine) or oceans (marine) result in well sorted laminar sheets, while those deposited by the wind (aeolian) are highly sorted and are dominated by silt sized particles.

Materials for clay barriers are intentionally selected to limit the sand fraction and maximize the clay and silt fractions. Clay fractions are preferred as to minimize pore space and limit rates of gas flux and water infiltration. Gravel and retained clay aggregates are undesirable, however they are commonly found in final covers despite efforts to sort naturally sourced materials. Sorting occurs when materials are excavated from natural environments, transported in trucks, crushed, and screened to remove undesired retained aggregate structure prior to construction. More recent clay barrier construction efforts have included material processing equipment to increase the plasticity of materials prior to installation (e.g. pug mills). The ideal clay barrier construction materials will behave more similarly to cohesive, and well sorted natural parent materials including lacustrine, marine, and to a lesser extent, aeolian deposits. Over regulatory timeframes (200-1000 years) the texture of placed soil materials will not appreciably change and represents a static feature, with few exceptions including the selective transport of fines out of materials by water.

Despite best management efforts, variation (both across and within sites) exists in the texture of in-service clay barriers. Such variability in soil texture is also common to natural lqandscapes at the field scale (Iqbal et al., 2005; Mzuku et al., 2005). Hutchings, et al., (2001) observed that particle size distribution within an in-service clay cap was highly variable and contained numerous localized zones of coarse gravels. Locations that were more sandy or gravelly were also associated with greater numbers of plant roots, indicating that textural discontinuities serve as initial locations of soil change. Similar observations were made in the soil survey that compliments this study (Williams et al., 2019).

Across four UMTRCA sites surveyed in Williams et al., (2019), the percent clay fraction in compressed clay barriers ranged from 8 - 68% between sites, representing 9 of the 12 USDA Soil Survey textural classifications (Figure 3.3). The range in soil texture was also shared in natural analog sites. The percent clay seperate, within sites, also varied by as much as 30% in two of the four sites studied indicating considerable heterogeneity in as-constructed condition. Barrier materials at Falls City, Shirley Basin, Bluewater, and Lakeview were of marine, lacustrine, aeolian, and lacustrine/fluvial deposition respectively. Such observations run counter to assumptions of disposal cell uniformity at construction. Given that soil texture influences the flow of liquids and gasses, impacts the dynamics of soil structural development, water holding capacity, and the suitability for vegetation establishment, such variations at construction may result in the development of a patchwork of heterogeneous in-service conditions across individual covers through time.

Figure 3.3: Distribution of soil texture across four UMTRCA clay barriers



### 3.5.2.4. *MINERALOGY OF CLAY BARRIERS*

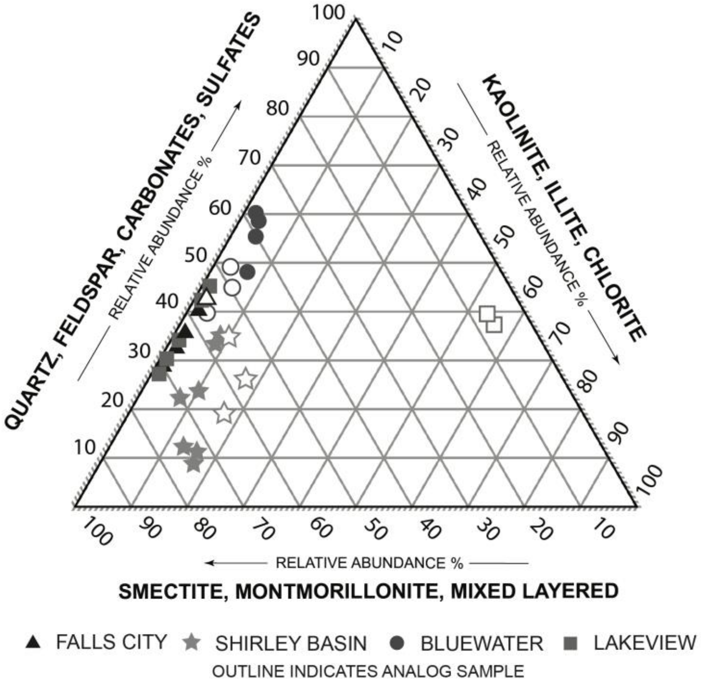
The chemical composition of natural parent materials exerts influence on soil development through both physiochemical and plant-soil feedbacks. The mineralogy of parent materials provides the original supply of plant nutrients that are released by weathering, influencing vegetation and soil development from subsequent organic inputs, physical modifications, and chemical transformations (Anderson, 1988). Soils formed from mafic rocks, such as basalt, are generally more fertile, with large amounts of calcium, magnesium and phosphorous, compared to those formed from felsic rock, including granite (Harley and Gilkes, 2000). Soils formed from ultramafic rocks, such as serpentinite, have poor fertility, and are composed of plant communities that have adapted to nutrient limitations. Soils formed from limestone and dolomite tend to be alkaline, while those formed in sandstones tend to be mildly acidic with a low supply of nutrients. The impact of soil pH on vegetation is varied with some plants preferring acidic over neutral soils (Marschner, 1991). Mancos shale is a common fill material for cover systems on the Colorado plateau, and the generation of sulfuric acid from mineral weathering can create acidic soils unfavorable for many plants (Potter, et al., 1985), in addition to Se and B toxicity (Mast et al., 2014), however endemic vegetation have adapted to exploit such soils (Comstock and Ehleringer, 1992). In some cases, acid-generating sulfide clays have been intentionally used for the construction of compressed clay barriers in waste covers to retard root growth with notable success (Robinson and Handel, 1995).

Clay barriers for waste isolation are intended to retain as-built compression, thereby limiting liquid and gas flux due to minimal pore space. The morphology of an ideal clay barrier at construction would be monolithic and free from morphology (aggregates, cracks, voids, roots, etc.) that would contribute to the diffusion of liquids or gasses. Additionally, the ideal clay barrier would be composed of smectitic clays, such as montmorillonite, that have a high liquid and plastic limit, swell in the presence of water, and display very low hydraulic conductivity when saturated and compressed. Smectites are comprised of layers of negatively charged aluminosilicate sheets held together by charge-balancing counter-ions including Na+, K+, Mg2+, and Ca2+. In the presence of water, smectite swells through the process of interfoliar cation hydration. Divalent cations, including Ca2+, have a higher affinity to water than monovalent cations, such as Na+. Under conditions of elevated Na+, dispersion of clay particles can occur thus reducing the swelling capacity of smectitic clays and increasing hydraulic conductivity (McNeal and Coleman, 1966). In the event of barrier drying, smectitic clays will fracture through desiccation and cracking processes. If physically protected from surface processes resulting in physical, chemical, or biological modification, and if enough moisture is maintained, reduced pore space in smectitic clay barriers can persist, representing an effective waste isolation barrier.

Clay barriers are made of materials sourced in economic proximity to wastes, and the ability to source high smectite clay materials is not always viable. Additionally, maintaining ample clay barrier saturation in high smectite clays, is dependent on other design and climate factors, and protection from desiccation cracking is not always accomplished in the most mineralogically favorable of clay barriers. In practice, clay barriers are composed of a diverse set of minerals including quartz, feldspar, carbonates, sulfates, 1:1 clay (e.g. illite and kaolinite), and 2:1 clay (e.g. smectite and montmorillonite). Clays dominated by kaolinite are more prone to shrink-swell and the formation of macropores than those dominated by montmorillonite, and soils dominated by kaolinite generally display higher rates of hydraulic conductivity (Ross, 1978; Frenkel et al., 1978). If natural clay mineralogy is inadequate to achieve desired compressibility standards for hydraulic isolation, commercial bentonite (Na-montmorillonite) is commonly added to improve the quality of naturally sourced materials (Kumar and Yong, 2002). Over regulatory timeframes (200-1000 years) clay mineralogy is not anticipated to appreciably change and is assumed to represent a static feature, with few exceptions.

The variation in clay barrier mineralogy, within and between, several cover systems in the UMTRCA program is displayed in Figure 3.4. The composition of 2:1 clay range from 38% to 76% across sites, and from 57% to 72% at Falls City, TX; 38 to 45% at Bluewater, NM; 57% to 76% at Shirley Basin, WY; and 65% to 71% at Lakeview, OR. The mineralogy within and between sites should be considered when interpreting engineering performance and comparing trends in soil change between sites.

Figure 3.4: Clay mineralogy of barriers in the UMTRCA program



### 3.5.2.5. *CONSTRUCTION DISCONTINUITIES IN CLAY BARRIERS*

Unlike highly sorted and uniformly manufactured materials including plastic or steel, natural soil materials are dominated by heterogeneities in texture, mineralogy, biotic activity and foreign objects including man made debris. Within the UMTRCA program, material specifications for acceptable grain size distribution and soil organic matter content have been established to manage heterogeneity, within acceptable limits, and material audits are typically performed on every 1,000-10,000 cubic meters of material used for the construction of clay barriers. Given the vast surfaces of individual covers in the UMTRCA program (6 - 200 ha), and the large volume of materials needed to construct them (millions of cubic meters), cover systems will inevitably contain various material discontinuities (Smith et al., 1997) reflecting landform heterogeneities in natural landscapes used for material sourcing. The presence of construction discontinuities is not commonly included in narrative form in site closure reports, though careful examination of photographs and figures can provide some useful clues. Excavations of in-service barriers have shown that aggregate structures, that were naturally formed in borrow material soil profiles, can be retained during clay barrier compression despite best management efforts to remove them (Waugh and Smith, 1997). The structuring and size of retained aggregates have considerable impacts to compression and hydraulic properties of clay barriers (Benson and Daniel, 1990). The occurrence of retained aggregate structures were liberally observed across all sites in this study (Williams et al., 2019). Given the clay content of desired barrier construction materials, the stability of retained aggregates can be considerable and long-lasting.

A clay barrier is a stratigraphy of individual mechanical depositional events composed of materials that can contain slight morphological variation (given borrow material heterogeneities), and construction variation (given moisture and compaction variations) that can lead to the emergence of horizontal inter-lift flow paths that may delaminate over time (Benson and Wang, 1996). In addition to physical variations in as-sourced or constructed barrier materials, chemical and biological variations can also be present (Schlesinger and Pilmanis, 1998). Taylor, et al., (2003) observed dead plant roots of varying sizes within an in-service clay barrier and suggested the possibility that they came from borrow materials. Construction debris including wooden stakes, ball bearings, bolts, and various other materials were all found in barriers excavated in this study. These relic structures have been hypothesized as initial places of soil change given the inherent variation in physical properties and subsequent matric potential gradients (Burt and Cox, 1993; Albright, 2006b; Benson et al., 2011). Retained aggregates, laminar compression planes between lift events, and zones of coarse gravels are commonly found enmeshed with the highest density of fine and very fine roots within in-service barriers, suggesting that such voids are the preferred locations of root penetration immediately post construction (Taylor, et al., 2003). Given textural differences, or edaphic feedbacks resulting in root establishment and macropore formation, structural discontinuities can also serve as locations for preferred water flow in barriers. In silty textured, functionally dispersive clay barriers, preferential flow paths may result in enlargement over time, and erosional channelization, or piping, under high intensity rain events common to the semi-arid southwestern United States. Erosional dynamics may also be influenced by clay mineralogy (e.g. sodicity) and relief (e.g. long side slopes designed for storm water management).

#### 3.5.2.6. *CONSTRUCTION TOPOGRAPHY AS RELIEF*

As a constructed landform, landform topography and relief are dependent on engineering design [Eq.3.2]. Relief describes the physical orientation of a landform in relation to relative elevation gain, slope, and aspect. In terrain with variable topography, soil moisture collects at lower points in the landscape with consequences to vegetation abundance and patterning. On a field scale, topography will create micro environments of drier or wetter locations than average. Additionally, relief and aspect influence the duration of daily and annual solar gain, resulting in hotter or colder microenvironments with impacts to soil reactions and plant productivity. Given solar gain, drier soils are expected on south facing slopes, which may impact rates of desiccation cracking in clay barriers, and subsequent performance for hydrologic and gas control.

The geometry and sharpness of hillslope topography also influences rates of soil drainage, soil depth, and wind velocity. Across several sites in the UMTRCA portfolio, the leeward slopes of rock armored disposal cells preferentially collect dust given decreased wind speeds. The establishment of vegetation has been observed to correspond with dust infill on leeward slopes (Chapter 2). Drainage, erosion, sediment transport, prolonged saturation, and the collection of soluble salts and carbonate can be significantly influenced by topography given the preferential movement of water downslope with gravity. Depressions on structures serve as low points and can be intentionally designed to facilitate drainage off disposal cells or be emergent from the settlement of saturated subsurface wastes that dewater over time (DOE, 2014). Prolonged saturation in compressed clay barriers occurring in low elevation drainages may also have impacts to long-term soil morphology due to decreased rates of desiccation/cracking and structuring. Given the inverse relationship between soil moisture and gas diffusivity, low points on cover systems that remain saturated will result in lower average annual radon diffusion (see Chapter 5).

### 3.5.3. VEGETATION AND SOIL DEVELOPMENT

Soils and organisms interact and evolve together (Jenny, 1980). Grassland soils are characterized by deep organic rich surface horizons, mixing by animals including earthworms and rodents, and general horizontal uniformity in soil morphology at the field scale (Six et al., 1998). Semi-arid and xeric shrubland soils are characterized by patchiness in nutrients, soil morphology, and soil hydraulic properties (Lyford and Qashu, 1969; Schlesinger, and Pilmanis, 1998; Bird et al., 2002). Soils in mixed temperate to subtropical forests have high leaf litter, and higher acidity given the presence of organic acids, resulting in increased mineral weathering and chemical horizonation (McKeague et al., 1983). Given the lifespan of individual trees, forest soils can be characterized by patchiness associated with root development, soil compaction, and episodic windfall and root churning (Pärtel and Wilson, 2002). Engineered disposal cells are present across all major biomes and vegetation development and vegetation patterning can have significant and irreversible impacts to as built soil engineering properties (Burt and Cox, 1993; Link et al., 1994; Smith et al., 1997; Waugh et al., 1999; Taylor, et al., 2003; Albright et al., 2006a; Fourie and Tibbet, 2007).

#### 3.5.3.1. *POTENTIAL EDAPHIC CONDITIONS AT CONSTRUCTION*

The edaphic conditions of waste covers at construction can vary considerably. It is common for waste disposal covers to contain adverse chemical conditions including metal toxicity, extreme pH values, salinity, and nutrient deficiencies that influence rates and patterns of root establishment and above ground biomass (Handel et al., 1999). It is widely understood that plants growing in nutrient deficient environments (i.e. $NO3^-$) will develop fast growing tap-roots with nominal root branching (Wiersum, 1958; Drew and Saker, 1975; Erickson, 1995). N, P, K and Fe nutrient deficiencies can affect root branching, root hair production, root diameter, and root growth angle (Forde and Lorenzo, 2001). The same trend in root development is found under conditions of Cd, Cr, Cu, Ni, Zn toxicity (Peralta et al., 2001).

The soil atmosphere above buried wastes may also inhibit plant growth. Anoxic conditions of municipal landfill covers are often indurated with methane, carbon dioxide, hydrogen sulfide, ammonia, and other metabolically inhibitory gases (Ham, 1979; Handel et al., 1999). Studies conducted by the United States Environmental Protection Agency (EPA) have shown damage to tree roots growing in high concentrations of noxious gases common to municipal landfills (Flower et al., 1977; Flower et al., 1981). Root inhibition by gases generated by decomposing municipal waste hinders, but does not necessarily prevent, revegetation of closed landfills (Gilman et al. 1981). However, not all hazardous wastes requiring burial (including uranium mill tailings in the UMTRCA program) will produce gases known to be detrimental to vegetation establishment, and if they do, they will only produce them for a short period of time given very low levels of decomposable organic matter in the subsurface (Smith et al., 1997). Given the various adaptations that native plants can make to adjust to native substrates and the immense heterogeneity in metal pollution, nutrient availability, soil pH and the composition and concentration of gasses trapped in the subsurface, few generalizations can be made about edaphic restrictions of engineered covers at construction.

### 3.5.4. INCORPORATING VEGETAION INTO DESIGN

The biotic condition of waste cover systems is primarily influenced by initial design and ongoing management. Given climate and site reuse goals, covers can be unvegetated and covered with rock armor or vegetated with mixed perennial grasses for surface stabilization. Covers are rarely, if ever, planted with vegetation other than grasses and forbs, however natural vegetation succession can be permitted depending on site specific waste characteristics, cover design, and site reuse goals. In the UMTRCA program, designs have largely favored static rock armor over vegetated designs for reasons including uncertainty in natural succession and unknown impacts associated with root development. When located in climates that can support diverse vegetation, rock armored covers represent far from equilibrium designs in relation to natural analog conditions, and their surfaces have been observed to change more rapidly over time when compared to planted designs (See Chapter 2).

### 3.5.5. BIOTIC CONDITION OF COVER

The biotic condition of an engineered cover can have considerable impacts to soil morphology. Processes of bioturbation by both plants and animals can physically break up compressed clay layers which can increase hydraulic conductivity and alter performance. Near surface soil layers (e.g. topsoil, infill, frost protection layers and rooting medium) can also be conditioned by biotic influences. Plant rooting not only accelerates rates of wetting and drying cycles but also promotes small scale soil-water heterogeneities and stress imbalances which can result in the propagation of microcracks due to evapotranspirative demand (Angers and Coren, 1998). Natural ecological succession can drastically alter the biotic condition of landforms though such changes remain difficult to predict on engineered landforms. A detailed review of decadal vegetation establishment and root patterning on engineered disposal cells of different design and climate is found in Chapter 4.

Given hydrologic impacts associated with natural succession and subsequent plant rooting in compressed clay barriers over regulatory timeframes, recent efforts have explored how conventional engineered clay covers may be transformed into evapotranspiration (ET) covers to redirect soil-water back into the atmosphere (Waugh, et al., 2009). However, a tradeoff exists given that plant roots may increase gas flux by accelerating the drying of clay barriers and creating preferential pathways for radon gas diffusion at UMTRCA sites (Link et al., 1994).

The establishment of vegetation on engineered covers can create habitat for animals (Waugh and Smith, 1997). Burrowing and tunneling animals can pose a threat to cover system performance from direct vertical displacement of wastes and surface erosion (Winsor and Whicker, 1980; McKenzie et al., 1982), accelerated drying and cracking of the compressed clay barrier through wind-induced ventilation from tunnel systems (Vogel et al., 1973), and increased rates of water infiltration and gas diffusion (Cadwell et al. 1989; Landeen 1994; Suter et al. 1993). The impact of animal burrowing on UMTRCA cover system performance has long been explored (Gano and States, 1982; Cline et al., 1982; Beedlow, 1984), resulting in numerous cover design and management suggestions intended to limit biological intrusion by animals (Hakonson et al., 1982a; Hakonson, 1986).

### 3.5.6. MANAGEMENT OF VEGETATION

The vegetation on engineered disposal cells can be actively or passively managed. In planted designs, grasses and small shrubs are occasionally managed through grazing by cattle or mowing and bailing. Vegetation encroachment on rock armored surfaces has been liberally observed across the UMTRCA portfolio and can be costly to manage (Waugh and Smith, 1997; Waugh et al., 2007; Waugh et al., 2009). Deep rooted plants (long considered a threat to engineering integrity) are often hand cut and treated with herbicide. The economic costs, and the human and environmental health risks associated with indefinite herbicide applications, have resulted in efforts to better understand the long-term impacts of plant rooting on rock armored cover systems (DOE, 2015; DOE, 2016). Evidence suggests that the presence of vegetation may enhance cover performance through increasing evaporative demand on some sites (Waugh, et al., 2009).

Management decisions can play a considerable role in the development of soil properties through time. Deep plant rooting, and the subsequent formation of root associated pore space, may be limited if vegetation is effectively controlled. However, some vegetation, including mesquite, are resistant to all but the most aggressive of management efforts (Streets and Stanley, 1938; Herndon, 1980). Live mesquite roots were observed in the top section of the radon barrier at Falls City, TX in-lieu of annual efforts to manage vegetation through cutting and bailing (Williams et al., 2019). The removal of biomass by haying can also have long term impacts to carbon deposition and nutrient cycling from reduced plant litter, which can alter long term vegetation density with implications to surface erosivity (Lal, 2009). Overgrazing can result in a deterioration of plant quality and increased risk of soil erosion, while properly managed grazing practices can result in increased pasture health, plant rooting, infiltration, and erosion control (Bilotta et al., 2007).

### 3.5.7. REGULATORY TIMEFRAMES

Soils and soil like materials change over time given the configuration of other soil forming factors. Time controls the number of cycles that pedogenic processes can result in morphological change. Waste isolation cells are unlike many natural soils in that they have a very well-defined time = 0 and are engineered to perform specific functions over a fixed number of years (i.e. the regulatory timeframe). While of potential intellectual interest, the timeframes beyond those specified by design criteria are less important to applied management. The processes that occur within those engineered lifetimes are most relevant to managers and regulators needing to understand feedbacks associated with Earth surface process, soil change and cover performance. However, longer term changes to as-designed performance, beyond regulatory timeframes, will likely be of considerable interest to future communities living in proximity to aging waste disposal cells.

The timeframes associated with maintaining satisfactory isolation greatly depend on the type of waste being buried. Disposal cells for municipal waste containment (i.e. household garbage) are generally required to perform for 30-50 years before such wastes decompose (40 CFR Part 258, Criteria for Municipal Solid Waste Landfills), while disposal cells for the isolation of radioactive uranium mill tailings are expected to last for 200 to 1,000 years (Public Law 95-604, Uranium Mill Tailings Radiation Control Act of 1978).

While considerable effort has been placed on investigating the long-term soil record from chronosequences that focus on soils between 3,000 to 3,000,000 years of age (Stevens and Walker, 1970; Huggett, 1998), relatively few pedogenic studies exist that explore decadal, and century long timescales relevant to soil change in waste cover systems (Richter, 2007; Richter et al., 2007). Considerable changes to as built soil morphology have occurred in as little as 5-years after construction from a mix of abiotic and biotic processes (Burt and Cox, 1993; Benson et al., 1995; Melchior, 1997; Benson et al, 2011). However, few studies have been performed to measure changes that may occur after 25-years from installation which represents a significant gap in our understanding of long-term cover performance. Natural analog soils, formed under similar forming factors to engineered soils, have been used to estimate the long-term direction of cover system change (Waugh et al., 1994a; Waugh et al., 1997). Such studies remain sparse, and a systematic understanding of soil processes and rates of change relevant to the timescales of engineered design lifetimes remains underdeveloped.

## 3.6. RESULTS: SITE FACTORS AND SOIL MORPHOLOGY OF IN-SERVICE COVERS

A series of 35 profiles were excavated across four in-service engineered soil covers at Falls City, TX (May, 2016), Bluewater, NM (June, 2016), Shirley Basin, WY (September, 2017), and Lakeview, OR (October, 2017). Profiles are associated with both fixed and variable soil forming factors. Detailed morphological characterization of soil and root structure are used to explore how different factorial combinations can be used to describe in-service soil condition. A summary of soil forming factors across the four sites is presented in Table 3.2. A graphical representation of soil structure under these soil forming factors is presented in Figure 3.5, with root morphology being presented in Figure 3.6. Complimentary soil survey data can be found in Williams et al., 2019.

Table 3.2: Soil forming factors at four engineered covers for waste containment in the UMTRCA program

| | **Cover Design (d)** | | | | **Climate (cl)** | | **Biota (o)** | | **Management (m)** | **Time (t)** |
|---|---|---|---|---|---|---|---|---|---|---|
| | Type | Depth to barrier (m)<br>*Design spec.* | Barrier texture (clay %)<br>*Average* | Mineralogy (2:1 clay %)<br>*Average* | Soil Moisture Regime | Soil Temperature Regime | Flora | Fauna | Strategy | Years since construction<br>(in 2017) |
| Bluewater, NM | Rock Armor<br>**CMB** | 0.15 m | 20% | 40% | Aridic-Ustic | Mesic | Russian thistle, bottlebrush, fourwing saltbush, Siberian elm | Ants, Rodents, Badgers | Hand removal of trees | 21 |
| Lakeview, OR | Planted rock<br>**CCB** | 0.6 m | 16% | 62% | Xeric | Frigid | Sagebrush, rabbitbrush, bitterbrush, mixed cool season grasses | Rodents, Badgers | Hand removal of trees | 28 |
| Falls City, TX | Planted grass<br>**PMB** | 1.0 m | 43% | 64% | Udic-Ustic | Hyperthermic | Mixed pasture dominated by coastal Bermuda grass, Mesquite | Ants | Mowing, hand removal of trees/shrubs on slope. | 22 |
| Shirley Basin WY | Planted grass<br>**PMB** | 1.0 m | 55% | 69% | Aridic-Ustic | Mesic | Mixed cool season grasses, sparse sagebrush | Rodents, Cattle | Grazing, hand removal of trees/shrubs on slope. | 17 |

Figure 3.5: Soil structure of UMTRCA covers under variable surface condition

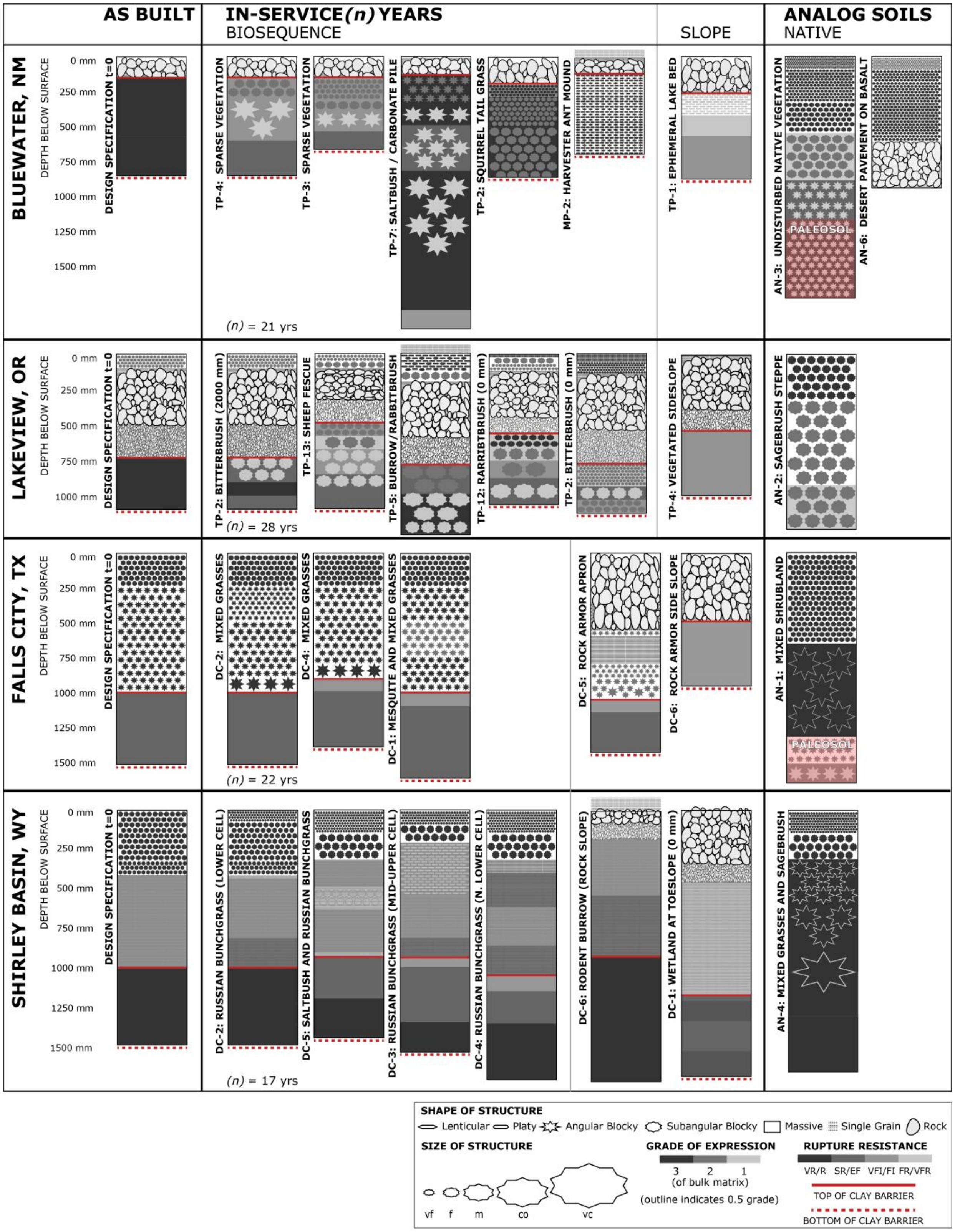
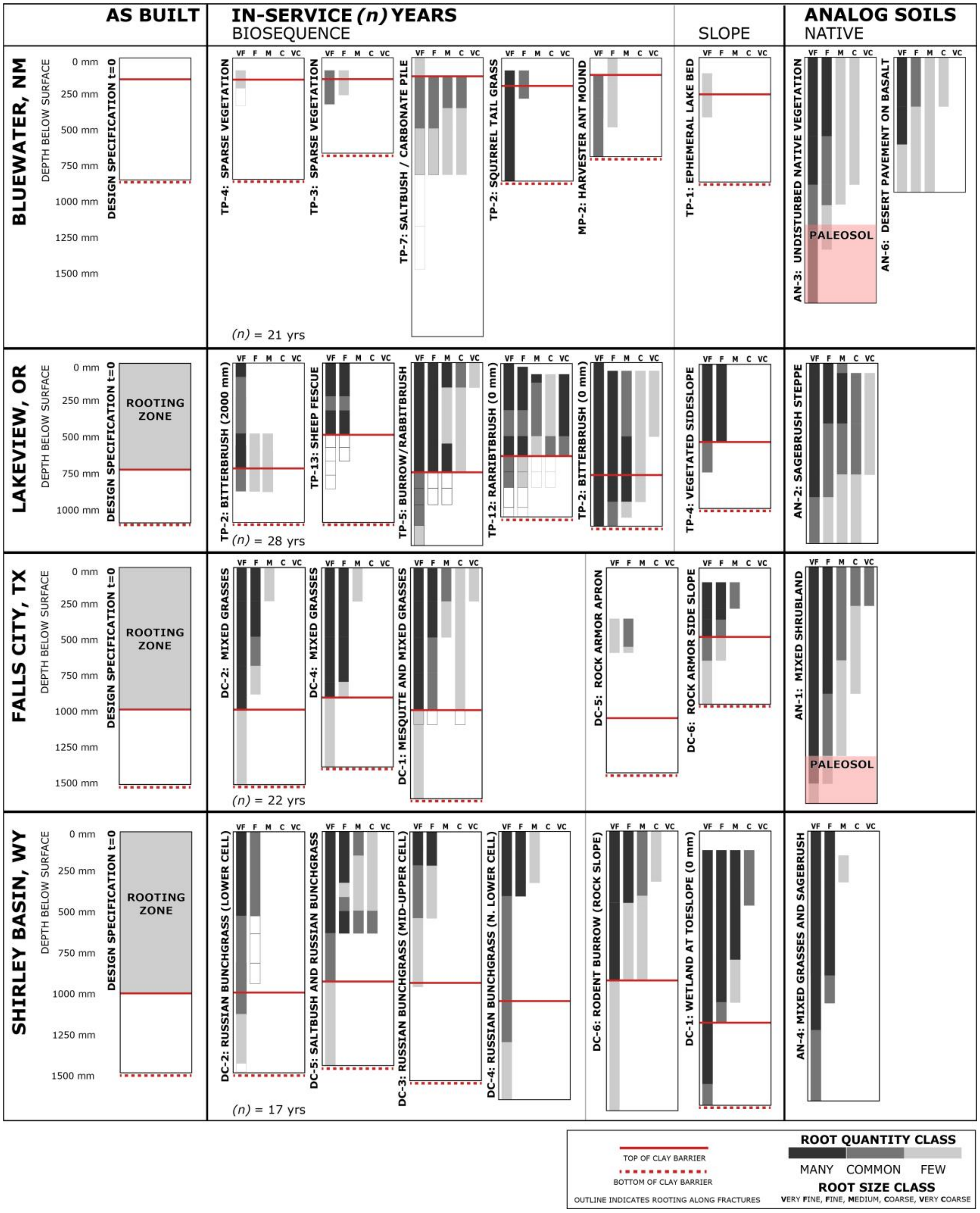


Figure 3.6: Root structure of UMTRCA covers under variable biotic condition



## 3.7. SOIL STRUCTURE AND ROOTING MORPHOLOGY OF IN-SERVICE COVERS

### 3.7.1. BLUEWATER, NEW MEXICO

A total of 11 profiles were excavated at the Bluewater, New Mexico site in June, 2016. After 21 years of service, the main disposal cell was characterized by surface condition patchiness (Chapter 2). Surface conditions include sparsely vegetated rock, zones of ephemeral ponding, zones of mixed perennial grass establishment, zones of mixed annual weed development, patches of fourwing saltbush, and infrequent harvester ant mounds. Management for deep rooting plants, including tamarisk and Siberian elm, consists of hand cutting and spraying. Noxious weeds are also sprayed as needed.

Several disposal cells of varying design and waste characteristics are found at the Bluewater site. The main disposal cell at Bluewater is a Shallow Compacted Mineral Barrier with an unplanted rock armor surface and no bedding layer. Among the profiles surveyed, rock armor thickness varied between 80 - 150 mm. The interstitial spaces of the rock armor were occasionally filled with organic materials from nearby vegetation, blown seeds, animal scat, aeolian dust, and anthropogenic debris including blasting caps, ball bearings, scrap metal, tire shards, and survey stakes. The surface of the clay barrier was in direct contact with overlying rock armor, and the minimum depth from ground surface to clay barrier was 80 mm. Clay barrier thickness ranged from 540 - 700 mm, with individual lift events ranging from 80 - 230 mm (average = 160 mm). One profile on the carbonate cell (TP-7) had a total depth of 2,580 mm, with the clay barrier accounting for 2,420 mm. With exception to the downslope ephemeral pond profile, clay barrier materials were dry, and very hard, below 250 mm from ground surface. Variation in as built condition was evident in variable rock armor thickness, clay barrier horizon thickness, variable color of clay barrier lift events, and slight variation in the gravel content and retained aggregate structure of clay barrier lift events.

*STRUCTURING IN THE CLAY BARRIER*

Originally designed as a monolithic compressed clay barrier without structure (i.e. massive), a diversity of soil structuring is now found within the clay barrier as a function of surface condition. Single grain, granular, platy, blocky, and massive structures are present, with decreased structuring observed with depth (Figure 3.5). The profile associated with the ephemeral lake (TP-1) had the least structural development and was characterized by weak platy structure, constrained to the first lift plane (460 mm). The sparsely vegetated profiles (TP-3 and TP-4) had blocky structures of mixed sizes (very fine to coarse) that increased with depth, and mixed grades decreasing with depth, to a depth not exceeding 590 mm. Profiles TP-1, TP-3, and TP-4 contained sections of clay barrier that remained massive and did not display emergent soil structuring.

The saltbrush profiles were characterized by blocky structure of mixed sizes (fine to coarse) that increased with depth, and mixed grades decreasing with depth. Profile TP-5, on the main cell, displayed structuring through the depth of the observed clay barrier

(740 mm). Profile TP-7, on the carbonate cell, displayed structuring to a depth of 1,580 mm with a remaining 1000 mm of clay barrier, devoid of structuring, below.

The profile associated with squirrel tail grass (TP-2) was characterized by granular structure in sediments collected in the rock armor infill. The clay barrier had blocky structure of mixed sizes (very fine to medium) that increased with depth, and mixed grades decreasing with depth. Structuring was observed through the depth of the observed profile to 880 mm. The profiles associated with harvester ant mounds (TP-6 and MP-2) were characterized by intermixed blocky and platy structures of sizes ranging from very fine to fine, through the depth of the clay barrier (not exceeding 820 mm).

#### *PLANT ROOTING IN THE CLAY BARRIER*

Plant rooting was found in the clay barrier of all profiles surveyed, regardless of surface condition (Figure 3.6). Rooting size, quantity, and depth corresponded to vegetation type, with saltbrush profiles (TP-5 and TP-7) having the greatest variation in root size and quantity. Sparsely vegetated profiles (TP-3 and TP-4) and the dry ephemeral lake bed, had the least abundance of roots. Squirrel tail grass profiles (TP-2 and MP-2) had the greatest overall rooting density and were dominated by very fine roots that were observed through the depth of the clay barrier. Dense root matts were commonly observed along vertical fracture planes in desiccated clay barrier materials. Several of the root filled fractures observed in TP-2 and TP-5 traveled through the depth of the clay barrier and into subsurface materials. Root benching was commonly observed at clay barrier lift event boundaries, in locations where underlying materials had a greater consistence. Such lift events served to restrict rooting in the bulk soil, with subsequent rooting being confined to fracture planes. Considerable organic matter accumulation was observed in the rock armor underneath vegetated conditions. Dead roots were observed sparingly in the clay barrier and may have been attributed to as-built borrow pit materials.

### 3.7.2. LAKEVIEW, OREGON

A total of nine profiles were excavated at the Lakeview site in October, 2017. After 28 years of service, the disposal cell was characterized by moderate surface condition patchiness, approaching that of the steppe environment found in the surrounding low-lands (Chapter 2). Surface conditions include sparsely vegetated interstitial spaces in-between shrubs, zones of mixed perennial grass establishment, bitterbrush, rabbitbrush, and very infrequent rodent burrows. The rock armor side slope was largely un-vegetated, with very infrequent patches of perennial grass establishment. Management for deep rooting plants, including juniper, consists of hand cutting and spraying. Noxious weeds are also sprayed as needed.

The disposal cell at Lakeview, Oregon is a Composite Capping Barrier with planted rock armor. On the top-deck of the disposal cell, topsoil thickness ranged from 10 - 200 mm (average = 110 mm) with zones of inconsistent topsoil application, surface scouring, and downward rock infill. An organic horizon composed of leaf litter was frequently observed in profiles associated with shrubs and ranged in thickness between 0 - 70 mm, with decreasing thickness at an increasing distance from the tap root. As a composite capping barrier, the surface of the clay barrier was underneath topsoil, rock armor, and gravel admixture layers that varied in thickness across the profiles surveyed. The minimum depth from ground surface to the top of the clay barrier was 510 mm, while the maximum depth from ground surface to clay barrier was 780 mm (average = 660 mm). Clay barrier thickness ranged from 330 - 650 mm (average = 450 mm), with individual lift events ranging from 70 - 160 mm (average = 100 mm). Considerable variation in as built condition was evident in variable horizon thickness, variable color of clay barrier lift events, and variation in the gravel content and retained aggregate structure of clay barrier lift events.

### *STRUCTURING IN THE CLAY BARRIER*

Blocky and massive structures were present in the clay barrier, with decreased structuring observed with depth (Figure 3.5). On the top deck of the disposal cell, the profiles associated with sparsely vegetated interstitial zones greater than 2000 mm from the tap root of shrubs (i.e. TP-2.2000 mm) had the least structural development and were characterized by weak blocky structure, constrained to the top two lift planes (940 mm). The profile associated with sheep fescue (TP-13) had blocky structures of mixed sizes (fine to medium) that increased with depth, and mixed grades decreasing with depth, to a depth not exceeding 820 mm. The profile associated with rodent burrowing (TP-5) contained a 270 mm high mound of transported materials on the surface, and the clay barrier had intermixed blocky structures of mixed sizes (course to medium) to a depth not exceeding 1400 mm. The profiles associated with the rock side-slope (TP-4A, TP-4B) were very moist, with active downslope water shedding observed, and no emergent soil structuring was evident. Profiles TP-2.2000 mm, TP2.2500 mm, TP-5, TP-13, and TP-4A/TP4B contained sections of clay barrier that remained massive and did not display emergent soil structuring. The profile associated with sparse vegetation (TP-10) had blocky structures of mixed sizes (medium to very coarse) that increased with depth, and mixed grades decreasing with depth.

The profile associated with rabbitbrush (TP-12) was characterized by blocky structure of mixed sizes (fine to coarse) that increased with depth, and mixed grades decreasing with depth. As distance from tap-root increased, grade decreased across all sizes, over a 2000 mm distance. Structuring was observed through the depth of the profile (1090 mm), across all TP-12 transect locations. Bitterbrush profile (TP-2) displayed blocky structure of mixed sizes (fine to coarse) that generally increased with depth, and mixed grades generally decreasing with depth. Bitterbrush profile (TP-11) had blocky structure (fine to medium) that increased with depth of shared grade.

In addition to correlation with surface condition, depth, and bioturbation, soil structuring at Lakeview is influenced by clay barrier depositional stratigraphy. Bands of larger sized structures were found in-between bands of smaller sized structures in profiles TP-5 and TP-2, even under shared rooting condition, suggesting that the physical, textural, or mineralogical condition of individual clay barrier lift events exerts some control to patterns of emergent structuring.

*PLANT ROOTING IN THE CLAY BARRIER*

Rooting size, quantity, and depth corresponded to vegetation type, with bitterbrush profiles (TP-2 and TP-11) having the greatest variation in root size (very fine to coarse) and quantity. Fine and very fine roots were observed in the bulk soil fraction, through the depth of the clay barrier (1100 mm), in profile TP-2. The sheep fescue profile (TP-13), and the interstitial spaces at lateral distances away from the taproot of shrubs, had the least abundance of roots. Roots were not observed through the depth of the clay barrier in TP-10, TP-13, or at 2000 mm away from the taproot associated with the bitterbrush at TP-2. Dense root matts were commonly observed along vertical fracture planes in desiccated clay barrier materials. Several of the root filled fractures observed in the rabbitbrush profile (TP-12) traveled through the depth of the clay barrier (1090 mm). Root benching was commonly observed at clay barrier lift event boundaries, in locations where underlying materials had a greater consistence. Such lift events served to restrict rooting in the bulk soil, with subsequent rooting being confined to fracture planes. The clay barrier generally restricted roots of medium size or larger, with exception to profiles directly underneath bitterbrush (TP-2 and TP-11), and within emergent fractures found in rabbitbrush profiles (TP-5 and TP-12). Medium, coarse, and very coarse roots were commonly observed to travel laterally along the top boundary of the clay barrier. Dead roots, of unknown origin, were commonly observed in the clay barrier.

### 3.7.3. FALLS CITY, TEXAS

A total of seven profiles were excavated at the Falls City site in May, 2016. After 22 years of service, the disposal cell was characterized by a uniform stand of mixed perennial forage grasses interspersed with honey mesquite. The rock armor side slope has patchy areas of vegetation, with deep rooted vegetation requiring active management by cutting and spraying. The top of the disposal cell is mowed up to three times per year with hay being used by nearby cattle ranchers. Management is intended to reduce fire risk and mesquite rooting.

The disposal cell at Falls City, Texas is a deep Planted Mineral Barrier with a topsoil layer overlying a thick rooting layer. On the top-deck of the disposal cell, topsoil thickness ranged from 240 - 250 mm (average = 250 mm) while the thickness of the rooting layer ranged from 680 - 750 mm (average = 730 mm). The minimum depth from ground surface to the top of the clay barrier was 930 mm, while the maximum depth from ground surface to clay barrier was 1000 mm (average = 970 mm). Clay barrier thickness ranged from 460 - 620 mm (average = 570 mm). Individual lift events were largely indiscernible. The as built condition of the cell was more uniform than the Bluewater or Lakeview sites.

*STRUCTURING IN THE CLAY BARRIER*

The clay barrier at Falls City is largely devoid of emergent soil structuring. Soil structuring is limited to the topsoil and rooting layers and composed of blocky structures of mixed sizes (fine to medium) that generally increased with depth, and mixed grades that generally remained consistent with depth. Variation in soil structuring in the topsoil and rooting layers is largely attributed retained borrow pit aggregates, and not through the process of emergent, in-situ, structuring. The soil structure, within the clay barrier is massive, with slight variation in rupture resistance in a limited portion of the barrier in contact with the rooting layer. The decreased rupture resistance in such zones can be attributed to plant rooting associated with honey mesquite. Retained aggregates are observed in the clay barrier, but compression and moisture appear to be enough to maintain uniform soil structuring upon visual morphological inspection. The profile observed on the side slope (DC-6) had a 270 mm rock armor cover, with 70% of the interstitial spaces containing mixed illuvial infill. Rocks were found atop a 200 mm sandy gravel drainage layer, with the top of the clay barrier observed at 470 mm below ground surface. The barrier was found in a saturated state with active water flow observed in the drainage layer.

#### *PLANT ROOTING IN THE CLAY BARRIER*

Rooting size, quantity, and depth corresponded to vegetation type, with the honey mesquite profile (DC-1) having the greatest variation in root size (very fine to coarse) and quantity, within the clay barrier. With exception to the profile associated with the rock armor apron (DC-5), very fine roots traveled through the depth of the clay barrier in all profiles observed. Fine roots were observed liberally in the top section of the rock side slope profiule (DC-6, representing the highest root mass in any profile observed at Falls City. Fine and coarse roots were observed along fracture planes in the top 80 mm of the barrier in DC-1. No roots were observed in the clay barrier of DC-5.

### 3.7.4. SHIRLEY BASIN, WYOMING

A total of eight profiles were excavated at the Shirley Basin site in September, 2017. After 17 years of service, the disposal cell was characterized by a uniform stand of mixed perennial forage grasses. The rock armor side slope has patchy areas of sediment infill interspersed with perennial grasses. Saltbush are observed very sparingly across the site. The top of the disposal cell is actively grazed by a herd of cattle managed by a neighboring rancher. Noxious weeds are sprayed as needed.

The disposal cell at Shirley Basin is a deep Planted Mineral Barrier with a topsoil layer overlying a thick, sandy, rooting layer. On the top-deck of the disposal cell, topsoil thickness ranged from 230 - 410 mm (average = 320 mm) while the thickness of the sandy rooting layer ranged from 570 - 680 mm (average = 630 mm). The minimum depth from ground surface to the top of the clay barrier was 890 mm, while the maximum depth from ground surface to clay barrier was 1140 mm (average = 990 mm). Clay barrier thickness ranged from 480 - 860 mm (average = 620 mm), with individual lift events ranging from 60 - 230 mm (average = 140 mm). The as built condition of the cell was more uniform than the Bluewater or Lakeview sites, and less uniform than the Falls City site.

*STRUCTURING IN THE CLAY BARRIER*

The clay barrier at Shirley Basin is devoid of emergent soil structuring. Soil structuring is limited to the topsoil layers and composed of blocky structures of mixed sizes (very fine to medium) that generally increased with depth, and well-developed grades that remained consistent with depth. The sandy rooting layer was single grain/massive and largely structureless with exception to occasional vertical fractures. Variation in sandy rooting layer materials was observed and characterized by horizontal iron staining along laminar planes. Soil structure, within the clay barrier, was massive with variation in rupture resistance found in different clay barrier lift events. Retained aggregates were observed in the clay barrier, but compression and moisture appear to be enough to maintain uniform soil structuring upon visual morphological inspection. The profile observed on the side slope (DC-6B) associated with rodent burrowing, had an 80 mm rock armor cover, located atop a 160 mm sandy/infilled gravel drainage layer, with a 970 mm sandy rooting layer underneath. The top of the clay barrier observed at 1170 mm below ground surface. The barrier was found in a saturated state and was wetter than the profiles observed on the main cell. The profile observed on the toe-slope (DC-1) associated with ephemeral ponding and wetland plant ecology, had a 340 mm rock armor cover, with 40 mm of infill dominated by plant litter, and 170 mm of illuvial fines. Rock armor was located atop a 150 mm sandy/infilled gravel drainage layer, with a 670 mm sandy rooting layer underneath. The top of the clay barrier was observed at 1160 mm below ground surface. The barrier was found in a saturated state with active drainage observed in the gravel layer.

*PLANT ROOTING IN THE CLAY BARRIER*

Rooting size, quantity, and depth within the clay barrier, varied nominally across the profiles observed on the main cell. Most roots larger than very fine were constrained to the top 600 mm of the profiles and within emergent fractures in the sandy rooting layer. Very fine roots traveled through the depth of the clay barrier in all profiles observed, with exception to DC-3. Some variation in rooting quantity was observed with some correlation to the consistence of clay barrier materials. No roots larger than very fine were observed in the clay barrier.

## 3.8. FACTORS ASSOCIATED WITH CLAY BARRIER MORPHOLOGY

The deep Planted Mineral Barriers (PMB) at Falls City and Shirley Basin display considerably less soil structuring and rooting in the clay barrier than the shallow Compressed Mineral Barrier (CMB) at Bluewater and the planted, shallow rock Composite Mineral Barrier at Lakeview. A combination of factors can be attributed to such observations including cover design, management, climate, vegetation, slope, and depth to ground surface. Greater soil structuring and plant rooting in the clay barrier also correspond to coarser soil texture and lower 2:1 clay percentages based on site averages (Table 3.2), however, the presence of cofactors including design, vegetation, climate and depth from ground surface likely exert control over profile water balance and, therefore rates of desiccation and cracking influenced by texture and mineralogy. Broadly, factors that control uniformity of surface condition (i.e. vegetation, management, cover design, etc.) also contribute to observed uniformity in clay barrier morphology through time. Conceptual site process models from construction to present, and corresponding soil structure in a deep PMB at Shirley Basin, and a shallow CMB at Bluewater are presented in Figure 3.7 and Figure 3.8, respectively.

Figure 3.7: Shirley Basin, WY. Deep Planted Mineral Barrier. Site factors, surface condition, and soil structural development over time.

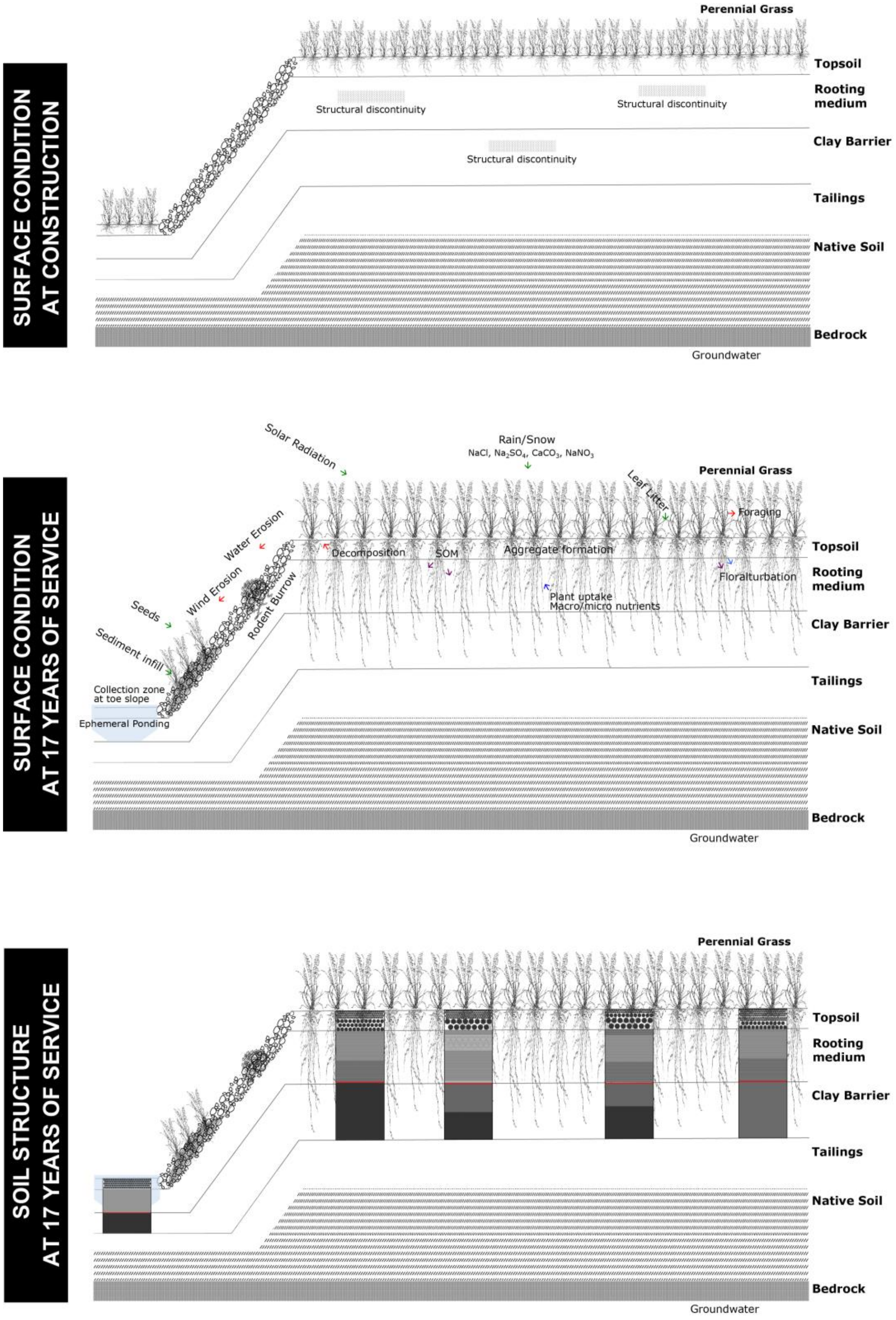
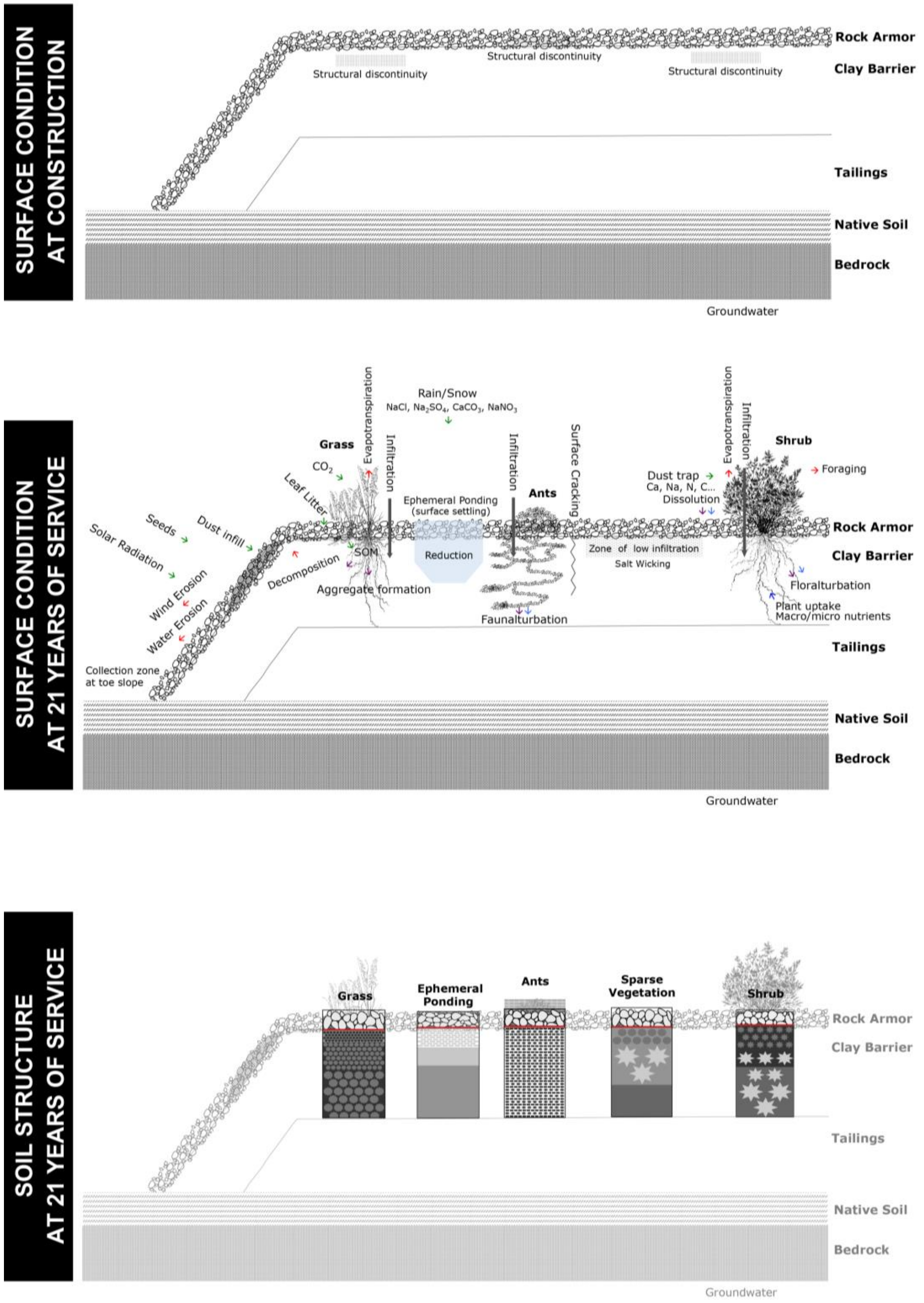


Figure 3.8: Bluewater, NM. Sallow Compressed Clay Barrier. Site factors, surface condition, and soil structural development over time.



### 3.8.1. DESCRIPTION OF SITE FACTORS AND SOIL MORPHOLOGY

Profiles associated with down slope collection basins displayed the least morphological development across all cover types and climates. Downslope profiles located in on-cell surface depressions (Bluewater TP-1), on rock armored side slopes (Lakeview TP-4, Falls City DC-6, Shirley Basin DC-6), and at rock armored toe slopes (Shirley Basin DC-1), all had clay barriers that were comparatively more saturated than other profiles on the same cell, and observation supported by detailed moisture profiles reported in Likos et al., (2019). The clay barrier observed in the side slope profile at Falls City (DC-6) displayed gleyic features, suggesting extended periods of saturation. In the absence of wetting and drying cycles, high smectite percentage, and sustained annual saturation, the down slope clay barriers generally maintained as designed soil structure, in-lieu of observed plant rooting.

Deep (PMBs that are managed by grazing, mowing, and spot removal of deep-rooted vegetation show greater resistance to changes in soil structure and plant rooting, over decadal timeframes, compared to the alternative designs studied. Such barriers are characterized by relative evenness of surface features, including vegetation. The Falls City cell requires active management of honey mesquite by periodic mowing. Under such management, rooting in the barrier is largely restricted to very fine roots. Rooting characteristics in the natural analog condition associated with mature mixed shrubland (Falls City AN-1), display very fine to medium sized plant rooting in soil materials of shared texture and compaction to clay barriers, at depths exceeding the bottom boundary of the clay barrier. This observation suggests that current vegetation management at Falls City is effective at minimizing plant rooting in the clay barrier. However, if management were to allow mesquite to establish on the cell, it is likely that the barrier would become more structured over time given observations in natural analog soils and the root patterning observed in the on-cell profile associated with honey mesquite (DC-1).

The PMB's at Falls City and Shirley Basin share many of the same design factors, however several flux factors are different. The climate at Falls City is hot and humid, while Shirley Basin is cold and semi-arid. Given rainfall and temperature, deep rooted vegetation is more abundant at Falls City than Shirley Basin, which results in the need for increased management. Natural plant rooting characteristics found at Shirley Basin (AN-4) show that plant rooting is limited to very fine roots at depths observed in the adjacent clay barrier, under shared vegetation and grazed management conditions found on the disposal cell. At Shirley Basin, plant rooting and soil structuring are remarkably similar between on-cell and natural conditions. Soil structuring is naturally inhibited in AN-4 at depths that correspond to the top boundary of the clay barrier (1000 mm), with root quantity and size also being of shared patterning. On-cell and analog observations suggest that the cell has reached a quasi-stable state of development and will likely behave similarly to surrounding natural soil environments if shared soil forming factors persist through time.

The shallow rock armored CMB at Bluewater was unplanted at construction and the surface is now characterized by a patchwork of emergent surface and subsurface conditions. Plant rooting and soil structural development varied considerably across the surface features surveyed at the Bluewater site. A mixture of soil forming factors are present that contribute to the variation in observed soil morphology. The profiles associated with harvester ant mounds (TP-6 and MP-2) displayed the greatest soil structural development, while a biosequence indicates that soil morphological development also corresponds to vegetation state with sparse annual weed profiles (TP-4 and TP-3) displaying the least morphological development and profiles of mixed perennial grasses (TP-2) and fourwing saltbush (TP-5 and TP-7) displaying the most soil development. The natural analog profile associated with mixed native vegetation in the borrow pit area (AN-3), displays soil structuring that very closely resembles the shape, size, grade and rupture resistance of the squirrel tail grass profile (TP-2). Additionally, plant rooting in AN-3 represents a sum combination of root characteristics observed in the on-cell saltbush (TP-5 and TP-7) and squirreltail grass (TP-2) profiles with shrubs contributing to the most observed rooting. Such observations indicate that the Bluewater disposal cell is transitioning away from as-built condition, and towards soil condition found in the surrounding natural environment.

The planted CCB, of moderate depth, at Lakeview is characterized by an emergent steppe environment with mixed grasses and shrubs. A biosequence at Lakeview indicates that soil morphological development corresponds to vegetation state with sparsely vegetated interstitial zones away from shrubs displaying the least morphological development, followed by mixed perennial grass profiles, rabbitbrush profiles, and bitterbrush profiles. The natural analog steppe profile (AN-2) displays soil structuring that closely resembles the shape, size, grade and rupture resistance of sheep fescue (TP-13), rabbitbrush (TP-12) and bitterbrush (TP-2) profiles, with some variations in depth corresponding to lift event material irregularities occurring within the clay barrier. Additionally, plant rooting in AN-2 represents a sum combination of root characteristics observed in the sheep fescue (TP-13), rabbitbrush (TP-12) and bitterbrush (TP-2) profiles with shrubs contributing to the most observed rooting. Such observations indicate that the Lakeview disposal cell is transitioning away from as-built condition, and towards soil condition found in the surrounding natural environment.

### 3.9. SECTION REVIEW

Earth surface processes are occurring unevenly across the four waste disposal cells surveyed with impacts to soil morphology. A conceptual framework of soil formation in engineered covers for waste containment has been used to describe soil condition in four in-service waste disposal cells of the UMTRCA portfolio. We find that a combination of factors including cover design, management, climate, vegetation, slope and depth to ground surface correspond to observed clay barrier morphology.

The deep PMB's at Falls City, Texas and Shirley Basin, Wyoming displayed considerably less soil structuring and rooting than the shallow CMB at Bluewater, New Mexico and planted rock CMB at Lakeview, Oregon. Profiles associated with down slope collection basins displayed the least morphological development across all cover types and climates. Biosequences at Bluewater and Lakeview show that soil morphological development, under fixed on-site factors, corresponds to emergent vegetation state with grasses and shrubs corresponding to greater morphological development at Bluewater and Lakeview, respectively.

Climate plays a role in regulating vegetation establishment on disposal cells of shared design at Falls City and Shirley Basin. The warmer and wetter site at Falls City corresponds to a greater incidence of shrub establishment, requiring added management. Given observations of rooting in the clay barrier under mowed mesquite conditions, and root morphology in adjacent natural analog soils under grazed woodland, it's likely that if management were changed to allow mesquite to establish on the cell, the clay barrier would become more structured over time with root diversity increasing substantially.

At Shirley Basin, plant rooting and soil structuring are remarkably similar between on-cell and natural conditions. The natural analog profile shows that soil structuring is nominal at depths that correspond to the top boundary of the clay barrier (1000 mm), with root quantity and size also being of shared pattern. Both on-cell and natural analog observations suggest that the disposal cell has reached a quasi-stable state of development (with exception to rock slopes of different design) and will likely behave similarly to surrounding natural soil environments if shared soil forming factors persist through time. Conversely, observations in natural analogs at Bluewater and Lakeview suggest that the clay barriers of each disposal cell are transitioning away from as-built condition, and towards soil condition found in the surrounding natural environment, after two decades of change. At all sites, the morphology of clay barriers, under the most developed on-cell surface conditions, closely resembles the soil morphology of adjacent natural analog conditions, suggesting that a significant opportunity exists to inform long-term cover morphology through investigation of analogs of shared factorial condition.

# 4. PEDOGENIC PROCESSES IN ENGINEERED SOILS FOR WASTE CONTAINMENT: A REVIEW

## 4.1. SUMMARY

Earth surface processes are occurring unevenly across engineered disposal cells for waste containment (Chapter 2). These changes are resulting in the emergence of soil morphology as described by soil forming factors (Chapter 3). Alterations to as built soil morphology are changing the engineering properties of disposal cells with impacts to long term performance (Chapter 5). This chapter provides a review of the rates and qualities of pedogenic processes in engineered soils for waste containment that are responsible for altering as built soil morphology. Special emphasis is placed on processes that may result in morphological development within the clay barrier of engineered waste disposal cells. Where data are particularly limited in the literature, this review is supplemented with observations and data from field investigations performed in Chapter 2 and Chapter 3. A conceptual framework is proposed that groups the emergence of pedogenic processes' that result in the expression of soil morphology into distinct time-steps. The framework can be used to explore relationships between soil forming factors, pedogenic process, and morphological development in engineered soils for waste containment.

## 4.2. BACKGROUND

Soils can be altered by additions, losses, transformations, and translocations and are the direct product of recurring Earth surface process through space and time (Simonson, 1959). Additions can include carbon and nitrogen from plant materials, aeolian dust, sediment deposition from overland flow, or cow manure from animal grazing. Losses can include organic matter decomposition and volatilization into carbon dioxide, wind or water erosion, the leaching of soluble salts, or the export of biomass from surface management by cutting and bailing. Transformations can include physical processes of desiccation-and-cracking or freeze thaw cycling, pedoturbation by plant roots and animal burrowing, humification of organic carbon into stable aggregates, or weathering of primary minerals into secondary products. Translocations can include soluble salt and carbonate movement within the profile, the deposition of plant debris in cracks and redistribution by thermal or moisture driven mixing, or the leaching of iron and manganese from redox reactions resulting in gleying.

The dynamic properties of soil change, and the self-organization of soil morphology through time, give rise to an abundance of natural soil diversity as seen in the many colors, textures, patterns and heterogeneities present across the worlds many soils. However, the inevitability of Earth surface process, and corresponding pedogenic processes that drive soil change, may run counter to conventional engineering efforts that rely on the rigid isolation of wastes through the structural maintenance of compressed clay barriers common to waste management systems across the planet, including those in the UMTRCA program.

The surface features of engineered covers in the UMTRCA program evolve as a function of design, climate, and management (Chapter 2). Such surface features result in considerable modifications to soil morphology over decadal time frames (Chapter 3). The intensity of soil morphological development directly corresponds to increases in radon diffusion coefficients and hydrologic flux, potentially decreasing cover protectiveness under some conditions (Chapter 5). This chapter provides a review of the qualities and rates of pedogenic processes in engineered soils for waste containment. Where data are particularly limited in the literature, we include data and observations from field investigations described in Chapter 3 and reported in Williams et al., (2019).

## 4.3. METHODS

### 4.3.1. LITERATURE REVIEW

A literature review of in-service compressed clay barrier performance was performed. Given the relative scarcity of literature explicit to the documentation of soil processes in engineered cover systems, additional supporting literature from natural conditions, like compressed clay cover systems in the UMTRCA program, are also included to provide additional support on mechanisms. Given that overall cover performance is largely regulated by the engineering properties *within* the clay barrier, the literature review focuses on processes that lead to the emergence of soil architecture *within* the compressed clay barrier itself.

### 4.3.2. SOIL SURVEY

A soil survey was performed across four UMTRCA covers as per methods described in Chapter 3, with a detailed discussion of site selection methodology and assumptions described by Waugh et al., (2019).

## 4.4. REVIEW OF PEDOGENIC PROCESSES IN ENGINEERED COVERS

This section first focuses on the initial drivers of soil change as dominated by physical processes including desiccation cracking, freeze-thaw cycling, clay dispersion, and erosion. The impacts associated with secondary processes including plant rooting, bioturbation by animals, and the formation of soil structure are then explored, followed by processes including the accumulation and redistribution of aeolian dust, soil organic carbon, soluble salts, calcium carbonate, oxidation reduction reactions, and the formation of secondary aggregates from broken down clay barrier and accumulated materials.

### 4.4.1. INITIAL CRACKING OF CLAY BARRIERS

There are two main mechanisms responsible for the formation of soil structure (a) those processes of aggregation that lead to the binding and stabilization of non-cohesive particles into larger particles; and (b) those processes of fragmentation that result in the breakdown of consolidated blocks within cohesive materials (Ghezzehei, 2012). The earliest stages of soil development in compressed clay barriers are due to fracturing from shrink/swell and desiccation/cracking phenomena associated with wetting and drying cycles (see Yesiller et al. 2000 and Albrecht and Benson, 2001, for detailed reviews on the subject). When bulk soils become saturated, the partial pressure of the system increases due to limited gas diffusion, resulting in the stress induced expansion and reorientation of platy silt and clay particles against rigid, non-reactive, sand particles. As soils dry, pressure recedes causing contraction along structural planes of weakness, likely small discontinuities (structural, textural, or compaction related) in otherwise uniformly conditioned, fine textured, cover materials (Benson and Wang, 1996; Hutchings, et al., 2001; Taylor et al., 2003). Upon soil rewetting, preferential flow occurs along legacy planes of weakness created during previous wetting/drying cycles (Omidi et al., 1996). Soil texture and mineralogy correspond to the degree of cyclic volume change with fine-textured soils of smectitic mineralogy resulting in the greatest volume change and the strongest degree of structural unit expression upon complete drying (DeJong and Warkentin, 1965). Finer-textured soils also tend to have less shear resistance and will break into smaller structural units resulting in increased cracking density (Southard and Buol, 1988). The speed of soil drying can also greatly influence crack size, with slow and even drying resulting in larger cracks, and fast uneven drying resulting in smaller cracks (Krisdani et al., 2008). In rock covered cover systems, thinner rock and rock fine layers that are in direct contact with underlying clay barriers can contribute to increased rates of desiccation. Cracking also results in the establishment of preferential flow paths. In dispersive soils, such flow paths may enlarge through time leading to surface rilling or erosional piping (Sherard et al., 1976).

As wetting and drying cycles continue through time, fractures may become reinforced through the deposition of dissolved solutes and soil organic matter churned from the surface (Blokhuis et al., 1990), which can lead to the preferential establishment of plant roots along fracture planes (Burt and Cox, 1993). Taylor, et al., (2003) suggested that the infill of coarser illuviated materials into emergent desiccation cracks may have been responsible for creating conditions suitable for secondary root intrusion at an engineered cover in NW Australia. Depth from ground surface, climate, and the composition of materials placed above the clay barrier have been shown to exert significant influence on rates and patterns of initial soil cracking in clay barriers (Benson et al., 1995; Albright et al., 2004; Albright et al., 2006).

### 4.4.2. FREEZE-THAW CYCLING

In frigid climates, initial fracturing from freeze-thaw cycling can also contribute to the development of irreversible porosity in high clay soils (Edwards and Cresser, 1992). In as little as two cycles, rates of hydraulic conductivity can more than triple in clay soils and increase by 100-fold in clays compressed wet of optimum, such as those employed for waste containment (Kim and Daniel, 1992). The thermal conductivity of compacted soils is greater than non-compacted soils, with freezing depth and thawing rate higher in compacted soils (Barnett, 1937). The amount and type of ground cover greatly influence the rate and depth of both freezing and thawing characteristics. Soils covered with leaf litter and mulch remain warmer, while uncovered soils are more prone to freezing (Kohnke and Werkhoven, 1963). Frost duration and depth are also influenced by vegetation type with coniferous woodlands remaining frozen longer and at greater depths, followed by deciduous forests, mixed meadows and grasslands (Post and Dreibelbis, 1942; Harris, 1972). Recurring cycles of ice nucleation can result in lenticular-platy soil morphology in uniformly textured soils.

The initial moisture content of soils also impacts frost characteristics and dry soils have been shown to freeze faster, and to greater depth, than wet soils (Willis et al., 1961). The presence and concentration of soluble salts also modifies freezing characteristics with higher concentrations of sodium chloride decreasing the freezing point of soils (Fuchs et al., 1978). Pore structure and soil texture also contribute to variation in freezing. Ice nucleation first occurs in large soil pores, with sustained lower temperatures being required to freeze water in smaller pores (Larson and Allmaras, 1971). Therefore, it can be expected that compressed clay barriers will require lower temperatures to freeze as compared to adjacent, non-compressed, natural clay soils with larger pore spaces. However, as clay barriers begin to develop pore structure, threats from freezing and thawing may increase as the temperature needed to nucleate ice decreases in response to increased pore size.

### 4.4.3. CLAY DISPERSION AND ERROSION

Soils with clay particles that detach and go into suspension in the presence of still water are termed *dispersive*. This is the result of repulsive surface charges between clay layers exceeding attractive forces (Holmgren and Flanagan, 1977). When clays disperse and become suspended in solution, they can be removed from the material by water resulting in the development of erosional pipes and tunnels. The removal of clay from barriers, and the development of such erosional features, can have significant consequences to the structural integrity and protectiveness of engineered waste covers.

Dispersive soils are generally formed from rocks that are low in both calcium and magnesium and contain minerals rich in sodium such as albite and amphibole (Paige-Green, 2008). Most dispersive clays described by Sherard et al., (1977), were found in alluvial environments including flood-plains, slope washes, lake bed deposits, and loess deposits, with some materials found in marine sediments that contained sodium rich pore waters. Methods including: Exchangeable Sodium Percentage (ESP), pH, conductivity, Sodium Absorption Ratio (SAR), Exchangeable Magnesium Percentage (EMgP), crumb test, double hydrometer test, and pinhole test, are commonly employed to characterize dispersivity in soils (Sherard et al., 1976; Harmse, 1980; Elges, 1985; Gerber and Harmse 1987; BSI 1990; Reeves et al, 2006). Given the many confounding soil properties, not one test is enough to determine material dispersivity (Richards and Reddy, 2007), and weighted rating criteria for the identification of dispersive soils are common practice (i.e. Bell and Walker, 2000).

In barriers made with clay minerals susceptible to dispersion (i.e. Na-montmorillonite or bentonite), erosional piping can initiate when water flows over planes of weakness. These fractures can be formed from natural processes including desiccation-cracking or freeze-thaw, or along structural planes of weakness formed during construction (i.e. the laminar interface between clay barrier lift events). Under flashy, high intensity and short interval rainfall events common to the western United States, large volumes of water can be pushed through these emergent cracks, specifically along downslope areas of waste disposal covers. Under saturated conditions, with moving water, dispersive clay barrier materials can be readily removed from areas surrounding cracks. As preferential flow paths enlarge, water volume and velocity increase further, thereby creating erosional piping or tunneling. Tunneling has been observed in soils with hydraulic conductivity as low as 1 x $10^{-7}$ m/s (Mitchell and Soga, 2005). As voids enlarge, they may collapse under the weight of surface materials resulting in visible surface depressions. Such erosional features pose a threat to cover system integrity.

#### 4.4.4. PLANT ROOTING

The morphology of as-built, compressed clay barriers can affect plant rooting through direct penetration resistance, limited hydraulic conductivity, minimal plant available volumetric water, and restricted gaseous diffusion rate (Taylor and Brar, 1991). The negative impact of soil compaction to plant rooting has been studied extensively (Ungar and Kaspar, 1994; Kozlowski, 1999). Depending on plant species and soil type, soil bulk density between 1.5 - 1.8 g $cm^3$ can significantly limit or stop root growth (Heilman, 1981; Simmons and Pope, 1987; Siegel-Issem et al. 2005). The as-built density of compressed clay barriers is commonly 1.75 g $cm^3$ (Goldman et al. 1988), which can result in the development of thick and short roots versus long and fine roots (Russell, 1977).

In lieu of the morphological and/or chemical limitations imposed on rooting by clay barriers at construction, the establishment of vegetation has been liberally observed (Burt and Cox, 1993; Waugh and Smith, 1997; Hutchings et al., 2001; Taylor et al., 2003; Williams et al., 2019). Considering that growth rates of fine roots can range from a few millimeters to a few centimeters per day (Pierret, et al., 2016), root development in cover systems can happen rapidly if enough moisture and nutrients are present and if mean annual temperatures are favorable.

Plant rooting not only accelerates rates of wetting and drying cycles but also promotes small scale soil-water heterogeneities and stress imbalances which can result in the propagation of microcracks due to evapotranspirative demand (Angers and Coren, 1998). Root size exerts a proportional influence on crack size with very fine roots and root hairs controlling the formation of the smallest cracks (Dorioz et al., 1993), and crack propagation extending to the outer boundaries of the rooted zone (Mitchell and VanGenechten, 1992). Cracks associated with plant root soil desiccation can be as wide as 5 cm depending on soil mineralogy, texture and climate (Ravina, 1983), with greater plant biomass generally corresponding to the formation of cracks of greater length and total area (Grevers and Jong, 1990).

During drought conditions at Rum Jungle, NT Australia Taylor et al., (2003) characterized an extensive network of desiccation cracks associated with root matts in excavated clay barriers with emphasis on polygonal blocky structures reinforced by dark staining from illuviated organic materials and iron oxidation. Similar features have been observed by others (Waugh and Smith, 1997; Albright et al., 2006). In compressed clay covers, the development of cracks from desiccation can also occur when overlying soils are saturated (Hackonson, 1986), indicating that the rate of water extraction by roots exceeds the rehydration rate of compressed clays underneath (Waugh, et al., 2006).

When plant roots expand into non-fractured, bulk soils, they exert pressure on surrounding particles resulting in the reinforcement of evolved macropore space through densification (Greacen et al., 1968; Dexter, 1987b). The localized compaction from densification around living roots can initially reduce infiltration rates (Guidi et al., 1985; Bruand et al., 1996), however when roots die, the resulting macropore cavities are commonly reinforced through decaying organic materials which can lead to increased hydraulic conductivity (Barley, 1954; Gish and Jury, 1983). Plant root morphology greatly influences long-term infiltration characteristics, with hydraulic conductivity increasing year-over-year under plants with large diameter, long and strait roots (e.g. alfalfa) (Meek et al., 1989; Meek et al., 1990). The pores formed by most roots are between 25-100 mm in size and are considered macropores (Gibbs and Reid, 1988; Fitzpartick, 1993; Lin et al., 1999a), which play a significant role in preferential flow (Beven and German, 1982). As such, the formation of macropores by roots is a primary controller of hydraulic properties in undisturbed soils (Edwards et al., 1989), including clay barriers for waste containment (Waugh and Smith, 1997; Taylor, et al., 2003; Waugh et al., 2007).

Given hydrologic impacts associated with natural succession and subsequent plant rooting in compressed clay barriers over regulatory timeframes, recent efforts have explored how conventional engineered clay covers may be transformed into evapotranspiration covers to redirect soil-water back into the atmosphere (Waugh, et al., 2009). However, a tradeoff exists given that plant roots may increase gas flux by accelerating the drying of clay barriers and creating preferential pathways for radon gas diffusion at UMTRCA sites (Link et al., 1994; Chapter 5).

The observance of dead roots in clay barriers has been reported at several sites (Hutchings et al., 2001; Taylor et al., 2003), however the full impact of root turnover to clay barrier evolution and performance remains understudied. In addition to the impacts to hydraulic properties, the deposition of dead roots into soil contributes to nutrient cycling (Gish and Jury, 1983; Aerts et al., 1992), stimulates the growth of bacteria (Rovira, 1965), is a growth substrate for fungi (Went and Stark, 1968), provides food for nematodes, arthropods and earthworms (Curry and Schmidt, 2007; Bonkowski et al., 2009), and increases aggregate stability (Tisdal and Oades, 1982; Oades, 1984). Rates of root turnover are highly variable within individual biomes (Yuan and Chen, 2010), amongst plant species located at the same site (Coleman et al., 2000; Withington et al., 2006), and amongst individuals of the same species in the same field (McCormack et al., 2012). Total root lifespan commonly ranges from days to weeks in both grasslands and forests (Hendrick & Pregitzer, 1997; Gill, 1998; Arnone et al., 2000; Tingey et al., 2000). In nutrient limited environments, including those likely present in many compacted clay barriers, Ryser, (1996) suggests that plants decrease rates of root turnover to avoid unrecoverable nutrient losses.

The development of vegetation on waste covers can also serve to reduce erosion risk. Plant establishment results in biostructural erosion control through the combined effects of reducing overland water flow velocity, and increasing soil shear strength (Gyssels et al., 2005) . Root architecture plays a considerable role in regulating slope stabalization and shallow erosion control (Reubens et al., 2007). Desirable root traits have been employed in engineered slopes to control against erosion root distribution, length, orientation, diameter, seasonal root mass variability (Stokes et al., 2009).

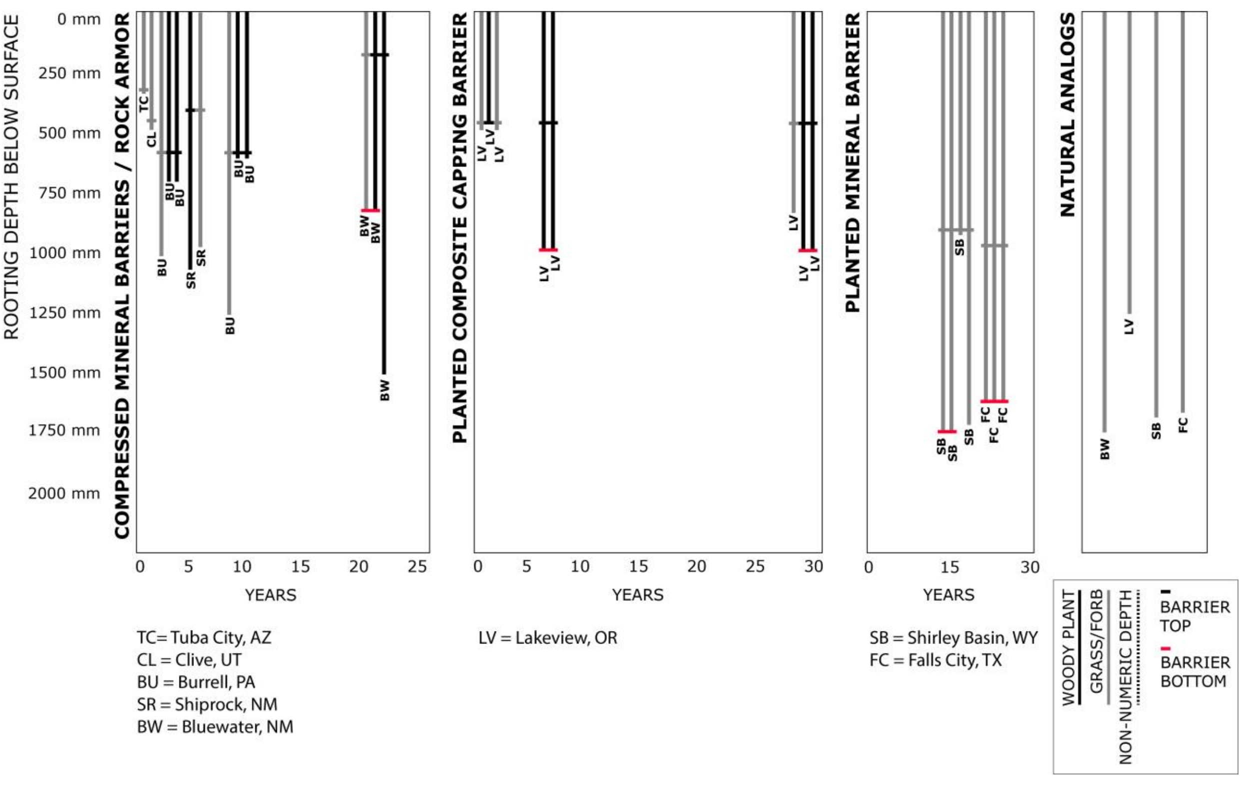
### 4.4.5. TIMEFRAMES AND PATTERNS OF PLANT ROOTING IN CLAY BARRIERS

Though variable depending on vegetation and climate, the time frames associated with root establishment within clay barriers generally correspond with the thickness of the rock and soil layers above the barrier with thinner layers corresponding to greater rooting risk (Hutchings et al., 2001). Anderson et al., (1993) suggests that a 2000 mm thick unconsolidated soil layer planted with native perennial shrubs and grasses is enough to isolate perennial grass roots above a compressed clay barrier at Idaho National Engineering Laboratory (INEL). However, a review of 1084 citations by Foxx et al., (1984) indicates that 7% of the native vegetation found to grow on clay textured soils across the western United States have rooting depths in excess of 4500 mm. A later systematic review on the role of biointrusion on UMTRCA barriers by Link, et al., (1994) suggests that soil layers exceeding 2000 mm may be ineffective at isolating the roots of many grasses, forbes, shrubs, and trees over periods longer than 100-years. Furthermore, Schenk and Jackson (2005) concluded that deep roots are most likely to occur in seasonally dry, semi-arid zones with fine-textured soils, suggesting that the majority of UMTRCA sites in the western United States are in zones most susceptible to deep rooting vegetation (see Figure 1.2). Long-term deep rooting is therefore an inevitability at most UMTRCA sites over long enough timeframes, in-lieu of active management.

While the influence of waste cover stratigraphy to long-term root morphology and rooting depth is presently unknown, it is likely that the long-term rooting depth in cover systems is not entirely consistent with native soils. Physical rooting restrictions imposed by initial clay barrier morphology, low rates of water percolation through clay barriers compared to native soils, and the presence of subsurface wastes that may pose restrictions to vegetative growth, may all contribute to variations in rooting characteristics on covers versus those natural soils in direct proximity to covers. A systematic accounting of root variation between engineered and native soils is required if soil morphological information from natural analogs is to be accurately used to estimate the long-term conditions of cover systems over service lifetimes.

A review of the literature on plant rooting characteristics of in-service rock armor and vegetated composite clay barriers provides an informative picture of timeframes and patterns of root development, with emphasis on the UMTRCA portfolio (Appendix B). Regardless of design or climate, initial plant rooting in compressed clay barriers generally occurs in zones of weakness either formed in-situ by shrink/swell or freeze/thaw, in zones of material heterogeneity created during construction, or from micro-heterogeneities in soil texture within constructed soils. After as little as four-years at a planted humid site, or as many as 20-years post construction, regardless of cover design or climate, very fine roots are found through the depth of most compressed clay barriers surveyed. A summary of plant rooting depth over time in UMTRCA covers is provided in Figure 4.1.

Figure 4.1: Plant rooting depth over time in UMTRCA covers



### 4.4.5.1. *ROOTING IN COMPRESSED MINERAL BARRIERS STABILIZED WITH ROCK ARMOR*

Initial plant rooting in rock armored Compressed Mineral Barriers (CMB's) is very patchy. Immediately following construction at an arid UMTRCA site in Tuba City, AZ, annual weeds dominated by Russian thistle, were preferentially found in surface depressions, or in zones of thinner rock armor, that had also collected wind-blown dusts and organic debris (Burt and Cox, 1993). Such development supports observations by Taylor et al., (2003) that discontinuities created during the construction process, or formed soon after, serve as preferred sites for initial surface change.

After two-years at Tuba City, AZ and at a semi-arid UMTRCA site in Clive, UT, roots from Russian thistle and *Halogeton ssp.* (respectively) enmeshed the bottom layer of rock armor and dust in-fill, spreading horizontally across the moist surface of the clay barriers. Weed mats began to dry the top of the clay barrier and create vertical desiccation cracks that became preferred locations for fine and very fine roots established to a depth of up to 50 mm (from top of barrier) (Burt and Cox, 1993).

After four-years, fine and very fine roots from Summer Cyprus (*Kochia sieversiana*) at an arid UMTRCA site in Shiprock, NM, and Japanese knotweed (*Fallopia japonica*) at a humid temperate UMTRCA site in Burrell, PA were found to extend into vertical fractures within the clay barrier to depths of 710 mm and 460 mm (from top of barrier), respectively. The deposition of plant debris into rock armor from annual weeds and/or tree leaf litter at Burrell, PA was observed to create a feedback that enabled the preferential establishment of additional vegetation (Burt and Cox, 1993).

At nine-years post construction at Burrell, PA, fine and very fine roots from Japanese knotweed were densely matted along vertical fractures through the depth of the clay barrier (600 mm from top of barrier), extending deeper into subsurface wastes (these roots were confined to the top 460 mm at year four). Dense fine and very fine root mats also collected horizontally along laminar compression planes between radon barrier lift events (Waugh and Smith, 1997). The rooting patterns of trees was starkly different at the Burrell site. Sycamore (*Platanus spp*), staghorn sumac (*Rhus typhina*), and black locust (*Robinia pseudoacacia*) were predominantly confined to the unconsolidated bedding and drainage layers (above the barrier), potentially as a result of edaphic sensitivities to tree rooting into clay caps due to acidic conditions, or prolonged exposure to anoxic conditions due to saturation (Robinson and Handel, 1995; Handel et al., 1997). Such rooting in unconsolidated layers intended to facilitate lateral drainage above the clay barrier has also been shown to correspond to lateral sediment clogging and decreased effectiveness of the drainage layer (DOE, 1992).

At 21-years post construction at a semi-arid UMTRCA site in Bluewater, NM very fine roots from squirrel tail grass (*Hordeum jubatum*) grew through the bulk soil fraction through the depth of the clay barrier (600 mm from top of barrier) (Williams et al., 2019). Thick root matting was also observed along vertical fracture planes. Course, medium, fine, and very fine roots from fourwing saltbush (*Atriplex canescens*) were observed in the bulk soil to a depth of 400 mm (from top of barrier), laterally benching above a dry and highly indurated horizon. Dense medium, fine and very fine root mats were found in fractures through the depth of the barrier (600 mm from top of barrier). In another profile, fourwing saltbush roots were found in the bulk soil to a depth of 760 mm (from top of barrier), and along fractures to a depth of 1650 mm (from top of barrier) (see Figure 3.6). After two-decades of service, plant rooting characteristics of the combined saltbrush and squirrel tail grass profiles (TP-2 and TP-5) closely resemble a natural analog adjacent to the cell (AN-3) (see Figure 3.6).

#### 4.4.5.2. *ROOTING IN A COMPOSITE CAPPING BARRIER*

In the first two-years following construction at a semi-arid UMTRCA site in Lakeview, OR, roots from crested wheatgrass (*Agropyron cristatum*) and big sagebrush (*Artemisia tridentata*) occupy the entirety of the soil layers above the compressed clay barrier, with very fine roots from crested wheatgrass beginning to occupy cracks developed in the clay barrier to a depth of less than 50 mm (from top of barrier).

At three-years following construction, roots from big sagebrush also populated cracks formed in the clay barrier to a depth of less than 50 mm (from top of barrier) (Burt and Cox, 1993).

At eight-years post construction at Lakeview, OR, roots from rubber rabbitbrush (*Ericameria nauseosa*) and big sagebrush occupied fractures through the depth of the clay barrier (450 mm from top of barrier) (Waugh et al., 1997).

After 29-years post construction at Lakeview, OR fine and very fine roots from antelope bitterbrush (*Purshia tridentata*) was observed through the depth of the clay barrier (450 mm from top of barrier) (Williams et al., 2019). At the same time, very fine and fine roots from rubber rabbitbrush traveled through the depth of the barrier but remained confined to cracks (little change from observations made 21-years prior). After three-decades of service, plant rooting characteristics of the Bitterbrush profile (DC-2) closely resemble a natural analog adjacent to the cell (AN-2), dominated by bitterbrush and big sagebrush (see Figure 3.6).

#### 4.4.5.3. *ROOTING IN PLANTED MINERAL BARRIERS*

Within four-years following construction at a warm and humid site in Albany, GA, roots from mixed Bermuda and rye grasses densely occupied the bulk soil of the control section in addition to the clay barrier, preferentially along fractures and blocky aggregates, to a depth of 450 mm (from top of barrier) (Albright et al., 2006). Over the same time period at a hot-humid subtropical site at Rum Jungle, NWT Australia, course and fine tree roots, from several species including *eucalyptus spp and Acacia spp*, occupied fractures through the depth of the clay barrier (300 mm from top of barrier) (Ryan, 1985; 1986). At 18-years post construction at the same site, roots from mixed tussock grassland vegetation occupied the entirety of the clay barrier (300 mm from top of barrier), preferentially along the cracks between polygon faces of emergent soil structure (Taylor, et al., 2003).

After eight-years post construction at a temperate maritime site in Hamburg, Germany, roots from mixed perennial forbs, including *Lotus corniculatus*, *Cirsium ssp.*, *Rumex ssp.*, and *Armoracia rusticana,* densely occupied the clay barrier (600 mm from top of barrier), resulting in a completely desiccated and brittle clay (Melchior, 1997).

After 10-years post construction at a temperate maritime site in Hertfordshire, UK, the majority of tree roots from Corsican pine (*Pinus nigra),* sycamore maple (*Acer pseudoplatanus),* and black alder (*Alnus glutinosa)* remained benched on-top-of the clay barrier (650 mm below surface), with exception to roots from black alder which traveled 300 mm into the clay barrier (from top of barrier) along fractures (Hutchings et al., 2001). At 15 years at the same site, black alder was found at depths of 450 mm into the clay barrier (from top of barrier) (Hutchings et al., 2006).

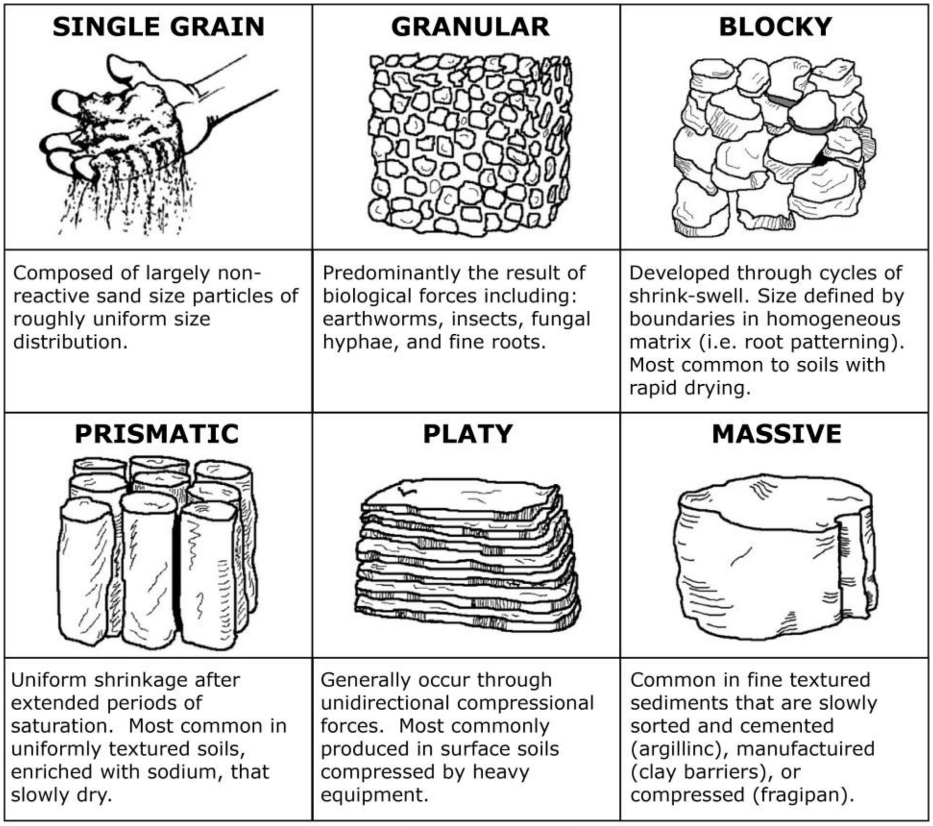
After 16-years post construction at a frigid, semi-arid UMTRCA site in Shirley Basin, WY very fine roots from Russian wildrye (*Psathyrostachys juncea*) occupied the bulk soil fraction of the clay barrier through the observed depth (850 mm from top of barrier) (Williams et al., 2019). Plant rooting characteristics closely resemble a natural analog profile with shared sediments and vegetation (Figure 3.6).

After 22-years post construction at a humid UMTRCA site in Falls City, TX very fine roots yellow bluestem (*Bothriochloa ischaemum var. songarica)*, populated the bulk soil fraction of the clay barrier through the observed depth (650 mm from top of barrier). Course and fine roots from honey mesquite (*Prosopis glandulosa*), traveled 80 mm into the clay barrier (from top of barrier) and laterally spread to distances greater than 2000 mm from plant center (Williams et al., 2019).

### 4.4.6. DEVELOPMENT OF SOIL STRUCTURE

Soil structure broadly encompasses the spatial arrangement of primary particles in soil and has significant implications to function and plant growth (Bronick and Lal, 2005). Soil structure exists across a spectrum from single grained, non-cohesive particles (e.g. sand dunes) to massive structures (e.g. monolithic clays with no internal features), with emphasis being placed on particles (e.g. soil aggregates) occurring somewhere in the middle of the spectrum (Ghezzehei, 2012; Schoeneberger, et al., 2012). A generalized description of major soil structure classes is outlined in Figure 4.2.

Figure 4.2: Soil structure and typical processes of formation



| **SINGLE GRAIN** | **GRANULAR** | **BLOCKY** |
|---|---|---|
| Composed of largely non-reactive sand size particles of roughly uniform size distribution. | Predominantly the result of biological forces including: earthworms, insects, fungal hyphae, and fine roots. | Developed through cycles of shrink-swell. Size defined by boundaries in homogeneous matrix (i.e. root patterning). Most common to soils with rapid drying. |
| **PRISMATIC** | **PLATY** | **MASSIVE** |
| Uniform shrinkage after extended periods of saturation. Most common in uniformly textured soils, enriched with sodium, that slowly dry. | Generally occur through unidirectional compressional forces. Most commonly produced in surface soils compressed by heavy equipment. | Common in fine textured sediments that are slowly sorted and cemented (argillinc), manufactuired (clay barriers), or compressed (fragipan). |

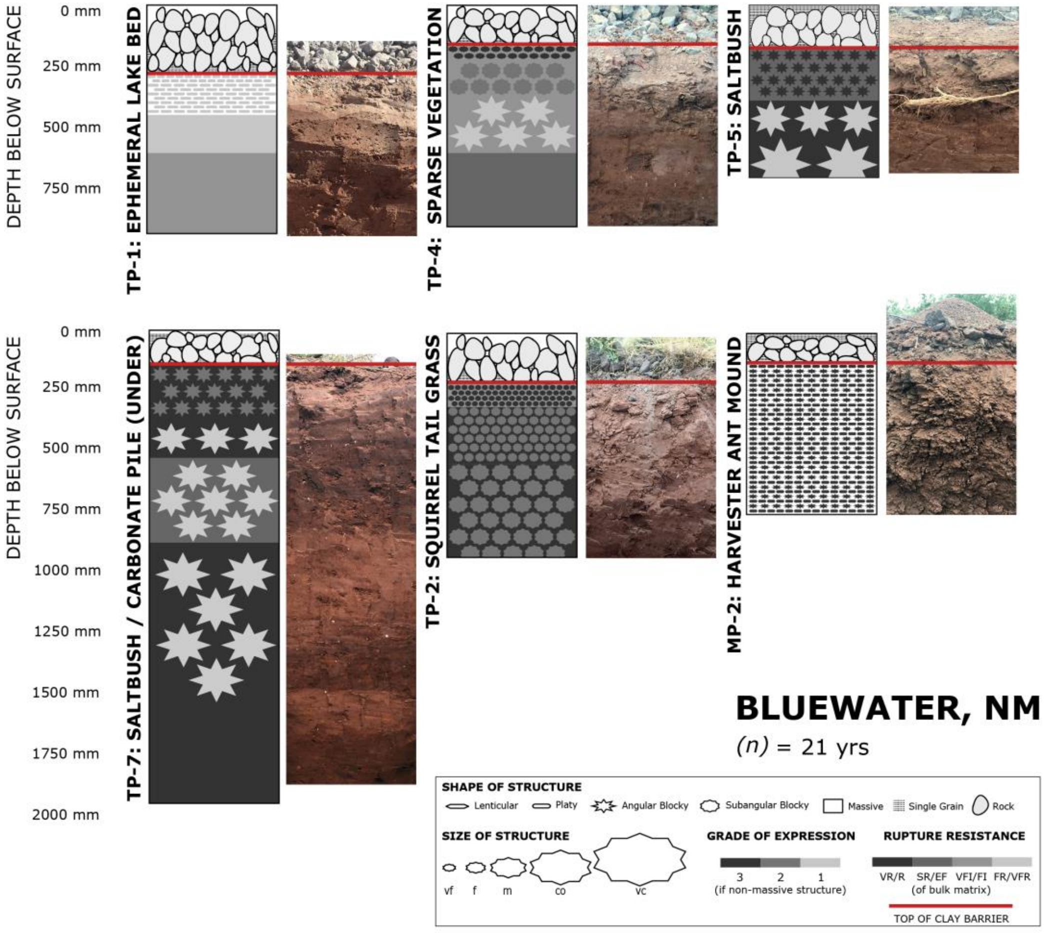
Images courtesy of the U.S. Department of Agriculture

### 4.4.6.1. *DECADAL DEVELOPMENT OF SOIL STRUCTURE IN SHALLOW COMPRESSED MINERAL BARRIERS*

After 21-years of service, the soil structure of a shallow Compressed Mineral Barrier at Bluewater, NM was influenced by surface condition (Chapter 3). Originally designed as a monolithic (massive) compressed clay barrier devoid of structure, single grain, granular, blocky, and massive structures were found with decreased structuring observed with depth (Figure 4.3). The Bluewater site was designed as an unvegetated rock cover and was characterized by emergent vegetation of mixed composition at the time of study (Chapter 2).

At locations that remained unvegetated, sparsely vegetated, or as lateral distance away from single shrubs increased, soil structure was less pronounced in both size and grade of expression. Smaller structure size was correlated with the abundance of fine and very fine roots, and by faunalturbation by burrowing animals including harvester ants. The least soil structuring was observed in down gradient conditions with seasonally higher saturation (i.e. locations of ephemeral ponding).

Figure 4.3: Soil structure in a shallow Compacted Mineral Barrier



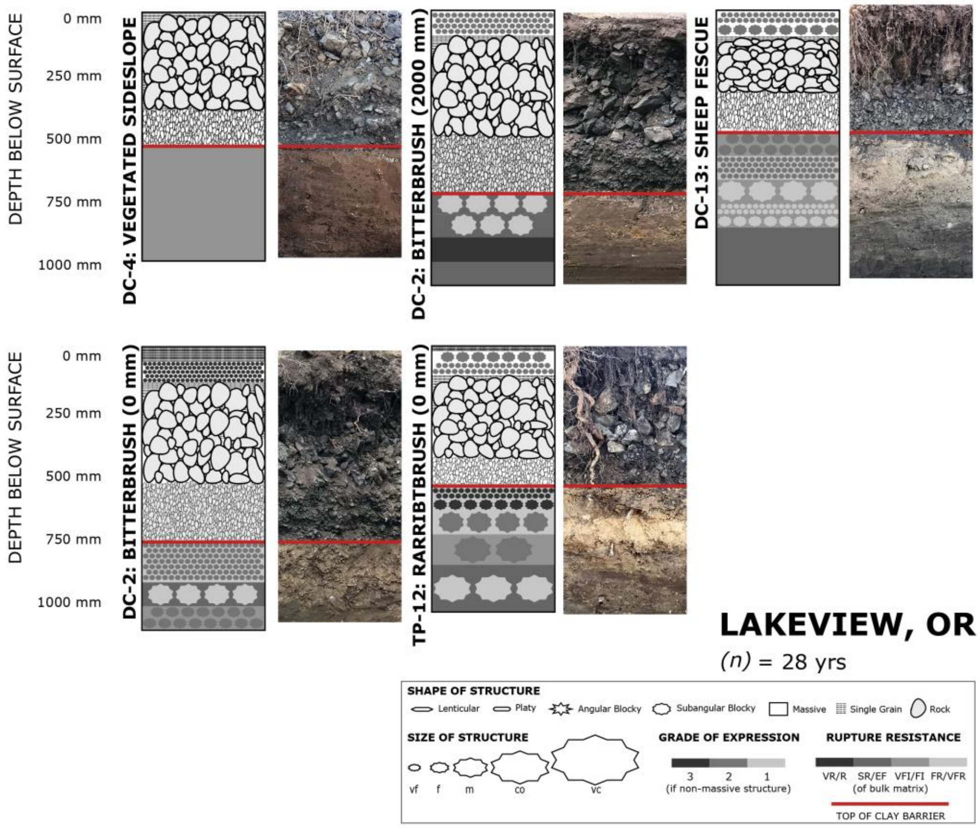
#### 4.4.6.2. *DECADAL DEVELOPMENT OF SOIL STRUCTURE IN COMPOSITE CAPPING BARRIERS*

After 28-years of service, clay barrier structuring in a planted Composite Capping Barrier of moderate depth, was influenced by surface condition at Lakeview, OR (Chapter 3). Originally designed as a monolithic (massive) compressed clay barrier, blocky structures of varying grades and sizes, were found with decreased structuring observed at depth (Figure 4.4). The Lakeview site was planted with grasses at construction and allowed to shift to a steppe ecosystem over time (Chapter 2).

At locations that had remained sparsely vegetated, or at lateral distances away from single shrubs, soil structure became less pronounced in both size and grade of expression. The least soil structuring occurred in unvegetated, rock covered, down-slope profiles with seasonally higher saturation.

In addition to correlation with surface condition, depth, and bioturbation, soil structuring at Lakeview was also influenced by clay barrier depositional stratigraphy. Bands of larger sized structures were found in-between bands of smaller sized structures, even under shared rooting condition (structure was not depth dependent), suggesting that the physical, textural, or mineralogical condition of individual clay barrier lift events can exert some control on patterns of emergent structuring.

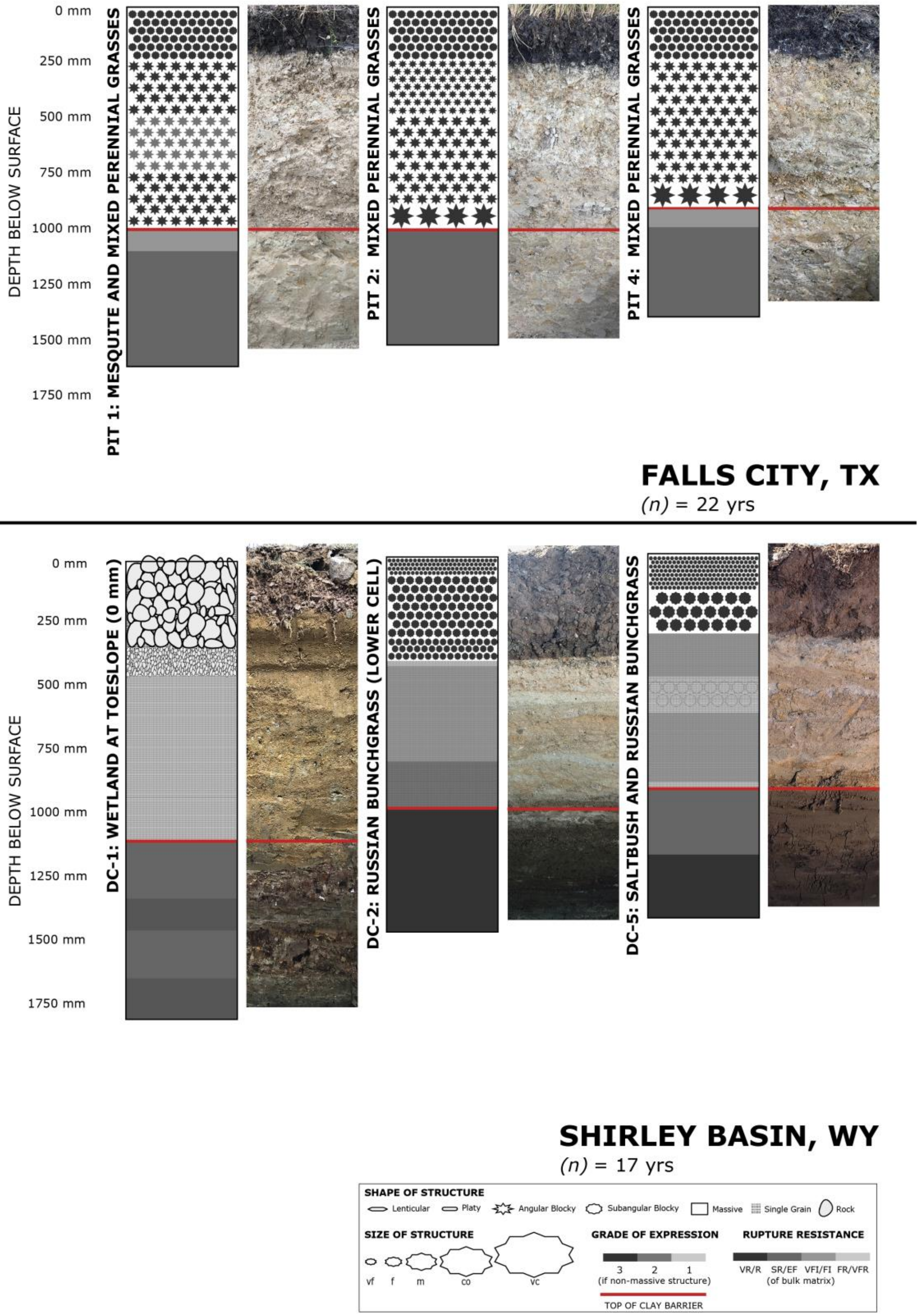
Figure 4.4: Soil structure in a shallow Composite Capping Barrier



#### 4.4.6.3. *DECADAL PERSISTENCE OF SOIL STRUCTURE IN DEEP PLANTED MINERAL BARRIERS*

The development of soil structure of deep Planted Mineral Barriers clay barriers, stabilized with mixed grassland vegetation, was nominal at the Falls City, TX, and Shirley Basin, WY sites after two decades of service (Figure 4.5). Visible structuring remained largely confined to the overburden and topsoil materials placed above the clay barriers to facilitate rooting. The depths from surface to compacted clay barrier ranged from 950-1100 mm at Falls City, NM and 950-1150 mm at Shirley Basin, WY. With exception to rock armored side slopes, the surface condition across both sites was relatively homogeneous (see Chapter 2). Across all the profiles on the planted areas at the Falls City and Shirley Basin sites, very fine plant roots were observed through the depth of the clay barrier (Figure 3.6). Given evaporative demand, deep rooting may make Planted Mineral Barriers clay barriers prone to root induced desiccation and cracking in the event of prolonged drought as vegetation extracts moisture from reserves deeper in the profile. Given barrier depth from ground surface, elevated soil moisture (Benson et al., 2019), the abundance of expandable 2:1 clay minerals (Chapter 3), and textures heavily dominated by the clay size fraction (Chapter 3), these barriers are expected to have a greater resilience to structural changes through time when compared to the shallow Compressed Mineral Barrier at Bluewater, of the Composite Mineral Barrier at Lakeview.

Figure 4.5: Soil structure in two deep Planted Mineral Barriers



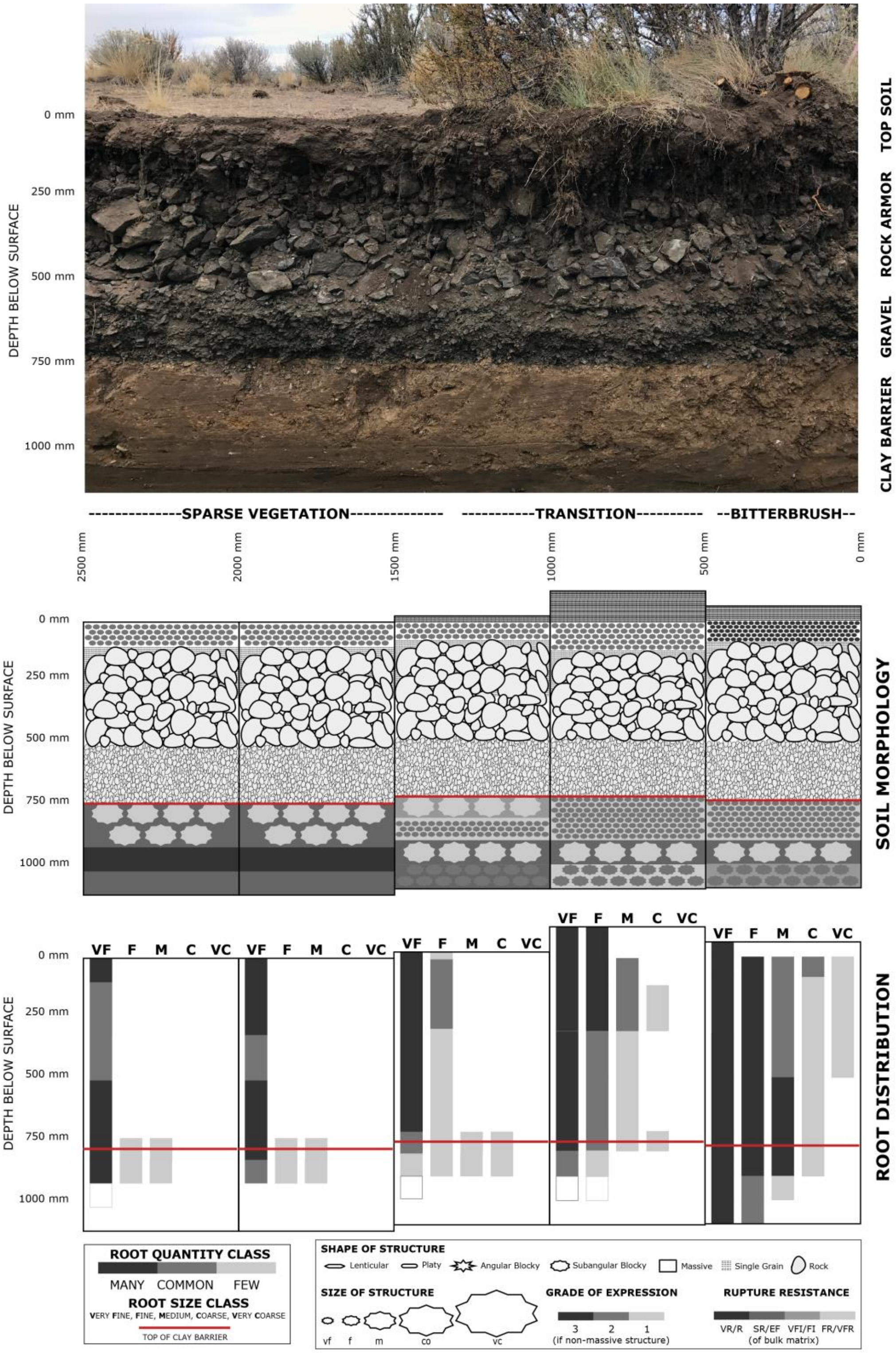
### 4.4.7. IMPACT OF VEGETATION PATTERNING ON SOIL CONDITION

The patterning of shrubs in semi-arid environments creates “islands of fertility” through the concentration of N, P, and K localized beneath canopies (Schlesinger and Pilmanis, 1998). For *Prosopis velutina* (velvet mesquite) a shrub common to the southwestern United States, the longevity of such nutrients is controlled by rates of mortality with soil nitrogen and carbon losses exceeding 75% 40-years after plant death (McClaran et al., 2008). Bulk density is also generally lower in soils under plants than in openings in semi-arid environments. Aggregate stability at the 250 µm scale, C:N ratio, and glomalin, are all highest under mesquite (*Prosopis glandulosa* Torr.) compared to sparsely vegetated interspaces (Bird et al., 2002). This corresponds to an average of nearly three times greater infiltration rate into soils under plants than in the openings of paloverde (*Cercidium microphyllum*) and creosote bush (*Larrea tridentata*) (Lyford and Qashu, 1969). The maintenance of these preferential flow paths is attributed to root conditioning in addition to microbial processes that stabilize emergent soil architecture through mechanisms including exudation of extracellular polysaccharides and aggregate enmeshment by mycorrhizal fungi (Morales et al., 2010). Such locations serve as biological “hot-spots” in semi-arid environments that correspond to higher rates of carbon turnover and nitrogen cycling (Bundt et al., 2001).

Dispersed shrub patterning has been found on UMTRCA disposal cells including Falls City, TX, Lakeview, OR and Bluewater, NM. The understory of shrubs including antelope bitterbrush (*Purshia tridentata*) and fourwing saltbush (*Atriplex canescens*) show considerable accumulation of plant litter that dissipates at lateral distances away from bushes. Gradients of litter accumulation were also observed at Rum Jungle, NT Australia (Taylor, et al., 2003). Leaf litter can serve as nutrient reservoir, habitat for soil invertebrates, insulator to reduce evaporation. At the rock armored, shallow, CMB at Bluewater, vegetation establishment tends to favor those locations with thinner rock armor, a trend also observed by Burt and Cox, (1993) during early plant establishment at locations of similar design and climate in the UMTRCA program.

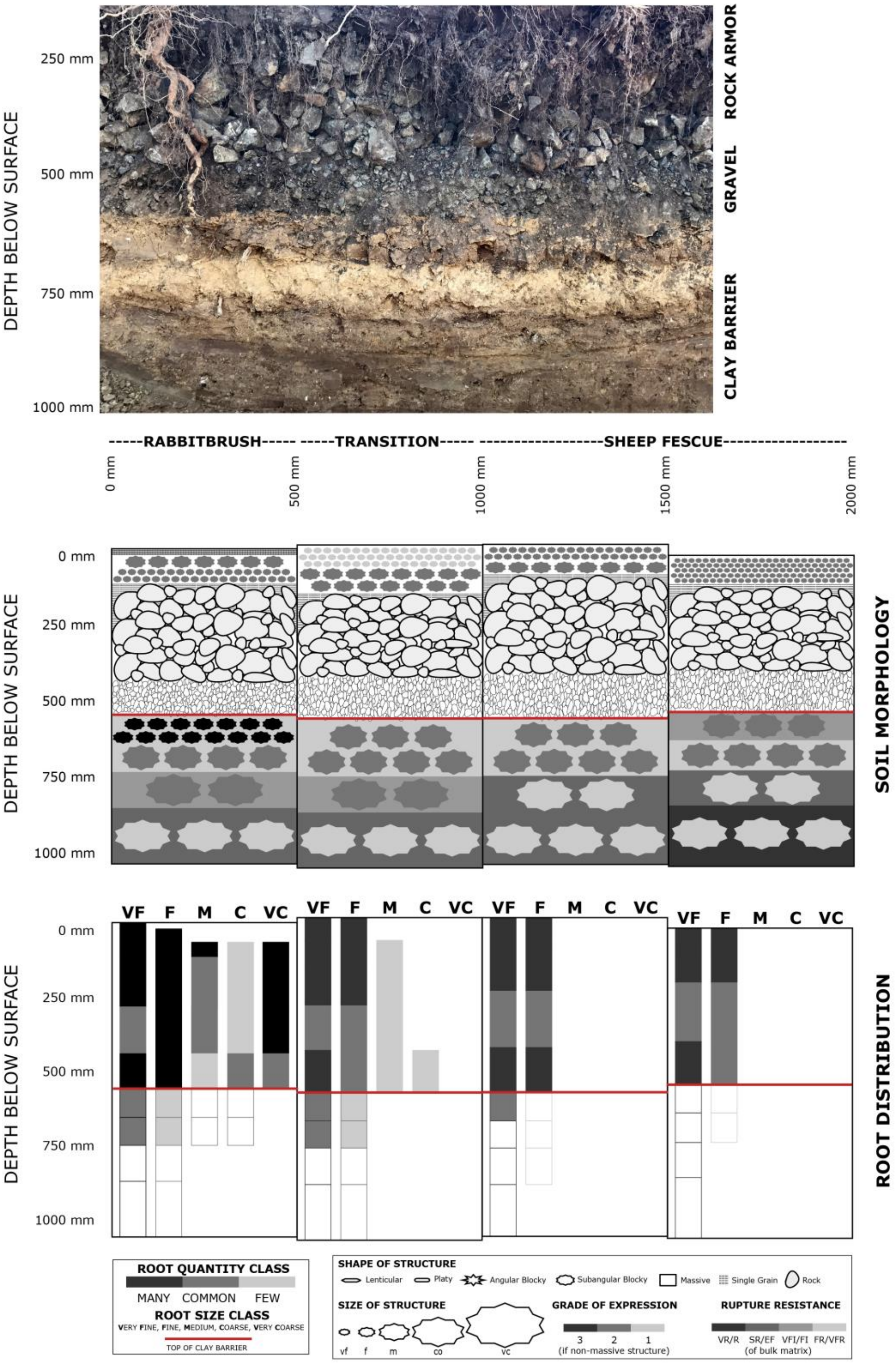
The soil survey conducted by Williams et al., (2019) shows that vegetation patterning influences soil structure and rooting density, with impacts dissipating with lateral distance from tap root representing an impact gradient. These impact gradients are observed across several cover designs, climates, and management strategies for vegetation including bitterbrush (Figure 4.6) and rabbitbrush (Figure 4.7) at Lakeview, OR; fourwing saltbush (Figure 4.8) and squirreltail grass (Figure 4.9) at Bluewater, NM; and honey mesquite (Figure 4.10) at Falls City, TX. Across these sites, vegetation influences root distribution, with root size and frequency dissipating with lateral distance away from taproot. Root benching and spreading are commonly observed at the top interface of the clay barrier, and at sequentially deeper clay barrier lift interfaces. Vegetation exerts influence over clay barrier soil structure at the shallow barrier sites, Bluewater (CMB) and Lakeview (CCB), but does not influence structure at Falls City (PMB). Lack of structuring at Falls City is attributed to depth, climate, and clay mineralogy with smectitic clays maintaining saturation given annual precipitation and physical isolation with depth.

Figure 4.6: Bitterbrush soil morphology impact gradient.



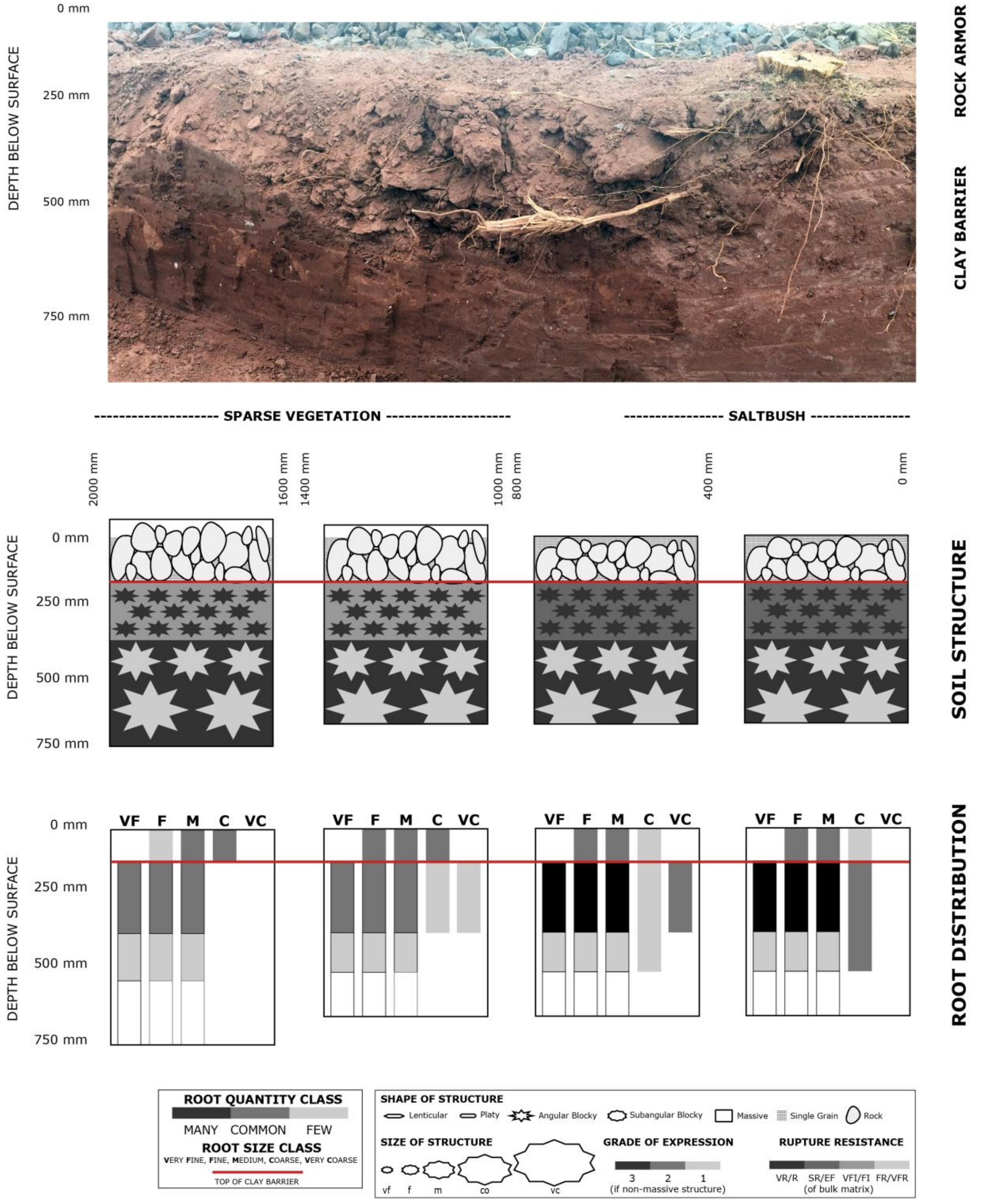
Lakeview, Oregon. Planted Composite Capping Barrier.

Figure 4.7: Rabbitbrush soil morphology impact gradient.



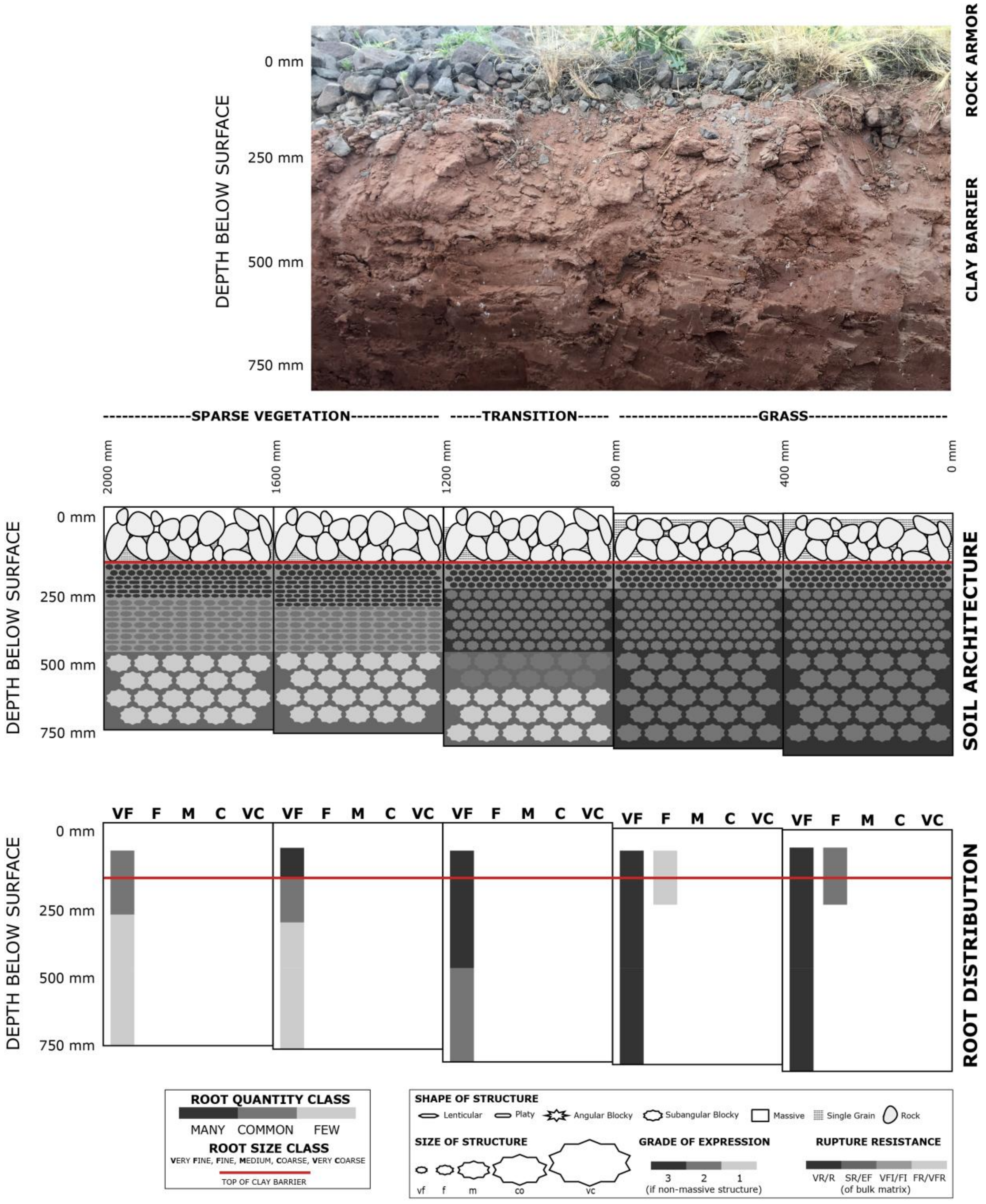
Lakeview, Oregon. Planted Composite Capping Barrier.

Figure 4.8: Fourwing saltbush soil morphology impact gradient.



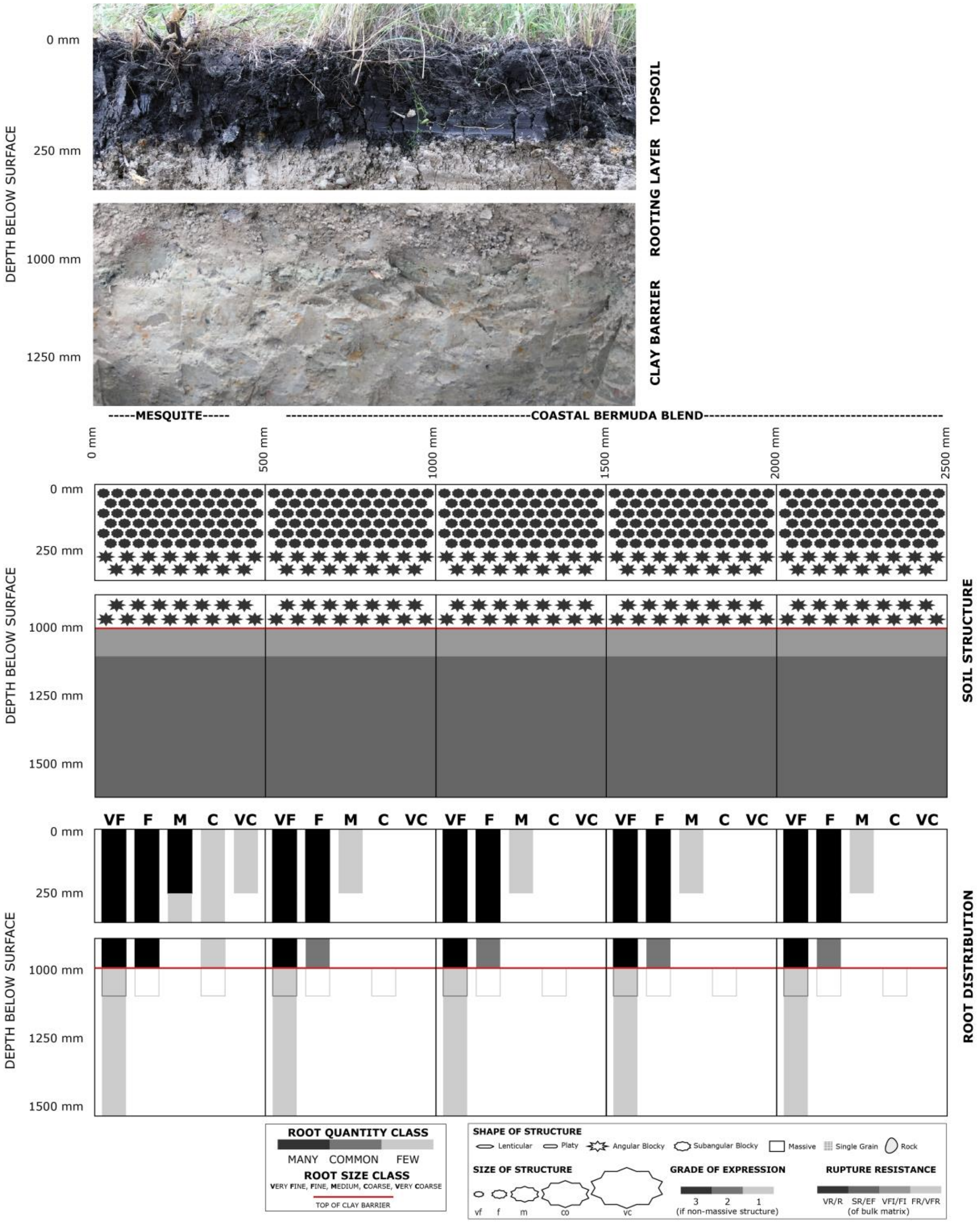
Bluewater, New Mexico. Shallow Compressed Mineral Barrier.

Figure 4.9: Squirreltail grass soil morphology impact gradient.



Bluewater, New Mexico. Shallow Compressed Mineral Barrier.

Figure 4.10: Honey mesquite soil morphology impact gradient.



Falls City, Texas. Deep Planted Mineral Barrier.

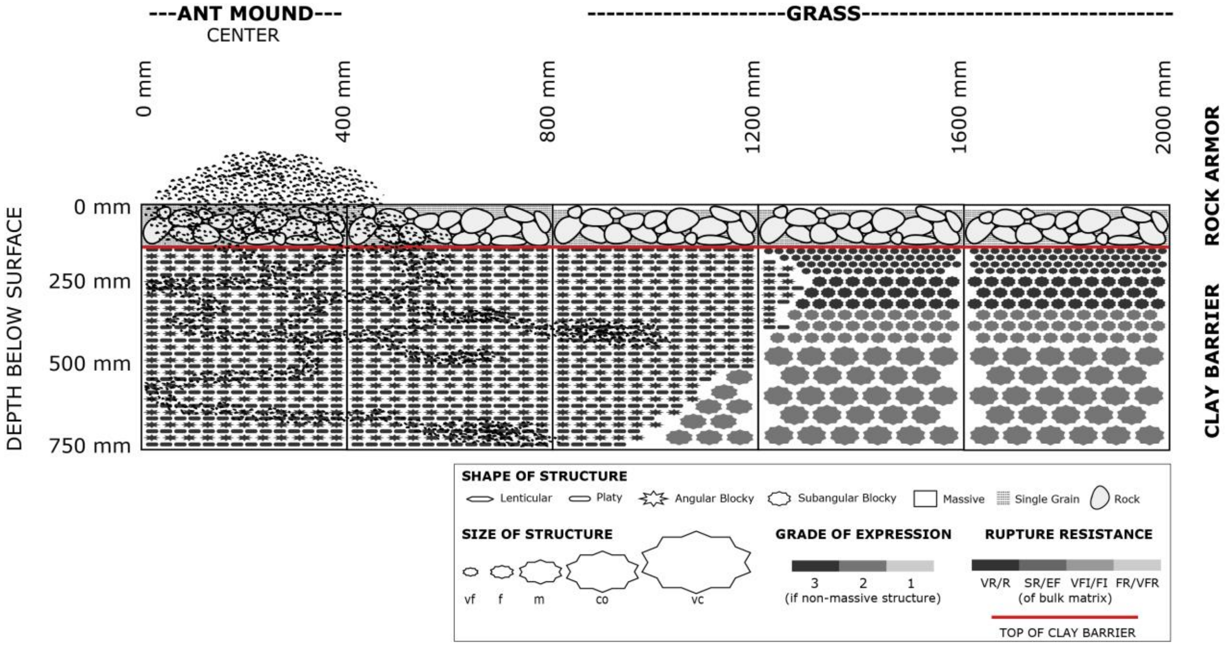
### 4.4.8. BIOTURBATION BY ANIMALS

The establishment of vegetation on engineered covers can create habitat for animals (Waugh and Smith, 1997). Burrowing and tunneling animals can pose a threat to cover system performance from direct vertical displacement of wastes and surface erosion (Winsor and Whicker, 1980; McKenzie et al., 1982) and accelerated drying and cracking of the compressed clay barrier through wind-induced ventilation from tunnel systems (Vogel et al., 1973) thereby increasing potential rates of water infiltration and gas diffusion (Cadwell et al. 1989; Landeen 1994; Suter et al. 1993). The impact of animal burrowing on UMTRCA cover system performance has long been explored (Gano and States, 1982; Cline et al., 1982; Beedlow, 1984), resulting in directed waste cover design and long-term management suggestions intended to limit biological intrusion by animals (Hakonson et al., 1982a; Hakonson, 1986).

The incidence of documented animal intrusions into DOE waste covers are numerous. At the Grand Junction UMTRCA site, prairie dogs burrowed through interim soil caps and transported mill tailings to the surface (McKenzie et al., 1982). At Hanford, Washington, a large mammal believed to be a coyote or badger burrowed into a waste trench (O'Farrell and Gilbert, 1975). At the Idaho National Engineering Laboratory (INEL), rodents have excavated through clay caps in excess of 1,200 mm thick (Arthur and Markham, 1983).

The physical extent of animal burrowing on cover systems can be extensive. At a single burial site at Los Alamos National Laboratory (LANL), pocket gophers excavated a total of 12,000 kg of soil per ha during a 1-year period, resulting in an estimated 8 $m^3$ void space across an estimated 2,800 m long tunnel network (Hakanson et al, 1982b). Ants are among the most important soil engineers in semi-arid areas (Cammeraat and Risch, 2008). Harvester ants (*Pogonomyrmex spp.*) can excavate nests that are 1,500 mm deep and occur up to 1,000 mm away from the center of the mound (MacKay, 1981). Nests from *Pogonomyrmex spp.* were shown to increase rates of infiltration up to 2,500 mm away from the center of the mound in clay loams at the INEL (Blom et al., 1994). Excavations of a *Pogonomyrmex spp.* mound on the Bluewater, NM UMTRCA cell (Figure 4.11) show direct excavation and structuring 1,300 mm away from the center of the mound to a depth of >750 mm. Across the WYE waste repository in the 300 Area at Hanford, a total of 358 *Pogonomyrmex spp.* colonies were counted, with the total volume of displaced material from single colonies averaging 1,774 cm3 per colony, at an annual soil displacement rate of 1 kg per colony, and average excavation depths exceeding 2300 mm (Fitzner et al. 1979). At Rum Jungle, NT Australia, a total of 18 large termite mounds were observed across the 36-ha disposal cell. When excavated, extensive termite galleries were found in clay barriers to the depth of wastes (>600 mm) (Taylor, et al., 2003). At moist sites, earthworm burrowing may cause the most significant changes to cover systems over time, although little work has been done on their activity in engineered cover systems for waste containment (Beedlow, 1984). Earthworms were observed in soil layers above clay barriers at the Shirley Basin, Lakeview, and Falls City UMTRCA sites though none were seen in the barrier (Williams et al., 2019).

Figure 4.11: Bioturbation by harvester ants.



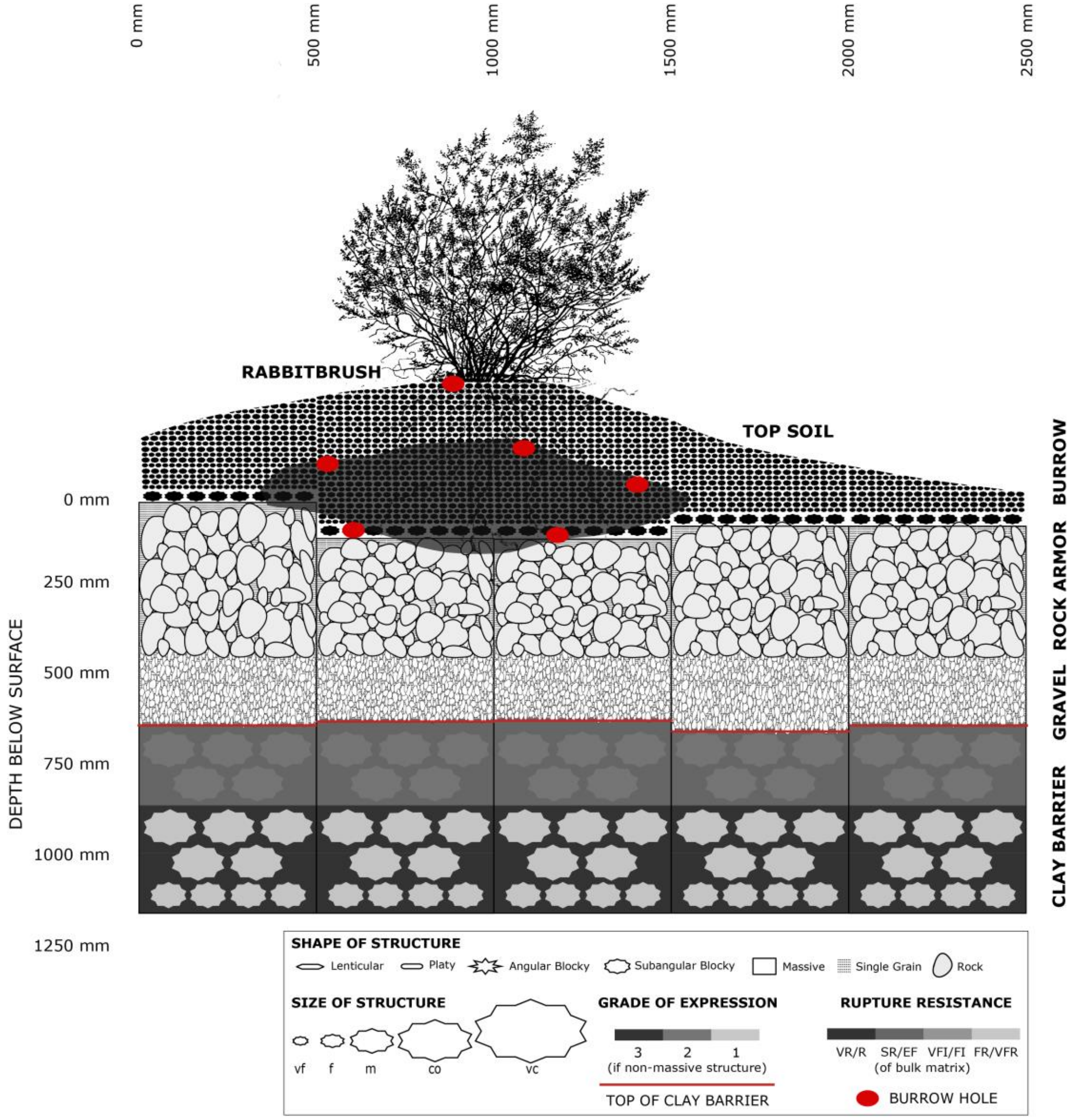
Bluewater, New Mexico. Shallow Compressed Mineral Barrier.

Patterns and intensities of bioturbation by invertebrates and small mammals are greatly influenced by vegetation, climate, and soil type. Most burrowing mammals, in semi-arid areas, prefer sparse vegetation in disturbed areas (McCloskey, 1976; Fitzner et al. 1979; O'Farrell, 1980; Kinlaw, 1999), conditions that are common in early successional environments across UMTRCA covers on the Colorado Plateau. Daily minimum and maximum temperatures also greatly influence total burrowing depth with deeper burrows being found in zones with temperature extremes (either hot or cold) as animals seek thermal stability (Kinlaw, 1999). Soil texture can also influence burrowing characteristics, with species to species variation being considerable. In a xeric shrub community in southeastern Oregon, chipmunk (*Eutamias minimus*) burrowing density was directly related to higher clay percentage, while an inverse relationship was found between pocket mice (*P*. *parvus*) burrow density and the percentage of clay (Feldhamer, 1979). Clay percentage and induration by carbonate (conditions like compressed clay barriers) have also been found to correspond to greater burrow complexity, total excavation volume and burrow length (Laundre and Reynolds, 1993). Additionally, animals with larger body mass are also generally more capable of excavating in soils with larger rock fragments (Kinlaw, 1999).

While large aggregate rock armor on disposal cells would seemingly isolate compressed clay layers from burrowing animals, large rocks attract burrowing mammals because they serve as protected sites against predation (Smith et al., 1997). The observation of burrows (both active and abandoned) on in-service UMTRCA covers has largely favored locations with rock armor, specifically slopes (see Chapter 2 and Appendix A). A review of factors that affect small mammal habitability on UMTRCA covers was compiled by

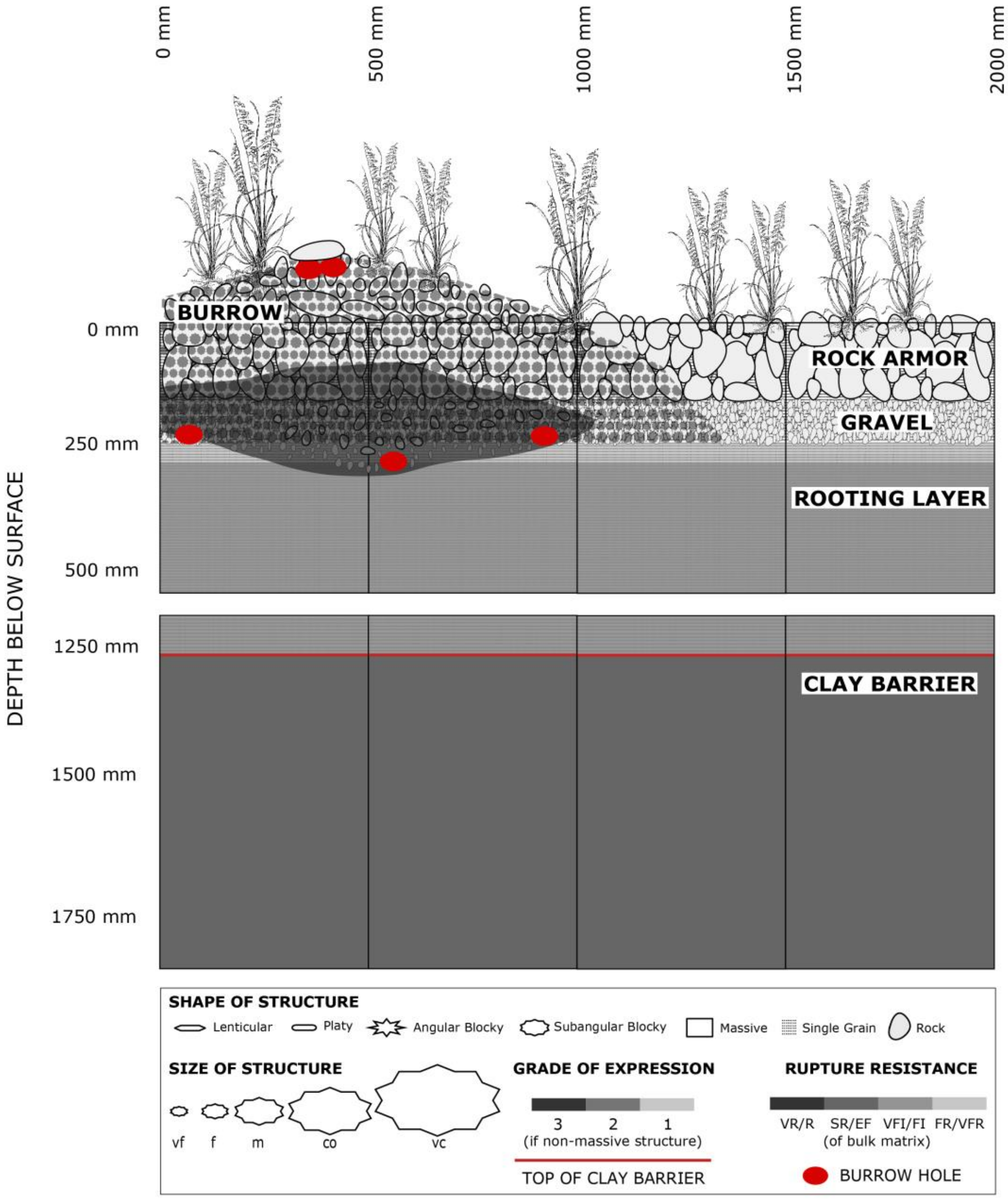
Gano and States (1982), however studies to determine long-term performance impacts associated with animal burrowing on in-service cover systems have been sparse (DOE, 2015; DOE, 2016). Rodent burrows were encountered at Lakeview (Figure 4.12) and Shirley Basin (Figure 4.13). At Lakeview, animal burrowing was isolated above rock armoring and did not influence clay barrier morphology. At Shirley Basin, burrowing extended through surface rock armor layers and into the top portion of the sandy rooting layer but terminated well above the clay barrier.

Figure 4.12: Rodent burrow perched above rock armor



Lakeview, Oregon. Shallow Composite Mineral Barrier.

Figure 4.13: Rodent burrow mixing rock armor and gravel layers



Shirley Basin, Wyoming. Deep, rock armored Composite Mineral Barrier on side slope.

### 4.4.9. ACCUMULATION AND REDISTRIBUTION OF AEOLIAN DUST, SOIL ORGANIC CARBON, SOLUBLE SALTS, AND CALCIUM CARBONATE

The accumulation and redistribution of aeolian dusts, soil organic matter, soluble salts and carbonate have been observed, with patterning connected to initial design and current surface condition (Williams et al., 2019). Given the direct and indirect influence of aeolian dust (Dietze et al., 2012; Turk and Graham, 2011), soil organic matter (Oades, 1984; Dexter et al., 2008), soluble salts (Gray and Schloker, 1969), and calcite (Flach et al., 1969) to soil physical properties relevant to engineering performance, an understanding of the rates and qualities of additions, transformations, translocations, and losses under variable site soil forming factors can aid in the long term, scenario based, forecasting of future barrier condition and performance.

#### 4.4.9.1. *AEOLIAN DUST*

Aeolian deposition is common in desert environments (Goldstein et al., 2008) where many UMTRCA disposal cells are located. In southern Colorado, individual events can deposit up to 2 g/m$^{-2}$ dust (Lawrence et al., 2010). Rock fragments that occur naturally on desert soil surfaces, and gravel applied as a mulch by ancient and traditional farmers, have both been shown to accelerate dust (silt and clay) accumulation (Goosens, 1994; Xiao-Yan and Lian-You, 2003). Dust deposition can lead to the formation of new soil horizons (McFadden et al., 1998); change the morphology, hydrology, chemistry, erodibility, fertility, and ecology of desert soil profiles (Dietze et al., 2012); and change the hydraulic conductivity and water storage capacity of soil profiles (Shafer et al., 2007; Reynolds et al., 2006; Turk and Graham, 2011). Desert pavements derived from aeolian deposition may have partially hydrophobic surfaces (Belnap, 2006). These conditions can lead to increased overland flow velocity and a greater potential for erosion (Rodríguez-Caballero et al. 2012). Also, calcium carbonate in dust can accumulate in the underlying soil profile (Van der Hover and Quade 2002), and nutrients and propagules in the dust can change the composition and productivity of desert ecosystems (Reynolds et al. 2001; Garner and Steinberger 1989).

The accumulation of aeolian dusts on rock armored covers has been observed on numerous UMTRCA sites (Burt and Cox, 1993; DOE, 2019). Beginning in 2001 at Bluewater, NM (6-years after construction), inspectors observed a 300-meter-wide zone on the eastern half (leeward) slope of the main tailing's disposal cell where the interstitial spaces of the rock riprap layer were filling with soil. Deposition in some locations appeared to be related to construction anomalies (depressions) that altered surface friction. In 2001, the dust layer was approximately 100 mm below the rock riprap surface and no vegetation was present. By 2004, annual weeds including Russian thistle (*Salsola tragus*) and burningbush (*Bassia scoparia*) had preferentially established in areas where dust was accumulating. By 2010, shrubs (fourwing saltbush; *Atriplex canescens*) and trees (Siberian elm; *Ulmus pumila*) were observed growing in the dust layers along the eastern slope. And by 2016, aeolian sediments nearly filled riprap interstices on the leeward sides of the Bluewater main tailings disposal cell cover with squirreltail (*Elymus elymoides*) and purple threeawn (*Aristida purpurea*) establishing as dominant species. During the same time period, considerably less dust accumulation was observed on the western half (windward side) of the main tailing's disposal cell. Dusts are also beginning to accumulate on the top portions of the of the main cell in areas where surface vegetation reduces wind velocity, thereby depositing sediments.

#### 4.4.9.2. *SOIL ORGANIC CARBON*

Organic matter content has a direct relationship with many soil physical and engineering properties. As soil organic carbon content increases, bulk density decreases (Curtis and Post, 1964; Saini, 1966), aggregation and total pore space increase (Kladivko and Nelson, 1979; Sanchez et al., 1989; Tiarks et al., 1974; Oades, 1984), infiltration capacity and hydraulic conductivity increase (Rawls et al., 1982; Dexter et al., 2008), and water holding capacity increases under higher tensions (Gupta et al.,1977). Soil organic carbon content also corresponds to the presence of soil arthropods and earthworms that further increase pore space through burrowing (Six et al., 2004).

In agricultural soils, the management of organic carbon is desired to improve the physical properties of soils for crop production (Bacon, 1929; Bayer, 1930). However, in engineered soils, including compressed clay barriers for waste containment, it is commonly accepted that soil organic matter content runs counter to desired engineering parameters including compressibility and hydraulic isolation (Franklin et al. 1973). In mineral soils, compressibility is sensitive to small changes in organic matter, particularly under higher rather than lower moisture contents common to clay barrier installation condition (Soane, 1990).

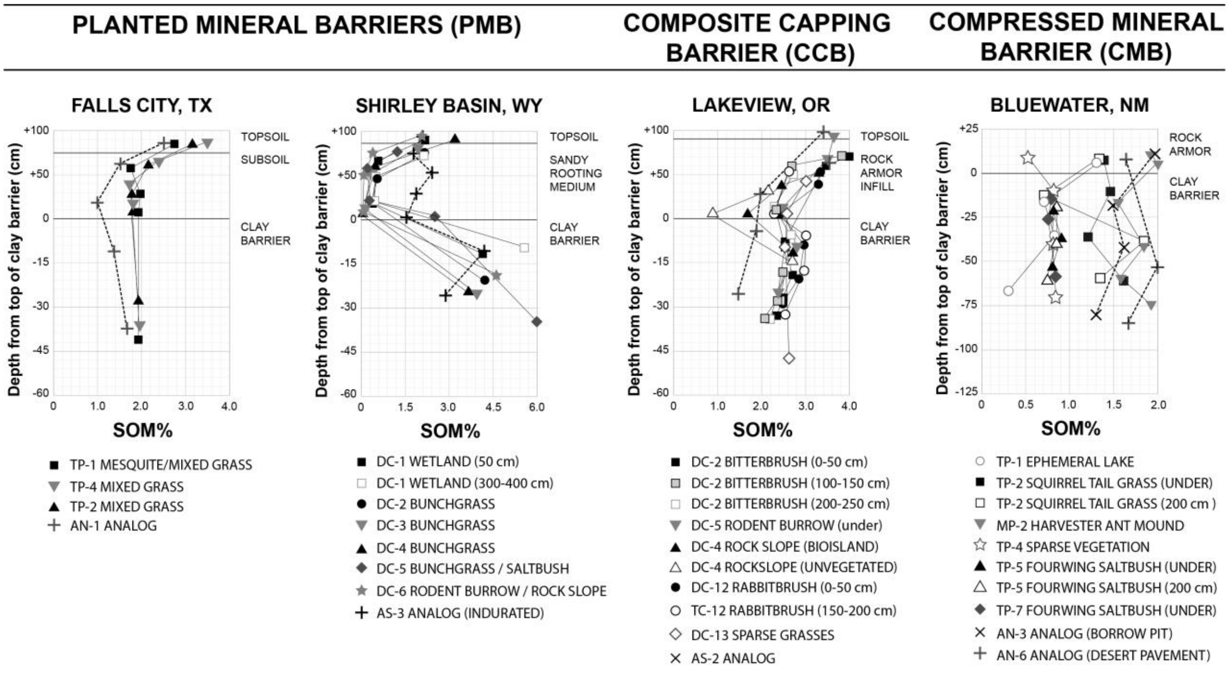
Native soil materials used for the construction of compressed clay barriers are selected for low carbon content, however, Earth surface and pedogenic processes may lead to the accumulation and redistribution of carbon from dust deposition, plant root turnover, leaf litter accumulation, and microbial transformation of organic matter into humic materials over time. Post construction soils can rapidly accumulate soil organic carbon (Roberts et al., 1988; Bendfeldt et al 2001; Schafer et al 1980; Biber et al., 2013), corresponding to increased water holding capacity (Roberts et al., 1988), the evolution of depth dependent soil structure (Schafer et al., 1980; Anderson, 1977; Roberts et al., 1988; Biber et al., 2013) and elevated rates of nitrogen cycling (Anderson, 1977).

In native vertic soils (high clay soils that are characterized by shrink/swell and the subsequent presence of slickenslides), increases in soil stability have been linked to higher amounts of the labile fraction of organic matter, as opposed to total organic carbon content (Crook, 1993; Lefroy et al., 1993). Additionally, surface vegetation type has been shown to considerably influence the total labile fraction of vertic soils (Cook, 1993). Given connections between vegetation, labile organic carbon content, and soil structuring, the management of vegetation on engineered disposal cells will likely have long term impacts to soil structuring and persistence.

The accumulation and distribution of soil organic carbon in compacted clay barriers, and associations with emergent structuring, have received little research attention to date. Given natural heterogeneity in excavated parent materials that are sourced across broad landscapes during clay barrier construction, the distribution of organic carbon in an engineered soil profile may not be a result of transformations or translocations occurring since construction, but as built heterogeneity from sourced materials and construction sequence. Additionally, no data exist to characterize as built spatial distribution of carbon in UMTRCA clay barriers, therefore direct links between observed soil process, carbon distribution, soil morphology, and performance remain challenging.

At the shallow rock armor cover at Bluewater, NM, profiles associated with perennial grasses and ants had the highest amounts of soil organic matter with depth (Figure 4.14) (Williams et al., 2019). At the shallow planted/rock cover at Lakeview, OR soil organic matter was greatest at the surface, dissipating with depth to the top of the radon barrier. Within the clay barrier at Lakeview, OR soil organic matter was highest at the top, decreasing slightly with depth across surface conditions observed. At the deep planted barriers at Falls City, TX and Shirley Basin, WY the top portion of the subsoil/rooting layers had a greater amount of soil organic matter than the lower section of the subsoil/rooting layers, indicating that additions of soil organic matter were happening at the surface, a trend that matches natural analogs in both areas. Soil organic carbon percentage in the clay barrier at Shirley Basin was higher than at other sites, and was represented, morphologically, by black mottles that were likely formed from organic materials deposited in riparian areas common to prior landforms.

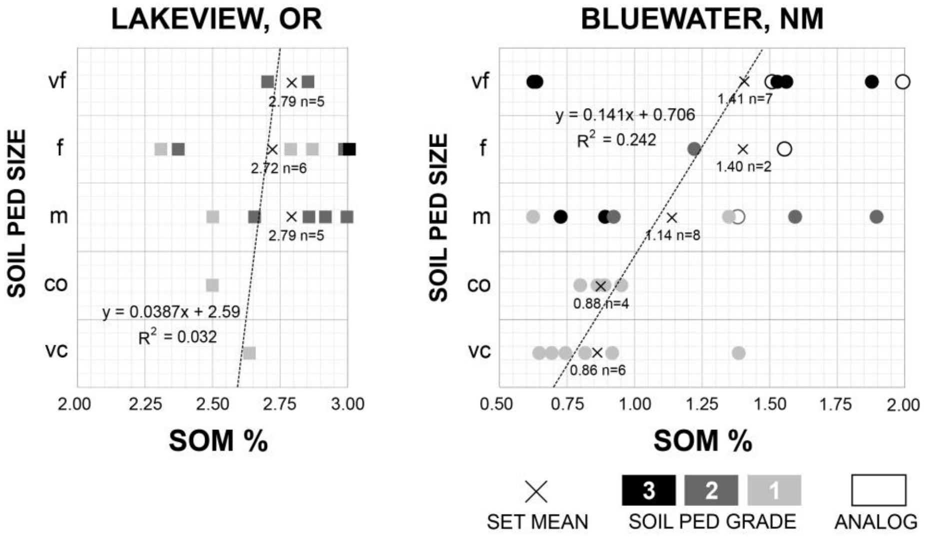
Figure 4.14: Distribution of soil organic carbon



From data presented in: Williams et al., (2019)

The relationship between the soil organic matter fraction and soil ped (structural unit) size in the clay barriers at Lakeview and Bluewater show weak trends (Figure 4.15). As soil organic carbon content increases, ped size tends to decrease at Bluewater ($R^2 = 0.242$). The trend is insignificant at Lakeview ($R^2 = 0.032$). Ped size contributes to the regulation of hydraulic conductivity (Benson et al., 1994; Lin et al., 1999a) with potential impacts to long term cover performance. As such, feedbacks between vegetation establishment, soil organic carbon deposition, and evolved soil ped size in bioturbated clay barriers is of importance. However, given the heterogeneity of clay barrier construction materials from borrow areas, the presence of co-factors that influence ped structuring (i.e. depth to ground surface, surface condition, and as construction heterogeneity), and the various co-occurring processes that influence crack size in clay barriers (see Section 4.4.1) untangling these processes is complex. At a highly simplified level, and given the significance of plant-soil feedbacks on near surface soil-carbon dynamics, shallow CMBs with emergent vegetation (such as Bluewater) are likely most susceptible to the emergence of carbon stabilized soil structure.

Figure 4.15: Relationship between soil organic matter percent and ped size



From data presented in: Williams et al., (2019)

### 4.4.9.3. *SOLUBLE SALTS*

The distribution of soluble salts within in-service clay barriers may serve as an indicator of the cumulative water balance within profiles, in addition to the predominant direction of water movement across waste covers given well known solubility gradients. The initial source of salts in/on waste covers is varied. Salts can accumulate on waste covers from aeolian deposition in semi-arid landscapes, from the desalination of soil materials used in construction, or from passive wicking from materials under the cover. In semi-arid and arid areas, the upward movement of contaminated salts from subsurface wastes through evaporative wicking has been identified as a potential vector for waste mobility (Young et al., 1986; DOE, 2014).

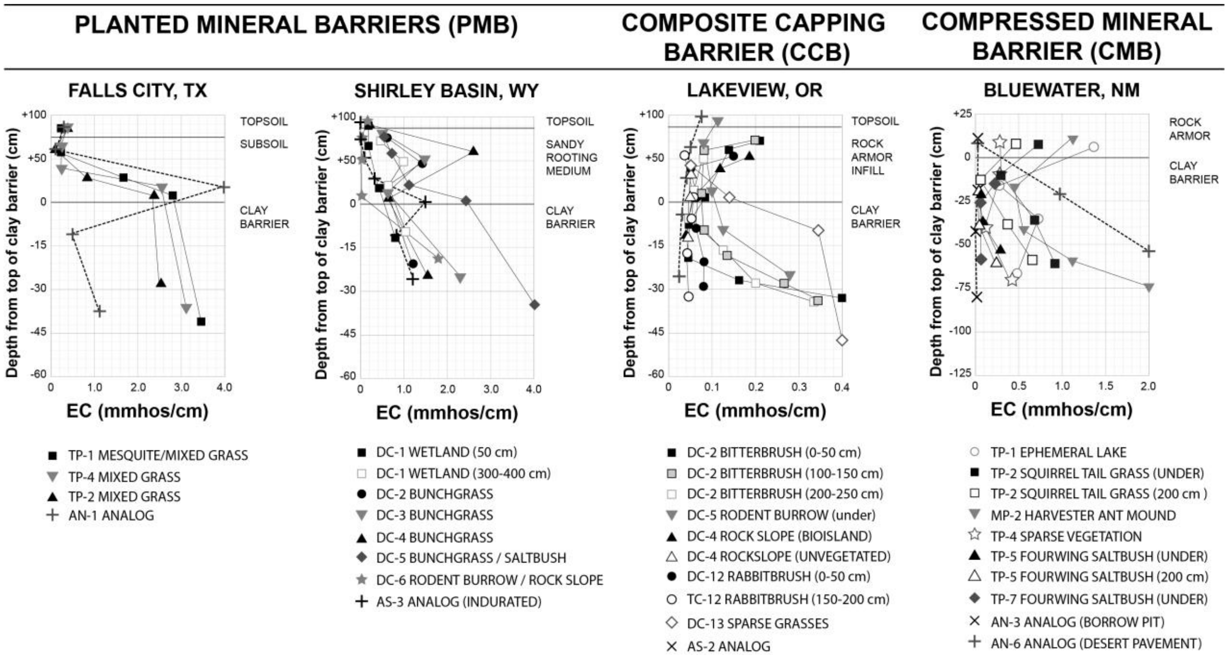
Given high solubility, many salts can remain dissolved in soil water until evaporation. If evaporation exceeds infiltration, salt accumulation will happen near the surface. If infiltration exceeds evaporation, salts will collect lower in the profile (Turk et al., 2011). The depth distribution of sodium chloride (NaCl), a highly soluble salt, can vary seasonally in a soil profile, occurring near the surface in drier months and low in the profile during monsoons (Jackson, et al., 1956), and may serve as a seasonal tracer of water balance.

Similar logic for measuring cumulative patterns is shared for tracking long-term radon diffusion given Pb210 gradients in clay barrier profiles (Fuhrmann et al., 2019b).

The distribution of soluble salts across four in-service UMTRCA disposal cells is presented in Figure 4.16. A bimodal distribution exists at Bluewater, NM and Lakeview, OR. Both sites were sampled at the average driest times of year (Waugh et al., 2019). Salt accumulation is occurring in near surface fines underneath rock armor, however within the clay barrier at Bluewater, NM, and Lakeview, OR, an accumulation of salts is occurring with increased depth from surface.

At Shirley Basin, WY, the general trend across the cell and in natural analog soils is an increasing amount of soluble salts with depth, indicating that infiltration is favored over evapotranspiration at the time of observation. At Falls City, TX, salts are leaching within the subsoil section and collecting along the surface of the clay barrier. The same salt distribution pattern is observed in the Falls City, TX analog profile with salt accumulation occurring on-top of the argillic horizon. The profiles at Falls City that are responsible for lateral drainage off the slope (DS-6 and DS-5) display elevated levels of soluble salts compared to on-cell averages, suggesting that salts are being removed from the cell as a function of relief.

Figure 4.16: Distribution of soluble salts (electrical conductivity)



From data presented in: Williams et al., (2019)

### 4.4.9.4. *CALCIUM CARBONATE*

The creation of pore space through physical and biotic processes dominate the discussion of soil change in clay barriers, however induration and cementation by materials including calcium carbonate ($CaCO_3$) may serve to block emergent pore space through time. Throughout the western United States, the deposition of atmospheric $CaCO_3$, as both dissolved ions in rainwater and solid particulates in dust, can be substantial. Aeolian dusts in southern Nevada and California can contain 10-30% $CaCO_3$ resulting in 1-6.6 g $CaCO_3$ $m^2$/y (Reheis et al, 1995). In southern New Mexico, aeolian dust can deposit 0.4 g $CaCO_3$ $m^2$/y, with rain delivering an additional 1.2 g $CaCO_3$ $m^2$/y (Birkeland, 1999). In central Texas, rain supplies an additional 2.3 g $CaCO_3$ $m^2$/y with no contributions from aeolian dust (Rabenhorst et al., 1984). Given depositional patterns throughout much of the Quaternary, appreciable amounts of CaCO3 are naturally present in native soils in the western United States, including those materials used for the construction of compressed clay barriers.

The precipitation of $CaCO_3$ as calcite in soils is driven by several factors including pore space, pH, $CO_2$ concentration, temperature, and pressure (Turk, et al., 2011). Calcite has a solubility of 0.06g $L^{-1}$, more soluble than silicate minerals, but much less soluble than many salts including sodium chloride (NaCl). The movement of water through the soil profile greatly influences the location of calcite precipitation. When evapotranspiration (ET) exceeds leaching, calcite will precipitate close to the soil surface or on the bottom of rocks in the profile. When leaching exceeds ET, calcite will precipitate lower in the profile or remain dissolved in soil solution as $CaCO_3$. Increased soil pH results in more $HCO_3^-$ and the production of more $CaCO_3$. Additionally, the removal of $CO_2$ from soil through diffusion in pore space, results in the production of additional $CaCO_3$. The precipitation of calcite is also significantly influenced by microorganisms. Both bacteria and fungi excrete $Ca^{2+}$ through cellular metabolism and subsequently reacts with $2HCO_3^-$ in soil solution resulting in $CaCO_3$ ($Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + H_2O + CO_2$). The microbial production of calcite and subsequent cementation can be so pronounced, that stimulating it has been proposed to stabilize engineered soils with low shear from erosion (DeJong et al., 2006; calcite Umar et al., 2016).

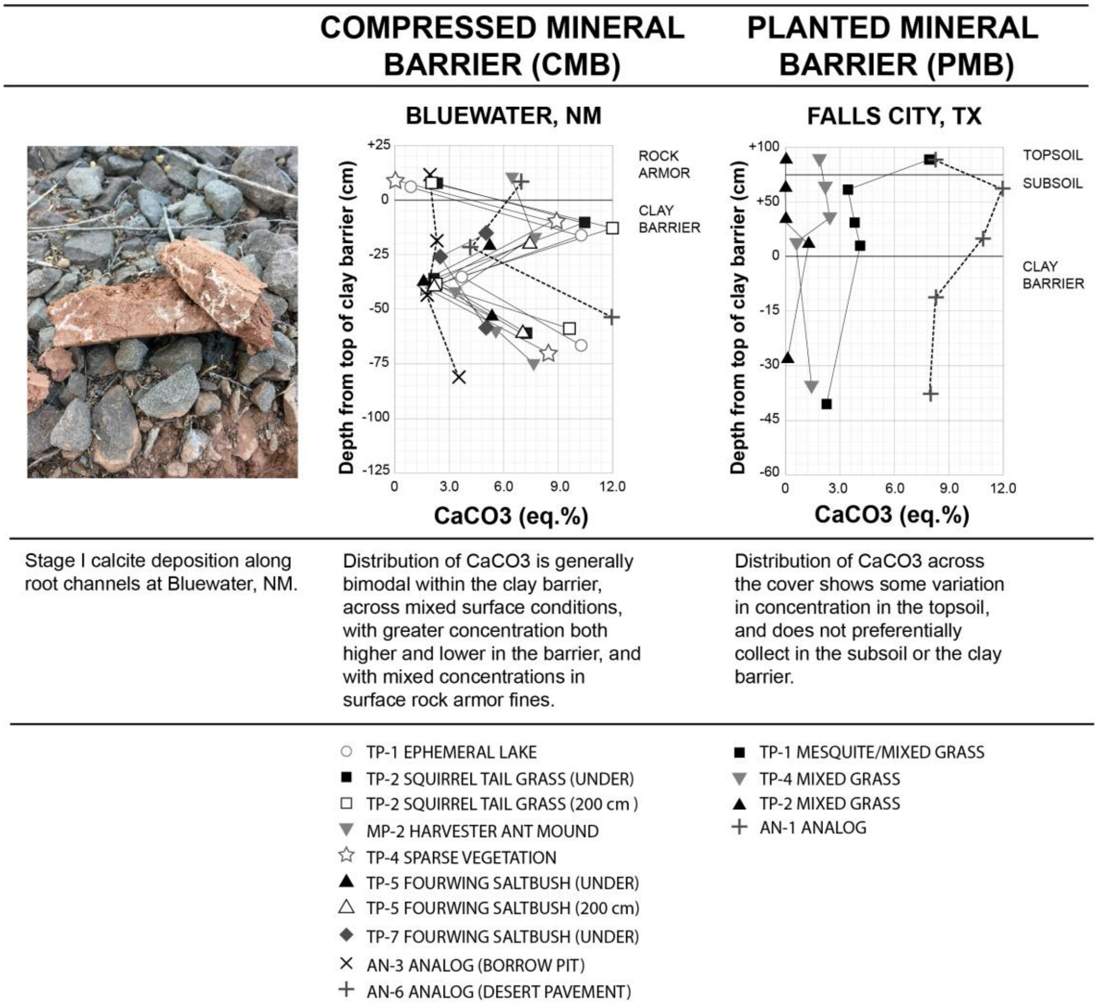
Patterning of calcite precipitation is driven by macropore morphology, and initially favors areas of fine plant rooting, large pores with rapid drying, and the undersides of gravels (Buol et al., 2011). After calcite has initially precipitated, additional crystallization will occur on preexisting calcite nodules. Not all calcite precipitation results in cementation, and physical impacts to soil morphology increase over time as pore space becomes indurated by nucleated crystals and associated clay complexes (Flach et al., 1969). Cementation by calcite is generally connected with high clay content and the presence of dissolved amorphous silica, as facilitated by calcite induced clay flocculation (McNeal and Coleman, 1966). Under such conditions, as individual calcite nodules grow and eventually merge, they can restrict hydraulic conductivity (Gile, et al., 1966). After enough cycles of evapotranspiration and calcite accumulation, pore space becomes sufficiently plugged and a thin, hard, dense, and strongly cemented laminar horizon can form restricting the movement of soil water. If appreciable amounts of calcite are found in a soil it is recognized as a calcic horizon if it is not cemented, and an a petrocalcic horizon if it is (Soil Survey Staff, 2003). Petrocalcic soils are largely concentrated in arid and semi-arid landscapes where annual evaporation exceeds infiltration.

As clay barriers age and become more porous, it is possible that induration by calcite may result in moderate self-healing and stabilized (or even reduced) hydraulic conductivity over time. Rates of soil cementation by calcite vary widely as a function of soil forming factors (Leeder, 1975; Wright, 1990). Stage IV calcite cementation has been observed on surfaces less than a few thousand years old (Hay & Reeder, 1978), however the majority of petrocalcic soils in the western United states have required closer to 100,000 years to form (Wright, 1990). On a young lava flow (estimated at <7,000 years of age) within the Bluewater site boundary, a calcic horizon has formed in a combination of aeolian and fluvial sediments (Williams, et al., 2019).

Patterning of calcite distribution on the main Bluewater disposal cell indicates that calcite is moving within the clay barrier post construction, regardless of surface condition, and is characterized by a bimodal distribution at the surface and bottom of the barrier (Figure 4.17) (Williams et al., 2019). Stage I calcite accumulation along former fine root channels was also observed within the clay barrier at Bluewater. The distribution of calcite at Falls City (deep planted design) does not exhibit considerable patterning in the profiles observed. However, calcite is preferentially accumulating at lower elevation locations on the Falls City disposal cell that were designed to facilitate drainage of water, indicating that soil forming factors, including climate and relief, are contributing to the flux of calcite off the disposal cell as opposed to accumulation within the compressed clay barrier. When coupled with the observed maintenance of clay barrier morphology at Falls City (Figure 3.5), and corresponding low hydraulic conductivity (Benson et al., 2019), lateral drainage is favored over infiltration across the cell.

At Shirley Basin, carbonate benches were commonly seen directly on-top of the compressed clay barrier (Williams et al., 2019). This observation indicates that carbonate was leaching through the more porous topsoil and that the low hydraulic conductivity of the compressed clay barrier limited further transport. Such a finding serves as a qualitative indicator that the clay barrier has been successful at limiting water transport, as intended. This observation is supported by the exceeding low hydraulic conductivity measurements observed at Shirley Basin (see Chapter 5). Cover design (planted and deep) along with very high clay texture (>60% clay), and mineralogy dominated by smectite in the barrier, are possible contributors to the persistence of limited diffusion through time.

Figure 4.17: Distribution of calcium carbonate (eq. %)



Stage I calcite deposition along root channels at Bluewater, NM.

Distribution of CaCO3 is generally bimodal within the clay barrier, across mixed surface conditions, with greater concentration both higher and lower in the barrier, and with mixed concentrations in surface rock armor fines.

Distribution of CaCO3 across the cover shows some variation in concentration in the topsoil, and does not preferentially collect in the subsoil or the clay barrier.

Profiles on barrier systems are displayed as solid lines. Analog profiles are displayed as dashed lines. From data presented in: Williams et al., (2019)

### 4.4.10. REDUCTION AND OXIDATION

Under saturated conditions, clay barriers can undergo redox processes that result in chemical transformations. When soil pore space is filled by water, and oxygen is depleted, microbially induced reduction results in the dissolution of redox sensitive compounds including Fe and Mn (hydr)oxides, nitrates, sulfides and sulfates resulting in selective losses from anoxic zones. In many fine textured soils, prolonged saturation leads to the reduction of iron from its oxidized (ferric) $Fe^{3+}$ state to its reduced and water soluble (ferrous) $Fe^{2+}$ state. The removal of iron from soil results in a grey or bluish color (gleying). For compressed clay barriers intended to limit gas diffusion, maintaining high barrier moisture is advantageous given the inverse relationship between soil moisture and gas diffusion (Nielson and Rogers, 1982; Rogers et al., 1984).

The observation of gleyic features within in-service clay barriers provides evidence that the design is (or has on average) maintained saturated conditions and may serve as an indicator that the barrier has been effective at limiting gas diffusion over time. Strong gleyic features were observed on the side slopes of Falls City, TX (DC-6), and Shirley Basin, WY (DC-6) (Williams et al., 2019). The corresponding radon diffusion coefficients at these two locations with gleyic features were the first and third lowest measured across 23 total measurements (Fuhrmann, et al., 2019a), supporting this hypothesis.

While clay barrier saturation may serve to limit gas flux to the surface, the impact of long-term barrier saturation to the hydraulic isolation of subsurface wastes is presently unknown. The gleyic features in both FC. DC-6 and SB. DC-6 were not observed at the bottom terminus of the clay barrier, but were perched above non-gleyed barrier lift events, suggesting that water in those profiles may be perched, and only very minimally hydraulically connected to the subsurface. The careful observation of gleyic features may serve as a helpful tool when interpreting clay barrier gas diffusion data or detailed Pb210 profiles (Fuhrmann, et al., 2019b).

#### 4.4.11. SECONDARY AGGREGATION OF BROKEN-DOWN CLAY BARRIERS

Given the monolithic initial conditions of compressed clay barriers, soil aggregation and stabilization are a secondary process that first requires barriers with massive structure to be broken down by the processes of desiccation/cracking, wetting/drying, fracture, root penetration, and bioturbation by animals, as described in previous sections. Once a compressed clay barrier turns into a collection of heterogeneous materials of mixed particle and pore sizes, the process of soil aggregation and stabilization may occur through well characterized pathways (Tisdal and Oades, 1982, Six et al., 2004).

The aggregation of soil particles involves several processes that are influenced by initial conditions, climate, mineralogy, soil organic carbon content, flora and fauna, and microorganisms. Aggregation requires the presence of organic binding agents which vary in chemical structure considerably (Kay, 1990). Tisdall and Oades (1982) classify organic binding agents into three broad categories based on their persistence: 1) polysaccharides (lasting weeks); 2) roots, fungal hyphae, bacterial, and algae (lasting months to several years); and 3) humic materials and polymers (lasting tens to hundreds of years).

Plant rooting in compressed clay barriers is likely the primary factor contributing to any observed stabilization of soil aggregates, given additions of soil organic matter through root turn-over and the enmeshment by root associated fungal hyphae (Haynes and Beare, 1997; Tisdall and Oades, 1979; Tisdall et al., 1997), particularly in semi-arid environments (Chaudhary et al., 2009). Microorganisms and root exudates can also contribute to the production of rhizosphere polysaccharides that can glue individual soil particles together (Watt et al., 1993; Traoré et al., 2000). The soil water regime can also contribute to the formation and stabilization of soil particles on plant roots (Watt et al., 1994), with root associated aggregate strength shown to increase through intense and frequent drying cycles from plant induced evapotranspiration (Horn and Dexter, 1989; Czarnes et al.

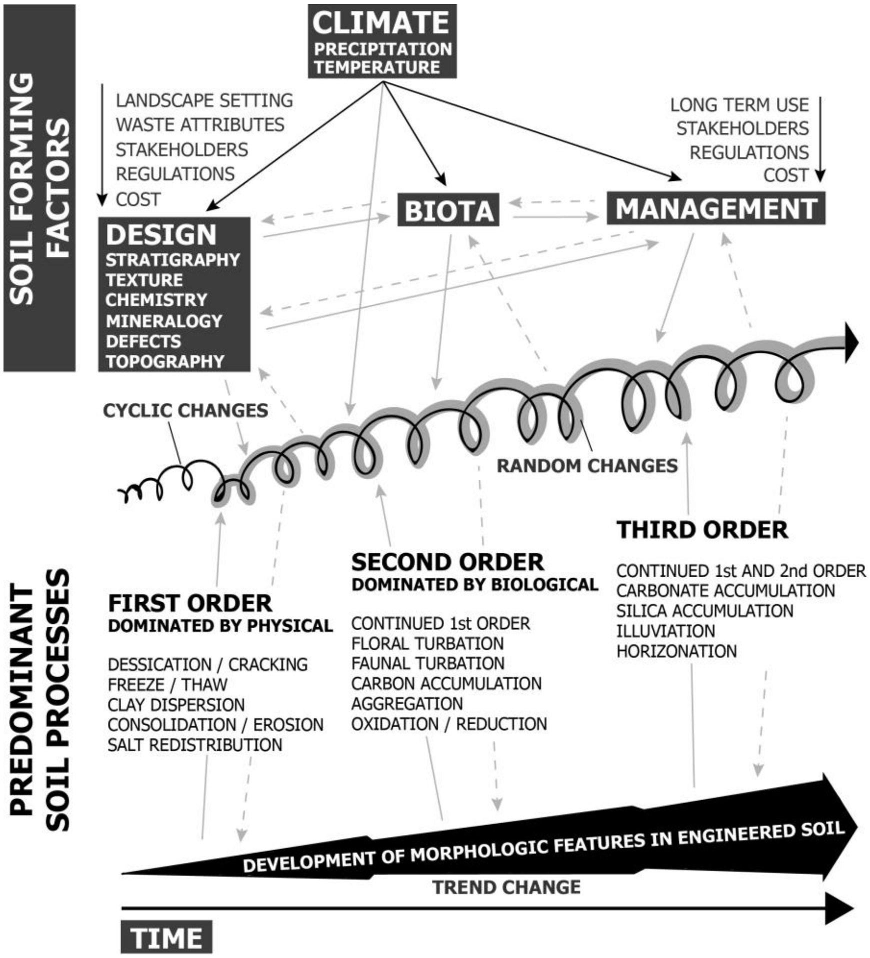
2000). In semi-arid environments, the emergence of secondary aggregates increases hydraulic conductivity (Bouma and Anderson, 1973; Boyle et al., 1989). As structuring in clay barriers increases and they shift from uniformly engineered towards dynamic and biological soils, the process of secondary aggregation and stabilization may become more pronounced with impacts to the long-term maintenance of emergent soil architecture. The stabalization of soil structure in clay barriers will likely impact hydraulic conductivity, water balance, and radon diffusion.

## 4.5. SOIL PROCESSES AND THE EMERGENCE OF SOIL MORPHOLOGY

Time plays a central role in the development of soil given recurring pedogenic processes that accumulate as morphological expressions (Lin, 2010). Targulian and Krasilnikov, (2007) provide a framework for categorizing soil processes that correspond to the observation of soil morphology in chronosequence studies of natural systems. The framework describes the characteristic times that specific pedogenic processes result in alterations to a soil body over 1 to 1-million-year timescales. Given that UMTRCA covers have regulatory timeframes between 1-1,000 years, a conceptual framework that captures the relative contribution of specific soil processes to the morphology of clay barriers in the UMTRCA portfolio through time is proposed (Figure 4.18). This framework is an extension of the factorial model proposed in Chapter 3 (Figure 3.1). Soil forming factors should not be considered responsible for the occurrence of specific soil processes, they are not forces. Rather, factors are definer variables that indicate how soils and ecosystems vary through space and time (Amundson and Jenny, 1991), with soil processes directly responsible for the creation and maintenance of soil morphology.

Three sequential phases are proposed which highlight the dominant processes that result in the expression of soil morphology, at that time step and under variable soil forming factors, over UMTRCA performance timeframes, With few exceptions, First Order processes have been widely observed in the months immediately following clay barrier construction (Kim and Daniel, 1992; Benson et al., 1995; Melchior, 1997) and are dominated by desiccation and cracking. Second Order processes have been observed annually and decadal (Burt and Cox, 1993; Link et al., 1995; Waugh et al., 1999) and are dominated by bioturbation by plants and animals. Given the inability to observe 100+ year old engineered cover systems, relationships between anticipated additions, transfers, transformations and losses to soil morphology are largely derived from trends observed from the literature on natural soils (e.g. Targulian and Krasilnikov, 2007). Third Order processes are anticipated to occur over the 100 to 1,000-year time period and emphasize the accumulation and redistribution of materials with impacts to aggregate structuring and horizonation, as supported by natural analog studies (Chapter 3).

Figure 4.18: Site factors, soil process, and morphological development in engineered soils for waste containment



Conceptual model of the co-evolution of soil process and morphology in engineered clay barrier systems based on Lin, (2010). Solid black arrows represent the dominant direction of influence. Solid gray arrows represent interactions. Dashed arrows represent a feedback between factors, change, soil processes, and morphology. The time step evolution of soil process is based on Targulian and Krasilnikov, (2007).

For those cover systems that cannot support vegetation (largely because of climate, cover design, aggressive management, or site-specific limitations) and if those surfaces are covered with rock armor for erosion control, First Order processes will likely persist indefinitely. An example would be the hot and arid UMTRCA site at Mexican Hat, UT. In such systems, physical and physiochemical processes dominate the development and/or maintenance of soil morphology through time. The formation of soil morphology in arid environments is generally a very slow process occurring over 100,000's of years (Wells et al., 1985), and episodic events (such as large rainstorms) play a significant role in the development of soil morphology, specifically erosion (Cable and Huxman, 2004; Schwinning et al., 2004). We would expect such episodic events to contribute significantly to soil change in these non-vegetated, arid environments. Over millennial time scales the accumulation and redistribution of mobile elements, including dust and carbonate from rainfall, may eventually lead to the formation of young desert pavements at arid locations.

Cover design, vegetation, and management can be used to describe the in-service soil morphology of clay barriers (Chapter 3). Shallow, CMB's have been observed to have more patchy soil development (between profiles on the same cell) when compared against deep PMB's as summarized in Table 4.1. As such, shallow CMB's have variable calcite and organic carbon distribution in the clay barrier, variable soil architecture occurring along impact gradients, along with a diversity in root distribution and structuring, while PMB's are characterized by relative evenness across metrics (see above sections for discussion).

The CMB at Bluewater, NM (strongly) and the PMB at Falls City, TX (weakly) are both categorized by Second Order soil processes, however soil forming factors, including deep barrier and managed vegetation, result in the relative stability of clay barrier morphology in the PMB through time. The design of the PMB at Falls City dissipates environmental fluxes (i.e. precipitation through evapotranspiration, thermal cycling through insulation, etc.) with the majority of soil processes characteristic of energy exchange occurring *above* the clay barrier in overburden materials (e.g. shrinking/swelling, desiccation/cracking, root growth, and soil structuring). Such a dynamic results in the resilient physical isolation of wastes through time. The main CMB at Bluewater was not designed with an adequate capacity to dissipate environmental fluxes; therefore, all soil processes must occur *within* the compressed clay barrier as a consumptive process, thereby resulting in morphological development through time. While a similar collection of soil processes occurs at both sites, the cumulative impacts of those processes are relatively stable and even in the PMB at Falls City and variable and uneven in the CMB at Bluewater showing the role that design, management, and vegetation have in buffering soil change and maintaining as-built barrier morphology.

Table 4.1: Summary of soil process in clay barriers of contrasting design

| | **Shallow CMB** | **Deep PMB** |
|---|---|---|
| | Bluewater, NM | Falls City, TX |
| Desiccation cracking in barrier | Yes. Uneven across surface conditions. Can be through depth of observed barrier. | Yes. Even. Observed in top 15 cm of clay barriers along planes of weakness from retained aggregate structures. |
| Freeze thaw in barrier | Possibly. The ephemeral lake freezes. | No |
| Plant rooting even / uneven | Uneven | Even |
| Soil structuring even / uneven | Uneven | Even |
| Bioturbation by animals impacting clay barrier | Yes | No |
| Soil organic carbon distribution is even / uneven | Uneven | Even |
| Distribution of soluble salts is even / uneven | Uneven | Mildly uneven |
| Distribution of calcium carbonate is even / uneven | Uneven | Even |
| Reduction / Oxidation is present | No | Yes |
| Clay barrier soil structure through time | Emergent | Relatively stable |

### 4.6. SECTION REVIEW

Earth surface processes are occurring unevenly across the UMTRCA portfolio of engineered disposal cells (Chapter 2). These changes result in the emergence of soil morphology within compressed clay barriers, as described by soil forming factors (Chapter 3). The development of soil morphology occurs in combination with numerous pedogenic processes over time and their study offers a way to classify barrier systems, understand how disposal cells function at present, and how they may evolve through time. A conceptual framework shows that soil change can be grouped into three sequential phases that highlight the dominant processes resulting in the expression of soil morphology, at that time step, over UMTRCA performance timeframes. First Order processes are dominated by physical process, Second Order processes are dominated by biotic process, and Third Order processes are dominated by recurring and cumulative effects of First and Second Order process.

Design, management, and vegetation contribute to buffering soil change *within* clay barriers and in maintaining as-built morphology through time. Deep, Planted Mineral Barriers (PMB's), including the Falls City, TX site, are observed to dissipate environmental fluxes *above* the clay barrier. Such systems result in the resilient physical isolation of wastes through time. Conversely, shallow, rock armored, Compressed Mineral Barriers (CMB's), including the Bluewater, NM site, were not designed with an adequate system to dissipate fluxes, therefore all soil processes must occur *within* the compressed clay barrier as a form of consumption, thereby resulting in morphological development through time. While a similar collection of soil processes is occurring at both sites, the cumulative impacts of those processes are stable and even in the PMB at Falls City and variable and uneven in the CMB at Bluewater showing the role that design, management, and vegetation have in buffering soil change and maintaining as-built barrier morphology.

# 5. SOIL MORPHOLOGICAL DEVELOPMENT AND ENGINEERED PERFORMANCE OF CONTRASTING WASTE COVER SYSTEMS

## 5.1. SUMMARY

A survey was conducted across four in-service UMTRCA covers to characterize soil morphology and engineering performance. Observations were used to construct a Soil Morphological Development Index (SMDI) that consolidates soil morphological descriptors including root density, pedality, porosity, water content, and texture into a single quantified value. The index was adapted from a method developed by Lin et al., (1999a) to quantitatively describe the hydraulic properties of high clay soils from standard soil survey metrics for use in pedotransfer functions (Lin et al., 1999b). Here we use the SMDI to measure relationships between soil morphology, hydraulic conductivity (*Ksat*), and radon diffusion coefficients (*D*) in clay barriers of variable surface condition in the UMTRCA portfolio. Across 39 large diameter block samples collected, we find that the SMDI predicts Ksat, as measured in a large-scale flexible-wall permeameter with a power law best fit model ($R^2$ of 0.721). Across 24 cover profiles monitored for radon with the two-flux method, we find that the SMDI predicts the calculated radon diffusion coefficient with an exponential best fit model ($R^2$ of 0.559).

Natural analog conditions are used to estimate long-term soil morphology and engineering performance. The SMDI values from natural analog soils, adjacent to disposal cells, were compared against values from clay barriers to determine the degree of morphological similarity. We find that natural analog conditions generally contain higher SMDI values, relative to adjacent waste covers. Clay barriers are also converging to analog SMDI values that correspond to bioturbation gradients of increasing intensity. Several profiles at Bluewater, NM (harvester ant mound, fourwing saltbush, and squirreltail grass) and Lakeview, OR (bitterbrush) have SMDI values that closely resemble natural analog conditions. Conversely, soil profiles at Falls City, TX and Shirley Basin, WY are characterized by the nominal development of soil morphology and have been more resilient to change through time. Given the trend towards natural analog conditions of higher SMDI value and the strong connection between SMDI, radon diffusion coefficients, and hydraulic conductivity, we expect UMTRCA covers to continue to evolve towards natural analog morphology, with impacts to cover performance. These trends suggest that natural analogs can serve as excellent predictors of long-term performance.

## 5.2. METHODS

A total of thirty-three soil profiles on four UMTRCA waste covers in the western United States were investigated. Six soil profiles were excavated at Falls City, eleven soil profiles at Bluewater, eight soil profiles at Shirley Basin, eight soil profiles at Lakeview. Characterization and sampling methods are described in Chapter 3. Soil profiles were selected to correspond to representative surface features present on each site and included a wide range of conditions (Chapter 2). A detailed discussion of site selection and surface characteristics can be found in Waugh et al., (2019). A natural analog site was also selected in proximity to each disposal cell to characterize the morphology of a soil with shared soil forming factors to the engineered cover. The determination of radon diffusion coefficients is described in Likos et al., (2019), while the determination of soil hydraulic properties is described in Benson et al., (2019).

### 5.2.1. CONSTRUCTION OF MORPHOLOGICAL DEVELOPMENT INDEX

A point system developed by Lin et al., (1999a) was used to quantitatively describe the hydraulic properties of high clay soils from standard soil survey metrics (Table 5.1). Lin et al., (1999a) assumed a hypothetical structureless and nearly impermeable clay as the reference soil, with the majority of the 96 soils used to construct the model classified as high clay soils. The reference soil, assigned one point (the lowest development value), was assumed to be massive, contain no macropores and no roots, and exist in a fully swollen saturated state. Points are assigned to each morphological class based on functional and/or empirical relationships between hydraulic properties and soil morphology given the amount of observed permeability increase through a best correlation "one-at-a-time" search method (Lin et al., 1999a). The reference case closely matches as constructed compressed clay barriers making it a good choice for use in quantifying emergent soil morphology as a function of cracking, structuring, and rooting with impacts to cover system performance.

The calculation of the SMDI is constrained to the compressed clay barrier, and is not associated with rooting, drainage, rock armor, frost protection, or topsoil layers. The computation of SMDI scores from adjacent natural analogs is constrained to the soil section corresponding to the average depth and thickness of the clay barrier. Given the observed depth dependence of soil morphological properties (Figure 3.5 and Figure 3.6), morphological development scores were calculated for each individual horizon using values from Table 5.1. Morphologic values within individual categories were multiplied to represent coupled effects. The index scores from individual features were then summed to produce a horizon development score (Eq. 5.1).

**Calculation of Soil Morphological Development Index (SMDI)**

$$\boldsymbol{SMDI} = (texture) + (pedality) + (macroporosity) + (root\ density) + (water\ content) \qquad \text{Eq. 5.1}$$

$$pedality = (ped\ grade)\ x\ (ped\ size)\ x\ (ped\ shape)$$

$$macroporosity = (pore\ quantity)\ x\ (pore\ size)\ x\ (pore\ type)$$

$$root\ density = (root\ quantity)\ x\ (root\ size)$$

When comparing SMDI to radon diffusion coefficients, a total profile development score was calculated based on the percent contribution of each horizon to the total profile thickness, corresponding to the depth and thickness of the clay barrier. Profile morphological development scores were then divided by the highest observed morphological score across all profiles, at all sites, to generate a relative SMDI score between 0 and 1 to allow for normalized comparison between profiles and sites. Normalized 0-to-1 scores are also used, from time to time, to compare trends *within* individual sites. A flow diagram for deriving SMDI is provided in Figure 5.1.

When comparing SMDI to hydraulic conductivity, scoring was constrained to the depth and thickness of the block monolith sample with the percent contribution of any individual horizon scores present in the monolith. Block sample SMDI scores were then divided by the highest observed morphological score across all block sections, at all sites, to generate a relative morphological development index score between 0 and 1 to allow for normalized comparison between all blocks, including those sampled from natural analog locations. Normalized 0-to-1 scores are also used, from time to time, to compare trends *within* individual sites.

SMDI scores were also calculated for the natural analogs, as constrained to the horizons occurring at the depth of the compressed clay barrier at that site. Individual cover profile scores were then divided by analog development scores to produce a percent of total profile development versus natural condition value to allow comparison between cover and analog morphology.

Figure 5.1: Flow diagram for deriving the morphological-development index (modified from Lin et al., 1999a)

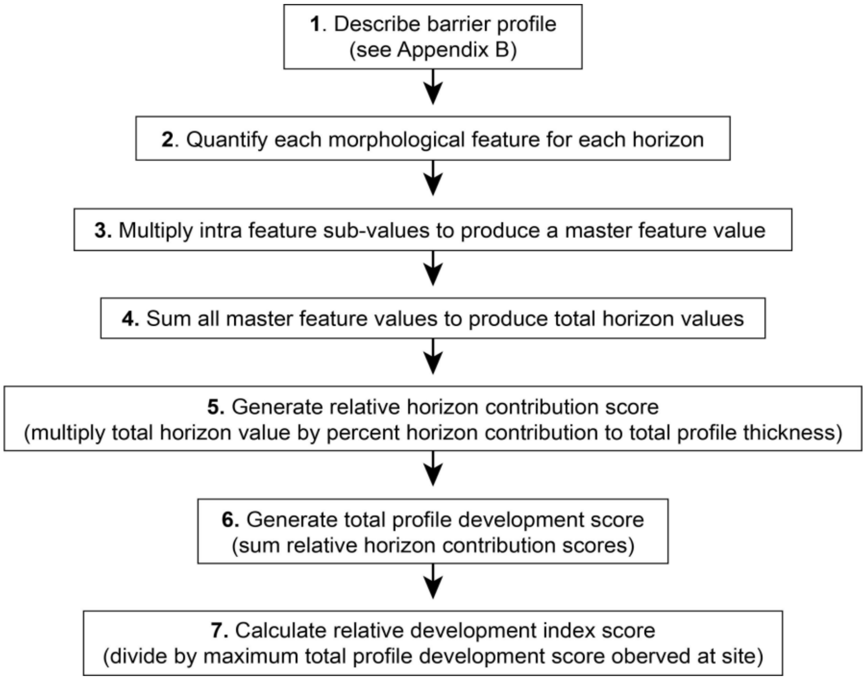


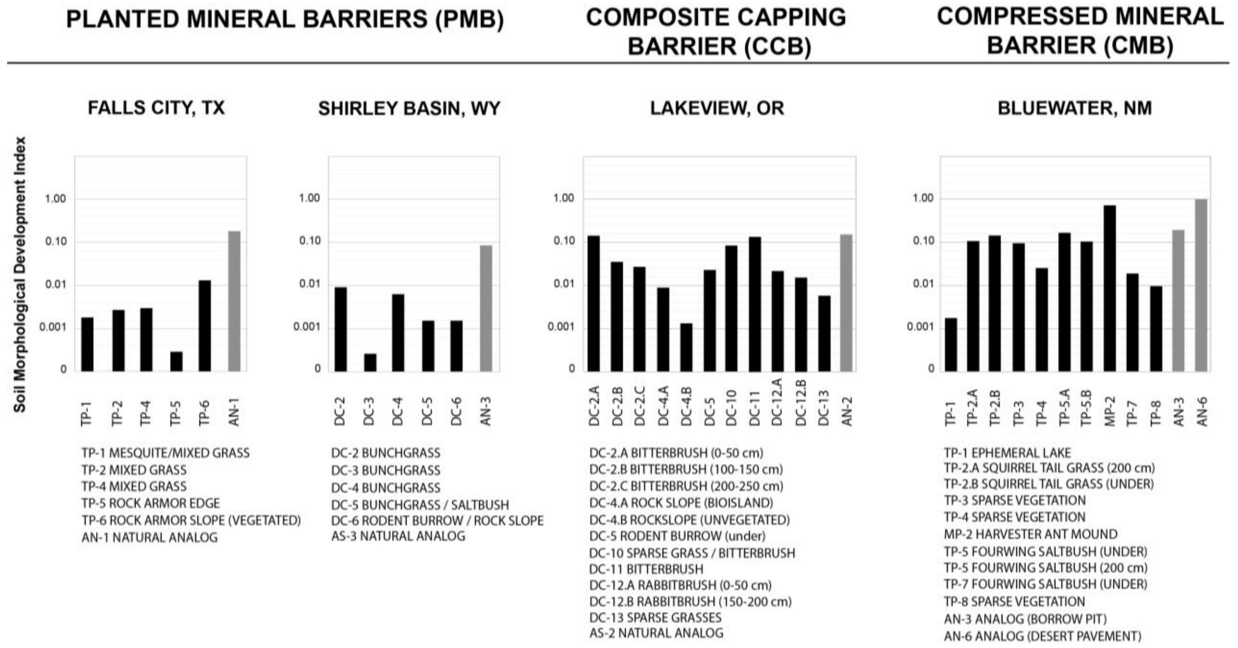
Table 5.1: Points for soil morphological classes (Lin et al., 1999a)

| Morphological Feature | Class | Points |
|---|---|---|
| **Texture** | Clay | 1 |
| | Silty clay | 2 |
| | Sandy clay | 3 |
| | Silty clay loam | 4 |
| | Clay loam | 5 |
| | Sandy clay loam | 6 |
| | Loam | 10 |
| | Silt loam | 13 |
| | Sandy loam | 15 |
| | Silt | 19 |
| | Loamy sand | 24 |
| | Sand | 27 |
| **Pedality**<br>Ped grade | Massive | 0 |
| | Weak | 1 |
| | Moderate | 5 |
| | Strong | 25 |
| | Single grain | 50 |
| Ped size | Very coarse | 1 |
| | Coarse / medium | 3 |
| | Fine / very fine | 18 |
| Ped shape | Massive | 0 |
| | Platy | 1 |
| | Prismatic | 10 |
| | Blocky | 10 |
| | Granular / single grain | 30 |
| **Macroporosity**<br>Quantity | Very few | 1 |
| | Few | 3 |
| | Common | 10 |
| | Many | 28 |
| | Very many | 60 |
| Size | Very fine | 1 |
| | Fine | 9 |
| | Medium | 49 |
| | Coarse | 60 |
| | Very coarse | 70 |
| | Extremely coarse | 75 |
| Type | Vugh | 1 |
| | Channel | 8 |
| | Fracture | 10 |
| | Packing void | 25 |
| **Root Density**<br>Quantity | Few / very few | 1 |
| | Common | 16 |
| | Many | 25 |
| Root size | Very coarse | 1 |
| | Coarse / medium | 13 |
| | Fine / very fine | 43 |
| **Water Content**<br>Quantity | Saturated | 1 |
| | Wet | 3 |
| | Moist | 7 |
| | Dry | 30 |
| | Very dry | 65 |

## 5.3. RESULTS AND DISCUSSION

The degree of soil morphological development, within the clay barrier section of the engineered covers observed, corresponds to design and surface condition evenness (Figure 5.2). A summary of morphological features and SMDI score calculations are presented in Appendix C. Williams et al., 2019 provides a full detail of the soil survey performed.

Figure 5.2 : Total soil morphological development index scores



The deep Planted Mineral Barriers (PMB's) at Falls City and Shirley Basin display the least overall soil morphological development, with scores dominated by sparse, very fine, plant roots. These sites also display the most uniform surface features across space and time (Figure 2.1) suggesting that even surface feature development corresponds to even soil morphological development (Figure 3.5 and Figure 3.6). At Falls City, profile development scores range from 0.006 to 0.021, while the development score of the natural analog was 0.284. The SMDI value at the Falls City analog is dominated by At Shirley Basin, profile development scores range from 0.006 to 0.012 while the development score of the natural analog was 0.091. The comparatively low SMDI score at the Shirley Basin natural analog indicates that the soil forming factors present in the landscape protect and maintain low levels of soil morphological development through time, suggesting that the cover at Shirley Basin will perform well over long time periods if existing soil forming factors are maintained.

The shallow Composite Capping Barrier (CCB) at Lakeview displayed considerable profile-to-profile variation in morphology, with on SMDI scores ranging from 0.004 to 0.202 compared to 0.235 at the natural analog, with bitterbrush profiles having the largest

SMDI scores on the cell. The unplanted, shallow Compressed Mineral Barrier (CMB) at Bluewater displayed the greatest variability in profile development with on cell scores ranging from 0.003 to 0.817 compared to natural analog scores of 0.323 and 1.000. The Bluewater site also had the greatest variability in surface feature development (see Chapter 2). Harvester ant mound, squirreltail grass, and fourwing saltbrush profiles all approached the SMDI values of adjacent natural analogs.

### 5.3.1. IMPACT OF MORPHOLOGY ON ENGINEERING PERFORMANCE

Clay barriers are engineered as monolithic structures to isolate wastes from liquid and gas transport, however pedogenic processes result in the emergence of soil morphology (Chapter 3 and Chapter 4) with potential alterations to as-built engineered performance. The SMDI is used to compare the degree of soil development against engineering performance metrics including radon diffusion coefficient (*D*) and saturated hydraulic conductivity (*Ksat*).

#### 5.3.1.1. *RADON DIFFUSION COEFFICIENTS*

Radium-226 (Ra-226) and radon (Rn-222) are daughter progeny of Uranium-238 (a component of mill tailings buried underneath UMTRCA waste covers). Rn-222 is a colorless, odorless, radioactive gas with a half-life of 3.8 days. With a low clay barrier diffusion coefficient, Rn-222 would decay several half-lives, significantly reducing in concentration as it travels to the surface.

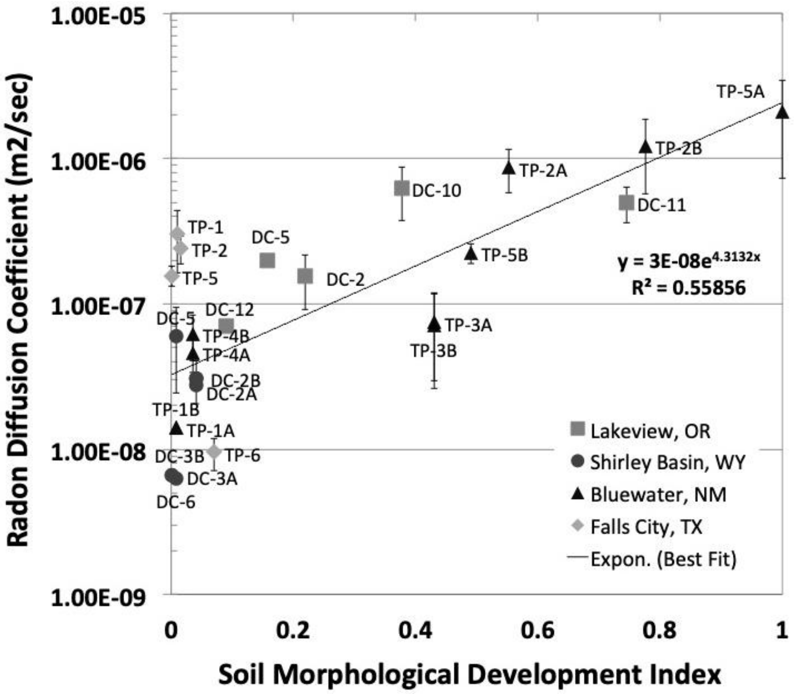
NRC accepted calculations of Rn-222 attenuation using the computer program RAECOM (Radiation Attenuation Effectiveness and Cover Optimization with Moisture Effects) as a basis for compliance (Nielson and Rogers, 1982; Rogers et al., 1984; NRC, 1989). The mathematical model implemented in RAECOM describes one-dimensional, steady-state radon diffusion through a two-phase multilayer system. The RAECOM program requires input data for the following properties of the tailings and cover layers: layer thickness, dry bulk density, porosity, moisture content, Ra-226 activity, and Rn-222 emanation coefficient. The development of soil morphology can directly impact barrier water content through altering infiltration, soil water holding capacity, and water balance through evapotranspiration by plants. Additionally, the development of soil morphology directly impacts the quality and quantity of barrier soil pore space with direct impacts to diffusion.

In coordination with soil observations, complimentary radon flux measurements were made with multiple flux chambers coupled to RAD-7 alpha-counters described by Likos et al., (2019). Radon diffusion coefficients were then determined based on measured fluxes at the top and bottom of the barrier (the 2-flux method) for comparison against modeled output from RAECOM, and for comparison against SMDI scores to explore how soil morphology impacts the *potential rate* of radon flux through observed clay barrier profiles.

### *SMDI OBSERVATIONS*

The impact of soil morphological development on radon diffusion is presented in Figure 5.3. Across all sites studied (23 paired top and bottom of the barrier measurements), a collective trend exists between increased radon diffusion and increased morphological development, with an exponential best fit model providing an $R^2$ of 0.558. Within individual sites, model trends are variable with the Falls City site (saturated barrier) resulting in an inverse relationship between diffusion and SMDI, and the Bluewater site (very dry barrier) having a strong positive relationship (Figure 5.4). Given gravimetric soil water content levels across the four sites (Likos et al., 2019), and the influence of soil moisture in regulating radon diffusion (NRC, 1989), the SMDI does not effectively weight the impact of soil moisture against radon diffusion in soils wetter than moist.

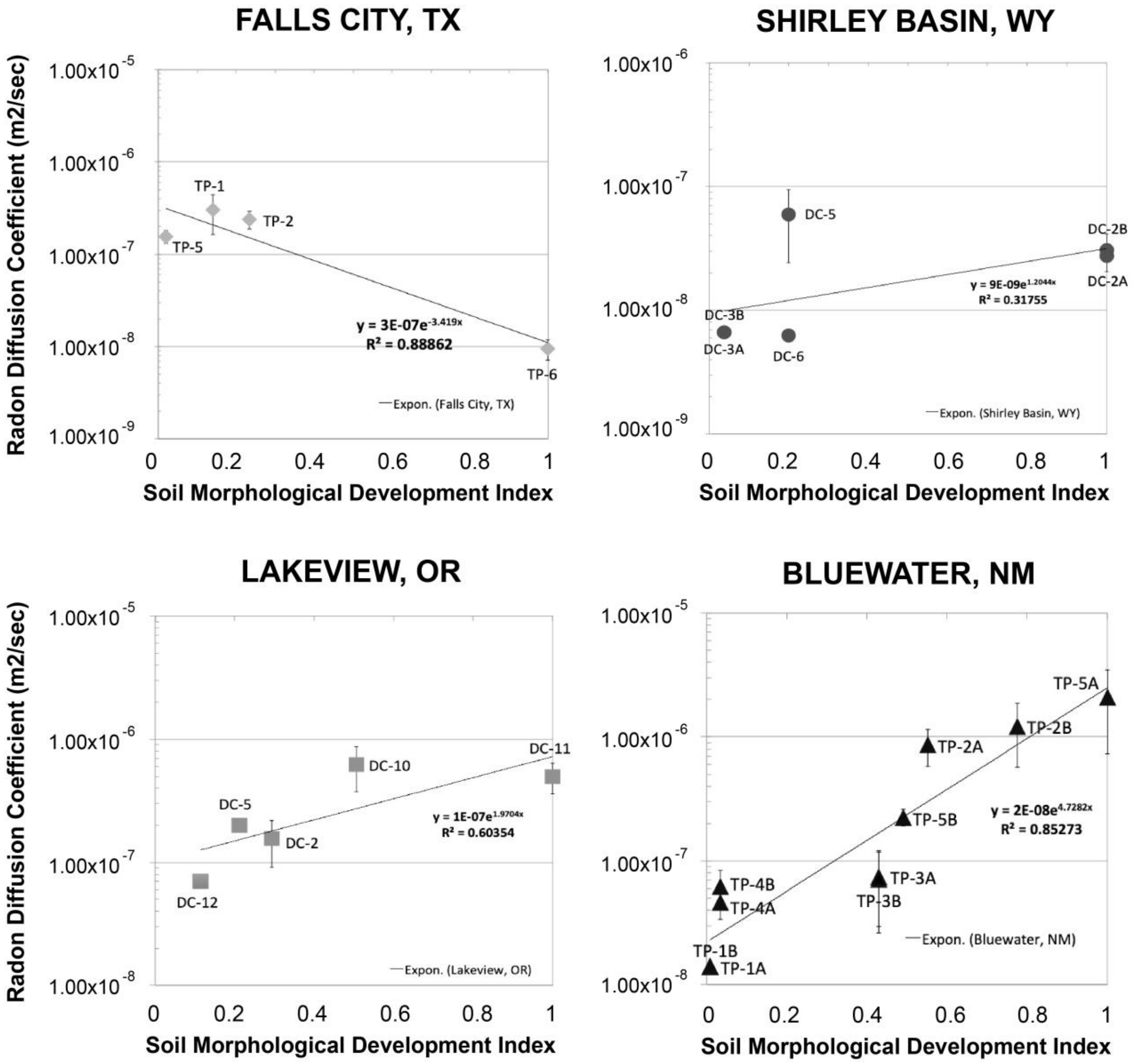
Figure 5.3: Impact of soil morphological development on radon diffusion coefficients, across all sites



At the Bluewater and Lakeview sites, the most developed profiles (resembling natural analog condition) display the largest radon diffusion coefficients. Diffusion coefficients do not appear to favor one dominant morphological trait over another with porosity, roots, and pedality all variably contributing to measured diffusion in Bluewater profiles TP-2 and TP-5. A, TP-5. B and Lakeview profiles DC-10 and DC-11 (Table 5.2).

At Falls City, SMDI scores do not adequately describe elevated radon diffusion coefficients. All the profiles at Falls City display very low SDMI scores, yet profiles TP-1, TP-2, and TP-5 have diffusion coefficients greater than 11 profiles with higher SMDI values, across sites. Profile TP-6 had a higher morphological development score than all other profiles at Falls City yet had the lowest diffusion coefficient. Gravimetric water content averaged 37.3% across the cover, with TP-6 having the highest water content at 42%. Plant rooting contributed to 96.5% of the SMDI score in TP-6, and when coupled with saturated soil conditions, the more space related to high SMDI score would be saturated with water, resulting in limited radon diffusion. In addition to the observation that the clay barrier at TP-6 was fully saturated during radon flux measurements, and given the inverse relationship between percent moisture saturation and gas diffusion, such findings suggest that there may also be variation in waste characteristics across the site that influence overall radon flux or that clay barrier materials disproportionately may serve as a background radon source.

Figure 5.4: Impact of soil morphological development on radon diffusion coefficients, within sites



#### 5.3.1.2. *SATURATED HYDRAULIC CONDUCTIVITY*

Early clay barrier designs in the UMTRCA program were not designed to limit meteoric water percolation. After EPA published draft groundwater quality standards, DOE refined the cover design process and placed greater emphasis on designing "low-permeability" clay barriers (DOE 1989). DOE informally adopted a standard specified in the Resource Conservation and Recovery Act of 1976 (RCRA) for designing low-permeability caps for disposal of hazardous waste in shallow-land burial facilities. RCRA guidance requires a compacted soil layer with a saturated hydraulic conductivity less than $10^{-9}$ meters per second (m/s) (EPA 1989). DOE design guidance indicated that low conductivity could be achieved with either highly compacted native soil or bentonite-amended soil (DOE 1989). The new guidance also provided a framework or checklist for selecting and designing cover components based on site-specific needs. This approach gave options for adding components to the original design including a thick "protection layer" intended to isolate the radon barrier from processes that could increase permeability such as freeze-thaw cracking and biointrusion (see Chapter 4).

Shortly after DOE adopted $10^{-9}$ m/s as a design target for the clay barrier, an increasing body of literature suggested that the saturated hydraulic conductivities of compacted soil layers achieved in the field were much greater than that predicted by laboratory tests. Processes that initiate these changes include freeze-thaw and desiccation cracking (Kim and Daniel 1992; Benson and Othman 1993; Albrecht and Benson 2001), retention of borrow soil structure during construction (NRC 2011; Albright et al. 2006), and biointrusion (Hakonson 1986; Suter et al. 1993; Bowerman and Redente 1998).

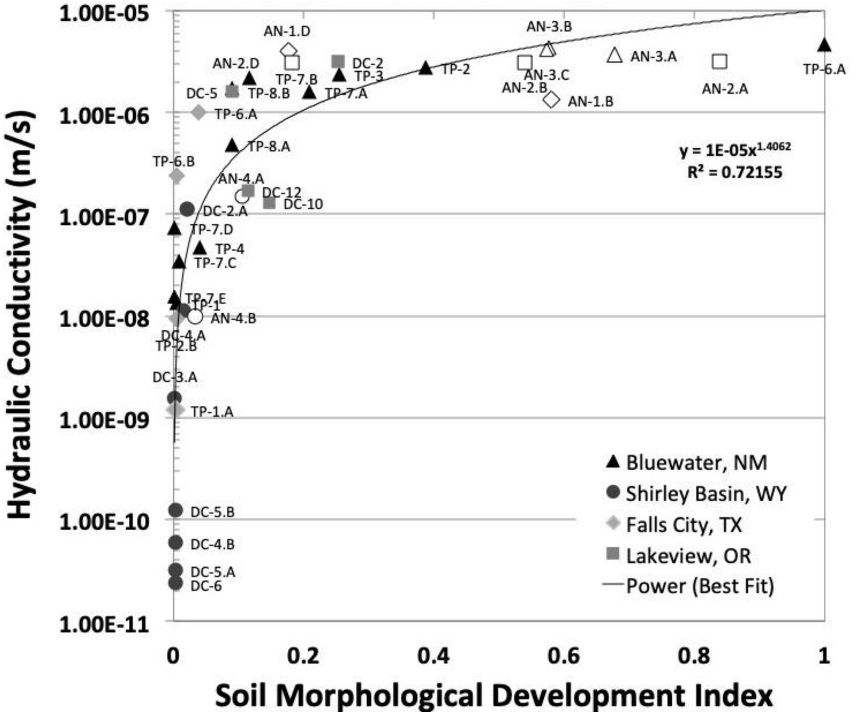
Researchers exhumed large soil block monoliths (400 mm diameter x 300 mm height) from clay barriers. Monoliths were then extracted, trimmed, and placed in large-scale flexible-wall permeameters for measurement of saturated hydraulic conductivity in accordance with the methods in ASTM D5084. Full reporting on block sampling, testing methodology, and interpretation of hydraulic properties of the clay barriers investigated in this study are reported in Benson, et al., (2019).

Soil morphological development index scores, constrained to the depth of the block sample, were used to compare against measured Ksat values to determine how the development of soil morphology impacts the *potential* movement of water through the compressed clay barrier.

##### *SMDI OBSERVATIONS*

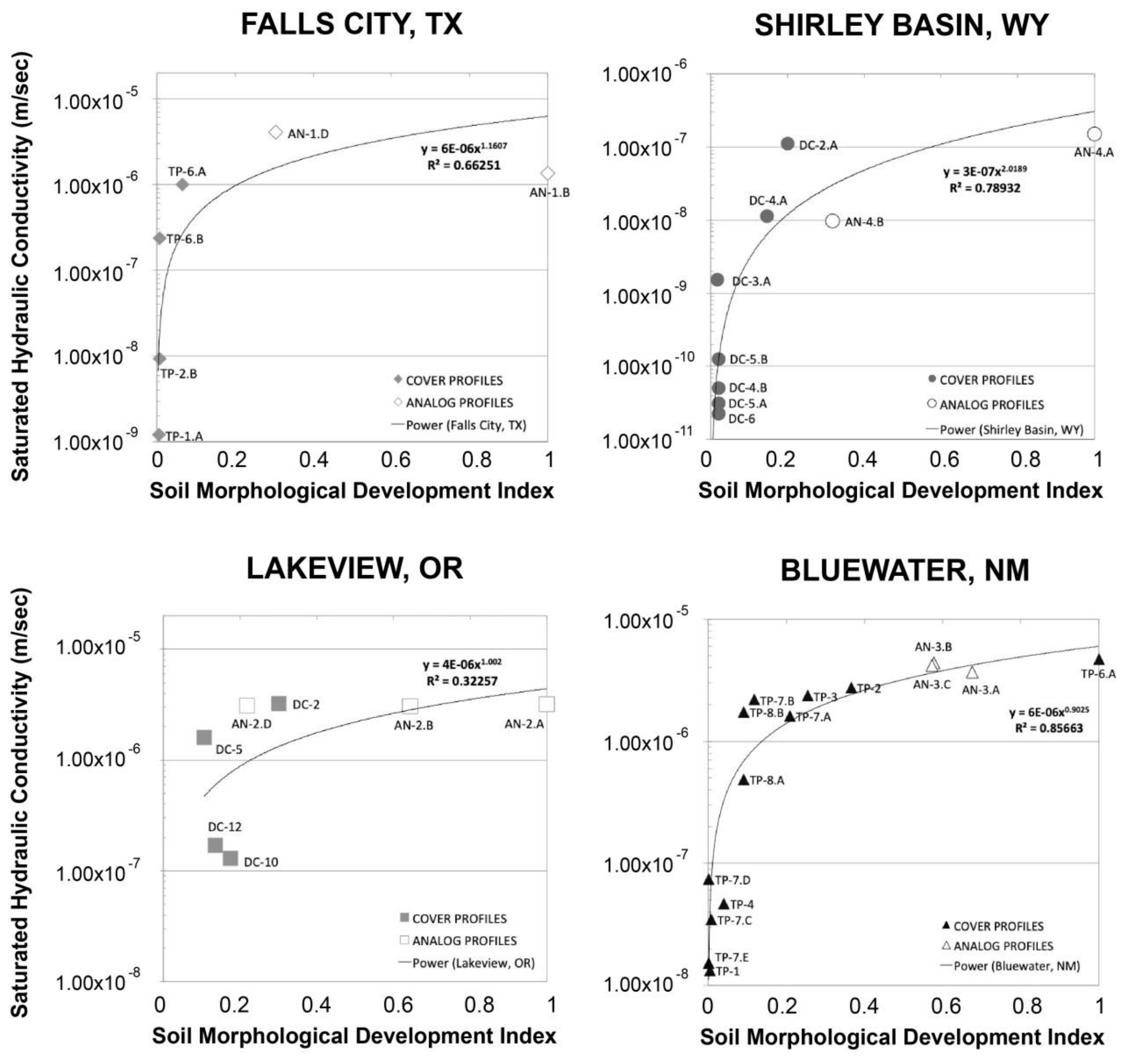
The impact of soil morphological development on Ksat is presented in Figure 5.5. Across all sites studied (39 large soil block monoliths exhumed), a collective trend exists between increased Ksat and increased SMDI, with a power law best fit model providing an $R^2$ of 0.721. Within individual sites, model trends are generally consistent, with the Bluewater site having a very strong positive relationship (Figure 5.6).

Figure 5.5: Impact of soil morphological development on saturated hydraulic conductivity, across all profiles and sites



Ksat values are highest for natural analog soils, with cover profiles deviating towards Ksat values in the $10^{-6}$ m/s range. At the Bluewater and Lakeview sites, the most developed profiles (resembling natural analog condition) display the highest Ksat values. On the Bluewater cell, the harvester ant mound and squirrel tail grass profiles have the highest SMDI and Ksat values. Within the carbonate cell saltbush profile (TP-7), depth plays a significant role on measured Ksat with a two-order of magnitude decrease in Ksat in blocks below 1250 mm compared to near surface blocks. On the Lakeview cell, the bitterbrush and rabbitbrush profiles have the highest Ksat values (many blocks for Lakeview are still being processed at the time of this publication). At both Falls City and Shirley Basin, depth contributes to observed variation in Ksat with values decreasing with depth. Across very low, shared, SMDI values at Shirley Basin, a three order of magnitude variation in Ksat is observed. The variation in Ksat, in-lieu of structuring is most likely attributed to as-built heterogeneity, and not due to emergent soil processes.

Figure 5.6: Impact of soil morphological development on saturated hydraulic conductivity, within sites



### 5.3.2. RELATIVE CONTRIBUTION OF INDIVIDUAL SOIL MORPHOLOGICAL FEATURES

The relative contribution of individual morphological features to total soil development are presented in Table 5.2. Soil morphological development within deep PMB's at Falls City and Shirley Basin are largely dominated by very fine root development. Pedality and porosity contributed very little across surface conditions at both sites, with exception to very small fractures observed at Shirley Basin, WY DC-3. This profile displayed the least morphological development at Shirley Basin, with the observed fractures disproportionately impacting total contribution to morphology given the lack of other emergent morphological features entirely. Rooting also dominated morphological development at the shallow CCB at Lakeview, however some profiles (i.e. DC-13) with lower total development did display a higher percentage contribution from pedality given a relative lack of other morphological features (i.e. roots).

Table 5.2: Relative contribution to morphological development score

| Site | Profile | % of Analog | Index Rank | Texture | Pedality | Porosity | Roots |
|---|---|---|---|---|---|---|---|
| Falls City, TX | TP-1 | 2% | 4 | 7.3% | 0.0% | 4.7% | 88.1% |
| | TP-2 | 4% | 3 | 4.4% | 0.0% | 2.1% | 93.6% |
| | TP-4 | 4% | 2 | 5.9% | 0.0% | 9.6% | 84.5% |
| | TP-5 | 0% | 5 | 100% | 0.0% | 0.0% | 0.0% |
| | TP-6 | 4% | 1 | 1.0% | 0.0% | 2.5% | 96.5% |
| | AN-1 | - | - | 0.05% | 38.5% | 5.4% | 56.1% |
| Bluewater, NM | TP-1 | 0% | 10 | 42.3% | 3.7% | 1.2% | 52.8% |
| | TP-2. A | 20% | 4 | 0.2% | 49.8% | 10.4% | 39.6% |
| | TP-2. B | 37% | 3 | 0.4% | 78.5% | 7.7% | 13.4% |
| | TP-3 | 17% | 6 | 0.7% | 85.8% | 0.06% | 13.4% |
| | TP-4 | 2% | 7 | 1.8% | 95.6% | 0.2% | 2.4% |
| | TP-5. A | 36% | 2 | 0.4% | 12.4% | 41.5% | 45.7% |
| | TP-5. B | 18% | 5 | 0.4% | 15.0% | 52.4% | 32.2% |
| | MP-2 | 119% | 1 | 0.1% | 40.2% | 52.2% | 7.5% |
| | TP-7 | 7% | 8 | 1.8% | 7.4% | 8.4% | 82.4% |
| | TP-8 | 6% | 9 | 5.6% | 81.0% | 4.2% | 9.2% |
| | AN-3 | - | - | 0.2% | 32.1% | 29.8% | 37.9% |
| | AN-6 | - | - | 0.02% | 38.6% | 44.6% | 16.8% |
| Lakeview, OR | DC-2. A | 101% | 1 | 0.5% | 5.3% | 1.2% | 93.0% |
| | DC-2. B | 26% | 4 | 2.3% | 19.9% | 3.3% | 74.5% |
| | DC-2.C | 22% | 5 | 2.7% | 3.5% | 3.9% | 89.9% |
| | DC-4. A | 0% | 11 | 100% | 0.0% | 0.0% | 0.0% |
| | DC-4. B | 2% | 9 | 17.6% | 0.0% | 0.0% | 82.4% |
| | DC-5 | 34% | 6 | 3.1% | 16.0% | 10.1% | 70.8% |
| | DC-10 | 24% | 3 | 1.4% | 5.2% | 0.5% | 92.9% |
| | DC-11 | 44% | 2 | 0.7% | 7.2% | 1.0% | 91.1% |
| | DC-12. A | 12% | 7 | 3.4% | 19.1% | 2.5% | 75.0% |
| | DC-12. B | 5% | 8 | 5.7% | 28.4% | 2.7% | 63.2% |
| | DC-13 | 2% | 10 | 19.5% | 66.5% | 14.0% | 0.0% |
| | AN-2 | - | - | 0.61% | 17.5% | 5.5% | 76.5% |
| Shirley Basin, WY | DC-2 | 21% | 1 | 1.3% | 0.0% | 0.0% | 98.7% |
| | DC-3 | 1% | 5 | 15.3% | 0.0% | 24.1% | 51.8% |
| | DC-4 | 25% | 2 | 1.1% | 0.0% | 0.0% | 98.9% |
| | DC-5 | 2% | 4 | 4.4% | 0.0% | 0.0% | 95.6% |
| | DC-6 | 6% | 3 | 4.4% | 0.0% | 0.0% | 95.6% |
| | AN-2 | - | - | 0.1% | 0.2% | 1.0% | 98.7% |

At the shallow, unplanted CMB at Bluewater, contributors to total profile morphological development varied considerably suggesting that a diversity of pedogenic processes are responsible for the formation of soil morphology at this site. Pedality was generally the dominant morphological feature, which is likely attributed to near surface thermal expansion and contraction in addition to newly emergent plant water induced desiccation and cracking (see Chapter 2). Subangular blocky structures dominated, with size and grade varying with depth and between surface conditions. The emergence of diverse morphological features, and the variable contributions to total soil morphological development within profiles, corresponds to the diversity of earth surface features present on the site (see Chapter 2). The total morphological development of MP-2 (harvester ant mound) and TP-5. A (fourwing saltbush) were similar at Bluewater, however morphological contributors to development were varied, with MP-2 dominated by porosity and pedality, and TP-5. A dominated by porosity and roots.

### 5.3.3. COMPARISON TO NATURAL ANALOGS

The SMDI values of natural analogs and cover profiles may be used to predict development trends over time or under varying soil forming factors including management or climate. Given that clay barriers are largely installed devoid of soil structure, differences in observed soil morphology between analog soils and cover profiles are expected to decrease over time as covers are subjected to shared background climate. The expression of soil morphology will also be dependent on other soil forming factors including engineering design, biota and management thereof, slope, and time.

The deep PMB's at Falls City and Shirley Basin display less deviation towards the soil morphology found in natural analogs when compared to the shallow CCB at Lakeview, and the shallow, unplanted CMB at Bluewater, over roughly the same time period since construction. In a single profile at both Lakeview (DC-2: bitterbrush) and Bluewater (MP-2: harvester ant mound), morphological development scores exceeded those observed at shared depths in natural analog soils, with 101% and 119% of total analog development, respectively. This indicates that these sites have not resisted change since construction, and that soil processes have, at some locations on the surface, transformed the clay barrier into a soil system that more closely resembles the natural environment.

Vegetation establishment exerts a considerable impact to the degree of soil morphological development at Bluewater. Unvegetated profiles (TP-1, TP-4, TP-8) display the lowest morphological development, and the prolonged saturated conditions of the ephemeral lake at TP-1 have resulted in the least overall morphological development across the site. The establishment of saltbush and perennial grasses dominated by *Elymus elymoides*, result in the formation of soil structure that more closely resembles that of the natural analog. As vegetation continues to become established across the Bluewater cell, soil morphology will shift considerably with ongoing impacts to cell performance. Patterns of soil morphological development are similar at Lakeview, and we would expect that continued shrub encroachment will result in a patchwork of soil morphological conditions as a function of shrub density and the vegetation composition of inter-shrub spaces.

Profile development at Falls City, approached 4% of that observed in a natural analog, while Shirley Basin, approached 24% of that observed in a natural analog. This indicates that these sites have been more resilient to change, and that the engineered clay barriers have largely remained intact at these sites since construction. Falls City is the most heavily managed site investigated, with annual mowing required on the top of the cell, and aggressive hand cutting and spraying of deep-rooted vegetation on the rock side slopes. Given that natural analog soil morphology is most influenced by plant roots at the Falls City, site, and that deep-rooted shrubs dominate the surrounding environment, surface management efforts are likely needed to maintain the as-designed soil morphology within the compressed clay barrier. The need for cutting and spraying has also increased over time since construction suggesting that even more effort may be needed to maintain as built condition as the cell continues to age (see Chapter 2). The profile with the largest overall profile development score (DC-6) is located on a rock armored side slope and is a location where emergent vegetation has become established. Given favorable plant establishment in interstitial rock armor spaces as a function of the design and high moisture from on-cell drainage, the rock armored side slopes at Falls City, are likely the most prone to ongoing soil morphological development under the current surface management strategy.

At Shirley Basin, a site with very similar design to Falls City, climate does not favor the growth of deep-rooted shrubs and surface management efforts largely consist of cattle grazing. The soil morphological development scores of the Shirley Basin, natural analog is the lowest of all-natural analogs studied across the four sites also suggesting that soil forming factors in the area favor the development of less soil morphology as compared to other sites observed.

## 5.4. SECTION SUMMARY

Soil morphological development indices are used to compare the degree of development between profiles on engineered covers for waste containment. A soil survey was performed across four UMTRCA cover systems to document soil morphology and construct soil morphological development index rankings. Cover systems that were deep and planted had the lowest morphological development scores, while covers that were shallow and unplanted had the highest morphological scores. The degree of soil morphological development also coincides with the observation of surface features that are the result of Earth surface processes. Sites with greater change in surface composition also display a higher degree of soil morphological development that more closely resembles natural analog soils than as built condition.

The soil morphological development index can be used to explore connections between soil morphology of engineered covers and performance metrics including hydraulic conductivity and radon diffusion. As soil morphological development scores increase, both radon diffusion coefficients and saturated hydraulic conductivity increase with a high degree of correlation, however limitations exist when using the SMDI to predict radon diffusion in saturated soils.

## 6. CONCLUSION

Changes to surface condition on engineered disposal cells are systematic as a function of cover design, climate, and management influence patterns of surface evolution. Annual inspection reports from the DOE-LM archive may be used to track the incidence of surface features and inform long-term surface evolution trends on UMTRCA waste disposal cells with shared factors. The deep and vegetated sites at Falls City and Shirley Basin behaved most evenly over space and time with the fewest increases or decreases to observed surface condition. The cold and semi-arid site at Shirley Basin displayed more surface feature evenness over time as compared to the hot and humid site at Falls City. Such variation was largely attributed to deep rooted shrub development at the hot and humid Falls City site that requires recurring annual management that has increased over time. The shallow sites with nominal active vegetation management at Bluewater and Lakeview are characterized by the cumulative, and patchy, emergence of both biological and geophysical surface features through time.

Earth surface processes are occurring unevenly across the four waste disposal cells surveyed with impacts to soil morphology. The deep PMB’s at Falls City, Texas and Shirley Basin, Wyoming displayed considerably less soil structuring and rooting than the shallow CMB at Bluewater, New Mexico and planted rock CMB at Lakeview, Oregon. Profiles associated with down slope collection basins displayed the least morphological development across all cover types and climates. Biosequences at Bluewater and Lakeview show that soil morphological development, under fixed on-site factors, corresponds to emergent vegetation state with grasses and shrubs corresponding to greater morphological development at Bluewater and Lakeview, respectively. Climate plays a role in regulating vegetation establishment on disposal cells of shared design at Falls City and Shirley Basin. The warmer and wetter site at Falls City corresponds to a greater incidence of shrub establishment, requiring added management

A conceptual framework of soil formation in engineered covers for waste containment has been used to describe soil condition in four in-service waste disposal cells of the UMTRCA portfolio. We find that a combination of factors including cover design, management, climate, vegetation, slope and depth to ground surface correspond to observed clay barrier morphology.

The development of soil morphology occurs in combination with numerous pedogenic processes over time and their study offers a way to classify barrier systems, understand how disposal cells function at present, and how they may evolve through time. A conceptual framework shows that soil change can be grouped into three sequential phases that highlight the dominant processes resulting in the expression of soil morphology, at that time step, over UMTRCA performance timeframes. First Order processes are dominated by physical process, Second Order processes are dominated by biotic process, and Third Order processes are dominated by recurring and cumulative effects of First and Second Order process.

Design, management, and vegetation contribute to buffering soil change *within* clay barriers and in maintaining as-built morphology through time. Deep, Planted Mineral Barriers (PMB's), including the Falls City, TX site, are observed to dissipate environmental fluxes *above* the clay barrier. Such systems result in the resilient physical isolation of wastes through time. Conversely, shallow, rock armored, Compressed Mineral Barriers (CMB's), including the Bluewater, NM site, were not designed with an adequate system to dissipate fluxes, therefore all soil processes must occur *within* the compressed clay barrier as a form of consumption, thereby resulting in morphological development through time. While a similar collection of soil processes is occurring at both sites, the cumulative impacts of those processes are stable and even in the PMB at Falls City and variable and uneven in the CMB at Bluewater showing the role that design, management, and vegetation have in buffering soil change and maintaining as-built barrier morphology.

Soil morphological development indices can be used to compare the degree of development between profiles on engineered covers for waste containment. A development index was used to explore connections between soil morphology within waste covers and performance metrics including hydraulic conductivity and radon diffusion. As soil morphological development scores increase, both radon diffusion coefficients and saturated hydraulic conductivity increase with a high degree of correlation.

Natural analog conditions are used to estimate long-term soil morphology and engineering performance. The SMDI values from natural analog soils, adjacent to disposal cells, were compared against values from clay barriers to determine the degree of morphological similarity. We find that natural analog conditions generally contain higher SMDI values, relative to adjacent waste covers. Clay barriers are also converging to analog SMDI values that correspond to bioturbation gradients of increasing intensity. Several profiles on the Bluewater, NM (harvester ant mound, fourwing saltbush, and squirreltail grass) and Lakeview, OR (bitterbrush) disposal cells have SMDI values that closely resemble natural analog conditions. Conversely, soil profiles at Falls City, TX and Shirley Basin, WY are characterized by the nominal development of soil morphology and have been more resilient to change through time. Given the trend towards natural analog conditions of higher SMDI value and the strong connection between SMDI, radon diffusion coefficients, and hydraulic conductivity, we expect UMTRCA covers to continue to evolve towards natural analog conditions over long enough time periods. These trends suggest that natural analogs can serve as excellent predictors of long-term performance.

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# 8. APPENDIX A: EARTH SURFACE PROCESS SURVEY

This appendix provides summarized, and pictoral evidence of Earth surface process observed during annual inspection reports at Falls City, TX; Bluewater, NM; Lakeview OR; and Shirley Basin, WY UMTRCA sites.

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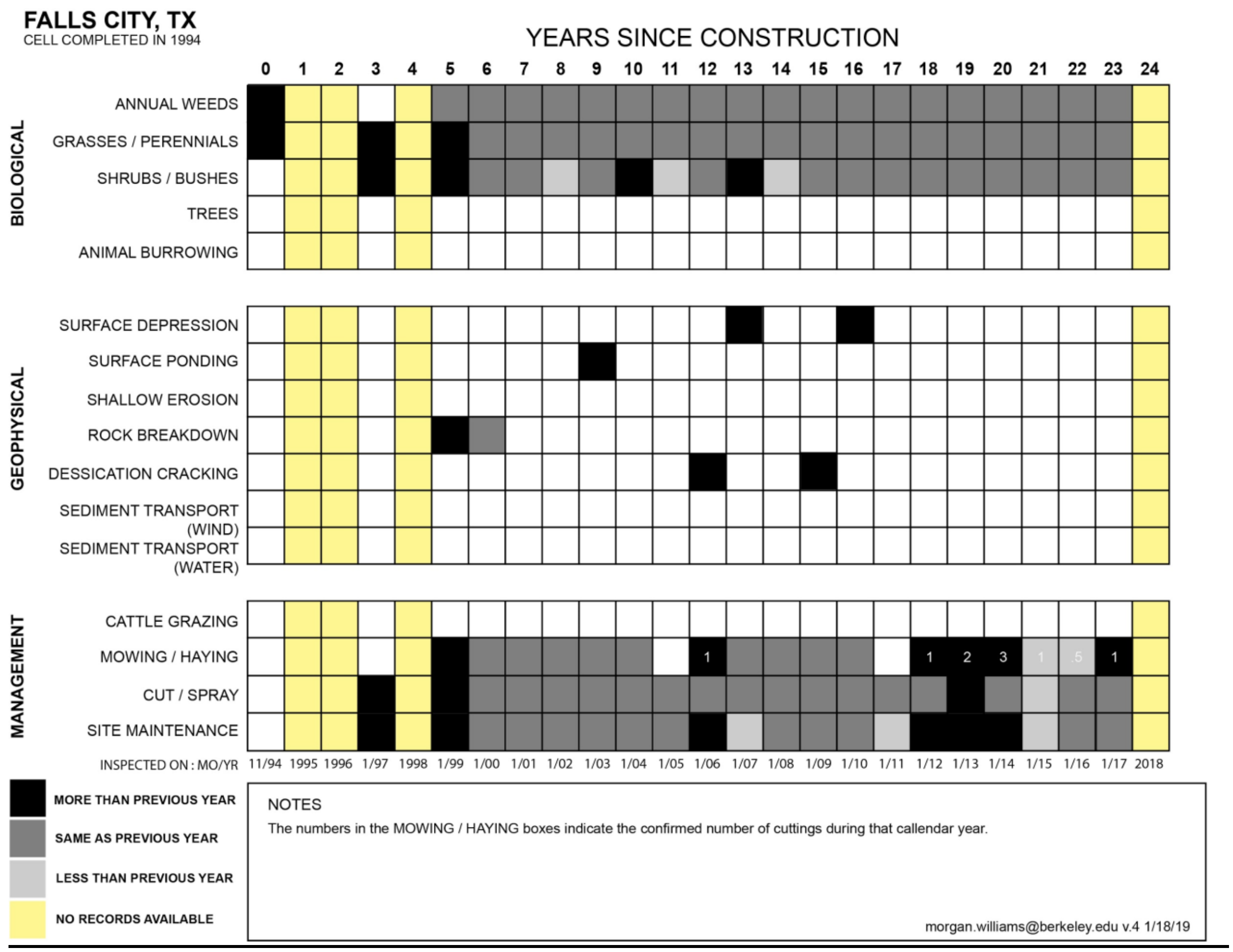
Figure A.1. Falls City, TX : Surface Process History



**FALLS CITY, TX**
CELL COMPLETED IN 1994

YEARS SINCE CONSTRUCTION

| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
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| GEOPHYSICAL | SURFACE DEPRESSION | | 🟨 | 🟨 | | 🟨 | | | | | | | | | ■ | | | ■ | | | | | | | | 🟨 |
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| | SHALLOW EROSION | | 🟨 | 🟨 | | 🟨 | | | | | | | | | | | | | | | | | | | | 🟨 |
| | ROCK BREAKDOWN | | 🟨 | 🟨 | | 🟨 | ■ | ▦ | | | | | | | | | | | | | | | | | | 🟨 |
| | DESSICATION CRACKING | | 🟨 | 🟨 | | 🟨 | | | | | | | | ■ | | | ■ | | | | | | | | | 🟨 |
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| MANAGEMENT | CATTLE GRAZING | | 🟨 | 🟨 | | 🟨 | | | | | | | | | | | | | | | | | | | | 🟨 |
| | MOWING / HAYING | | 🟨 | 🟨 | | 🟨 | ■ | ▦ | ▦ | ▦ | ▦ | ▦ | | ■ 1 | ▦ | ▦ | ▦ | ▦ | | ■ 1 | ■ 2 | ■ 3 | ░ 1 | ░ .5 | ■ 1 | 🟨 |
| | CUT / SPRAY | | 🟨 | 🟨 | ■ | 🟨 | ■ | ▦ | ▦ | ▦ | ▦ | ▦ | ▦ | ▦ | ▦ | ▦ | ▦ | ▦ | ▦ | ▦ | ■ | ▦ | ░ | ▦ | ▦ | 🟨 |
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| | INSPECTED ON : MO/YR | 11/94 | 1995 | 1996 | 1/97 | 1998 | 1/99 | 1/00 | 1/01 | 1/02 | 1/03 | 1/04 | 1/05 | 1/06 | 1/07 | 1/08 | 1/09 | 1/10 | 1/11 | 1/12 | 1/13 | 1/14 | 1/15 | 1/16 | 1/17 | 2018 |

■ MORE THAN PREVIOUS YEAR
▦ SAME AS PREVIOUS YEAR
░ LESS THAN PREVIOUS YEAR
🟨 NO RECORDS AVAILABLE

NOTES
The numbers in the MOWING / HAYING boxes indicate the confirmed number of cuttings during that callendar year.

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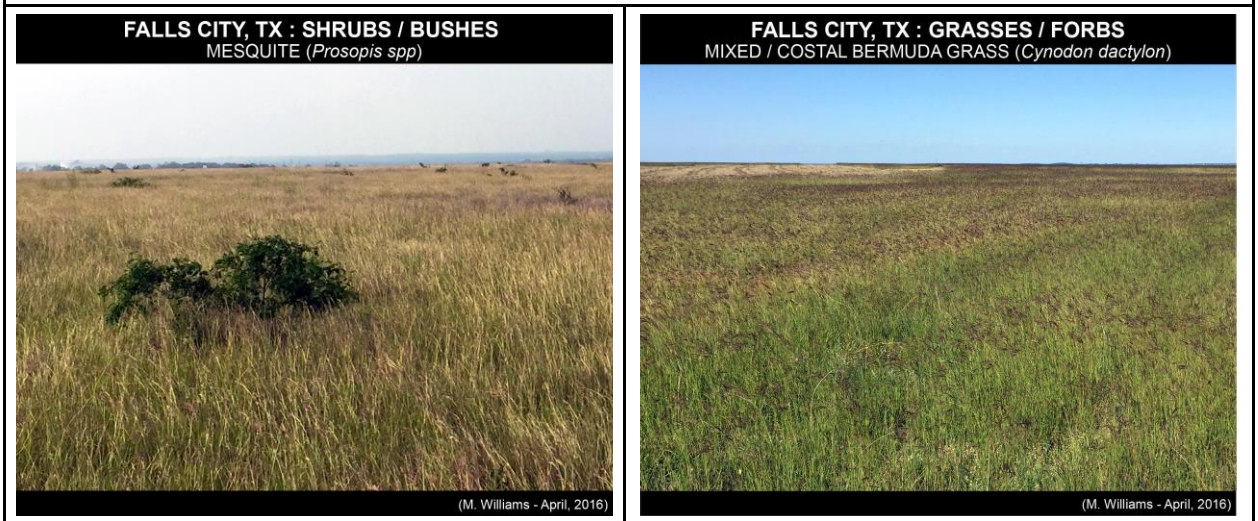
Table A.1. Timeline of Key Events at The Falls City, TX Disposal Cell

| Year | Category | Observation |
|---|---|---|
| 1994 | | Cell construction completed. Grasses seeded in the spring. |
| 1994 | Biological | Top cell grass vegetation is variable and patchy in spots. Dominated by bermuda grass. |
| 1997 | Biological | Top cell grass vegetation evenly established. No extensive bare spots observed. |
| 1997 | Biological | A total of 5 deep rooted plants (greasewood and other sp.) occurring on NE and SE slopes. Cut. |
| 1999 | Geophysical | Minor rock armor breakdown observed. Monitoring program established. |
| 1999 | Biological | Even stand of (primarily) bunchgrass on top cell. Several other grass species also present (coastal bermuda, kleingrass and others). |
| 1999 | Biological | Deep rooted plants observed on rock slopes now include greasewood, upland willow, palo verde, others. All cut and sprayed. |
| 1999 | Management | Local rancher retainer to cut hay and manage occasional weeds. Cut and spray of deep rooted plants found on cell. |
| 2000 | Biological | Woody shrubs (mesquite and likely others) identified on top-deck. Mowed with grasses for management. |
| 2002 | Management | Deep rooted plants on cell rock armor slopes almost eliminated due to extensive cut and spray management. |
| 2003 | Geophysical | 2 inches of standing water observed ponded on northwest edge of top-deck rock armor boundary. Cell actively shedding water. |
| 2004 | Biological | Deep rooted plants on cell rock armor slopes return. Some trees are 7 ft high. Cut and sprayed. |
| 2006 | Geophysical | Abundant surface soil cracking observed due to ongoing drought in region. |
| 2007 | Geophysical | Slight rock slump observed on SW corner of rock slope. |
| 2008 | Applied Science | T-post study installed to monitor any movement occuring on SW corner of sockslope. |
| 2009 | Geophysical | Abundant surface soil cracking observed due to ongoing drought in region. |
| 2010 | Geophysical | Small depressions in rock armor observed on NW slope after significant rainfall event (4.95 in / 3 days). |
| 2010 | Biological | Deep rooted plants on cell rock armor slopes recurring, annual issue. Require active cutting and spraying. |
| 2012 | Climate | Drought in region continues. |
| 2015 | Management | DOE to determine if controlled grazing will be beneficial for vegetation management and turf vitality. |
| 2016 | Applied Science | DOE-LM / NRC Soil Morphology study conducted in May. |

Figure A.2. Falls City, TX : Surface Features Characteristic of Biological Processes



**FALLS CITY, TX : SHRUBS / BUSHES**
MESQUITE (*Prosopis spp*)

(M. Williams - April, 2016)

**FALLS CITY, TX : GRASSES / FORBS**
MIXED / COSTAL BERMUDA GRASS (*Cynodon dactylon*)

(M. Williams - April, 2016)

**FALLS CITY, TX : ANIMAL BURROWING**
ANTMOUND (UNKNOWN SPECIES)

(M. Williams - April, 2016)

**FALLS CITY, TX : MIXED VEGETATION**
ANNUAL WEEDS AND PALO VERDE (*Parkinsonia florida*)

(DOE-LM - January, 2004)

Figure A.3. Falls City, TX : Surface Features Characteristic of Geophysical Processes

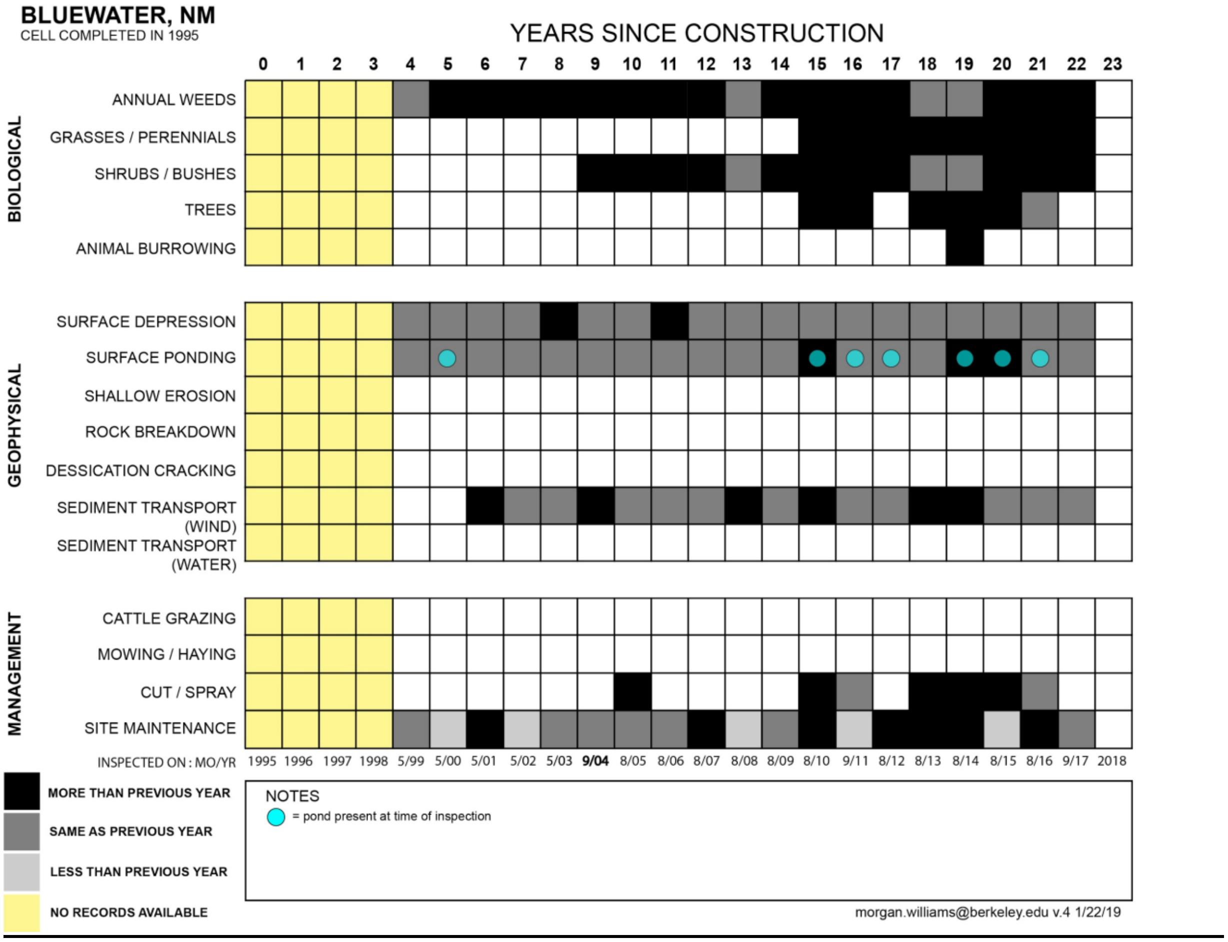
FALLS CITY, TX : ROCK ARMOR BREAKDOWN
FRACTURES DEVELOPING ALONG PLANES OF WEKNESS
(DOE-LM - January, 2001)

FALLS CITY, TX : ROCK ARMOR SETTLEMENT
DEPRESSION OBSERVED AFTER RAINFALL EVENT
(DOE-LM - January, 2010)

FALLS CITY, TX : DESSICATION CRACKING
VEGETATION DENSITY LOW IN THIS AREA
(M. Williams - April, 2016)

FALLS CITY, TX : MINOR EROSION
IN AREAS OF POOR INITIAL RE-VEGETATION
(DOE-LM - November, 1994)

Figure A.4. Bluewater, NM : Surface Process History



**BLUEWATER, NM**
CELL COMPLETED IN 1995

YEARS SINCE CONSTRUCTION

| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
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| | ANIMAL BURROWING | 🟨 | 🟨 | 🟨 | 🟨 | | | | | | | | | | | | | | | | ■ | | | | |
| **GEOPHYSICAL** | SURFACE DEPRESSION | 🟨 | 🟨 | 🟨 | 🟨 | ▩ | ▩ | ▩ | ▩ | ■ | ▩ | ▩ | ■ | ▩ | ▩ | ▩ | ▩ | ▩ | ▩ | ▩ | ▩ | ▩ | ▩ | ▩ | |
| | SURFACE PONDING | 🟨 | 🟨 | 🟨 | 🟨 | ▩ | ▩ ● | ▩ | ▩ | ▩ | ▩ | ▩ | ▩ | ▩ | ▩ | ▩ | ■ ● | ▩ ● | ▩ ● | ▩ | ■ ● | ■ ● | ▩ ● | ▩ | |
| | SHALLOW EROSION | 🟨 | 🟨 | 🟨 | 🟨 | | | | | | | | | | | | | | | | | | | | |
| | ROCK BREAKDOWN | 🟨 | 🟨 | 🟨 | 🟨 | | | | | | | | | | | | | | | | | | | | |
| | DESSICATION CRACKING | 🟨 | 🟨 | 🟨 | 🟨 | | | | | | | | | | | | | | | | | | | | |
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| | SEDIMENT TRANSPORT (WATER) | 🟨 | 🟨 | 🟨 | 🟨 | | | | | | | | | | | | | | | | | | | | |
| **MANAGEMENT** | CATTLE GRAZING | 🟨 | 🟨 | 🟨 | 🟨 | | | | | | | | | | | | | | | | | | | | |
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| | INSPECTED ON : MO/YR | 1995 | 1996 | 1997 | 1998 | 5/99 | 5/00 | 5/01 | 5/02 | 5/03 | **9/04** | 8/05 | 8/06 | 8/07 | 8/08 | 8/09 | 8/10 | 9/11 | 8/12 | 8/13 | 8/14 | 8/15 | 8/16 | 9/17 | 2018 |

■ **MORE THAN PREVIOUS YEAR**
▩ **SAME AS PREVIOUS YEAR**
░ **LESS THAN PREVIOUS YEAR**
🟨 **NO RECORDS AVAILABLE**

NOTES
● = pond present at time of inspection

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Table A.2. Timeline of Key Events at The Bluewater, NM Disposal Cell

| Year | Category | Observation |
|---|---|---|
| 1995 | | Disposal cell completed |
| 1997 | | Site transferred to DOE-LM |
| 1999 | Geophysical | Evidence of 4-5 acre pond is present given evaporite ring in depression on lower cell (on top of slime tailings). |
| 1999 | Biological | Few widely scattered, dead, russian thistle observed on cell. |
| 2000 | Geophysical | At time of inspection, a 1 acre pond is present that is 8in deep at maximum. |
| 2001 | Management | Fence intentionally cut by adjacent landowner to let livestock in to graze. |
| 2001 | Geophysical | Evaporative deposits observed in lower cell collection depression, determined to be carbonate materials (calcite and dolomite). |
| 2001 | Geophysical | 1000 ft wide zone of dust accumulation on eastern slope of main cell observed. Red dust located 3-4 inches beneath rock surface. No vegetation present. |
| 2002 | | Cows present on site (not part of management strategy). |
| 2003 | Management | Fence locks cut and left open to allow cattle to graze on site. |
| 2003 | Management | Local sub-contractor hired to periodically survey site to remove livestock, survey for trespassing and repair fences. |
| 2003 | Geophysical | Secondary depression on lower cell appears. |
| 2004 | Biological | Few rabbitbrush and fourwing saltbush appear on cell for first time (upland cell / sandy material). |
| 2004 | Biological | Weeds (russian thistle) begin establishing in wind blown fines on east slope. |
| 2005 | Biological | Tamarisk found close to main cell (cut/sprayed). |
| 2006 | | High rainfall year |
| 2006 | Geophysical | Secondary depression on lower cell visually increases year-over-year. |
| 2006 | Management | Fence intentionally cut by adjacent landowner to let livestock in to graze. |
| 2007 | Management | Fence intentionally cut by adjacent landowner to let livestock in to graze. |
| 2008 | Management | Fence intentionally cut by adjacent landowner to let livestock in to graze. |
| 2009 | Management | Fence intentionally cut by adjacent landowner to let livestock in to graze. |
| 2009 | Biological | Saltbush and Rabbitbrush remain largely confined to upper (sandy) portion of main disposal cell. |
| 2009 | Management | Significant trespass event. Equipment stolen from on-site power sub-station. |
| 2010 | Management | Tumbleweed collecting along eastern fence line allows windblown sand to accumulate. Accumulation is significant enough to form a passable land bridge, over which livestock have crossed and accessed the site. |

| | | |
|---|---|---|
| 2010 | Biological | Shrubs (sp. TBD) begin establishing in wind blown fines on east slope. |
| 2010 | Biological | Siberian elm first seen establishing on main cell (cut/sprayed). |
| 2010 | Biological | Siberian elm found in wind blown fines on east slope (cut/sprayed). |
| 2011 | Biological | Grasses found establishing in wind blown fines on east slope. |
| 2011 | Biological | First widespread establishment of grass observed on main cell. |
| 2012 | Applied Science | LiDAR flown |
| 2012 | Applied Science | NRC Radon measurements taken on ponded area (AC Canisters). All measurements at background levels. |
| 2013 | | Dry year (plant stress visible) |
| 2013 | Biological | Siberian elm become more commonly observed on main cell (all cut/sprayed) |
| 2014 | | Dry year (plant stress visible) |
| 2014 | Applied Science | Baseline vegetation survey conducted across entire property. |
| 2015 | | Wet year |
| 2015 | Geophysical | On 9/15 surface pond was 10.1 ac in area holding 2.2 million gallons of water. |
| 2015 | Biological | Tamarisk first seen establishing on main cell (cut/sprayed). |
| 2015 | Management | Siphon installed to remove ponded water from lower cell. |
| 2016 | Geophysical | 2.1 million gallons present in ponded area (8/16). |
| 2016 | Applied Science | LiDAR Flown |
| 2016 | Geophysical | 1997 (construction topography) compared to 2016 LiDAR indicate 4ft of settlement in lower cell slimes area. Rate of settlement decreases between 2012 and 2016 LiDAR events. |
| 2016 | Geophysical | Largest surface pond to date calculated at 4.3 million gallons of water. |
| 2016 | Applied Science | NRC/DOE-LM Soil Morphology study conducted in June. |
| 2016 | Biological | Saltbush and Rabbitbrush remain largely confined to upper (sandy) portion of main disposal cell, though few scattered shrubs do occur on lower portions of cell at this time. |
| 2017 | Management | 854,000 gallons of water removed from cell in two siphon events (3/29) and (10/4). |

Figure A.5. Bluewater, NM : Surface Features Characteristic of Biological Processes

**BLUEWATER, NM : ANNUAL WEEDS**
RUSSIAN THISTLE (*Salsola spp*)

(DOE-LM - August, 2006)

**BLUEWATER, NM : PERENNIAL GRASSES**
SQUIRRELTAIL GRASS (*Elymus elymoides*)

(M. Williams - October, 2015)

**BLUEWATER, NM : SHRUBS / BUSHES**
FOURWING SALTBUSH (*Atriplex canescens*)

(M. Williams - June, 2016)

**BLUEWATER, NM : TREE ESTABLISHMENT**
SIBERIAN ELM (*Ulmus pumila*)

(M. Williams - June, 2016)

**BLUEWATER, NM : ANIMAL BURROWING**
HARVESTER ANTS (*Pogonomyrmex spp*)

(M. Williams - June, 2016)

**BLUEWATER, NM : ANIMAL BURROWING**
POSSIBLE BADGER EXCAVATION

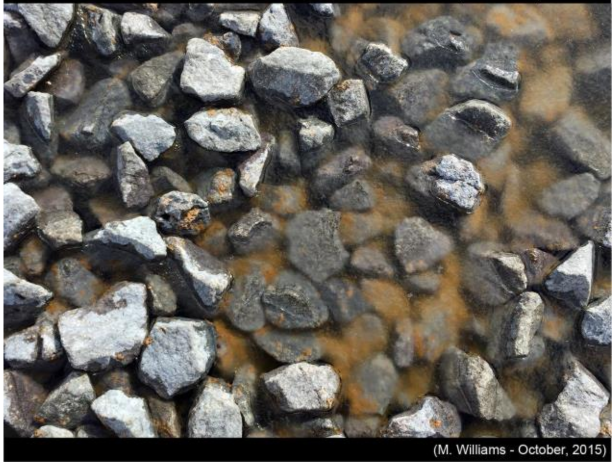
(DOE-LM - August, 2014)

**BLUEWATER, NM : RODENT BURROW**
LIKELY A ROCK SQUIRREL (*Spermophilus variegantes*)

(M. Williams - April, 2015)

**BLUEWATER, NM : VEGETATION PATTERNING**
PLANTS ESTABLISHING IN AEOLIAN DEPOSITED DUSTS

(M. Williams - June, 2016)



**BLUEWATER, NM : BIOMASS ACCUMULATION**
ALGAL GROWTH IN EPHEMERAL LAKEBED (under ice)

(M. Williams - October, 2015)

Figure A.6. Bluewater, NM : Surface Features Characteristic of Geophysical Processes


**BLUEWATER, NM : EVAPORITE PRECIPITATION**
CARBONATE ON ROCK ARMOR IN EPHEMERAL LAKE BED
(M. Williams - June, 2016)


**BLUEWATER, NM : SURFACE DEPRESSION**
SETTLEMENT INTO SUBSURFACE VOIDS FROM INSTALLATION
(DOE-LM - August, 2014)

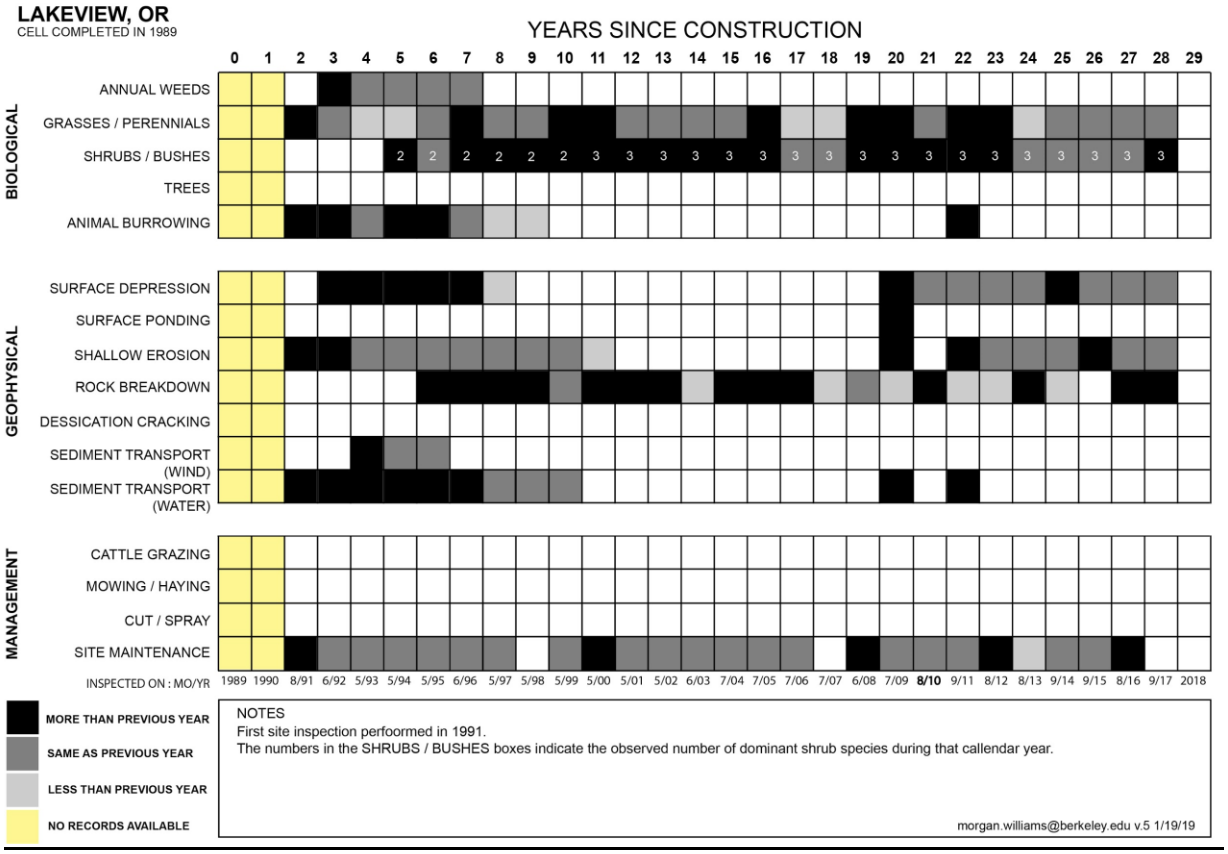

**BLUEWATER, NM : EMPEMERAL LAKE**
ESTIMATED 10.3 ACRES OF STANDING WATER ON LOWER CELL
(DOE-LM - August, 2015)


**BLUEWATER, NM : AEOLIAN DUST DEPOSITION**
DUST COLLECTION ON LEEWARD SLOPE OF CELL
(M. Williams - June, 2016)


**BLUEWATER, NM : SEDIMENT COLLECTION**
FINE SEDIMENT TRANSPORTED INTO EPHEMERAL LAKEBEDS
(M. Williams - April, 2015)

DUST DEPOSITION UNDER SALTBUSH

Figure A.7. Lakeview, OR : Surface Process History



**LAKEVIEW, OR**
CELL COMPLETED IN 1989

YEARS SINCE CONSTRUCTION

| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 |
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| | GRASSES / PERENNIALS | 🟨 | 🟨 | ■ | ▨ | ░ | ░ | ▨ | ■ | ▨ | ▨ | ■ | ■ | ▨ | ▨ | ▨ | ▨ | ■ | ░ | ░ | ■ | ■ | ▨ | ■ | ■ | ░ | ▨ | ▨ | ▨ | ▨ | |
| | SHRUBS / BUSHES | 🟨 | 🟨 | | | | ■ 2 | ▨ 2 | ■ 2 | ■ 2 | ■ 2 | ■ 2 | ■ 3 | ■ 3 | ■ 3 | ■ 3 | ■ 3 | ■ 3 | ▨ 3 | ▨ 3 | ■ 3 | ■ 3 | ■ 3 | ■ 3 | ■ 3 | ▨ 3 | ▨ 3 | ▨ 3 | ▨ 3 | ■ 3 | |
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| | ANIMAL BURROWING | 🟨 | 🟨 | ■ | ■ | ▨ | ■ | ■ | ▨ | ░ | ░ | | | | | | | | | | | | | ■ | | | | | | | |
| GEOPHYSICAL | SURFACE DEPRESSION | 🟨 | 🟨 | | ■ | ■ | ■ | ■ | ■ | ░ | | | | | | | | | | | | ■ | ▨ | ▨ | ▨ | ▨ | ■ | ▨ | ▨ | ▨ | |
| | SURFACE PONDING | 🟨 | 🟨 | | | | | | | | | | | | | | | | | | | ■ | | | | | | | | | |
| | SHALLOW EROSION | 🟨 | 🟨 | ■ | ■ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ░ | | | | | | | | | ■ | | ■ | ▨ | ▨ | ▨ | ■ | ▨ | ▨ | |
| | ROCK BREAKDOWN | 🟨 | 🟨 | | | | | ■ | ■ | ■ | ■ | ▨ | ■ | ■ | ■ | ░ | ■ | ■ | ■ | ░ | ▨ | ░ | ■ | ░ | ░ | ■ | ░ | | ■ | ■ | |
| | DESSICATION CRACKING | 🟨 | 🟨 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | SEDIMENT TRANSPORT (WIND) | 🟨 | 🟨 | | | ■ | ▨ | ▨ | | | | | | | | | | | | | | | | | | | | | | | |
| | SEDIMENT TRANSPORT (WATER) | 🟨 | 🟨 | ■ | ■ | ■ | ■ | ■ | ■ | ▨ | ▨ | ▨ | | | | | | | | | | ■ | | ■ | | | | | | | |
| MANAGEMENT | CATTLE GRAZING | 🟨 | 🟨 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | MOWING / HAYING | 🟨 | 🟨 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | CUT / SPRAY | 🟨 | 🟨 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | SITE MAINTENANCE | 🟨 | 🟨 | ■ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | | ▨ | ■ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | | ■ | ▨ | ▨ | ▨ | ■ | ░ | ▨ | ▨ | ■ | | |
| | INSPECTED ON : MO/YR | 1989 | 1990 | 8/91 | 6/92 | 5/93 | 5/94 | 5/95 | 6/96 | 5/97 | 5/98 | 5/99 | 5/00 | 5/01 | 5/02 | 6/03 | 7/04 | 7/05 | 7/06 | 7/07 | 6/08 | 7/09 | **8/10** | 9/11 | 8/12 | 8/13 | 9/14 | 9/15 | 8/16 | 9/17 | 2018 |

| | |
|---|---|
| ■ | **MORE THAN PREVIOUS YEAR** |
| ▨ | **SAME AS PREVIOUS YEAR** |
| ░ | **LESS THAN PREVIOUS YEAR** |
| 🟨 | **NO RECORDS AVAILABLE** |

NOTES
First site inspection perfoormed in 1991.
The numbers in the SHRUBS / BUSHES boxes indicate the observed number of dominant shrub species during that callendar year.

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Table A.3. Timeline of Key Events at The Lakeview, OR Disposal Cell

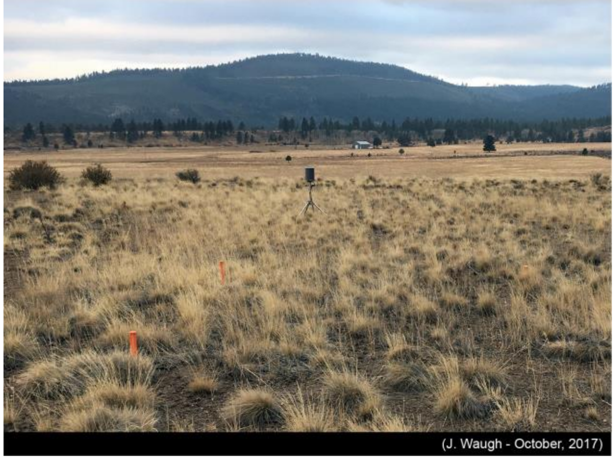
| Year | Category | Observation |
|---|---|---|
| 1989 | | Cell construction completed. Decision made to apply top-soil on-top of rock armor and seed with grasses in the fall. |
| 1991 | Biological | Moderate grass cover on cell cover (well established but patchy) |
| 1991 | Applied Science | Vegetation survey and root excavation performed (Burt and Cox, 1993) |
| 1991 | Geophysical | Minor rill erosion along top slope / rock armor boundary. Sediment moving off of top slope into rock armor. |
| 1991 | Biological | Badger holes (2) present at downslope embankment past rock armor. |
| 1992 | Geophysical | Areas of top soil settling into rock armor. Topsoil observed as “thin”. Vegetation is not well established in areas of thin/settled top soil. |
| 1992 | Geophysical | Minor rill erosion along top slope / rock armor boundary continues. |
| 1992 | Biological | Volunteer grasses begin to establish in north rock-armor side slope in parallel rows. Rows look to appear along rock dump lines where finer material was placed at the end of a load. |
| 1992 | Biological | Badger holes remain active |
| 1993 | Geophysical | Topsoil settlement into rock armor continues to expand in total area. |
| 1993 | Geophysical | Wind scouring of bare topsoil is evident. |
| 1993 | Biological | Grass cover on top slope decreasing year-over-year. |
| 1994 | Geophysical | Topsoil settlement into rock armor continues to expand in total area. |
| 1994 | Biological | Crested wheatgrass, hard fescue, and big bluestem poorly established after 4 seasons. NW 10-20% cover. SP-3 10% cover. South 15-20% cover. |
| 1994 | Biological | Volunteer grasses now present on cover: intermediate wheatgrass, slender wheatgrass, sandberg bluegrass. Lupine and winterfat also present. |
| 1994 | Biological | Encroachment of bushes/shrubs first seen with isolated rabbitbrush in SP-3, and isolated sagebrush on southern portion of cell. Deep rooted plants predicted to outcompete grasses given near surface soil settlement, hydrology, and successional dynamics in the area. |
| 1995 | Geophysical | Topsoil settlement into rock armor continues to expand in total area. |
| 1995 | Geophysical | Rock armor breakdown first observed. Estimated that 10-15% of rock armor is crumbling because of weathering. |
| 1995 | Biological | Badger holes (3) present and active |
| 1996 | Biological | Rabbitbrush and sagebrush continue increasing in density year-over-year. |
| 1997 | Applied Science | Ongoing rock breakdown study initiated |
| 1997 | Applied Science | Root structures rabbitbrush and sagebrush excavated and studied on the site. |
| 1997 | Biological | Many mature rabbitbrush and few sagebrush now present across the cell with 20-100’s of immature downwind plants. Without intervention, it is predicted that the rabbitbrush population will continue to increase |

| | | |
|---|---|---|
| | | followed by increases in sagebrush, bitterbrush, and, in time, serviceberry, chokecherry, and juniper populations. |
| 1999 | Applied Science | NRC Radon study performed (AC Canisters). |
| 1999 | Applied Science | Leaf area index of site vegetation performed. |
| 1999 | Applied Science | Soil profile study on the cell to determine rooting density and pattern. |
| 1999 | Biological | First bitterbrush seen establishing on cell. |
| 2001 | Applied Science | Leaf area index of site vegetation performed. |
| 2002 | Management | Rock armor continues to deteriorate. New rock size calculation performed by U.S. Army Corps of Engineers. NRC approves new rock spec (lower than design) to fit most recent Army Corps calculation. |
| 2003 | Biological | Density of rabbitbrush, sagebrush and bitterbrush continues to significantly increase across the cell. Shrub and bush cover on cell now exceeds density observed in off cell “native” locations. |
| 2003 | Applied Science | Leaf area index of site vegetation performed. |
| 2003 | Applied Science | Saturated hydraulic conductivity measurements taken across surface conditions of cell and natural analog sites. |
| 2004 | Applied Science | Field investigations at the Lakeview site indicate that a combination of soil development and root intrusion by the deep-rooted shrubs have increased the hydraulic conductivity of the compacted soil layer (radon barrier) in the cell cover. The saturated hydraulic conductivity (permeability) of the radon barrier ranges between $1x10^{-6}$ and $1x10^{-4}$ centimeters per second (cm/s). The design target was $1x10^{-7}$ to $1x10^{-8}$ cm/s. |
| 2005 | Applied Science | Percolation flux lysimeters installed on the site to measure water movement into tailings. |
| 2005 | Biological | Density of rabbitbrush, sagebrush and bitterbrush increases significantly year-over-year. Corresponds to high snowpack. |
| 2005 | Geophysical | 2 earthquakes occured (magnitude 3.4 and 3.6) roughly 15 miles away from the disposal cell. |
| 2006 | Biological | Grass cover decreases year-over-year due to drought in the region. |
| 2006 | Applied Science | Findings from natural analog studies in the area indicate that soil development and plant succession on the cover may lead to an increase in evapotranspiration, keeping the radon barrier unsaturated and, hence, effectively offsetting the increase in permeability. |
| 2007 | Biological | Grass cover continues to decrease because of ongoing drought in the region. |
| 2009 | Geophysical | Considerable top-soil settlement into rock armor observed. Patches between 4in to 18in common. |
| 2009 | Geophysical | 25 individual rills observed on top cell cover / rock slope interface. Rills reach a maximum size of 11x20x4 inches (WxLxH). |
| 2009 | Applied Science | Rock Durability index was developed. It was found that (63.4 percent) of the rocks monitored on the west side slope were classified as having a general durability class of “highly durable” or “durable.” |

| | | |
|---|---|---|
| 2009 | Applied Science | Percolation flux lysimeters indicate that cumulative percolation through the radon barrier averaged 996 millimeters during 2006, 186 millimeters during 2007, 444 millimeters during 2008, and 155 millimeters during 2009. |
| 2009 | Applied Science | Side Slope rock study shows patterning of smaller particle size rocks occur in streaks down the slope. |
| 2010 | Biological | Grass cover thin and stressed because of drought in the region. |
| 2010 | Applied Science | Borehole studies on cell indicate that significant saturation of subsurface tailings is not occuring, and that additional studies were not warranted with respect to slope stability. |
| 2011 | Geophysical | Checkerboard erosional patterning occuring on cell cover in areas where grass has thinned since construction. |
| 2011 | Geophysical | Transport of top-soil through erosion onto rock armor is observed. |
| 2011 | Biological | Two small rodent burrows (1in diameter each) found on the cell. Some subsurface soil transport evident. |
| 2013 | Biological | Grass cover continues to thin and is stressed because of drought in the region (and possible moisture competition from more established shrubs). |
| 2014 | Geophysical | Top-soil settlement into rock armor accelerates. Common to see patches between 4 to 30 inches on cell cover. |
| 2014 | Geophysical | Additional transport of top-soil through erosion onto rock armor is observed. |
| 2015 | | Drought in the area continues |
| 2015 | Geophysical | Growth of rill features along top-slope rock armor interface evident |
| 2016 | | Drought in the area continues |

Figure A.8. Lakeview, OR : Surface Features Characteristic of Biological Processes

**LAKEVIEW, OR : GRASSES / FORBS**
MIXED / WHEATGRASS (*Elymus ssp*)



(J. Waugh - October, 2017)

**LAKEVIEW, OR : SHRUBS / BUSHES**
RUBBER RABBITBRUSH (*Ericameria nauseosa*)

(J. Waugh - October, 2017)

**LAKEVIEW, OR : SHRUBS / BUSHES**
BIG SAGEBRUSH (*Artemisia tridentata*)

(A. Michaud - October, 2017)

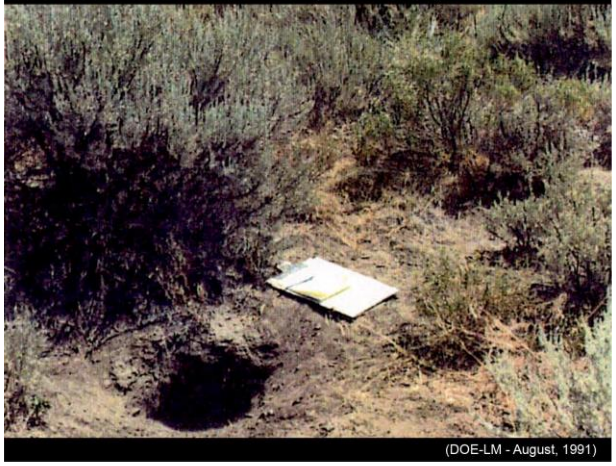
**LAKEVIEW, OR : SHRUBS / BUSHES**
BITTERBRUSH (*Purshia tridentata*)

(J. Waugh - October, 2017)

**LAKEVIEW, OR : GRASSES / FORBS**
BUNCHGRASSES ON ROCK SLOPE (*Elymus ssp*)

(M. Williams - October, 2017)

**LAKEVIEW, OR : ANIMAL BURROWING**
BADGER HOLE (*Tadidea taxus*)



(DOE-LM - August, 1991)

**LAKEVIEW, OR : ANIMAL BURROWING**
LIKELY CA. GROUND SQUIRREL (*Otospermophilus beechey*)

(J. Waugh - October, 2017)

**LAKEVIEW, OR : ANIMAL BURROWING**
HARVESTER ANTS (*Pogonomyrmex ssp*)

(M. Williams - October, 2017)

Figure A.9. Lakeview, OR : Surface Features Characteristic of Geophysical Processes

**LAKEVIEW, OR : SOIL SETTLEMENT**
TOPSOIL SETTLING INTO VOIDS IN ROCK ARMOR

(DOE-LM - August, 2010)

**LAKEVIEW, OR : SHALLOW EROSION**
CHECKERBOARD EROSIONAL PATTERNS

(DOE-LM - September, 2011)

**LAKEVIEW, OR : ROCK BREAKDOWN**
ROCK ARMOR FRACTURING

(DOE-LM - June, 2001)

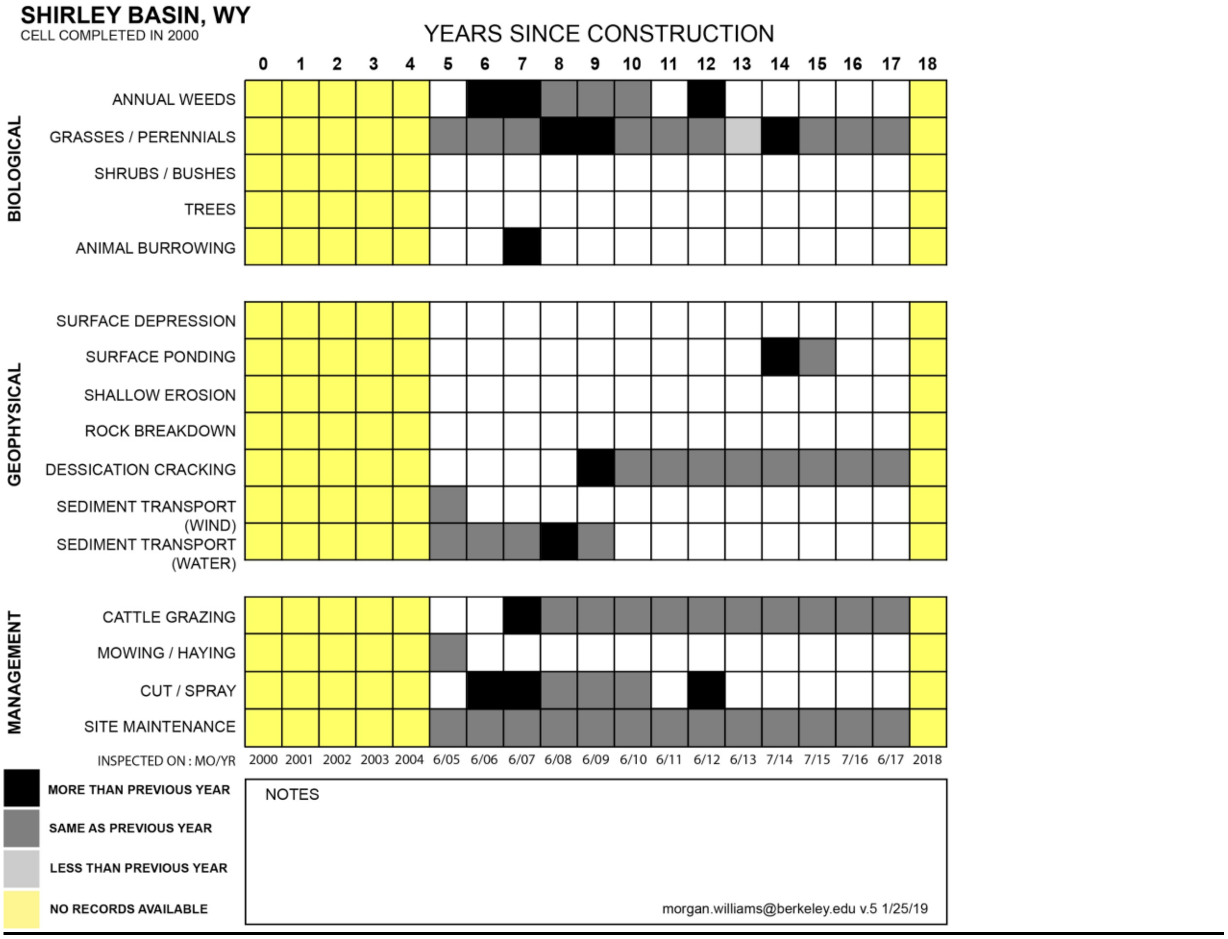
**LAKEVIEW, OR : SHALLOW EROSION**
MINOR RILL DEVELOPMENT IN UNVEGETATED AREA

(M. Williams - May, 2017)

**LAKEVIEW, OR : SEDIMENT TRANSPORT**
OVERLAND FLOW MOVING TOPSOIL INTO ROCK ARMOR

(DOE-LM - September, 2011)

Figure A.10. Shirley Basin, WY : Surface Process History



**SHIRLEY BASIN, WY**
CELL COMPLETED IN 2000

YEARS SINCE CONSTRUCTION

| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BIOLOGICAL | ANNUAL WEEDS | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | | ■ | ■ | ▨ | ▨ | ▨ | | ■ | | | | | | 🟨 |
| | GRASSES / PERENNIALS | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | ▨ | ▨ | ▨ | ■ | ■ | ▨ | ▨ | ▨ | ░ | ■ | ▨ | ▨ | ▨ | 🟨 |
| | SHRUBS / BUSHES | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | | | | | | | | | | | | | | 🟨 |
| | TREES | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | | | | | | | | | | | | | | 🟨 |
| | ANIMAL BURROWING | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | | | ■ | | | | | | | | | | | 🟨 |
| GEOPHYSICAL | SURFACE DEPRESSION | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | | | | | | | | | | | | | | 🟨 |
| | SURFACE PONDING | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | | | | | | | | | | ■ | ▨ | | | 🟨 |
| | SHALLOW EROSION | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | | | | | | | | | | | | | | 🟨 |
| | ROCK BREAKDOWN | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | | | | | | | | | | | | | | 🟨 |
| | DESSICATION CRACKING | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | | | | | ■ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 🟨 |
| | SEDIMENT TRANSPORT (WIND) | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | ▨ | | | | | | | | | | | | | 🟨 |
| | SEDIMENT TRANSPORT (WATER) | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | ▨ | ▨ | ▨ | ■ | ▨ | | | | | | | | | 🟨 |
| MANAGEMENT | CATTLE GRAZING | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | | | ■ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 🟨 |
| | MOWING / HAYING | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | ▨ | | | | | | | | | | | | | 🟨 |
| | CUT / SPRAY | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | | ■ | ■ | ▨ | ▨ | ▨ | | ■ | | | | | | 🟨 |
| | SITE MAINTENANCE | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 🟨 |
| | INSPECTED ON : MO/YR | 2000 | 2001 | 2002 | 2003 | 2004 | 6/05 | 6/06 | 6/07 | 6/08 | 6/09 | 6/10 | 6/11 | 6/12 | 6/13 | 7/14 | 7/15 | 7/16 | 6/17 | 2018 |

■ MORE THAN PREVIOUS YEAR
▨ SAME AS PREVIOUS YEAR
░ LESS THAN PREVIOUS YEAR
🟨 NO RECORDS AVAILABLE

NOTES

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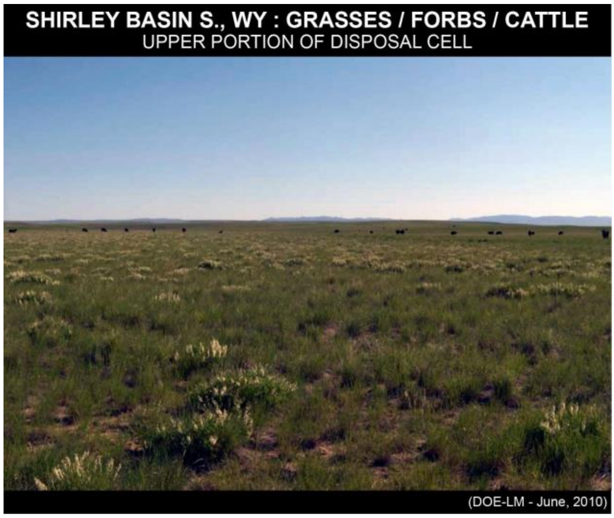
| Table A.4. Timeline of Key Events at The Shirley Basin, WY Disposal Cell | | |
|---|---|---|
| **Year** | **Category** | **Observation** |
| 2000 | | Cell construction completed |
| 2005 | Biological | Thick and even grass cover |
| 2005 | Geomorphic | Evidence of accumulated windblown sediment in rock armor |
| 2005 | Geomorphic | Possible movement of sediment from overland flow off upper cell into rock armor |
| 2005 | Biological | Bottom half of middle section of rock armor slope has grasses growing in it. Coincides with area that has sediment in the rock armor. |
| 2005 | Management | Site mowed and hay baled |
| 2006 | Management | Grazing license established with local rancher. Site grazed from 2006 onward. Trade for fence maintenance and ensuring that no trespassing is occuring. |
| 2007 | Biological | Badger holes observed |
| 2008 | Biological | Wetland vegetation occurring at toe slope of rock armor. Seasonally wet. |
| 2009 | Geomorphic | Surface soil cracking is first observed on toe slope of rock armor. Occurs later in the season when wet soils dry out. |
| 2013 | Biological | Vegetation shows minor drought stress, thinner in plances. |
| 2014 | Geomorphic | Ephemeral pond present at time of inspection at toe slope of rock armor. Same area as wetland vegetation are establishing. |
| 2014 | Biological | Pronounced game trails seen on the site. |

Figure A.11. Shirley Basin, WY : Surface Features Characteristic of Biological Processes

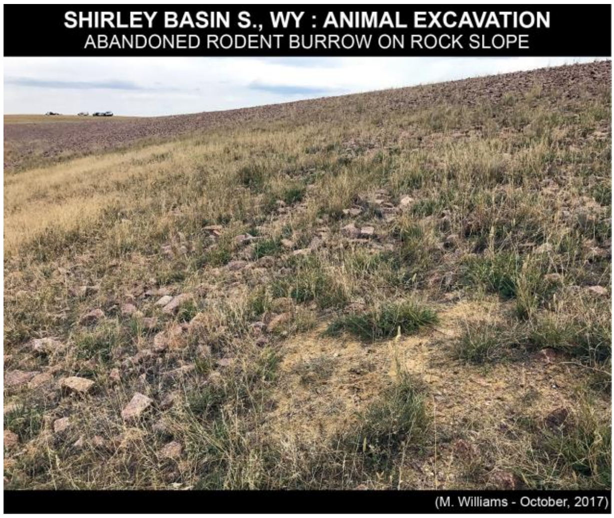


**SHIRLEY BASIN S., WY : GRASSES / FORBS / CATTLE**
UPPER PORTION OF DISPOSAL CELL

(DOE-LM - June, 2010)

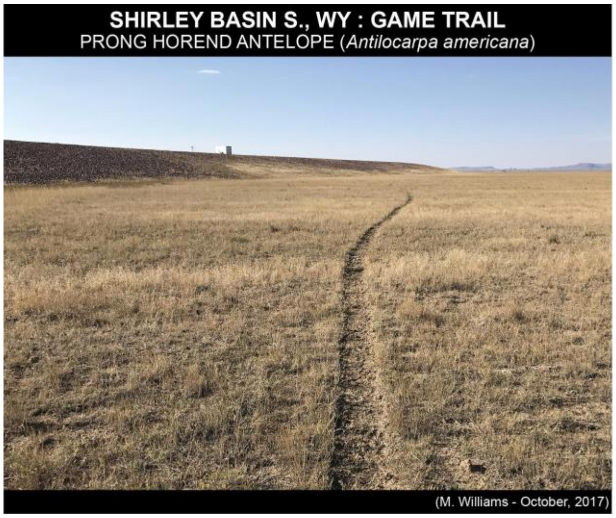
**SHIRLEY BASIN S., WY : VEGETATION GRADIENT**
WETLAND TO VEGETATED ROCK ARMOR

(M. Williams - October, 2017)



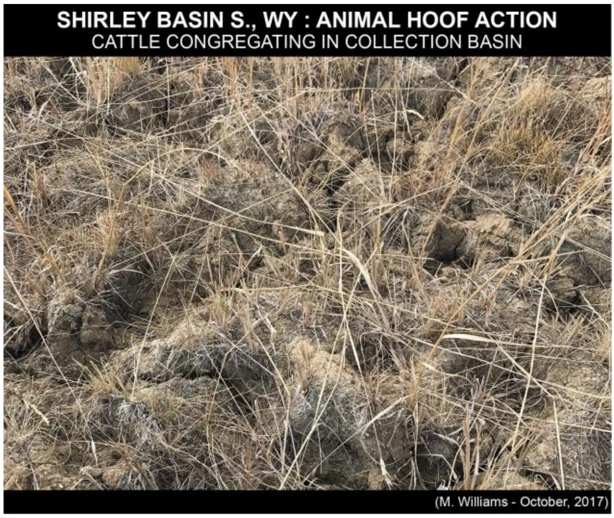
**SHIRLEY BASIN S., WY : ANIMAL EXCAVATION**
ABANDONED RODENT BURROW ON ROCK SLOPE

(M. Williams - October, 2017)



**SHIRLEY BASIN S., WY : GAME TRAIL**
PRONG HOREND ANTELOPE (*Antilocarpa americana*)

(M. Williams - October, 2017)



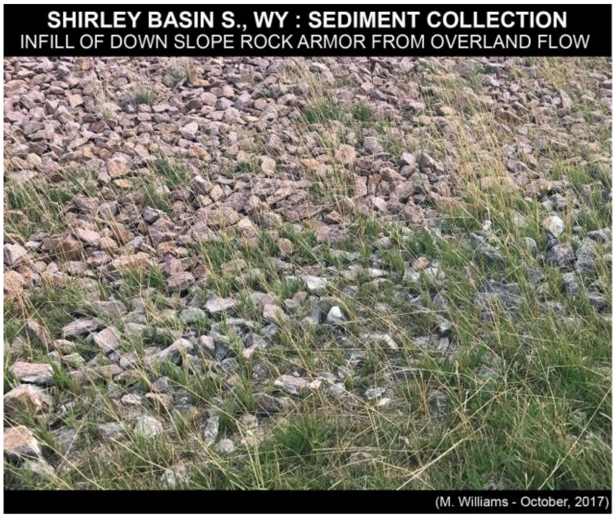
**SHIRLEY BASIN S., WY : ANIMAL HOOF ACTION**
CATTLE CONGREGATING IN COLLECTION BASIN

(M. Williams - October, 2017)

Figure A.12. Shirley Basin, WY : Surface Features Characteristic of Geophysical Processes

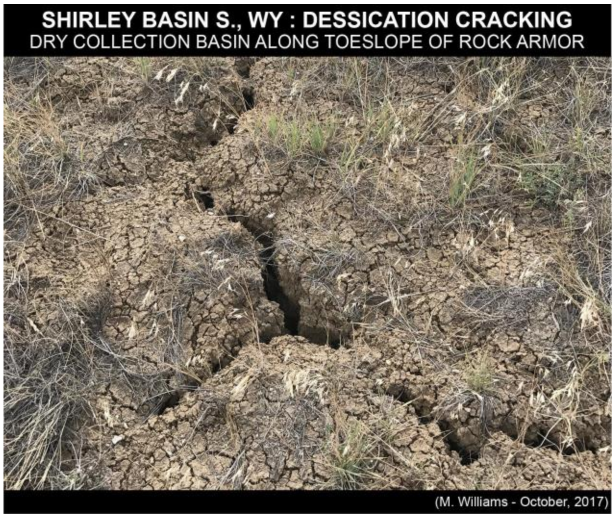
SHIRLEY BASIN S., WY : EPHEMERAL WETLAND
ALONG TOESLOPE OF ROCK ARMOR

(DOE-LM - June, 2008)



SHIRLEY BASIN S., WY : SEDIMENT COLLECTION
INFILL OF DOWN SLOPE ROCK ARMOR FROM OVERLAND FLOW

(M. Williams - October, 2017)



SHIRLEY BASIN S., WY : DESSICATION CRACKING
DRY COLLECTION BASIN ALONG TOESLOPE OF ROCK ARMOR

(M. Williams - October, 2017)

# 9. APPENDIX B: REVIEW OF ROOTING CHARACTERISTICS IN ENGINEERED CLAY BARRIER SYSTEMS

## TABLE A.3.1: REVIEW OF EMERGENT ROOTING CHARACTERISTICS FOUND IN ENGINEERED CLAY BARRIER SYSTEMS

| **Location** | **Climate zone** | **Species** | **Cover age (yrs)** | **Thickness of clay barrier** | **Max rooting depth into clay barrier**<br>------------------<br>(% penetration) | **Depth of material above clay barrier** | **Rooting description** | **Reference** |
|---|---|---|---|---|---|---|---|---|
| **COMPACTED MINERAL BARRIERS STABILIZED WITH ROCK ARMOR** | | | | | | | | |
| Green River, UT USA | Hot, semiarid, mixed grassland | Russian thistle | 2 | 90 cm<br>Design spec. | none<br>**0%** | 45 cm<br>Rock Armor / Bedding | Dust deposited in rock voids. Only plant on cell growing in deposits. Roots confined to this material. | Burt and Cox, 1993 |
| Tuba City, AZ USA | Hot, semiarid, mixed grassland | Russian thistle | 2 | 110 cm<br>Design spec. | <2.5 cm<br>vf<br>**2.2%** | 30 cm<br>Rock Armor / Bedding | Dust deposited in rock voids. Most roots growing in this material. Plants growing in zones with thinner rock armor than avg. | Burt and Cox, 1993 |
| South Clive, UT USA | Hot, semiarid, mixed grassland | *Halogeton ssp.* | 2 | 210 cm<br>Design spec. | <5 cm<br>vf<br>**2.4%** | 45 cm<br>Rock Armor / Bedding | Dust deposited in rock voids. Most roots growing in this material. | Burt and Cox, 1993 |
| Burrell, PA USA | Temperate, humid, woodland | Tree-of-heaven (*Ailanthus altissima*) | 4 | 90 cm<br>Design spec. | ≥ 10 cm<br>m / f<br>**11.1%** | 60 cm<br>Rock Armor / Bedding | Coarse/medium roots confined to bedding layer. Fine roots in clay barrier | Burt and Cox, 1993 |
| Burrell, PA USA | Temperate, humid, woodland | American sycamore (*Plantanus occidentalis*) | 4 | 90 cm<br>Design spec. | ≥ 10 cm<br>m / f<br>**11.1%** | 60 cm<br>Rock Armor / Bedding | Coarse/medium roots confined to bedding layer. Fine roots in clay barrier | Burt and Cox, 1993 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Burrell, PA USA | Temperate, humid, woodland | Box elder (*Acer negundo*) | 4 | 90 cm<br>Design spec. | ≥ 10 cm<br>m / f<br>**11.1%** | 60 cm<br>Rock Armor / Bedding | Coarse/medium roots confined to bedding layer. Fine roots in clay barrier | Burt and Cox, 1993 |
| Burrell, PA USA | Temperate, humid, woodland | Japanese knotweed (*Fallopia japonica*) | 4 | 90 cm<br>Design spec. | 15 cm<br>m / f<br>46 cm<br>f / vf<br>**51.1%** | 60 cm<br>Rock Armor / Bedding | Taproot stops and spreads at top of clay barrier. m/f roots to 15 cm. f/vf along fractures to 46 cm. | Burt and Cox, 1993 |
| Burrell, PA USA | Temperate, humid, woodland | Giant mullen (*Verbascum thapsus*) | 4 | 90 cm<br>Design spec. | <10 cm<br>f / vf<br>**11.1%** | 60 cm<br>Rock Armor / Bedding | roots largely confined to bedding layer | Burt and Cox, 1993 |
| Shiprock, NM USA | Hot, semiarid, mixed grassland | Salt cedar (*Tamarix pentandra*) | 4 | 200 cm<br>Design spec. | 10 - 71 cm<br>**35.5%** | 40 cm<br>Rock Armor / Bedding | Large lateral roots at 15cm, fine roots to 71 cm. Along fractures. | Burt and Cox, 1993 |
| Shiprock, NM USA | Hot, semiarid, mixed grassland | Summer cyprus (*Kochia sieversiana*) | 6 | 200 cm<br>Design spec. | ≥ 56 cm<br>**28%** | 40 cm<br>Rock Armor / Bedding | - | Burt and Cox, 1993 |
| Burrell, PA USA | Temperate, humid, woodland | Japanese knotweed (*Fallopia japonica*) | 9 | 90 cm<br>Design spec. | >60 cm<br>f / vf<br>**66.6%** | 60 cm<br>Rock Armor / Bedding | Taproot spreads at top of clay barrier. f/vf along fractures. Matting of f/vf horizontally along compression planes | Waugh and Smith, 1997 |
| Burrell, PA USA | Temperate, humid, woodland | Sycamore (*Platanus spp*) | 9 | 90 cm<br>Design spec. | <5 cm<br>vf<br>**5.5%** | 60 cm<br>Rock Armor / Bedding | vc/c/m roots clogging drainage layer. Minimal vf rooting in top section or clay barrier. | Waugh and Smith, 1997 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Burrell, PA USA | Temperate, humid, woodland | Staghorn sumac (*Rhus typhina*) | 9 | 90 cm<br>Design spec. | <5 cm<br>vf<br>**5.5%** | 60 cm<br>Rock Armor / Bedding | vc/c/m roots clogging drainage layer. Minimal vf rooting in top section or clay barrier. | Waugh and Smith, 1997 |
| Burrell, PA USA | Temperate, humid, woodland | Black locust (*Robinia pseudoacacia*) | 9 | 90 cm<br>Design spec. | <5 cm<br>vf<br>**5.5%** | 60 cm<br>Rock Armor / Bedding | vc/c/m roots clogging drainage layer. Minimal vf rooting in top section or clay barrier. | Waugh and Smith, 1997 |
| Bluewater, NM | Hot, semiarid, mixed grassland | Squirrel tail grass | 21 | 60 cm<br>Design spec. | >60 cm<br>3vf<br>**100%** | 20 cm<br>Rock Armor | 3vf roots in bulk soil through depth of barrier. Root matting in fractures. | Williams et al., 2019 |
| Bluewater, NM | Hot, semiarid, mixed grassland | Fourwing Saltbush | 21 | 60 cm<br>Design spec. | >60 cm<br>3vf<br>**100%** | 20 cm<br>Rock Armor | c/m/f/vf roots to depth of 40 cm. m/f/vf roots along fractures through depth of barrier. | Williams et al., 2019 |
| **VEGETATED COMPOSITE CAPPING BARRIERS AND PLANTED MINERAL BARRIERS** | | | | | | | | |
| Lakeview, OR USA | Cool, semiarid, sagebrush steppe | Crested wheatgrass | 2 | 80 cm<br>Design spec. | <5 cm<br>f / vf<br>**6.3%** | 45 cm<br>Rock Armor / Bedding | - | Burt and Cox, 1993 |
| Lakeview, OR USA | Cool, semiarid, sagebrush steppe | Big sagebrush | 2 | 80 cm<br>Design spec. | none<br>**0%** | 45 cm<br>Rock Armor / Bedding | Taproot stops at interface of radon barrier, tertiary roots spread laterally. | Burt and Cox, 1993 |
| Lakeview, OR USA | Cool, semiarid, sagebrush steppe | Tall wheatgrass<br>*Agropyron spp.*<br>Crested wheatgrass | 3 | 80 cm<br>Design spec.. | <5 cm<br>f / vf | 45 cm<br>Rock Armor / Bedding | - | Burt and Cox, 1993 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Fescue<br>*Festuca spp.* | | | **6.3%** | | | |
| Lakeview, OR<br>USA | Cool, semiarid, sagebrush steppe | Big sagebrush<br>Valley lupine | 3 | 80 cm<br>Design spec. | 5 cm<br>f / vf<br>**6.3%** | 45 cm<br>Rock Armor / Bedding | Taproot stops at interface of radon barrier, tertiary roots spread laterally. Some in barrier. | Burt and Cox, 1993 |
| Rum Jungle, NT<br>Australia | Humid, subtropical, woodland | *eucalyptus spp* | 3 | 30 cm<br>Design spec. | 15 cm<br>m / f<br>>30 cm<br>f / vf<br>**100%** | 45 cm<br>Sandy clay loam / gravely sand | co/m roots travel horizontally along planes of weakness created by compacted lift layers. f/vf roots travel vertically along fractures through the clay barrier and into wastes. | Ryan, 1985; 1986 |
| Rum Jungle, NT<br>Australia | Humid, subtropical, woodland | *Acacia holosericea* | 3 | 30 cm<br>Design spec. | 5 cm<br>m / f<br>>30 cm<br>f / vf<br>**100%** | 45 cm<br>Sandy clay loam / gravely sand | Majority of roots in unconsolidated soils above barrier. f/vf roots travel along fractures through clay barrier and into wastes | Ryan, 1985; 1986 |
| Albany, GA<br>USA | Warm, humid, mixed grassland | Mixed Bermuda and rye grasses | 4 | 45 cm<br>Design spec. | 45 cm<br>vf<br>**100%** | 15 cm<br>Sandy clay loam | Well formed blocky and laminar aggregates to 60 cm depth. Rooting around aggregate edges. Roots typically exist along fractures but occur in bulk soil, as well.. Crack and rooting density decrease with depth. | Albright et al., 2006 |
| Hamburg, Germany | maritime temperate | Mixed pasture of: | 8 | 60 cm<br>Design spec. | 60 cm<br>vf | 100 cm<br>Topsoil / | Plant roots have massively intruded | Melchior, 1997 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | *Lotus corniculatus*,<br>*Cirsium ssp.*,<br>*Rumex ssp.*,<br>*Armoracia rusticana* | | | **100%** | geotextile / sandy drainage layer | and completely grown through the soil liner. Soil was hard, brittle, and and very dry with 2mm wide cracks. | |
| Lakeview, OR USA | Cool, semiarid, sagebrush steppe | Rubber rabbitbrush (*Ericameria nauseosa*) | 8 | 45 cm | - | 45 cm<br>Rock Armor / Bedding | Taproot stops at interface of radon barrier, tertiary roots spread laterally. f/vf roots travel vertically along fractures into barrier. | Waugh et al., 1997 |
| Lakeview, OR USA | Cool, semiarid, sagebrush steppe | Big sagebrush (*Artemisia tridentata*) | 8 | 45 cm | - | 45 cm<br>Rock Armor / Bedding | Taproot stops at interface of radon barrier, tertiary roots spread laterally. f/vf roots travel vertically along fractures into barrier. | Waugh et al., 1997 |
| Lakeview, OR USA | Cool, semiarid, sagebrush steppe | Antelope bitterbrush (*Purshia tridentata*) | 8 | 45 cm | - | 45 cm<br>Rock Armor / Bedding | Taproot stops at interface of radon barrier, tertiary roots spread laterally. f/vf roots travel vertically along fractures into barrier. | Waugh et al., 1997 |
| Hertfordshire, UK | Temperate, maritime, woodland | Black alder<br>*Alnus glutinosa* | 10 | 100 cm<br>Design spec. | 6 - 30 cm<br>**30%** | 57 - 71 cm<br>Fill Soils | Fine/medium. Along fractures. | Hutchings et al., 2001 |
| Hertfordshire, UK | Temperate, maritime, woodland | Corsican pine<br>*Pinus nigra var. maritima* | 10 | 100 cm<br>Design spec. | 1 - 2 cm<br>**2%** | 55 - 70 cm<br>Fill Soils | Fine. Minor intrusion along top interface. | Hutchings et al., 2001 |
| Hertfordshire, UK | Temperate, maritime, woodland | Sycamore maple<br>*Acer pseudoplatanus* | 10 | 100 cm<br>Design spec. | 0 - 3 cm<br>**3%** | 62 - 65 cm<br>Fill Soils | Fine. Minor intrusion along top interface. | Hutchings et al., 2001 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Hertfordshire, UK | Temperate, maritime, woodland | Black alder<br>*Alnus glutinosa* | 15 | 100 cm<br>Design spec. | > 45 cm<br>**45%** | 55 - 85 cm<br>Fill Soils | | Hutchings et al., 2006 |
| Rum Jungle, NT Australia | Humid, subtropical, woodland | mixed tussock grassland | 18 | 30 cm<br>Design spec. | 15 cm<br>m / f<br>>30 cm<br>f / vf<br>**100%** | 45 cm<br>Sandy clay loam / gravely sand | Most f/vf roots located along the cracks between polygon faces of emergent soil structure. Some in bulk soil. Root density decreases with depth. | Taylor, et al., 2003 |
| Rum Jungle, NT Australia | Humid, subtropical, woodland | *Acacia auriculiformis* | 18 | 30 cm<br>Design spec. | 5 cm<br>m<br>>30 cm<br>f / vf<br>**100%** | 45 cm<br>Sandy clay loam / gravely sand | Majority of roots in unconsolidated soils above barrier. f/vf roots travel along fractures through clay barrier and into wastes. Root density decreases with depth. | Taylor, et al., 2003 |
| Rum Jungle, NT Australia | Humid, subtropical, woodland | *eucalyptus ssp.* | 18 | 30 cm<br>Design spec. | 10 cm<br>co / m<br>>30 cm<br>f / vf<br>**100%** | 45 cm<br>Sandy clay loam / gravely sand | Dense vc/co/m rooting in the unconsolidated soils above barrier. co/m roots in top section of barrier, with f/vf roots travel along fractures through clay barrier and (≥ 5cm) into wastes. Root density decreases with depth. | Taylor, et al., 2003 |
| Falls City, TX USA | Humid | Honey mesquite | 22 | 65 cm<br>Design spec. | 8 cm<br>co / f<br>**12.3%** | 100 cm<br>topsoil/rooting medium | co and f roots travel 8 cm into barrier | Williams et al., 2019 |

|  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
| Falls City, TX<br>USA | Humid | yellow bluestem (*Bothriochloa ischaemum var. songarica)*, | 22 | 65 cm<br>Design spec. | 65 cm<br>vf<br>**100%** | 100 cm<br>topsoil/rooting medium | vf roots travel through depth of barrier in the bulk soil fraction. | Williams et al., 2019 |
| Shirley Basin, WY<br>USA | Frigid<br>semi arid | Russian bunchgrass | 16 | 85 cm<br>Design spec. | 85 cm<br>f<br>**100%** | 85 cm<br>topsoil/rooting medium | f roots travel through depth of barrier in the bulk soil fraction. | Williams et al., 2019 |
| Lakeview, OR<br>USA | Cool, semiarid, sagebrush steppe | Rubber rabbitbrush (*Ericameria nauseosa*) | 29 | 45 cm | 45 cm<br>vf, f<br>**100%** | 45 cm<br>Rock Armor / Bedding | F and vf roots travel through depth of barrier along fractures | Williams et al., 2019 |
| Lakeview, OR<br>USA | Cool, semiarid, sagebrush steppe | Antelope bitterbrush (*Purshia tridentata*) | 29 | 45 cm | 45cm<br>vf, f<br>**100%** | 45 cm<br>Rock Armor / Bedding | F and vf roots travel through depth of barrier along fractures and in bulk soil | Williams et al., 2019 |

# 10. APPENDIX C: MORPHOLOGICAL DEVELOPMENT INDEX SCORING

|  |  |  |  |  |  | Pedality |  |  | Macroporosity |  |  | Root Density |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | **Profile ID** | **Barrier Horizon** | **Horizon Thickness (cm)** | **Grav. Water GWC %** | **Texture** | **Grade** | **Size** | **Shape** | **Quantity** | **Size** | **Type** | **Quantity** | **Size** | **Total** | **Profile Dev. Score** |
| **Falls City, Texas** | 1 | Rn 1.a | 8 | 32% | SiC | m | n/a | m | vf | vf | f | vf | vf | **56** | **29** |
|  |  |  |  | **1** | **2** | 0 | 0 | 0 | 1 | 1 | 10 | 1 | 43 |  |  |
|  |  | Rn 1.b | 54 | 36% | SiC | m | n/a | m | n/a | n/a | n/a | vvf | vf | **25** |  |
|  |  |  |  | **1** | **2** | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 43 |  |  |
|  | 2 | Rn 1.a | 10 | 38% | SiC | m | n/a | m | vvf | vf | f | vf | vf | **51** | **47** |
|  |  |  |  | **1** | **2** | 0 | 0 | 0 | 1 | 1 | 10 | 1 | 43 |  |  |
|  |  | Rn 1.b | 42 | 38% | SiC | m | n/a | m | n/a | n/a | n/a | vf | vf | **46** |  |
|  |  |  |  | **1** | **2** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 43 |  |  |
|  | 4 | Rn 1.a | 22 | 32% | SiC | m | n/a | m | vf | vf | f | vf | vf | **56** | **52** |
|  |  |  |  | **1** | **2** | 0 | 0 | 0 | 1 | 1 | 10 | 1 | 43 |  |  |
|  |  | Rn 1.b | 23 | 32% | SiCL | m | n/a | m | n/a | n/a | n/a | vf | vf | **48** |  |
|  |  |  |  | **1** | **4** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 43 |  |  |
|  | 5 | Rn 1.a | 6 | 37% | SiCL | m | n/a | m | n/a | n/a | n/a | n/a | n/a | **5** | **5** |
|  |  |  |  | **1** | **4** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  |  |
|  |  | Rn 2.b | 31 | 39% | SiCL | m | n/a | m | n/a | n/a | n/a | n/a | n/a | **5** |  |
|  |  |  |  | **1** | **4** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |  |  |
|  | 6 | Rn 1.a | 19 | 44% | SiCL | m | n/a | m | vf | vf | f | vf \| f/c | f \| vf | **402** | **197** |
|  |  |  |  | **1** | **4** | 0 | 0 | 0 | 1 | 1 | 10 | 1 \| 8 | 43 \| 43 |  |  |
|  |  | Rn 1.b | 10 | 42% | SiCL | m | n/a | m | n/a | n/a | n/a | f | vf | **48** |  |
|  |  |  |  | **1** | **4** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 43 |  |  |
|  |  | Rn 1.c | 16 | 40% | SiCL | m | n/a | m | n/a | n/a | n/a | f | vf | **48** |  |
|  |  |  |  | **1** | **4** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 43 |  |  |
|  | Analog 1 | Btk1 | 33 | 30% | SiC | s | f | b | f \| f | f \| vf | f \| v | f \| c \| m \| m | co \| m \| f \| vf | **7147** | **3222** |
|  |  |  |  | **1** | **2** | 25 | 18 | 10 | 3 \| 3 | 9 \| 1 | 10 \| 1 | 1 \| 16 \| 25 \| 25 | 13 \| 13 \| 43 \| 43 |  |  |
|  |  | Btk2 | 29 | 30% | C | w | vc | b | vf \| vf | vf \| vf | f \| v | f \| f \| m \| m | co \| m \| f \| vf | **2279** |  |
|  |  |  |  | **1** | **1** | 1 | 1 | 10 | 1 \| 1 | 1 \| 1 | 10 \| 1 | 1 \| 1 \| 25 \| 25 | 13 \| 13 \| 43 \| 43 |  |  |
|  |  | Btk3 | 36 | 34% | C | w | vc | b | vf \| vf | vf \| vf | f \| v | f \| c \| m | m \| f \| vf | **1879** |  |
|  |  |  |  | **1** | **1** | 1 | 1 | 10 | 1 \| 1 | 1 \| 1 | 10 \| 1 | 1 \| 16 \| 25 | 13 \| 43 \| 43 |  |  |
|  |  | 2Btk/Cr | 26 | 38% | C | m | m | b | f | f | f | f \| c | f \| vf | **1153** |  |
|  |  |  |  | **1** | **1** | 5 | 3 | 10 | 3 | 9 | 10 | 1 \| 16 | 43 \| 43 |  |  |

| | Profile ID | Barrier Horizon | Horizon Thickness (cm) | Grav. Water GWC % | Texture | Pedality | | | Macroporosity | | | Root Density | | Total | Profile Dev. Score |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Grade | Size | Shape | Quantity | Size | Type | Quantity | Size | | |
| **Bluewater, New Mexico** | 1 | Rn 1 | 20 | 11% | SCL | w | m | pl | vf | vf | v | vf | vf | **60** | **31** |
| | | | | **7** | **6** | 1 | 3 | 1 | 1 | 1 | 1 | 1 | 43 | | |
| | | Rn 2 | 14 | 12% | SCL | m | n/a | m | n/a | n/a | n/a | n/a | n/a | **13** | |
| | | | | **7** | **6** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| | | Rn 3 | 33 | 11% | SL | m | n/a | m | n/a | n/a | n/a | n/a | n/a | **22** | |
| | | | | **7** | **15** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| | 2.A (away) | Rn 1 | 15 | 8% | SL | s | f | b | f | f | f | c | vf | **5503** | **1552** |
| | | | | **30** | **15** | 25 | 18 | 10 | 3 | 9 | 10 | 16 | 43 | | |
| | | Rn 2 | 23 | 11% | SCL | m | m | b | c | vf | f | f | vf | **306** | |
| | | | | **7** | **6** | 5 | 3 | 10 | 10 | 1 | 10 | 1 | 43 | | |
| | | Rn 3 | 21 | 14% | C | w | m | b | f | vf | f | f | vf | **111** | |
| | | | | **7** | **1** | 1 | 3 | 10 | 3 | 1 | 10 | 1 | 43 | | |
| | 2.B (under) | Rn 1 | 11 | 4% | SL | s | vf | b | c \| f | f \| vf | f \| v | c \| m | f \| vf | **7246** | **2501** |
| | | | | **65** | **15** | 25 | 18 | 10 | 10 \| 3 | 9 \| 1 | 10 \| 1 | 16 \| 25 | 43 \| 43 | | |
| | | Rn 2 | 23 | 9% | SCL | m | f | b | c | vf | f | m | vf | **2111** | |
| | | | | **30** | **6** | 5 | 18 | 10 | 10 | 1 | 10 | 25 | 43 | | |
| | | Rn 3 | 36 | 20% | C | m | m | b | c | vf | f | m | vf | **1332** | |
| | | | | **3** | **1** | 5 | 3 | 10 | 10 | 1 | 10 | 25 | 43 | | |
| | 3 | Rn 1.a | 12 | 7% | SL | s | f | b | f | vf | v | f \| c | f \| vf | | **1233** |
| | | | | **30** | **15** | 25 | 18 | 10 | 3 | 1 | 1 | 1 \| 16 | 43 \| 43 | **5279** | |
| | | Rn 1.b | 8 | 9% | SCL | m | m | b | n/a | n/a | n/a | n/a | n/a | **186** | |
| | | | | **30** | **6** | 5 | 3 | 10 | 0 | 0 | 0 | 0 | 0 | | |
| | | Rn 1.c | 18 | 8% | SCL | w | co | b | n/a | n/a | n/a | n/a | n/a | **66** | |
| | | | | **30** | **6** | 1 | 3 | 10 | 0 | 0 | 0 | 0 | 0 | | |
| | | Rn 2 | 16 | 9% | SCL | m | n/a | m | n/a | n/a | n/a | n/a | n/a | **36** | |
| | | | | **30** | **6** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| | 4 | Rn 1.a | 7 | 5% | SL | m | f | b | f | vf | v | vf | vf | **1026** | **129** |
| | | | | **65** | **15** | 5 | 18 | 10 | 3 | 1 | 1 | 1 | 43 | | |
| | | Rn 1.b | 12 | 9% | SL | w | vc | b | f | vf | v | vf | vf | **101** | |
| | | | | **30** | **15** | 1 | 1 | 10 | 3 | 1 | 1 | 1 | 43 | | |
| | | Rn 2 | 22 | 11% | SCL | w | vc | b | n/a | n/a | n/a | n/a | n/a | **23** | |
| | | | | **7** | **6** | 1 | 1 | 10 | 0 | 0 | 0 | 0 | 0 | | |
| | | Rn 3 | 28 | 11% | SCL | m | n/a | m | n/a | n/a | n/a | n/a | n/a | **13** | |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **7** | **6** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| 5.A (under) | Rn 1 | 25 | 6% | SCL | s | m | b | m \| c | f \| vf | f \| v | c \| m \| m \| m | co \| m \| f \| vf | **6034** | **2796** |
| | | | **65** | **6** | 25 | 3 | 10 | 28 \| 10 | 9 \| 1 | 10 \| 1 | 16\| 25 \| 25 \|25 | 13 \| 13 \| 43 \| 43 | | |
| | Rn 2.a | 15 | 6% | SL | w | co | b | c \| vf | vf \| vf | f \| v | c \| f \| f \| f | co \| m \| f \| vf | **518** | |
| | | | **65** | **15** | 1 | 3 | 10 | 10 \| 1 | 1 \| 1 | 10 \| 1 | 16 \| 1 \| 1 \| 1 | 13 \| 13 \| 43 \| 43 | | |
| | Rn 2.b | 16 | 5% | SL | w | vc | b | vf | vf | f | n/a | n/a | **100** | |
| | | | **65** | **15** | 1 | 1 | 10 | 1 | 1 | 10 | 0 | 0 | | |
| 5.B (away) | Rn 1 | 15 | 5% | SCL | s | m | b | m \| c | f \| vf | f \| v | c \| c \| c | m \| f \| vf | **4935** | **1371** |
| | | | **65** | **6** | 25 | 3 | 10 | 28 \| 10 | 9 \| 1 | 10 \| 1 | 16 \| 16 \| 16 | 13 \| 43 \| 43 | | |
| | Rn 2.a | 23 | 8% | SCL | w | co | b | c \| vf | vf \| vf | f \| v | f \| f \| f | m \| f \| vf | **266** | |
| | | | **30** | **6** | 1 | 3 | 10 | 10 \| 1 | 1 \| 1 | 10 \| 1 | 1 \| 1 \| 1 | 13 \| 43 \| 43 | | |
| | Rn 2.b | 21 | 7% | SCL | w | vc | b | c | vf | f | n/a | n/a | **146** | |
| | | | **30** | **6** | 1 | 1 | 10 | 10 | 1 | 10 | 0 | 0 | | |
| MP-2 | Rn 1.a | 20 | 5% | SCL | s | vf | b | vm \| f | f \| vf | f \| v | c \| f | f \| vf | **10705** | **9517.5** |
| | | | **65** | **6** | 25 | 18 | 10 | 60 \| 3 | 9 \| 1 | 10 \| 1 | 16 \| 1 | 43 \| 43 | | |
| | Rn 1.b | 19 | 6% | SCL | s | vf | b | vm \| f | f \| vf | f \| v | c \| f | f \| vf | **10705** | |
| | | | **65** | **6** | 25 | 18 | 10 | 60 \| 3 | 9 \| 1 | 10 \| 1 | 16 \| 1 | 43 \| 43 | | |
| | Rn 2.a | 29 | 6% | L | s | vf | b | vm \| f | f \| vf | f \| v | c | vf | **10676** | |
| | | | **65** | **10** | 25 | 18 | 10 | 60 \| 3 | 9 \| 1 | 10 \| 1 | 16 | 43 | | |
| | Rn 2.b | 12 | 6% | L | w | co | b | m \| f | f \| vf | f \| v | c | vf | **3316** | |
| | | | **65** | **10** | 1 | 3 | 10 | 28 \| 3 | 9 \| 1 | 10 \| 1 | 16 | 43 | | |
| 7 | Rn 1.a | 24 | 5% | SCL | m | m | b | f \| f | f \| vf | f \| v | c \| c \| c \| c | co \| m \| f \| vf | **2221** | **330.6** |
| | | | **65** | **6** | 5 | 3 | 10 | 3 \| 3 | 9 \| 1 | 10 \| 1 | 16\| 16 \| 16 \|16 | 13 \| 13 \| 43 \| 43 | | |
| | Rn 1.b | 12 | 5% | SCL | w | co | b | n/a | n/a | n/a | f \| f \| c \| c | co \| m \| f \| vf | **1438** | |
| | | | **65** | **6** | 1 | 3 | 10 | 0 | 0 | 0 | 1 \| 1 \| 16 \| 16 | 13 \| 13 \| 43 \| 43 | | |
| | Rn 2 | 37 | 6% | SCL | w | co | b | n/a | n/a | n/a | f \| f \| f \| f | co \| m \| f \| vf | **148** | |
| | | | **65** | **6** | 1 | 3 | 10 | 0 | 0 | 0 | 1 \| 1 \| 1 \| 1 | 13 \| 13 \| 43 \| 43 | | |
| | Rn 3 | 36 | 8% | SCL | w | vc | b | n/a | n/a | n/a | n/a | n/a | **16** | |
| | | | **30** | **6** | 1 | 1 | 10 | 0 | 0 | 0 | 0 | 0 | | |
| | Rn 4 | 33 | 9% | SCL | w | vc | b | n/a | n/a | n/a | n/a | n/a | **16** | |
| | | | **30** | **6** | 1 | 1 | 10 | 0 | 0 | 0 | 0 | 0 | | |
| | Rn 5 | 34 | 9% | SCL | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | **6** | |
| | | | **30** | **6** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| | Rn 6 | 36 | 11% | SCL | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | **6** | |
| | | | **7** | **6** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| | Rn 7 | 23 | 13% | SCL | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | **6** | |
| | | | **7** | **6** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| 8 | Rn 1 | 22 | 8% | SCL | s | f | b | vf \| vf | vf \| vf | f \| v | f | vf | **960** | **452.4** |
| | | | **30** | **6** | 5 | 18 | 10 | 1 \| 1 | 1 \| 1 | 10 \| 1 | 1 | 43 | | |
| | Rn 2 | 21 | 9% | SCL | m | f | b | vf | vf | f | f | vf | **959** | |

<table>
<tr><td></td><td></td><td></td><td></td><td><b>30</b></td><td><b>6</b></td><td>5</td><td>18</td><td>10</td><td>1</td><td>1</td><td>10</td><td>1</td><td>43</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Rn 3</td><td>37</td><td>9%</td><td>SCL</td><td>m</td><td>vc</td><td>b</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td><td><b>56</b></td><td></td></tr>
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<tr><td></td><td></td><td>Rn 4</td><td>16</td><td>13%</td><td>SCL</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td><td><b>6</b></td><td></td></tr>
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<tr><td></td><td>Analog 3</td><td>Bt 1</td><td>21</td><td>6%</td><td>SCL</td><td>s</td><td>vf</td><td>b</td><td>m | c | m</td><td>f | f | f</td><td>f | c |v</td><td>f | f | m | m</td><td>co | m | f | vf</td><td><b>10174</b></td><td><b>4059</b></td></tr>
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<tr><td></td><td></td><td>Bt 2</td><td>29</td><td>6%</td><td>SCL</td><td>s</td><td>f</td><td>b</td><td>c | c | c</td><td>f | f | f</td><td>f | c |v</td><td>f | f | m | m</td><td>co | m | f | vf</td><td><b>8392</b></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td><b>65</b></td><td><b>6</b></td><td>25</td><td>18</td><td>10</td><td>10 | 10 | 10</td><td>9 | 9 | 9</td><td>10|8|1</td><td>1 | 1 | 25 | 25</td><td>13 | 13 | 43 | 43</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Btk</td><td>39</td><td>7%</td><td>SCL</td><td>m</td><td>m</td><td>b</td><td>c | c | c</td><td>f | f | f</td><td>f | c |v</td><td>f | f | c | m</td><td>co | m | f | vf</td><td><b>3655</b></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td><b>30</b></td><td><b>6</b></td><td>5</td><td>3</td><td>10</td><td>10 | 10 | 10</td><td>9 | 9 | 9</td><td>10|8|1</td><td>1 | 1 | 16 | 25</td><td>13 | 13 | 43 | 43</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Btm</td><td>12</td><td>9%</td><td>SCL</td><td>w</td><td>m</td><td>b</td><td>vf</td><td>vf</td><td>f</td><td>f | c | c</td><td>m | f | vf</td><td><b>1435</b></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td>30</td><td><b>6</b></td><td>1</td><td>3</td><td>10</td><td>1</td><td>1</td><td>10</td><td>1| 16 | 16</td><td>13 | 43 | 43</td><td></td><td></td></tr>
<tr><td></td><td></td><td>CB</td><td>33</td><td>9%</td><td>CL</td><td>s</td><td>f</td><td>b</td><td>c | f</td><td>f | vf</td><td>f | v</td><td>f | c</td><td>f | vf</td><td><b>6139</b></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td><b>30</b></td><td><b>5</b></td><td>25</td><td>18</td><td>10</td><td>10 | 3</td><td>9 | 1</td><td>10 | 1</td><td>1 | 16</td><td>43 | 43</td><td></td><td></td></tr>
<tr><td></td><td></td><td>2 Btk</td><td>36</td><td>9%</td><td>SCL</td><td>s</td><td>f</td><td>b</td><td>c | f</td><td>f | vf</td><td>f | v</td><td>c</td><td>vf</td><td><b>6097</b></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td><b>30</b></td><td><b>6</b></td><td>25</td><td>18</td><td>10</td><td>10 | 3</td><td>9 | 1</td><td>10 | 1</td><td>16</td><td>43</td><td></td><td></td></tr>
<tr><td></td><td>Analog 6</td><td>B</td><td>32</td><td>NM</td><td>C</td><td>s</td><td>vf</td><td>b</td><td>vm | f | m</td><td>f | f | f</td><td>f | c|v</td><td>f | f | c | m</td><td>co | m | f | vf</td><td><b>12158</b></td><td><b>11656</b></td></tr>
<tr><td></td><td></td><td></td><td></td><td><b>65</b></td><td><b>1</b></td><td>25</td><td>18</td><td>10</td><td>60 | 3 | 28</td><td>9 | 9 | 9</td><td>10|8|1</td><td>1 | 1 | 16 | 25</td><td>13 | 13 | 43 | 43</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Bk</td><td>26</td><td>NM</td><td>CL</td><td>s</td><td>vf</td><td>b</td><td>vm | f</td><td>f | vf</td><td>f | v</td><td>f | f | m</td><td>m | f | vf</td><td><b>11039</b></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td><b>65</b></td><td><b>5</b></td><td>25</td><td>18</td><td>10</td><td>60 | 3</td><td>9 | 1</td><td>10 | 1</td><td>1 | 1 | 25</td><td>13 | 43 | 43</td><td></td><td></td></tr>
<tr><td></td><td></td><td>CBk</td><td>34</td><td>NM</td><td>CL</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td><td>n/a</td><td>f | f | f</td><td>m | f | vf</td><td><b>105</b></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td><b>30</b></td><td><b>6</b></td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1 | 1 | 1</td><td>13 | 43 | 43</td><td></td><td></td></tr>
</table>

| | | | | | | Pedality | | | Macroporosity | | | Root Density | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Profile ID** | **Barrier Horizon** | **Horizon Thickness (cm)** | **Grav. Water GWC %** | **Texture** | **Grade** | **Size** | **Shape** | **Quantity** | **Size** | **Type** | **Quantity** | **Size** | **Total** | **Profile Dev. Score** |
| **Shirley Basin South, WY** | DC-2 | Rn 1 | 12 | 21% | SC | n/a | n/a | n/a | n/a | n/a | n/a | f/c | vf | **347** | **112.6** |
| | | | | **3** | **3** | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 43 | | |
| | | Rn 2 | 16 | 24% | C | n/a | n/a | n/a | n/a | n/a | n/a | vf | vf | **44** | |
| | | | | **3** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 1.0 | 43 | | |
| | | Rn 3 | 12 | 26% | C | n/a | n/a | n/a | n/a | n/a | n/a | vf | vf | **44** | |
| | | | | **3** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 1.0 | 43 | | |
| | | Rn 4 | 8 | 28% | C | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | **1** | |
| | | | | **3** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| | DC-3 | Rn 1.a | 6 | 25% | C | n/a | n/a | n/a | vf | vf | f | vvf | vf | **33** | **4.15** |
| | | | | **3** | **1** | 0 | 0 | 0 | 1 | 1 | 10 | 0.5 | 43 | | |
| | | Rn 1.b | 5 | 28% | C | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | **1** | |
| | | | | **3** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| | | Rn 2 | 13 | 31% | C | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | **1** | |
| | | | | **1** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| | | Rn 3 | 14 | 27% | C | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | **1** | |
| | | | | **3** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| | | Rn 4 | 16 | 28% | C | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | **1** | |
| | | | | **3** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| | | Rn 5 | 6 | 29% | C | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | **1** | |
| | | | | **3** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| | DC-4 | Rn 1 | 16 | 30% | C | n/a | n/a | n/a | n/a | n/a | n/a | f/c | vf | **345** | **89.75** |
| | | | | **1** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 43 | | |
| | | Rn 2 | 16 | 26% | C | n/a | n/a | n/a | n/a | n/a | n/a | vf | vf | **44** | |
| | | | | **3** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 43 | | |
| | | Rn 3 | 13 | 21% | C | n/a | n/a | n/a | n/a | n/a | n/a | vf | vf | **44** | |
| | | | | **3** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 43 | | |
| | | Rn 4 | 15 | 24% | C | n/a | n/a | n/a | n/a | n/a | n/a | vvf | vf | **23** | |
| | | | | **3** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 43 | | |
| | | Rn 5 | 19 | 23% | C | n/a | n/a | n/a | n/a | n/a | n/a | vvf | vf | **23** | |
| | | | | **3** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 43 | | |
| | | Rn 6 | 7 | 23% | C | n/a | n/a | n/a | n/a | n/a | n/a | vvf | vf | **23** | |
| | | | | **3** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 43 | | |
| | DC-5 | Rn 1 | 19 | 32% | C | n/a | n/a | n/a | n/a | n/a | n/a | vvf | vf | **23** | **23** |
| | | | | **1** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 43 | | |
| | | Rn 2 | 12 | 31% | C | n/a | n/a | n/a | n/a | n/a | n/a | vvf | vf | **23** | |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **1** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 43 | | |
| | | Rn 3 | 22 | 32% | C | n/a | n/a | n/a | n/a | n/a | n/a | vvf | vf | **23** | |
| | | | | **1** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 43 | | |
| | DC-6 | Rn 1 | 18 | 28% | C | n/a | n/a | n/a | n/a | n/a | n/a | vvf | vf | **23** | **23** |
| | | | | 3 | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 43 | | |
| | | Rn 2 | 19 | 26% | C | n/a | n/a | n/a | n/a | n/a | n/a | vvf | vf | **23** | |
| | | | | **3** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 43 | | |
| | | Rn 3 | 20 | 26% | C | n/a | n/a | n/a | n/a | n/a | n/a | vvf | vf | **23** | |
| | | | | **3** | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 43 | | |
| | Analog 4 | Btk 2 | 15 | NM | C | w | vc | b | vf | vf | f | c \| m | f \| vf | **1784** | **772** |
| | | | | **3** | **1** | 1 | 1 | 10 | 1 | 1 | 10 | 16 \| 25 | 43 \| 43 | | |
| | | Bx 1 | 14 | NM | C | n/a | n/a | n/a | vf | vf | f | m | vf | **1086** | |
| | | | | **3** | **1** | 0 | 0 | 0 | 1 | 1 | 10 | 25 | 43 | | |
| | | Bx 2 | 47 | NM | C | n/a | n/a | n/a | vf | vf | f | f/c | vf | **355** | |
| | | | | **3** | **1** | 0 | 0 | 0 | 1 | 1 | 10 | 8 | 43 | | |

| | | | | | | Pedality | | | Macroporosity | | | Root Density | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Profile ID** | **Barrier Horizon** | **Horizon Thickness (cm)** | **Grav. Water GWC %** | **Texture** | **Grade** | **Size** | **Shape** | **Quantity** | **Size** | **Type** | **Quantity** | **Size** | **Total** | **Profile Dev. Score** |
| **Lakeview, OR** | DC-2 under | Rn 1 | 10 | 32% | L | m | m | b | f \| f | vf \| vf | f \| v | f \| m \| m \| m | co \| m \| f \| vf | **2681** | **2347.6** |
| | | | | **1** | **10** | 5 | 3 | 10 | 3 \| 3 | 1 \| 1 | 10 \| 1 | 1 \| 25 \| 25 \| 25 | 13 \| 13 \| 43 \| 43 | | |
| | | Rn 2 | 9 | 31% | SL | m | m | b | f \| f | vf \| vf | f \| v | f \| m \| m \| m | co \| m \| f \| vf | **2686** | |
| | | | | **1** | **15** | 5 | 3 | 10 | 3 \| 3 | 1 \| 1 | 10 \| 1 | 1 \| 25 \| 25 \| 25 | 13 \| 13 \| 43 \| 43 | | |
| | | Rn 3 | 7 | 27% | L | w | co | b | vf | vf | f | f \| c \| m | m \| f \| vf | **1826** | |
| | | | | **3** | **10** | 1 | 3 | 10 | 1 | 1 | 10 | 1 \| 16 \| 25 | 13 \| 43 \| 43 | | |
| | | Rn 4 | 7 | 28% | SL | m | m | b | f | vf | f | c \| m | f \| vf | **1958** | |
| | | | | **3** | **15** | 5 | 3 | 10 | 3 | 1 | 10 | 16 \| 25 | 43 \| 43 | | |
| | DC-2 100cm | Rn 1 | 11 | NM | L | w | co | b | f \| f | vf \| vf | f \| v | vf \| f \| f \| c | co \| m \| f \| vf | **830** | **611.2** |
| | | | | **3** | **10** | 1 | 3 | 10 | 3 \| 3 | 1 \| 1 | 10 \| 1 | 1 \| 1 \| 1 \| 16 | 13 \| 13 \| 43 \| 43 | | |
| | | Rn 2 | 9 | NM | SL | m | f | b | f \| f | vf \| vf | f \| v | f \| f \| c | m \| f \| vf | **942** | |
| | | | | **3** | **15** | 5 | 3 | 10 | 3 \| 3 | 1 \| 1 | 10 \| 1 | 1 \| 1 \| 16 | 13 \| 43 \| 43 | | |
| | | Rn 3 | 8 | NM | L | w | co | b | n/a | n/a | n/a | n/a | n/a | **40** | |
| | | | | **3** | **10** | 1 | 3 | 10 | 0 | 0 | 0 | 0 | 0 | | |
| | | Rn 4 | 14 | NM | L | m | m | b | n/a | n/a | n/a | n/a | n/a | **160** | |
| | | | | **3** | **10** | 5 | 3 | 10 | 0 | 0 | 0 | 0 | 0 | | |
| | DC-2 250cm | Rn 1 | 11 | NM | L | w | m | b | f \| f | vf \| vf | f \| v | f \| f \| c | m \| f \| vf | **830** | **517.9** |
| | | | | **3** | **10** | 1 | 3 | 10 | 3 \| 3 | 1 \| 1 | 10 \| 1 | 1 \| 1 \| 16 | 13 \| 43 \| 43 | | |
| | | Rn 2 | 9 | NM | SL | w | m | b | f \| f | vf \| vf | f \| v | f \| f \| c | m \| f \| vf | **822** | |
| | | | | **3** | **15** | 1 | 3 | 10 | 3 \| 3 | 1 \| 1 | 10 \| 1 | 1 \| 1 \| 16 | 13 \| 43 \| 43 | | |
| | | Rn 3 | 8 | NM | L | n/a | n/a | n/a | n/a | n/a | n/a | vf | vf | **53** | |
| | | | | **3** | **10** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 43 | | |
| | | Rn 4 | 14 | NM | L | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | **10** | |
| | | | | **3** | **10** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| | DC-4 bare | Rn 1 | 37 | 51% | Si | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | **19** | **19** |
| | | | | **1** | **19** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| | DC-4 grass | Rn 1 | 10 | 37% | Si | n/a | n/a | n/a | n/a | n/a | n/a | f/c | vf | **363** | **109.5** |
| | | | | **1** | **19** | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 43 | | |
| | | Rn 2 | 28 | 45% | Si | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | **19** | |
| | | | | **1** | **19** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| | DC-5 | Rn 1 | 10 | 29% | Si | m | co | b | c | f | f | c | vf | **957** | **440.5** |
| | | | | **3** | **19** | 5 | 3 | 10 | 10 | 1 | 10 | 16 | 43 | | |
| | | Rn 2 | 10 | 30% | Si | m | co | b | c | 9 | f | c | vf | **957** | |
| | | | | **3** | **19** | 5 | 3 | 10 | 10 | 1 | 10 | 16 | 43 | | |
| | | Rn 3 | 13 | 28% | L | w | m | b | vf | vf | f | vf | vf | **93** | |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  | **3** | **10** | 1 | 3 | 10 | 1 | 1 | 10 | 1 | 43 |  |  |
|  | Rn 4 | 15 | 28% | L | n/a | n/a | n/a | n/a | n/a | n/a | vf | vf | **53** |  |
|  |  |  | **3** | **10** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 43 |  |  |
| DC-10 | Rn 1 | 10 | 32% | Si | m | m | b | vf | vf | f | c \| m | f \| vf | **1942** | **875.3** |
|  |  |  | **1** | **19** | 5 | 3 | 10 | 1 | 1 | 10 | 16 \| 25 | 43 \| 43 |  |  |
|  | Rn 2 | 10 | 46% | Si | w | co | b | vf | vf | f | f \| m | f \| vf | **1177** |  |
|  |  |  | **1** | **19** | 1 | 3 | 10 | 1 | 1 | 10 | 1 \| 25 | 43 \| 43 |  |  |
|  | Rn 3 | 8 | 39% | L | w | vc | b | n/a | n/a | n/a | n/a | n/a | **20** |  |
|  |  |  | **1** | **10** | 1 | 1 | 10 | 0 | 0 | 0 | 0 | 0 |  |  |
|  | Rn 4 | 8 | 30% | L | w | vc | b | n/a | n/a | n/a | n/a | n/a | **20** |  |
|  |  |  | **1** | **10** | 1 | 1 | 10 | 0 | 0 | 0 | 0 | 0 |  |  |
| DC-11 | Rn 1 | 16 | 29% | Si | m | m | b | f | f | f | f \| c \| c \| m | co \| m \| f \| vf | **2183** | **2084.8** |
|  |  |  | **3** | **19** | 5 | 3 | 10 | 3 | 1 | 10 | 1 \| 16 \| 16 \| 25 | 13 \| 13 \| 43 \| 43 |  |  |
|  | Rn 2 | 11 | 17% | Si | m | m | b | f | 9 | f | f \| c \| c \| m | co \| m \| f \| vf | **2183** |  |
|  |  |  | **7** | **19** | 5 | 3 | 10 | 3 | 1 | 10 | 1 \| 16 \| 16 \| 25 | 13 \| 13 \| 43 \| 43 |  |  |
|  | Rn 3 | 10 | 27% | L | m | m | b | vf | vf | f | c \| m | f \| vf | **1933** |  |
|  |  |  | **3** | **10** | 5 | 3 | 10 | 1 | 1 | 10 | 16 \| 25 | 43 \| 43 |  |  |
|  | Rn 4 | 7 | 30% | L | m | m | b | n/a | n/a | n/a | c \| m | f \| vf | **1923** |  |
|  |  |  | **3** | **10** | 5 | 3 | 10 | 0 | 0 | 0 | 16 \| 25 | 43 \| 43 |  |  |
| DC-12 under | Rn 1 | 11 | 35% | Si | m | f | b | vf | vf | f | f \| c | f \| vf | **1660** | **589.8** |
|  |  |  | **1** | **19** | 5 | 18 | 10 | 1 | 1 | 10 | 1 \| 16 | 43 \| 43 |  |  |
|  | Rn 2 | 11 | 31% | Si | m | m | b | vf | vf | f | f \| c | f \| vf | **910** |  |
|  |  |  | **1** | **19** | 5 | 3 | 10 | 1 | 1 | 10 | 1 \| 16 | 43 \| 43 |  |  |
|  | Rn 3 | 12 | 30% | L | m | co | b | vf | vf | f | n/a | n/a | **170** |  |
|  |  |  | **1** | **10** | 5 | 3 | 10 | 1 | 1 | 10 | 0 | 0 |  |  |
|  | Rn 4 | 19 | 37% | L | w | co | b | vf | vf | f | n/a | n/a | **50** |  |
|  |  |  | **1** | **10** | 1 | 3 | 10 | 1 | 1 | 10 | 0 | 0 |  |  |
| DC-12 away | Rn 1 | 11 | NM | Si | m | m | b | vf | vf | f | c | vf | **867** | **251.7** |
|  |  |  | **1** | **19** | 5 | 3 | 10 | 1 | 1 | 10 | 16 | 43 |  |  |
|  | Rn 2 | 11 | NM | Si | m | m | b | vf | vf | f | vf | vf | **222** |  |
|  |  |  | **1** | **19** | 5 | 3 | 10 | 1 | 1 | 10 | 1 | 43 |  |  |
|  | Rn 3 | 12 | NM | L | w | co | b | vf | vf | f | n/a | n/a | **50** |  |
|  |  |  | **1** | **10** | 1 | 3 | 10 | 1 | 1 | 10 | 0 | 0 |  |  |
|  | Rn 4 | 19 | NM | L | w | co | b | n/a | n/a | n/a | n/a | n/a | **40** |  |
|  |  |  | **1** | **10** | 1 | 3 | 10 | 0 | 0 | 0 | 0 | 0 |  |  |
| DC-13 | Rn 1 | 11 | 24% | L | m | m | b | f | f | f | n/a | n/a | **190** | **82.06** |
|  |  |  | **3** | **10** | 5 | 3 | 10 | 3 | 1 | 10 | 0 | 0 |  |  |
|  | Rn 2 | 11 | 25% | L | m | co | b | f | 9 | f | n/a | n/a | **190** |  |
|  |  |  | **3** | **10** | 5 | 3 | 10 | 3 | 1 | 10 | 0 | 0 |  |  |
|  | Rn 3 | 6 | 28% | Si | w | co | b | vf | vf | f | n/a | n/a | **59** |  |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **3** | **19** | 1 | 3 | 10 | 1 | 1 | 10 | 0 | 0 | | |
| | | Rn 4 | 4 | 25% | Si | w | co | b | vf | vf | f | n/a | n/a | **59** | |
| | | | | **3** | **19** | 1 | 3 | 10 | 1 | 1 | 10 | 0 | 0 | | |
| | | Rn 5 | 34 | 42% | Si | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a | **19** | |
| | | | | **1** | **19** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| | Analog 2 borrow | Bt.1 | 34 | NM | Si | s | f | b | c \| c \| c | f \| f \| f | f\|c\|v | c \| m \| m \| m | co \| m \| f \| vf | **8912** | **5124** |
| | | | | **3** | **19** | 25 | 18 | 10 | 10 \| 10 \| 10 | 9 \| 9 \| 9 | 10\|8\|1 | 16 \| 25 \| 25\|25 | 13 \| 13 \| 43 \| 43 | | |
| | | Bt.2 | 28 | NM | Si | m | m | b | f \| f | vf \| vf | c \| v | f \| c \| m \| m | co \| m \| f \| vf | **2567** | |
| | | | | **3** | **19** | 5 | 3 | 10 | 3 \| 3 | 1 \| 1 | 8 \| 1 | 1 \| 16 \| 25 \| 25 | 13 \| 13 \| 43 \| 43 | | |
| | | B/Cr | 15 | NM | L | m | m | b | vf \| vf | vf \| vf | c \| v | f \| f \| f \| m | co \| m \| f \| vf | **1313** | |
| | | | | **3** | **10** | 5 | 3 | 10 | 1 \| 1 | 1 \| 1 | 8 \| 1 | 1 \| 1 \| 1 \| 25 | 13 \| 13 \| 43 \| 43 | | |