CHARACTERIZATION AND MODELING OF ALLUVIUM BENEATH FORTYMILE WASH, NEVADA

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ABSTRACT

Yucca Mountain, Nevada, is being investigated by the U.S. Department of Energy (DOE) for a potential high-level radioactive waste repository. Natural barriers are evaluated for their effectiveness in isolating radioactive waste from the accessible environment. The valley-fill alluvium beneath Fortymile Wash constitutes an important component of the natural barrier system. The U.S. Nuclear Regulatory Commission (NRC) Risk Insights Baseline Report (2004) determined that retardation of radionuclides in the saturated alluvium is of high significance to waste isolation. The alluvium beneath Fortymile Wash is currently modeled as a homogenous hydrogeologic unit in the DOE saturated zone site-scale model. Geological and geophysical surveys conducted in the area, however, have shown evidence of strong spatial variability in the alluvium. The heterogeneity in the alluvium and lack of measurements suggest that a significant amount of model uncertainty exists. An approach to study this uncertainty is described in this report.

Facies distribution, when modeled under a probabilistic framework, can be used to generate images of subsurface heterogeneity and link geology to hydraulic parameters required for stochastic flow and transport simulations. Driller's lithology logs collected from Nye County Early Warning Drilling Program and prior geologic studies of outcrop exposures were used to define quantitative models for the proportions, geometry, and spatial distribution of geologic materials that have distinctive hydraulic properties (i.e., hydrofacies). A transition probability/Markov chain geostatistical method was used to represent the geometry and juxtapositioning of facies and to generate conditional random realizations of facies distribution. In contrast to traditional geostatistical approaches, the transition probability statistics are not limited by the Gaussian distribution assumption and can be used to integrate observable geologic information.

Analysis of borehole lithology data revealed that the volumetric proportions of facies vary considerably with depth. The lack of stationarity with respect to depth was circumvented by dividing the alluvium into three layers, with facies in each layer having stationary proportions. A separate Markov chain model was defined for each layer. The results show that interconnected facies form preferential flow paths, and a large variability exists in the flow path pattens. The effect of flow path variability on potential radionuclide transport can then be evaluated via stochastic simulations. As a result, this report provides a way of representing uncertainty in the alluvial architecture within the site-scale, saturated zone models.

Reference

NRC. "Risk Insights Baseline Report." ML040560162. Washington, DC: NRC. 2004.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: No CNWRA-generated original data are contained in this report.

ANALYSES AND CODES: The analyses in this report are documented according to Geosciences and Engineering Division quality assurance procedures in Scientific Notebook 746E.

The Transition Probability Geostatistical Software module (Carle, 1999) included in GMS Version 6.0 (Environmental Modeling Research Laboratory, 2006) was used to construct Markov chain models of facies spatial variability and generate realizations of facies distributions. GMS Version 6.0 and Transition Probability Geostatistical Software were placed under software control in accordance with the Geosciences and Engineering Division Technical Operating Procedure (TOP)–018. The GMS Version 6.0 interface was validated in accordance with Geosciences and Engineering Division TOP–018. The Geosciences and Engineering Division maintains three user licenses for GMS Version 6.0, which contain all codes and documentation. All inputs and outputs for analyses contained herein are documented in Scientific Notebook 746E.

References

Environmental Modeling Research Laboratory. “GMS Version 6.0.” Salt Lake City, Utah: Environmental Modeling Research Laboratory, Brigham Young University. 2006.

Carle, S. F. “T-PROGS: Transition Probability Geostatistical Software, Version 2.1.” Davis, California: University of California. 1999.

1 INTRODUCTION

This report provides the U.S. Nuclear Regulatory Commission (NRC) with preliminary results obtained from modeling facies distribution in the valley-fill alluvium beneath Fortymile Wash in southern Nevada.

Yucca Mountain, Nevada, is being investigated by the U.S. Department of Energy (DOE) for a potential geologic repository for permanent disposal of high-level nuclear waste. A critical regulatory requirement for the potential geologic repository at Yucca Mountain is that it must include both natural and engineered barriers [10 CFR 63.113(a)].

The saturated zone below Yucca Mountain is expected to act as a natural barrier to the migration of radionuclides by delaying the transport and reducing the concentrations of radionuclides before they reach the accessible environment. Several site-scale models have been developed by DOE to describe the geology of the saturated zone and characterize flow and transport processes within it (Bechtel SAIC Company, LLC, 2004a–c). These site-scale models, while providing a basic understanding of groundwater flow and potential radionuclide transport in the saturated zone system, are subject to a number of uncertainties that can be significant to total system performance (Bechtel SAIC Company, LLC, 2003). The uncertainties can be attributed mainly to data limitations, conceptualization of the saturated zone system, and resolution of the numerical grids.

In the conceptual model of saturated zone flow in the Yucca Mountain vicinity, groundwater flows southerly from recharge areas of higher precipitation at higher elevations north and northwest of Yucca Mountain, coalesces in the Fortymile Wash, and flows toward the Amargosa desert (Bechtel SAIC Company, LLC, 2004b). The DOE site-scale saturated zone flow domain is a 30-km by 45-km [18.6- by 28.0 mi] region that includes faults, fault zones, and 19 hydrostratigraphic units. In the DOE baseline flow model, the flow domain was discretized with a numerical grid having uniform horizontal spacing of 500 m [1,640 ft] and variable vertical spacing ranging from 10 m [32.8 ft] near the water table to 550 m [1,804 ft] at the bottom of the domain. The flow model was calibrated based on multiple criteria, including water-level measurements, lateral flow boundary conditions, and hydrochemistry. In addition to the 19 hydrostratigraphic units, specific features (e.g., faults, fault zones, and areas of chemical alteration) that were deemed to potentially impact groundwater flow were assigned their own permeability zones during the model calibration process, resulting in 27 permeability zones subject to calibration.

Model uncertainty in the site-scale saturated zone flow model arises from a number of sources (Bechtel SAIC Company, 2004b, Section 6.8). One of these is the representation of the shallow alluvial aquifer in Fortymile Wash, considered one of the most important saturated zone components that strongly affect the local flow system and potential radionuclide transport. The alluvial aquifer not only contains the likely flow paths but also serves as an important retardation mechanism for many radionuclides. The geometry and geologic structure of the valley-fill alluvium, however, are poorly represented in the DOE site-scale saturated zone flow model—a homogeneous unit is used to represent the entire valley-fill alluvium. During the calibration process, a portion of the alluvium zone was designated as the alluvium uncertainty zone (a specific feature) to account for uncertainty in the geometry of the alluvium zone (Zyvoloski, et al., 2003). Because of the inherent uncertainty associated with the parameterization approach, inversion based on water level data alone does not guarantee uniqueness in

parameter structure or parameter values. In addition, homogenization of alluvium neglects any preferential flow paths. Physical and chemical heterogeneity in the alluvium can significantly affect potential radionuclide transport. The saturated zone radionuclide transport abstraction model that DOE is considering for the Total System Performance Assessment–License Application will likely be based on the DOE site-scale saturated zone groundwater and transport models (Bechtel SAIC Company, LLC, 2003). Realistic representation of the alluvium beneath Fortymile Wash can be important to identification of potential preferential flow paths in the alluvium and their effect on radionuclide transport.

Several ongoing and planned projects focus on improved characterization of the hydrologic and transport properties of alluvium. The ongoing Nye County Early Warning Drilling Program, currently in Phase V of the investigation, intends to provide important information on geology and hydrology in the Yucca Mountain vicinity. Previously, Ressler, et al. (2000) conducted a study of alluvial sediments found in outcrops in the entrenched channel of Fortymile Wash. An eight-facies alluvium model was proposed by Ressler, et al. (2000) based on grain size, sedimentary structures, and geometry. The facies are distinguished mainly by inferred depositional processes that result in different sediment deposits. Inter-layering of these facies may compartmentalize groundwater flow through the alluvial aquifer. Murray, et al. (2002) analyzed outcrop and subsurface data to infer stratigraphy in the valley-fill alluvium. Winterle and Farrell (2002) provided a preliminary summary of hydrogeologic properties of the Fortymile Wash alluvial aquifer based on the Early Warning Drilling Program drilling data (up to Phase II) available at that time. Painter, et al. (2001) evaluated the effect of alluvium heterogeneity on radionuclide transport. The probability distribution of alluvium hydraulic conductivity was assumed to be log-normal, and the spatial covariance was assumed to be exponential. Bertetti and Werling (2005) conducted laboratory experiments using samples of alluvium and groundwater collected from Fortymile Wash to determine sorption of Neptunium-237 on the alluvium.

Few studies have attempted to quantify facies distributions beneath Fortymile Wash in a probabilistic framework, which offers a way of representing uncertainty in the alluvial architecture. This report provides a basis for modeling flow path variability in the alluvium and for building process models that can be potentially applied to assessing flow and transport uncertainty in the alluvium. The specific objectives of this study are to analyze borehole lithology logs collected from Nye County Early Warning Drilling Program and to apply the results to generating geologically plausible, three-dimensional images of the facies distributions. Although only Early Warning Drilling Program borehole lithology logs and outcrop studies conducted by Ressler, et al. (2000) are considered in this study, data collected from other sources, such as geophysical surveys and geomorphology maps, can be potentially assimilated in the future. Insights from this study may be used to (i) evaluate abstractions and models used to support the DOE Total System Performance Assessment—License Application code, (ii) support review of DOE compliance with appropriate regulatory standards (e.g., the Individual Protection Standard and the Groundwater Protection Standard), and (iii) provide insights for possible future modeling studies of saturated zone radionuclide transport models for the Yucca Mountain region.

The organization of this report is as follows. Chapter 2 provides a brief review of existing approaches for facies modeling, with emphasis on the transition probability/Markov chain approach; Chapter 3 presents analyses of Nye County Early Warning Drilling Program lithology logs and results of facies characterization and modeling; and Chapter 4 summarizes the findings and discusses plans for future work.

2 MODELING OF FACIES ARCHITECTURE

2.1 Background

By definition, facies refers to the part of the rock body differentiated from others by appearance or composition or a kind of rock distinguished from other more or less related kinds (Dictionary of Geological Terms, 1984). The differentiating factors can be lithology, fossil content, hydraulic properties, or distinctive characteristics measured in geophysical logs (Walker, 1984). This report is mainly concerned with defining facies based on lithology (primarily grain size and sorting) which, in turn, have distinctive hydraulic properties (or hydrofacies). Thus, geologic materials are divided into lithofacies which are also hydrofacies. The general term “facies” will be used hereafter to refer to the lithofacies which are also hydrofacies.

Complex geologic processes such as deposition and diagenesis create scale-dependent heterogeneity in sedimentary aquifers. Many scale classification schemes have been proposed. For example, Dagan (1989) classified the formation scales into pore, laboratory, and field scale. Koltermann and Gorelick (1996) suggested linking heterogeneity scale with specific depositional processes that affect permeability and proposed a classification as follows, in order of increasing size of geologic features: multiple pores, depositional flow regime features, stratification, channels, depositional environments, and sedimentary basins. Groundwater flow and transport models require specification of hydraulic properties at every cell or node. Complete, three-dimensional characterization of hydraulic properties for field-scale problems is never feasible. Various models must be used to infer the distributions (or images) of geologic architectures at unmeasured locations to fill in the data gaps.

Koltermann and Gorelick (1996) classified approaches to create images of sedimentary deposits into three categories: structure imitating, process imitating, and descriptive. Structure-imitating methods use spatial statistics, probabilistic rules, and deterministic constraints to constrain the geometry of spatial patterns in sediments. Process-imitating methods construct images of heterogeneity through mathematical models of subsurface flow and transport or the geologic processes governing sedimentary basin formation and filling. Descriptive methods produce images of subsurface architecture by combining site-specific and regional data with conceptual depositional models and expert opinions.

Geostatistical methods, one of the main structure-imitating methods (Koltermann and Gorelick, 1996), imitate facies or hydraulic property distributions through generating multiple, equally likely realizations. The greatest strengths of geostatistical methods are their capability to condition upon the existing data and their representation of uncertainty at unsampled locations.

With the traditional geostatistical methods (cf., Isaaks and Srivastava, 1989), variogram functions are fit to second-order statistics derived from raw data, and then either interpolation methods (e.g., kriging) or simulation techniques (e.g., simulated annealing) are applied to generate spatial images. Such methods are predominantly used to directly generate hydraulic property fields using, for example, measurements of water level and hydraulic conductivity. It is generally hard to assimilate geologic observations (e.g., facies types and volumetric proportions) using the traditional geostatistical methods. In addition, the Gaussian assumption invoked in the traditional geostatistical methods is seen to be too restrictive to produce realistic subsurface images (e.g., Painter, 2003). There are many situations where the gradational and abrupt facies contacts, juxtaposition relationships between facies, and complex patterns of

spatial variability (e.g., buried channels formed by meandering streams) need to be represented. These modeling needs are better handled by methods that are not dependent on the Gaussian assumption.

A transition probability/Markov chain geostatistical method is selected in this study to model the facies pattern in the alluvium beneath Fortymile Wash. This method was first introduced by Davis (1986) and Doveton (1994) and later formalized by Carle and Fogg (1997, 1996) and Carle, et al. (1998). The Transitional Probability Geostatistical Software package developed by Carle (1999) has been integrated into GMS since Version 5. The transition probability/Markov chain geostatistical method readily incorporates geologic information into Markov chain models of spatial variability to produce geologically plausible realizations of subsurface heterogeneity. It has been applied to modeling hydrofacies architectures in many alluvial aquifer systems (e.g., Weissmann, et al., 1999; Weissmann and Fogg, 1999; Ritzi, et al., 2000; Proce, et al., 2004; Dai, et al., 2005).

In general, four steps are involved in applying transition probability/Markov chain method to aquifer characterization: (i) develop an indicator database, (ii) analyze indicator statistics, (iii) fit Markov chain models to measured data, and (iv) use the results from (iii) in estimation or simulation. The theory behind transition probability/Markov chain geostatistical method is briefly reviewed in the next section.

2.2 The Transition Probability/Markov Chain Approach

The transition probability from a facies *k* to a facies *j* is a conditional probability defined as (Carle and Fogg, 1996)

$$t_{jk}(\mathbf{h}) = \Pr\left\{k \text{ occurs at } \mathbf{x}+\mathbf{h} \mid j \text{ occurs at } \mathbf{x}\right\} \tag{2-1}$$

where

h — separation vector
x — spatial location

By definition, the transition probability approach is Markovian because the probability that facies *k* occurring at **x** + **h** is only dependent on what happens at **x**.

The first step in transition probability modeling is categorizing borehole lithology records into facies. Technically, this is simply labeling each core sample with an indicator representing one of the facies, as illustrated in Figure 2-1. In practice, however, there are circumstances where field lithologic descriptions are inadequate to make a proper assignment or core samples fall into more than one category. Other borehole logs (e.g., gamma, formation resistivity, density, optical televiewer) augmented by expert opinions are required. Once the classification is done,

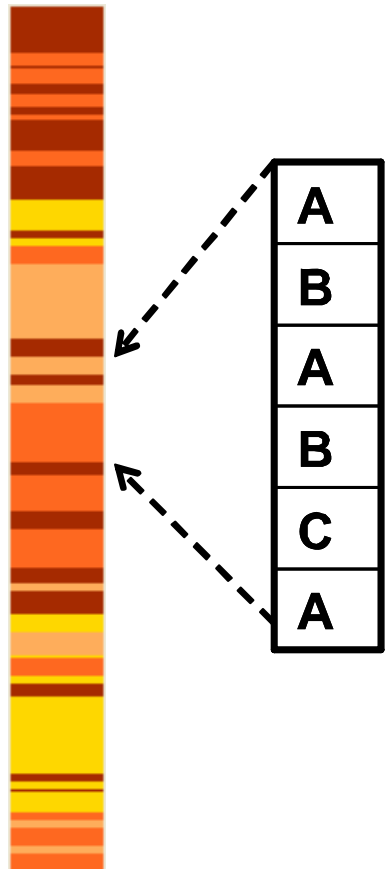


Figure 2-1. Illustration of Facies Classification. The Selected Color Sequences Are Translated into Facies Codes ABABCA.

a transition probability matrix is then calculated. For example, the transition probability matrix for a *K*-facies system along a direction ϕ is defined as

$$\mathbf{T}(h_\phi) = \begin{bmatrix} t_{11}(h_\phi) \dots t_{1K}(h_\phi) \\ \vdots \quad \ddots \quad \vdots \\ t_{K1}(h_\phi) \dots t_{KK}(h_\phi) \end{bmatrix} \tag{2-2}$$

where h_ϕ is lag distance along ϕ, the diagonal entries in **T** represent the transition probabilities from one category to itself (i.e., auto-transition probability), and the off-diagonal entries represent the transition probabilities from one category to another (i.e., cross-transition probability). A Markov chain model applied to one-dimensional categorical data in a direction ϕ assumes the following matrix (Carle and Fogg, 1997) exponential form

$$\mathbf{T}(h_\phi) = \exp(\mathbf{R}_\phi h_\phi) \tag{2-3}$$

where $\mathbf{R}_\phi$ is a matrix of transition rates in the direction ϕ

$$\mathbf{R}_\phi = \begin{bmatrix} r_{11}(h_\phi) \ldots r_{1K}(h_\phi) \\ \vdots \quad \ddots \quad \vdots \\ r_{K1}(h_\phi) \ldots r_{KK}(h\phi) \end{bmatrix} \tag{2-4}$$

with the entries r_{jk} describing the rate of change from category j to category k per unit length in the direction ϕ. Most geological applications of Markov chains employ an embedded analysis, in which the transition probabilities of embedded occurrences (i.e., from one discrete occurrence of a facies to another) is considered. The entries of a transition probability matrix can be translated to entries in the transition rate matrix shown in Eq. (2-4) (see Carle, 1999).

As illustrated in Figure 2-2, the parameters of the Markov chain model are related to observable spatial attributes in the following ways (Carle and Fogg, 1996; Weissmann, et al., 1999):

(1) The sills of transition probability (i.e., asymptotic values the transition probabilities reach with increasing lag distance) reflect volumetric proportions of the facies. The row sums of $\mathbf{R}_\phi$ must equal zero, and the column sums must satisfy.

$$\sum_{j=1}^{K} p_j r_{jk,\phi} = 0 \tag{2-5}$$

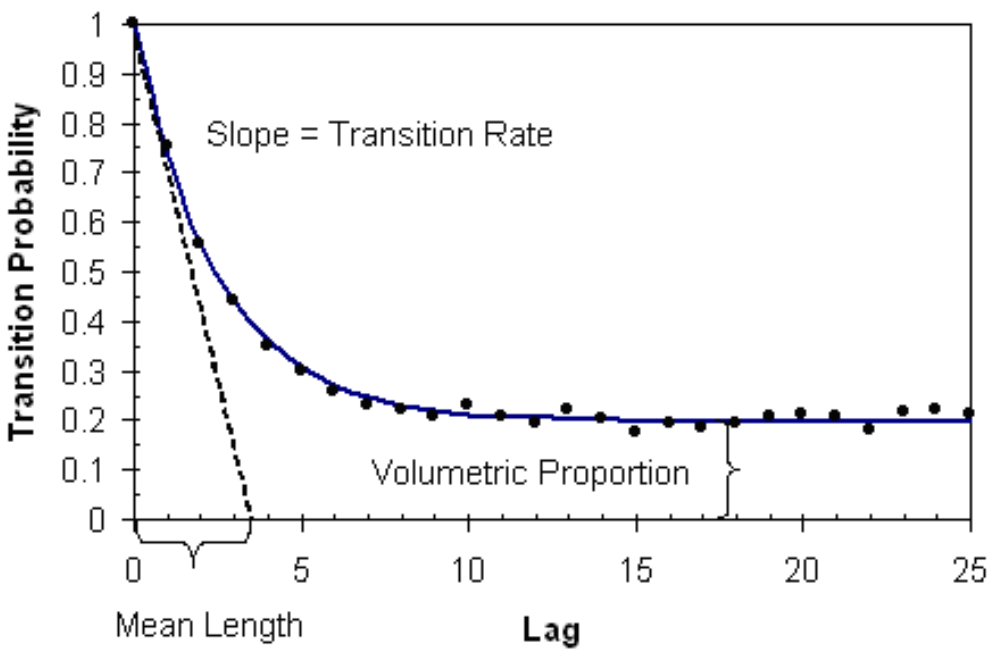


Figure 2-2. A Sketch Plot Showing Relationships Between Markov Chain Model and Observable Geologic Information. Mean Length Is the Intersection of the Tangent of Auto-Transition Probability Curve at the Origin with the Ordinate Axis, and Volumetric Proportion Is the Sill of the Transition Probability Curve.

where p_j are volumetric proportions of facies j in the system:

(2) Transition rates correspond to the slope of the transition probability at $h_\phi = 0$, namely, $r_{jk,\phi} = \partial t_{jk}(0) / \partial h_\phi$

(3) The mean length $L_{k,\phi}$ of a facies k in a direction ϕ can be calculated by dividing the total length of k by the total number of occurrences of k along ϕ. The mean length is also the intersection of the tangent of auto-transition probability curve at the origin with the ordinate axis. Mathematically, the auto-transition rate $r_{kk,\phi}$, relates to the mean length $L_{k,\phi}$ by

$$r_{kk,\phi} = -\left(\mathbf{1} / L_{k,\phi}\right) \tag{2-6}$$

(4) The juxtapositional tendencies (i.e., the tendencies for facies to occur adjacent to other facies) can be observed from the relative magnitudes of transition rates.

Markov chain models can be developed for any direction using measured transition probabilities; alternatively, Markov chain models can be developed from semi-quantitative information about volumetric proportions, mean facies lengths, and estimates of juxtapositional tendencies. A variety of other information, such as fence diagrams, outcrop maps and geophysics survey maps, can be assimilated as well. Once Markov chain models are developed, they can be used directly in geostatistical simulations to generate different realizations of facies distributions, from which the hydraulic property distributions can be inferred, and the impact of heterogeneity on flow and transport behavior can be assessed.

In reality, the lateral Markov chain models (along the strike and dip directions) are generally much more challenging to develop than the vertical ones because of lack of borehole coverage in the lateral directions. The combination of Walther's Law and the transition probability approach is usually invoked to allow for a logical approximation of lateral spatial variability from the vertical spatial variability. Walther's Law of correlation of facies states that facies that occur in conformable vertical successions of strata also occur in laterally adjacent environments (Prothero, 1990). In practice, a logical method for generating three-dimensional models of spatial variability would be first to develop the vertical Markov chain model using borehole lithology logs and then apply Walther's Law and geologic knowledge to develop lateral Markov chain models. This is the methodology that will be followed in this preliminary study.

2.3 Geostatistical Simulation

Once Markov chain models are developed along all principal directions, geostatistical simulation can be performed to generate plausible images of facies distribution. Simulations conditioned on existing data provide an important means for accessing data uncertainty while honoring known information.

A two-step simulation procedure is suggested by Carle and Fogg (1996). First, a sequential indicator simulation algorithm (Deutsch and Journel, 1992) is used to generate an initial distribution of transition probabilities through solving a transition probability-based co-kriging system. Then, starting from the initial configuration generated by the sequential indicator simulation, simulated quenching is used to improve the match between modeled and measured

transition probabilities. As a result, conditioning is maintained by disallowing changes of facies at measurement locations. The simulation algorithm described above is implemented in Transitional Probability Geostatistical Software (Carle, 1999) and interfaced via GMS.

In summary, these are the most desirable aspects of the simulation approach followed in this study (Proce, et al., 2004): (i) the algorithm maps facies into cells defined on three-dimensional grids that can be directly incorporated into groundwater flow and transport models, (ii) the realizations are made to honor existing data and statistical attributes of stratigraphy, and (iii) equiprobable interpolations between boreholes can be generated to quantify model uncertainty.

3 ANALYSES AND RESULTS

Yucca Mountain is bounded by actively subsiding sedimentary basins currently being filled with alluvium and eolian strata by alluvial-fan, braided-stream, and eolian depositional systems. Potter, et al. (2002) provided a general description of alluvium units located in the vicinity of Yucca Mountain:

> Sedimentologic properties of the various alluvial units are closely similar. Fluvial deposits are predominantly sandy gravel with inter-bedded gravely sand and sand. Fluvial facies present in these deposits include coarse-grained channel bars and intervening finer grained swales. The grain size of the bars and swales is dependent on their position in the landscape and the sediment source. The deposits associated with depositional bars include non-indurated cobble-boulder gravel and a finer grained sand and gravel deposits. The deposits associated with swales include a finer grained, silt-rich, sandy gravel and gravely sand.

Fortymile Wash, located east of Yucca Mountain, is the largest tributary of the upper Amargosa River. Sedimentological studies specifically targeting the alluvium in Fortymile Wash are rather limited (Ressler, et al., 2000; Murray, et al., 2002; Guertal, et al., 1994). Nye County Early Warning Drilling Program, a subregional-scale hydrogeologic study and monitoring program designed to help protect Nye County water supply interests (Nye County Nuclear Waste Repository Project Office, 2005), has provided much useful information on the alluvium beneath Fortymile Wash since its inception.

Nye County posted driller's lithology logs for many Early Warning Drilling Program boreholes on its website (http://www.nyecounty.com). The locations of all existing and planned Early Warning Drilling Program wells are shown in Figure 3-1. At the beginning of the analyses, all lithology logs were downloaded and classified, and a Microsoft Access database was created to store Nye County well information and lithology logs.

3.1 Selection of Boreholes

Boreholes selected for this preliminary study are listed in Table 3-1. Most boreholes listed in Table 3-1 were drilled to help (i) define valley-fill stratigraphic sequence and groundwater flow paths down-gradient of the proposed repository, (ii) provide water level and water chemistry data of alluvium and underlying Tertiary deposits, and (iii) support the characterization of transport parameters (Nye County Nuclear Waste Repository Project Office, 2005). Note that the recently drilled boreholes 22PC and 19PB, which are not shown in Figure 3-1, are close to borehole clusters 22 and 19, respectively.

The criteria for selecting boreholes for this study are (i) boreholes should penetrate relative thick alluvium sequences, (ii) boreholes are located close to the present-day Fortymile Wash channel, and (iii) detailed cutting sample logs are available.

Drilling methods mix unconsolidated materials to varying degrees and therefore may introduce biases in the drill cuttings. Most of the boreholes listed in Table 3-1 were drilled using the air-rotary reverse-circulation drilling method. Compared with other methods, the air-rotary reverse-circulation method intends to minimize cross-contamination between formation units and provide drill cuttings that are relatively uncontaminated by drilling fluids (Nye County

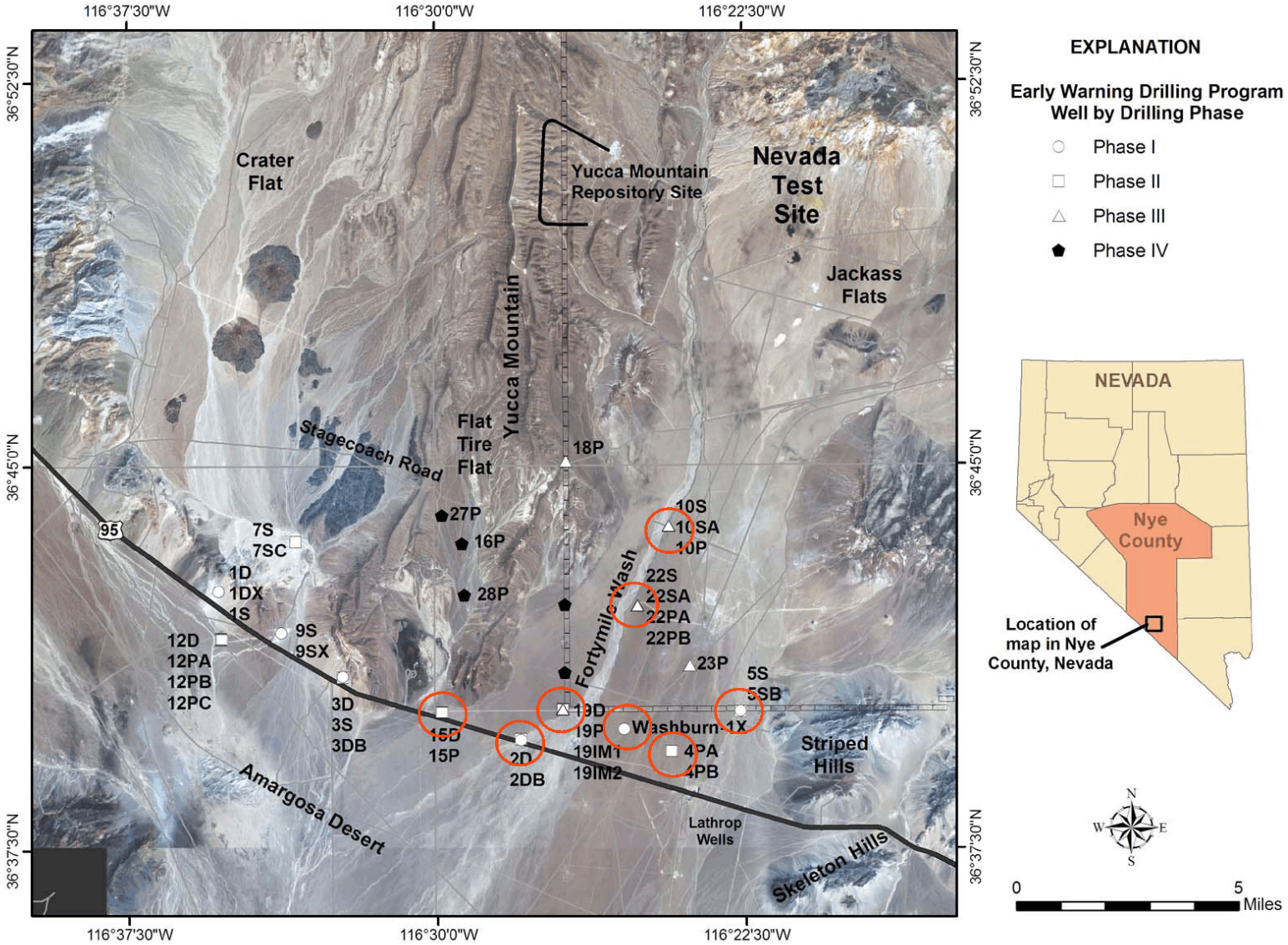


Figure 3-1. Locations of the Current Nye County Early Warning Drilling Program Wells

Table 3-1. Information of Selected Early Warning Drilling Program Boreholes			
Well Name	**Drilled Depth* (m†)**	**Length of Alluvium in Database (m)**	**Water Table Depth (m)**
2DB	937	308	89
5S	366	366	113
4PB	259	259	100
10SA	366	241	117
Washburn 1X	201	201	109
15P	88	84	64
22PC	TBD‡	93	TBD
19PB	TBD	86	TBD

*—measured below ground surface
†—1m = 0.3048 ft
‡TBD–To be determined

Nuclear Waste Repository Project Office, 2005). The air-rotary reverse-circulation can still disturb the particle size of alluvial drill cuttings from *in-situ* conditions mainly because of the grinding action of the drill bit on alluvial clasts. In the unsaturated zone, the grinding is not significant because of lack of water; however, fines may be lost as dust from the sample collection system. It is understood that the cutting logs may be biased to some degree with the biases introduced either by the driller's interpretation or by the drilling method used. Nevertheless, invaluable insights about the alluvium structure can still be obtained from analyzing these logs. The results may be approximate, but the uncertainty can be reduced by conditioning on other data.

3.2 Facies Models

Two facies models are identified: one based on grain-size distribution and the other on sediment origin.

3.2.1 Model Based on Grain Size

Most Early Warning Drilling Program lithology logs were classified under the Unified Soil Classification System, a popular system describing the texture and grain size of a soil (American Society for Testing and Materials, 1985). It is thus reasonable to choose a classification based on grain size distribution. On the basis of lithology logs, a four-facies model consisting of gravel, sand, muddy sand, and mud was established. Each of the facies has relatively distinguishable hydraulic and sedimentologic characters (i.e., hydrofacies), thus allowing facies distribution to be associated with hydraulic property distributions. The gravel facies consists of clast-supported cobbles to boulder conglomerate in a matrix of sand or well-cemented medium. Gravel clasts are volcanic in origin and subangular to sub-rounded.

The sand facies consists of medium to coarse sand with varying concentrations of gravel and displays cross stratification. The muddy sand facies consists of fine-grained sand in a matrix of silt, with occasional gravel. The mud facies consists primarily of silt and clay with occasional fine sand. A wide range of conductivity exists among the four facies, as well as in each single facies. The conductivity of gravel facies spans two orders of magnitude; sand, four or more; and mud and clay up to five (Bear, 1979).

Table 3-2 gives a partial list of Unified Soil Classification System designations found in lithology logs and the corresponding facies type assignment. Figure 3-2 shows a typical example of hand-written driller's log. In the last two columns of the plot, the Unified Soil Classification System symbols were added, and facies types were assigned based on the lithologic descriptions. The classification was then stored in the database. For many of the cutting samples, the facies type could easily be assigned based on lithologic descriptions. There were instances where the lithologic description alone was inadequate to make a unique assignment, best judgement had to be made based on the adjacent cutting samples or other forms of borehole logs (e.g., borehole resistivity measurements).

Except where noted, all facies analyses utilizing Early Warning Drilling Program lithology logs will assume the grain-size model defined herein. In general, the more facies included in a facies model, the greater the needs for parameters and computational time. The four-facies model was drawn from the existing lithology logs; however, it can be easily expanded to include a larger number of facies, or shrunken into a smaller set of facies.

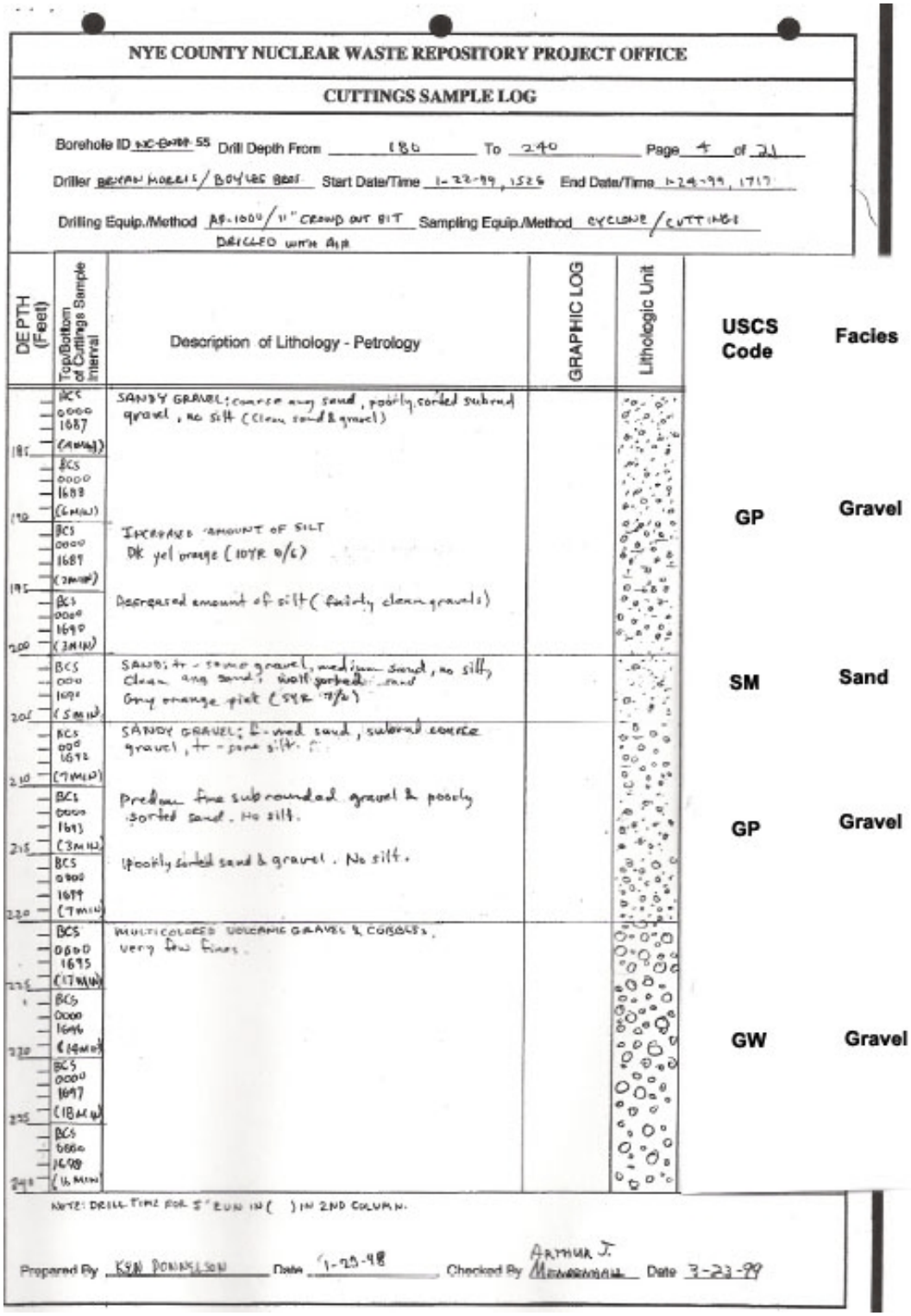
3.2.2 Model Based on Sediment Architecture

Ressler, et al. (2000) identified an eight-facies classification for Fortymile Wash alluvium based on the structure and geometry of sediments found in the outcrops. The eight sedimentary facies can be condensed into two dominant facies: braided channel facies about 10 m [32.8 ft] thick and sandy paleosol facies about 1–2 m [3.28–6.56 ft] thick. The channel facies (including facies F1–F5 and F8 in the detailed model of Ressler, et al., 2000) are more permeable and volumetrically dominant, whereas paleosol facies (facies F6 and F7) are less permeable but may form important flow barriers in the alluvial aquifer. Such a model echoes the depositional

Table 3-2. Examples of Facies Classification

USCS* Symbol	Description	Facies Category
gw	Well-graded gravel	Gravel
gw-gm	Well-graded gravel with silt and sand	Gravel
gc	Clayey gravel	Gravel
sw	Well-graded sand	Sand
gw-sw	Gravelly sand	Sand
sw-sm	Well-graded sand with silt and gravel	Sand
sc	Clayey sand	Muddy sand
cl	Clay	Mud

*USCS—Unified Soil Classification System



NYE COUNTY NUCLEAR WASTE REPOSITORY PROJECT OFFICE

CUTTINGS SAMPLE LOG

Borehole ID NC-EWDP-55 Drill Depth From 180 To 240 Page 4 of 21

Driller BRYAN MORRIS / BOYLES BROS Start Date/Time 1-22-99, 1526 End Date/Time 1-24-99, 1717

Drilling Equip./Method AP-1000 / 11" CROWN OUT BIT DRILLED WITH AIR Sampling Equip./Method CYCLONE / CUTTINGS

DEPTH (Feet)	Top/Bottom of Cuttings Sample Interval	Description of Lithology - Petrology	GRAPHIC LOG	Lithologic Unit	USCS Code	Facies
185	BCS 0000 1687 (4MIN)	SANDY GRAVEL; coarse ang sand, poorly sorted subrnd gravel, no silt (clean sand & gravel)			GP	Gravel
190	BCS 0000 1688 (6MIN)					
195	BCS 0000 1689 (3MIN)	INCREASED AMOUNT OF SILT Dk yel orange (10YR 6/6)				
200	BCS 0000 1690 (3MIN)	Decreased amount of silt (fairly clean gravels)				
205	BCS 000 1691 (5MIN)	SAND; tr - some gravel, medium sand, no silt, clean ang sand; well sorted sand Gray orange pink (5YR 7/2)			SM	Sand
210	BCS 000 1692 (7MIN)	SANDY GRAVEL; f-med sand, subrnd coarse gravel, tr - some silt.			GP	Gravel
215	BCS 0000 1693 (3MIN)	Predom fine subrounded gravel & poorly sorted sand. No silt.				
220	BCS 0000 1694 (7MIN)	Poorly sorted sand & gravel. No silt.				
225	BCS 0000 1695 (17MIN)	MULTICOLORED VOLCANIC GRAVEL & COBBLES, very few fines.			GW	Gravel
230	BCS 0000 1696 (14MIN)					
235	BCS 0000 1697 (18MIN)					
240	BCS 0000 1698 (6MIN)					

NOTE: DRILL TIME FOR 5' RUN IN ( ) IN 2ND COLUMN.

Prepared By KEN DONALDSON Date 1-25-98 Checked By ARTHUR J. MONTOYA Date 3-23-99

Figure 3-2. A Typical Example of Driller's Cutting Sample Log Used in the Analyses. The Last Two Columns in the Figure (Unified Soil Classification System Codes and Facies) Were Added to Illustrate How Lithologic Descriptions Were Translated into Facies in the Grain-Size Model. Some Logs Were More Readable Than Others.

process and provides an alternative representation of the alluvium facies distribution in Fortymile Wash. The inter-layering of thicker, more permeable facies with thinner, less permeable facies, may stratify and compartmentalize flow paths through the alluvial aquifer. Figure 3-3, taken from Ressler, et al. (2000), shows an example of conceptual alluvium models developed from their outcrop study. The yellow- and white-colored facies, which correspond to Facies F6 and F7 in Ressler, et al. (2000), are less permeable paleosols, and the other colors represent more permeable braided-channel facies. The pattern of inter-layering can be clearly observed from the figure.

The extremely coarse grain and unconsolidated nature of most lithology in the alluvium make it difficult to apply the traditional methods, such as core analysis, to determining hydraulic properties. Ressler, et al. (2000) estimated hydraulic properties using three different techniques: (i) laboratory analyses of disturbed samples that were repacked from field samples, (ii) laboratory analyses of samples collected as large intact blocks in the field, and (iii) estimates based on grain-size distribution. Estimates of the total porosity in the facies range from 0.21 to 0.42, and hydraulic conductivity varies at least three orders of magnitude between different facies. In general, the coarser-grained channel facies have lower porosities and higher hydraulic conductivities than do the finer-grained paleosol facies. The large variation in hydraulic properties, as determined by Ressler, et al. (2000), further supports the idea of representing heterogeneity within the alluvium.

Assume that the channel and paleosol facies occur in approximately equal numbers, the volumetric proportions are only a function of the average geometries of the unit types and can be determined from the mean lengths (Ritzi, 2000)

$$\frac{p_c}{p_p} = \frac{L_c}{L_p} \tag{3-1}$$

where p represents volumetric proportion, L represents mean length, and the subscripts c and p correspond to the channel facies and paleosol facies, respectively. Eq. (3-1) is only valid when facies occur in equal numbers and there are no biases in estimates of their thicknesses derived from drilling records (Proce, et al., 2004). In reality, facies do not occur in equal numbers and there are biases in thicknesses and proportions derived from raw data. Ritzi (2000) introduced a factor to account for such biases.

Identification of the paleosol facies within Early Warning Drilling Program lithology logs, however, is potentially difficult. The paleosol facies, which Ressler, et al. (2000) identified on outcrop exposure and in the 19PB sonic log, are not generally identifiable in the other borehole logs. Nevertheless, a transition probability/Markov chain model based on the Ressler, et al. (2000) sediment origin model can still be constructed using representative values obtained from the literature study (e.g., Lunt, et al., 2004). It is important to realize that the two facies models developed in this section are not mutually exclusive, and the relevant parts of each can be combined through geologic reasoning.

3.3 Volumetric Proportion Analyses

Volumetric proportions of facies provide important indication of facies distributions over space. Two sets of analyses were performed using the Early Warning Drilling Program lithology logs and the results are presented next.

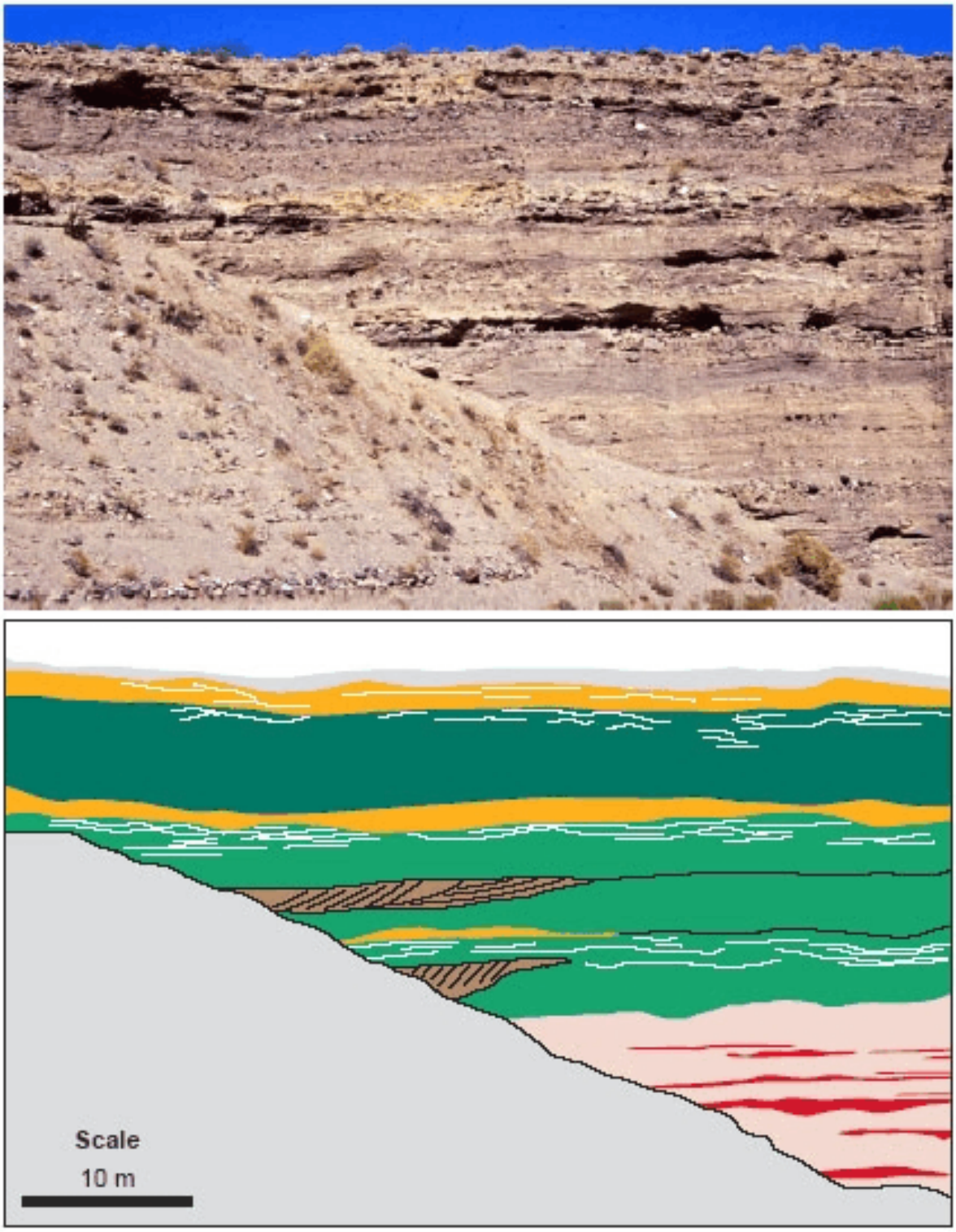


Figure 3-3. A Conceptual Alluvium Model Based on the Outcrop Study. The Golden- and White-Colored Facies Correspond to Less Permeable Paleosols (After Ressler, et al., 2000).

3.3.1 Along Fortymile Wash Channel

In the first analysis, only Boreholes 2DB, 19PB, 22PC, and 10SA were selected. The four boreholes are aligned along the present-day Fortymile Wash channel, as can be seen from the aerial photograph shown in Figure 3-1. Nye County Nuclear Waste Repository Project Office (http://www.nyecounty.com) constructed a stratigraphy fence diagram across the four boreholes based on the drill cuttings (Figure 3-4). The inferred stratigraphy roughly shows a two-layer alluvium structure. The top 100 m [328.1 ft] of the cross section consists of well-graded sand with silt and gravel. The bottom portion of the alluvium in the cross section is mainly silty sand with gravel, except near 200 m [656.2 ft] below ground surface in 2DB where a thick layer of clay starts to appear.

To calculate volume proportions, all 479 cutting sample records from the 4 boreholes were classified using the grain-size model and sorted in descending order according to depth below ground surface. The maximum penetrated thickness (defined as the distance between the highest and lowest depths) was divided uniformly into 20-m [66-ft] intervals. Because all samples were classified based on 1.5-m [5-ft] spacing, the volume proportion of each facies within a certain depth interval was calculated by dividing the number of cutting sample records belonging to each facies type by the total number of cutting sample records collected from that interval.

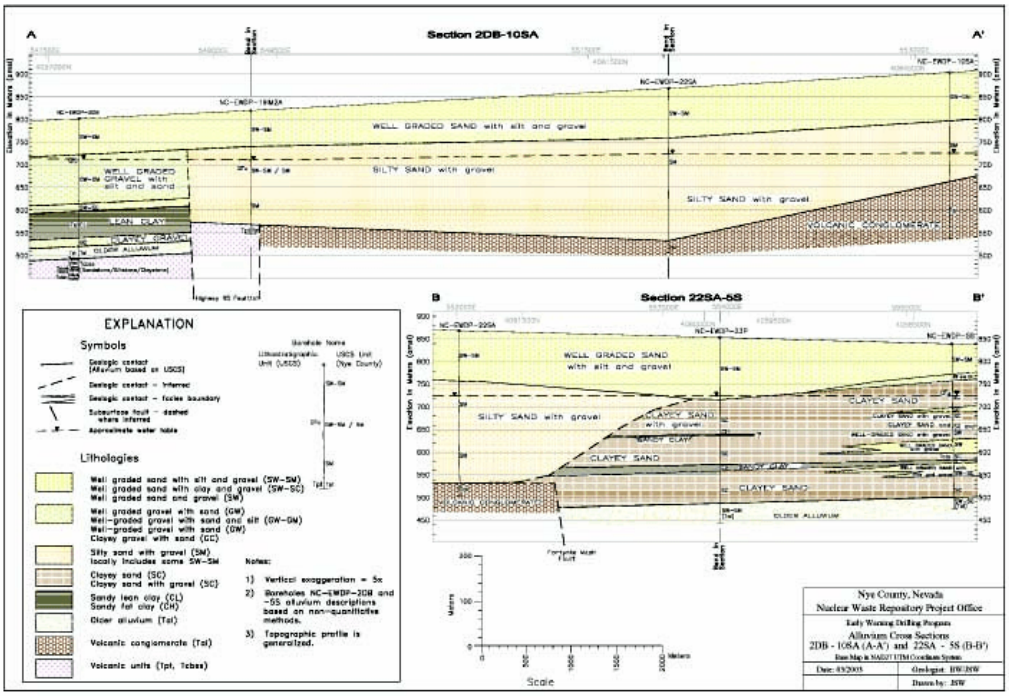


Figure 3-4. Stratigraphy Fence Diagrams for Cross Section 2DB–10SA (A-A′) and 22SA–5S (B-B′) (After Nye County Nuclear Waste Repository Project Office). Note That the Fence Diagrams Were Built Based Solely on Borehole Lithology and a Large Variation May Exist Between Boreholes.

Figure 3-5 shows the results: Figure 3-5a shows the number of records versus depth, and Figure 3-5b shows the vertical distribution of cumulative volumetric proportions of the four facies. To avoid bias caused by using records from one well, only depth intervals containing more than 20 records were included in the analyses. The volumetric proportions are not constant over depth, suggesting statistical nonstationarity in the vertical direction. No clear trend with depth can be discerned, however. To circumvent the nonstationarity issue, the whole domain is partitioned into layers of relatively constant volumetric proportions, and a balance between volumetric proportion variability and model parsimony is sought. Three layers of stationary structures were identified from the plot using the above strategy. The first layer extends from 820 to 860 m [2,690 to 2,821 ft] and consists of relatively constant proportions of gravel, sand, and muddy sand. The second layer is from 720 to 820 m [2,362 to 2,690 ft] and consists of gravel, sand and muddy sand. Compared with the first layer, the second layer has a higher proportion of muddy sand and a lower proportion of sand. The lower layer is from 660 to 720 m [2,165 to 2,362 ft] and mainly consists of gravel and muddy sand. The number of data for the portion below 720 m [2,165 ft] is insufficient to support the analysis because all data were from Borehole 2DB.

3.3.2 Lower-Valley Area

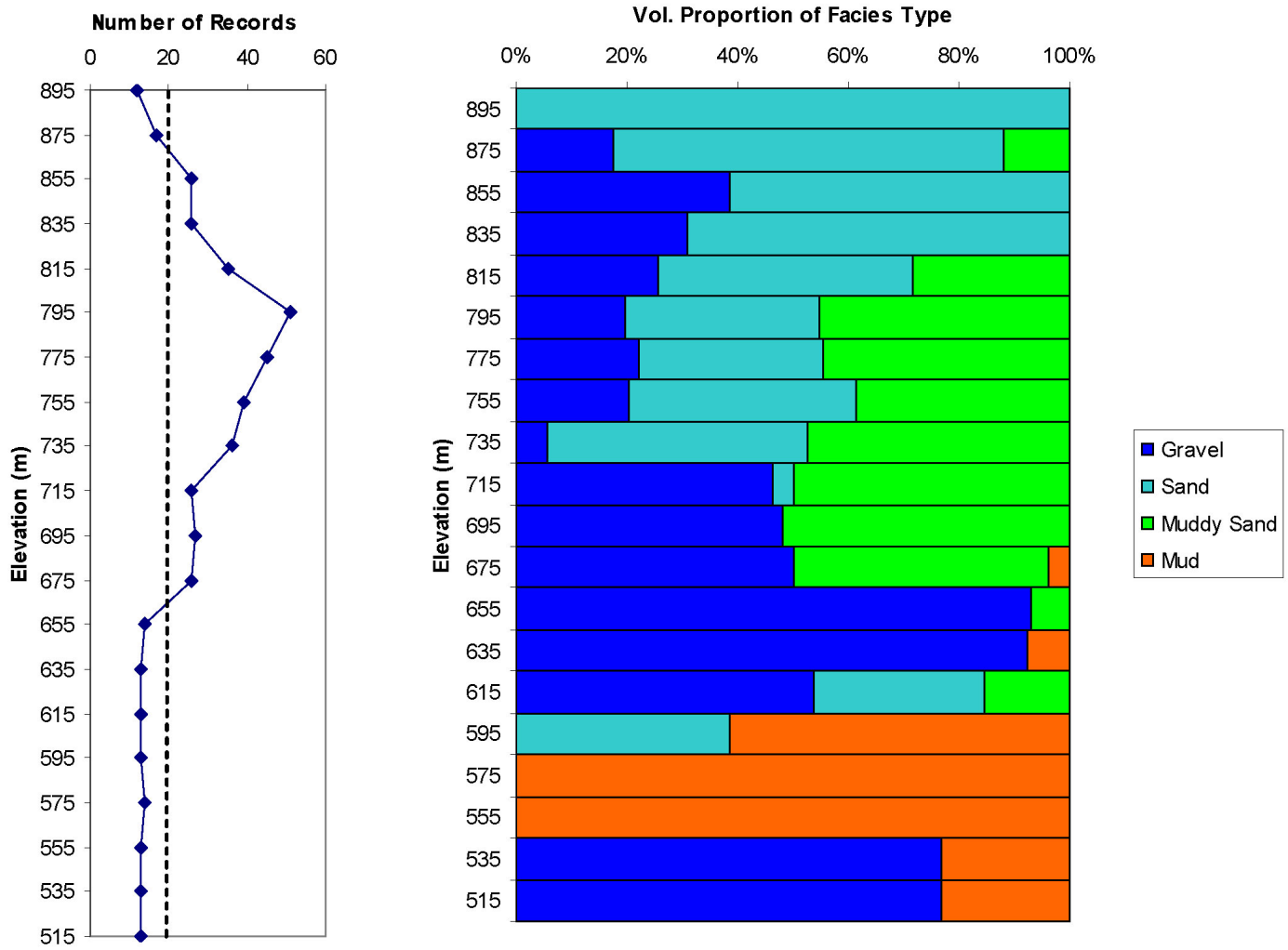
In the second analysis, all Early Warning Drilling Program boreholes in Table 3-1 were included except 22PC and 10SA. Volume proportions in boreholes located in the lower part of the Fortymile Wash basin, an area intersected by the 18-km [11.2-mi] compliance boundary, were analyzed.

A total of 857 cutting sample records were extracted from the database and processed using the procedure described in Section 3.3.1. The resulting volumetric proportions are plotted in Figure 3-6, along with the number of records pertaining to each 20-m [66-ft] interval. Again, the results shown in Figure 3-6 suggest statistical non-stationarity over depth, potentially caused by different depositional processes. From the volumetric proportion plot, three structural layers can be identified. The upper layer, extending from 760 to 820 m [2,493 to 2,690 ft], is comprised of similar proportions of gravel, sand, and muddy sand; the middle layer, extending from 620 to 760 m [2,034 to 2,493 ft], is comprised of relatively similar proportions of all four facies and the proportion of mud facies is small compared with other facies; and the lower layer below 620 m [2,493 ft] is mainly comprised of clay-dominant mud facies.

The data from the lower-valley area will be used in the next section to demonstrate the development of Markov chain models. Different Markov chain models will be developed for each layer to properly characterize the facies distribution while maintaining the stationarity assumption. Such a strateagy has been used in the works of Weissmann and Fogg (1999) and Proce, et al. (2004).

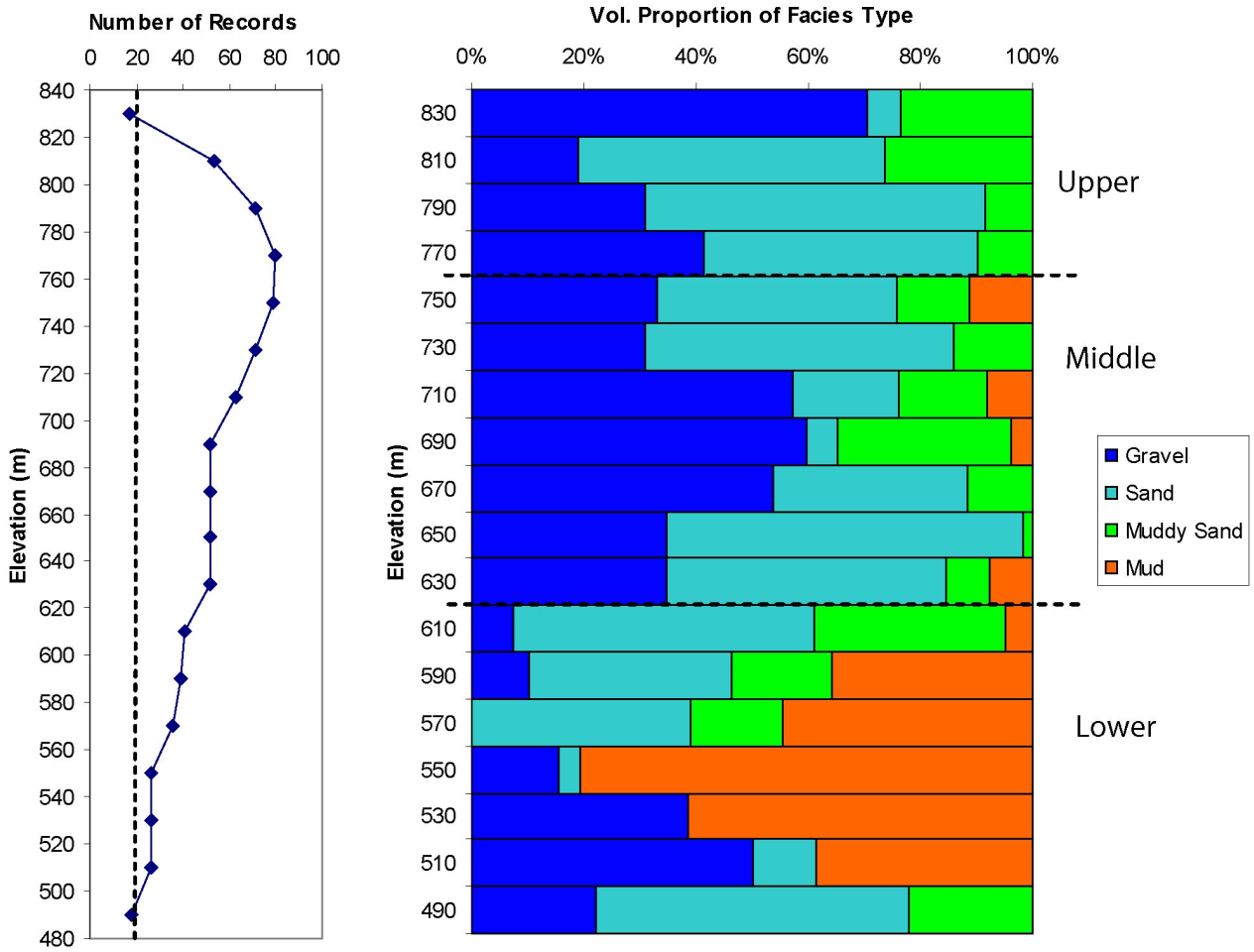
3.4 Lower-Valley Markov Chain Models

Vertical Markov chain models for the lower-valley area are developed by fitting embedded exponential transition probabilities to borehole lithology logs. The resulting Markov chain model parameters are summarized in Table 3-3. Note that the upper layer does not contain mud facies, and parameters in Table 3-3 reflect the mean values in each layer. The sand facies has the longest mean lengths in the first two layers, while the mud facies has the longest mean lengths in the third layer.



(a) (b)

Figure 3-5. Volumetric Proportion Analysis for Boreholes 10SA, 22PC, 19PB and 2DB. (a) Number of Cutting Sample Records Grouped in 20-m [65.6-ft] Intervals as a Function of Depth Below Ground Surface. Note That Intervals With Fewer Than 20 Cutting Samples Were Ignored During the Analysis. (b) Volumetric Proportions.



(a) (b)

Figure 3-6. Volumetric Proportion Analysis for Boreholes in Lower Fortymile Wash Area. (a) Number of Cutting Sample Records Grouped in 20-m [65.6-ft] Intervals as a Function of Depth Below Ground Surface. T(b) Volumetric Proportions. The Alluvium Is Divided into Three Layers of Structures (Layers Boundaries Are Indicated in Dashed Lines) Based on this Analysis. A Balance Between Volumetric Proportion Variability and Model Parsimony Was Sought When Determining the Number of Layers for Representing the Alluvium.

Table 3-3. Vertical Markov Chain Model Parameters for the Lower-Valley Area					
		Facies			
Layer	Parameter	Gravel	Sand	Muddy Sand	Mud
1	Volumetric Proportion	0.32	0.55	0.13	—*
	Mean Length (m†)	7.39	16.62	3.43	—
2	Volumetric Proportion	0.30	0.55	0.11	0.04
	Mean Length (m)	5.15	16.51	5.24	4.14
3	Volumetric Proportion	0.17	0.28	0.14	0.41
	Mean Length (m)	8.38	10.10	10.29	13.04

*— there is no mud species in the upper layer
†—1m = 0.3048 ft

Figure 3-7 shows measured transition probability data and fitted Markov chain models for the middle layer. The auto-transition probability plots are shown along the diagonal direction, whereas cross-transition probability plots are in the off-diagonal positions. The Markov chain models were developed through the embedded transition probability approach (Carle, 1999), which prescribes cross-transition rates in terms of conditional probabilities of embedded occurrences and the auto-transition rates in terms of mean lengths [see Eq. (2-6)]. Note that the mean lengths in Table 3-3 were calculated by GMS based on the first two lags of measured transition probability data (dashed lines in Figure 3-5). This strategy performs well when the data is abundant. It may not yield the best overall fit for the current case, as can be observed from some sub-plots in Figure 3-7. Further improvement in curve-fitting can be achieved by adjusting mean lengths and embedded transition probabilities manually. The three-layer approximation may be another factor that resulted in misfits in some facies. From a different perspective, the measured transition probabilities reflect biases in the raw data, so curves that fit the measured transition probabilities best are biased too. Ritzi (2000) and Proce, et al. (2000) discussed methods for reducing biases in the Markov chain models. They suggested that models should be developed separately from the measured transition probabilities. The bivariate statistics that yields the measured transition probabilities may be less reliable than the univariate statistics of volumetric proportions, facies thickness, and others.

Developing Markov chain models for lateral directions is more challenging because lack of data. Walther's Law of correlation of facies (see Chapter 2) and the vertical Markov chain models are invoked here to make logical approximations of facies distribution along the lateral directions. Such an approach requires prior knowledge of length- (i.e., along dip direction) -to-thickness and width- (i.e., along strike direction) -to-thickness ratios. Lunt, et al. (2004) developed a quantitative, three-dimensional depositional model of gravelly, braided rivers. The depositional model quantitatively represents the geometry of the different scales of strataset, the spatial

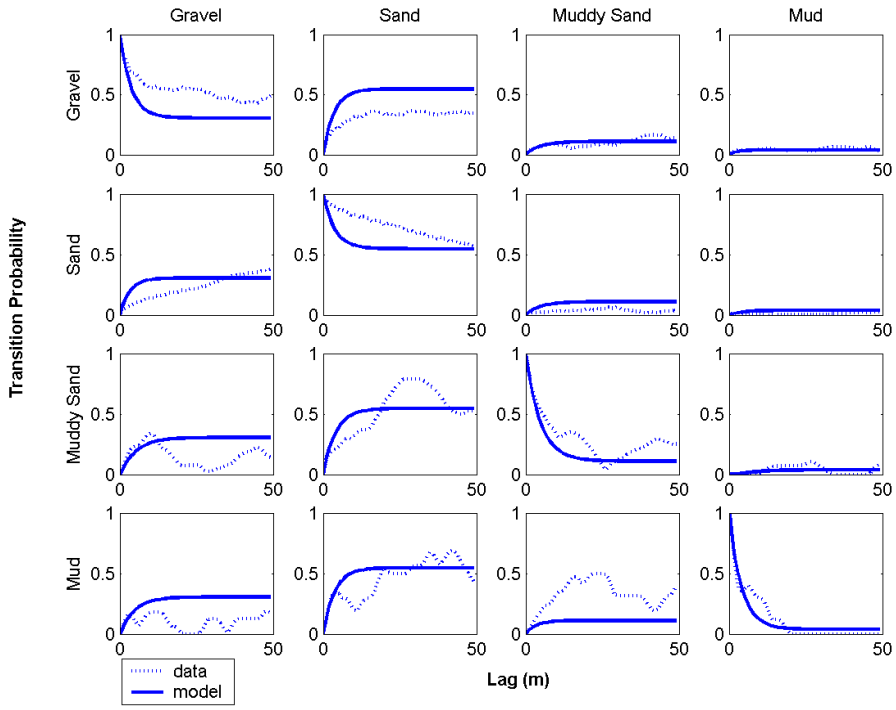


Figure 3-7. Auto- and Cross-Transition Probability Plots for the Middle Layer. The Auto-Transition Probability Curves Are Located along the Diagonal Direction and the Cross-Transition Probability Curves Are Located at Off-Diagonal Positions. The Dotted Lines Correspond to Measured Transition Probabilities and Solid Lines to Fitted Markov Chain Models.

relationships among them, and their sediment texture distribution. Lunt, et al. (2004) provide aspect ratios for lengths associated with the geometry of simple and compound large-scale strata sets of the kind which occur in Fortymile Wash. The length-to-thickness aspect ratio ranges from 20 to 500, and the length-to-width aspect ratio ranges from approximately 2 to 5. They state that because the dimensions of such deposits tend to scale with channel depth and width, the aspect ratios should be applicable to rivers of different size. By knowing the thicknesses from borehole records and by using aspect ratios within the range defined by Lunt, et al. (2004), different credible, three-dimensional Markov chain models can be developed.

Three cases are developed to demonstrate different possible scenarios; the facies aspect ratios for the strike and dip directions for these are listed in Table 3-4. In Case I, all facies have relatively small aspect ratios in both of the lateral directions, representing a case of rather discontinuous facies distributions. In Case II, the facies have longer mean lengths in both directions and the aspect ratios of facies along the dip direction are longer than those along the strike direction Case III represents a highly continuous facies distribution where the mean lengths are longer and wider than the previous two cases. Because the mean lengths and transition rates along any direction must satisfy Eqs. (2-5) and (2-6), the aspect ratios along the lateral directions also reflect these inherent constraints.

It is emphasized that the three cases explored here only represent some of the many credible scenarios. To narrow down the list, additional information such as geophysics survey data and expert opinions must be used to characterize the lateral facies mean lengths in Fortymile Wash alluvium.

Table 3-4. Aspect Ratios for Cases I, II, and III						
	Layer	**Direction**	**Gravel**	**Sand**	**Muddy Sand**	**Mud**
I	1	Strike	10	8	10	—*
		Dip	10	8	10	—
	2	Strike	9	5	10	10
		Dip	9	5	10	10
	3	Strike	10	10	10	9
		Dip	10	10	10	9
II	1	Strike	11	13	15	—
		Dip	33	39	44	—
	2	Strike	15	9	10	12
		Dip	46	28	29	37
	3	Strike	10	8	5	8
		Dip	29	24	15	23
III	1	Strike	27	28	29	—
		Dip	68	62	59	—
	2	Strike	38	25	29	24
		Dip	96	55	58	49
	3	Strike	24	20	10	19
		Dip	60	50	19	44
*— there is no mud species in the upper layer						

3.5 Lower-Valley Facies Distribution Simulation

The three sets of Markov chain models described in Section 3.4 are used to simulate facies distributions. A synthetic domain of sizes 5 km by 5 km by 320 m [3.1 mi by 3.1 mi by 1,050 ft] was set up and was discretized by a uniform numerical grid. The cell spacing is 50 m [164 ft] in both lateral directions and 2 m [6.6 ft] in the vertical direction. The resulting numerical grid consists of 1.6 million cells. The origin of the domain is located at {547,414 m; 4,057,021 m; 500 m [1.79 x 10^6 ft; 1.33 x 10^7 ft; 1,640 ft]} in UTM NAD27 projection. Note that the test domain spans all three structural layers identified in Section 3.3.2. The facies distribution in each structural layer was simulated separately and then the results from all layers were put together. Note that the *y* axis is parallel but opposite to the dip direction and the *x* axis is parallel to the strike direction. Continuity at the structural layer interfaces can be enforced by a sequential

indicator simulation algorithm (Deutsch and Journel, 1992) such that there is no abrupt change of facies at the interfaces.

One realization from each of the three cases was selected and plotted in Figures 3-8a–c, respectively. The first two structural layers were sliced in order to show the interior textures of the facies map. The patterns manifested in those images reflect the parameters (i.e., mean lengths, volume proportions) used in constructing the Markov chain models. The patterns also illustrate stochastically reasonable potential preferential flow paths, which correspond to connected high transmissive facies. Spatial variability of flow paths increases the variance of mass residence times within the alluvium: residence times will be lower within the preferential flow paths of connected gravel and sand and longer within the muddy sand and mud facies, as compared to the uniform residence time in a homogeneous domain with average permeability. Because the difference in permeability between lower- and higher-permeability facies is over orders of magnitude (Ressler, et al., 2000), the variance in mass residence time is expected to be large (e.g., Desbarats, 1990; Ritzi, et al., 2000) and may be important to represent within saturated zone site-scale transport simulations. As stated by Scheibe and Murray (1998), transport simulations should reflect the maximum entropy in transport metrics, and approaches to parameterization should allow for that maximum entropy to be expressed. Note that the parameterization that leads to maximum entropy in transport behavior is not necessarily the permeability field with maximum entropy. Geologic structure, reducing entropy in permeability from that of Gaussian random fields, can give rise to the greater entropy in transport metrics. Therefore, it is important to represent the geologic structure.

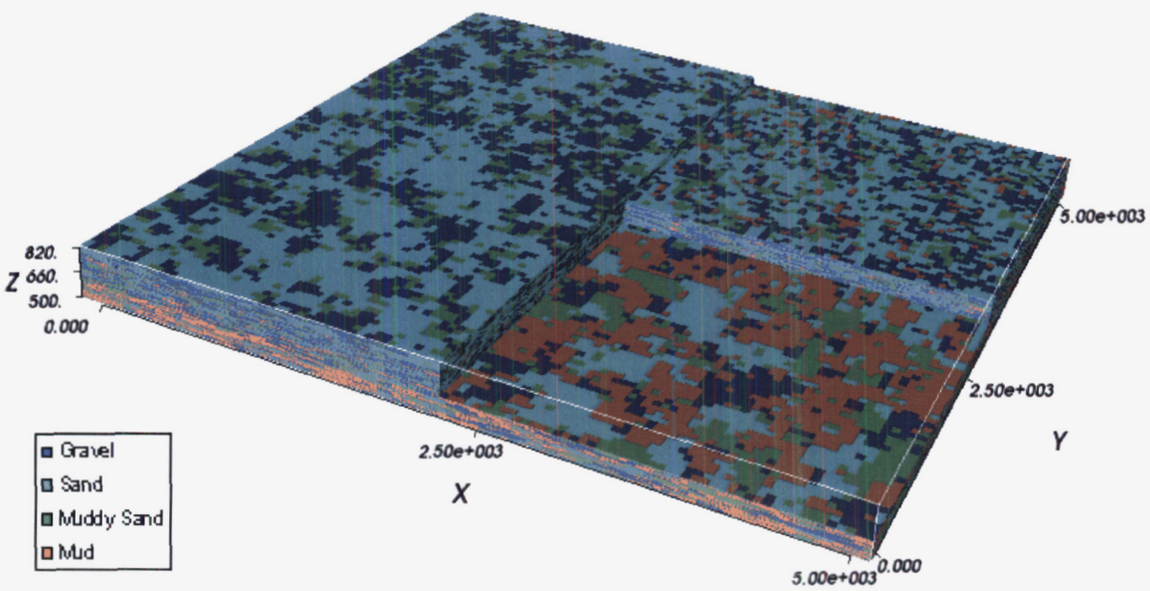


Figure 3-8a. Simulation Based on Markov Chain Models Developed for the Lower-Valley Area in Fortymile Wash: Case I

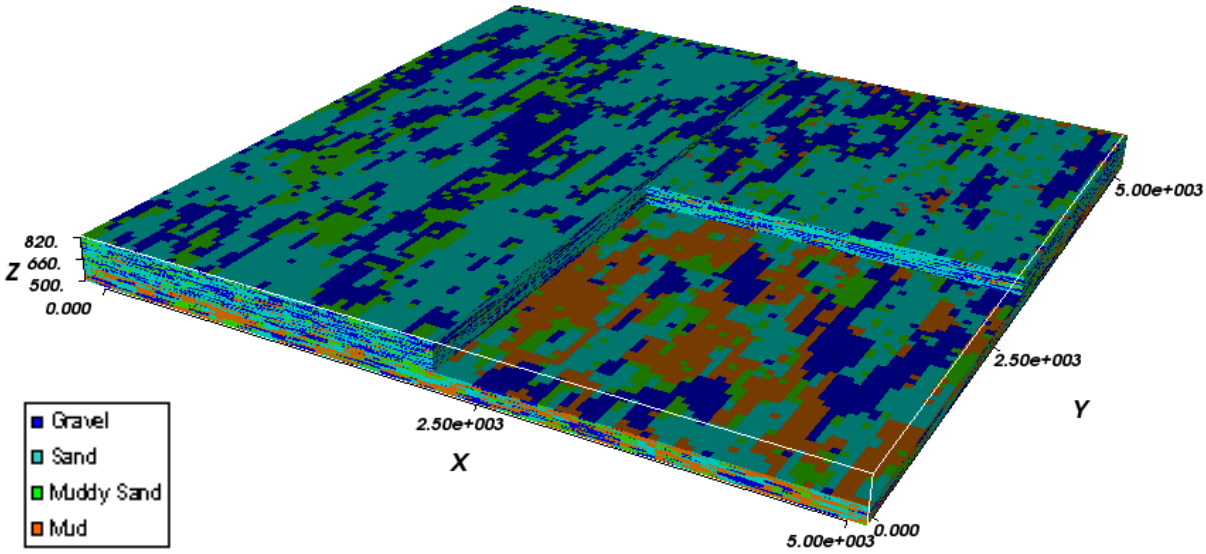


Figure 3-8b. Simulation Based on Markov Chain Models Developed for the Lower-Valley Area in Fortymile Wash: Case II

Simulations of four facies can be changed into simulations with fewer facies if transport simulations justify doing so. For example, the Case II realization shown in Figure 3-8b can be converted to a binary facies model by combining the gravel and sand facies and combining the muddy sand and mud facies. The resulting image is shown in Figure 3-9.

Upscaling techniques may be required to transform the problem from the facies model scale to the scale appropriate for existing flow and transport models so that model calibration and stochastic simulation can be performed at reasonable costs. Caution must be used when performing such upscaling tasks because many techniques are only valid when certain assumptions are met (e.g., flow through a perfectly layered system and log-normal conductivity distribution) (de Marsily, et al., 2005; Zinn and Harvey, 2003). It is important that upscaled fields preserve the continuity and interconnectedness manifested in the original facies maps.

3.6 Simulation Using the Alternative Facies Model

The binary facies model established by Ressler, et al. (2000) is investigated as an alternative model for facies distribution in alluvium (see Section 3.2.2). Using Eq. (3-1) and the estimated mean lengths {10 m [32.8 ft] for channel facies and 1.5 m [4.9 ft] for paleosol facies}, the volumetric proportions were found to be 0.870 and 0.130 for channel facies and paleosol facies, respectively. The vertical Markov chain model can then be constructed with the mean lengths and volumetric proportions determined here. Because of lack of data in lateral directions, lateral

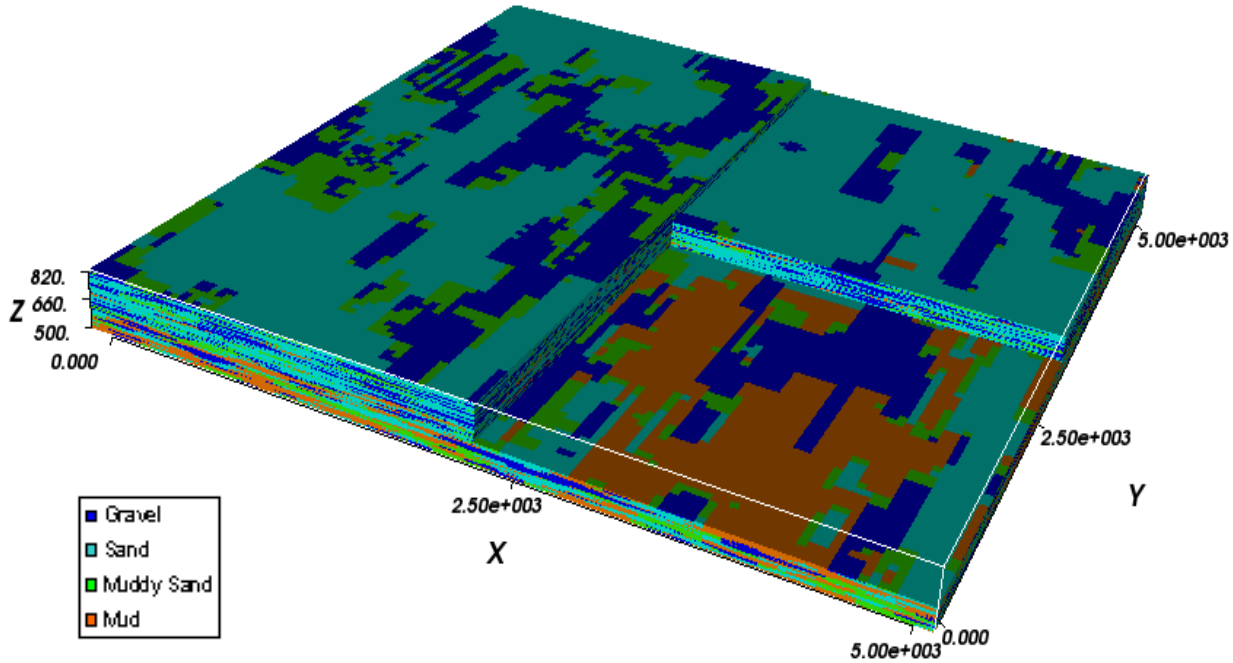


Figure 3-8c. Simulation Based on Markov Chain Models Developed for the Lower-Valley Area in Fortymile Wash: Case III

Markov chain models are constructed using the empirical aspect ratios suggested in the study conducted by Lunt, et al. (2004).

Although the binary facies model may be a parsimonious model for the facies in the upper and middle layer for the lower-valley area, it may not be applicable to the lower layer. Because the two facies models are not mutually exclusive, it would be appropriate to create a multi-layer model which has, in the upper and middle layer, open-framework gravel and paleosols along with some combinations of the facies in the grain-size model (e.g., sand-gravel mixtures/sand and muddy sand/mud mixtures).

Figure 3-10 shows an unconditioned realization of the binary facies model. The domain size is 5 km [3.1 mi] in both lateral directions and 50 m [164 ft] in the vertical direction. The lateral grid spacing is 50 m [164 ft]. The vertical discretization was set to 0.5 m [0.15 ft] to properly simulate the distribution of paleosol facies. The aspect ratio used for both facies was 100 in the strike direction and 500 in the dip direction.

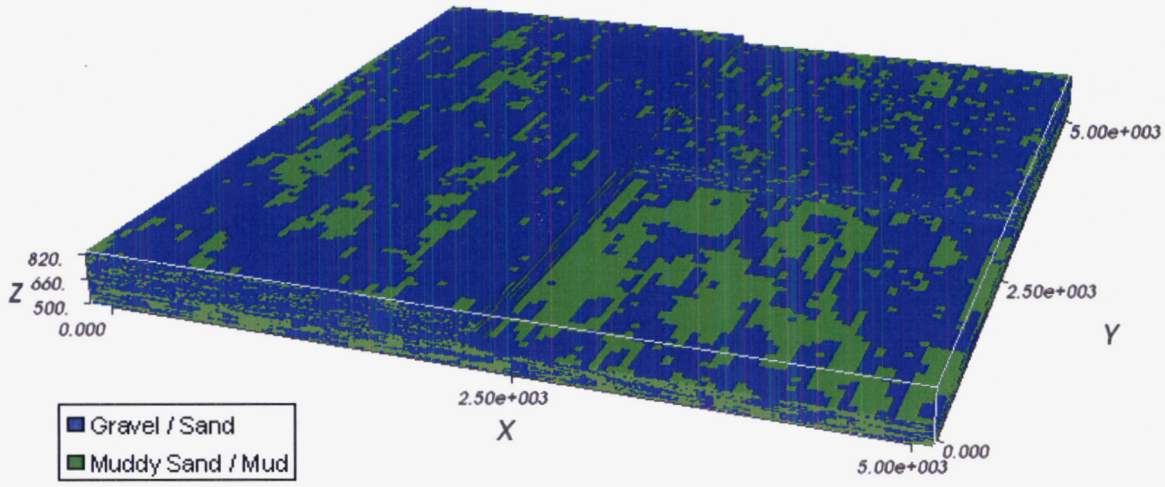


Figure 3-9. A Binary Facies Model Derived from Case II, Where the Gravel and Sand Facies Are Lumped Into One Facies, and Muddy Sand and Mud Facies Are Lumped into the Other

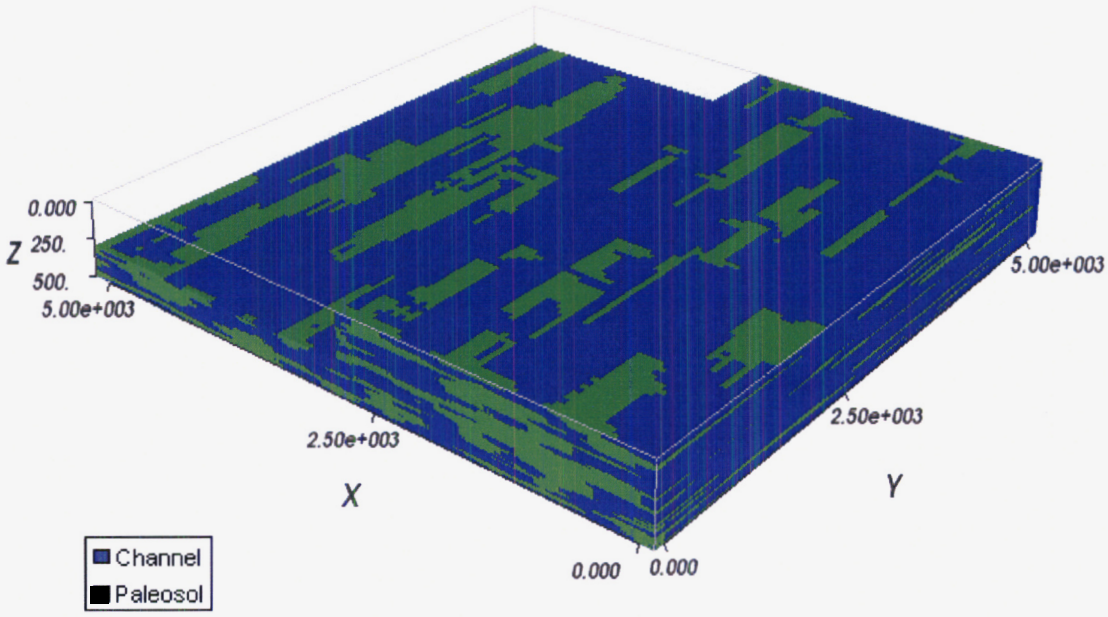


Figure 3-10. An Unconditioned Realization of Facies Map Based on the Sediment Origin Model of Ressler, et al. (2000)

3.7 Linkage With Flow and Transport Models

The transition probability/Markov chain approach for modeling alluvium heterogeneity has been demonstrated in this chapter. This approach can be used to simulate radionuclide travel times in the alluvium in a stochastic fashion. To use this approach to generate material sets for either a local- or site-scale model, the following steps are recommended:

(1) Conduct additional studies to characterize lateral distribution of facies in the Fortymile Wash area. This may include, but is not limited to, analyzing alluvium data from additional drillers' logs that were not included in the current analyses and conducting an extensive search for data that were related to the study area (e.g., Nevada Test Site data on analog basins, other data sets in Fortymile Wash or Amargosa Desert). Preliminary analyses were performed using 136 Schlumberger resistivity soundings collected by Greenhaus and Zablocki (1982) in Amargosa Desert, Nevada. The sounding curves were first discretized and the spatial correlations of resistivity were used to construct three-dimensional maps of surface resistivity. Visual comparison between the interpolated surface resistivity map and Early Warning Drilling Program borehole lithology showed a certain degree of correlation. To find a quantitative correlation model between resistivity and lithology, further analysis is required to eliminate the effect of water salinity on resistivity. The layer partitioning scheme presented in this chapter should be revisited whenever additional data are incorporated.

(2) Modeling of the alluvium heterogeneity requires a refined grid. Stochastic simulation of flow and transport processes are often performed on coarser scales to achieve computational efficiency. Upscaling from the facies scale to the flow model scale is thus necessary. Upscaling has been an active topic of research in hydrogeology and the petroleum industry. Recent literature reviews can be found in Wen and Gómez-Hernández (1996), Renard and de Marsily (1997), and Farmer (2002). Both porosity and permeability need to be upscaled. Porosity upscaling is usually done through volume averaging. The simplest techniques for computing grid block permeability are power averaging procedures (e.g., the harmonic averaging method). More robust and accurate upscaling schemes, however, require the solution of the fine-scale flow equation over the coarse region. The accuracy of the upscaling model can often be improved considerably through the use of the specialized gridding techniques (e.g., Durlofsky, et al., 1996, 1997). For example, flow-based gridding techniques enforce higher levels of grid refinement in high flow regions and coarser representation in lower flow regions. This allows the coarsened model to capture important features of the fine-permeability field without sacrifying the computational speed. It is believed that the current problem can benefit from sophisticated gridding techniques.

(3) Transport modeling requires a geochemistry database, which has been investigated extensively by CNWRA (e.g., Bertetti and Werling, 2005). The effect of chemical heterogeneity can be modeled by assigning different distribution parameters for different facies and performing transport modeling.

4 SUMMARY

The alluvial aquifer beneath Fortymile Wash is considered an important component of the natural barrier system for delaying potential radionuclide transport. The alluvium is treated as a homogeneous geologic unit in U.S. Department of Energy (DOE) saturated zone site-scale models. The lack of resolution in the alluvium can either result in an overly conservative flow model (if high transmissivity values are assigned to the entire alluvium unit) or underestimate potential fast flow paths (if calibrated effective hydraulic properties fail to capture interconnectedness in the formation). Characterizing alluvium facies distributions provides a realistic means to understand physical and chemical heterogeneity in the alluvium, thus reducing the uncertainty associated with radionuclide transport in the alluvium. Facies distributions lead to hydraulic property distributions (e.g., hydraulic conductivity, porosity) required for flow process models and also provide basis for modeling distribution of geochemical parameters, such as distribution coefficients and mineral surface areas.

The transition probability/Markov chain geostatistical method, capable of incorporating observable geologic information such as borehole lithology, volumetric proportions, and mean facies lengths, is adopted in this report to generate geologically plausible, three-dimensional facies maps. Two facies models were established for the alluvium: one based on grain-size distribution and the other on sediment origins. Facies in the former model were identified through studying driller cutting logs, whereas facies in the latter model were a simplified version of the eight-facies model based on the outcrop studies of Ressler, et al. (2000).

The initial study area was restricted to a region near the present-day Fortymile Wash channel, which is dominated by thick alluvium sequences. Analyses of the Nye County Early Warning Drilling Program lithology data indicated that the alluvium beneath the lower Fortymile Wash basin can be approximately represented by three geostatistical stationary layers, each characterized by relatively stationary proportions of facies in the grain-size distribution model. Markov chain models were then constructed for each layer, from which conditional realizations of facies maps were generated. Similarly, unconditioned simulations were performed using the sediment origin model of Ressler, et al. (2000).

Because of lack of borehole coverage in the lateral direction, Walther's Law of correlation of facies was invoked to build lateral Markov chain models in this study. The aspect ratios suggested by Lunt, et al. (2004) were used to simulate different scenarios of facies distributions. Drastically different facies patterns can be constructed by varying the aspect ratios.

The approach investigated in this report can be used to construct an embedded local-scale model for saturated zone and apply it in stochastic transport simulations. To investigate the effects of heterogeneity in alluvium, the following analysis steps may be undertaken in the future:

(1) Construct a refined local-scale process model for the alluvium using boundary conditions obtained from the Center for Nuclear Waste Regulatory Analyses saturated zone site-scale model.

(2) Model the effect of chemical heterogeneity by assigning different distribution parameters for different alluvium facies and performing transport modeling. This would be an extension of the work done by Painter, et al. (2001).

(3) Conduct stochastic simulations to evaluate uncertainty in associated flow and transport in the alluvium.

5 REFERENCES

American Society for Testing and Materials. "Classification of Soils for Engineering Purposes: Annual Book of American Society for Testing and Material Standards (D2487-83)." Vol. 04.08. pp. 395-408. 1985.

Bear, J. *Hydraulics of Groundwater*. New York, City , New York: McGraw-Hill Inc. 1979.

Bechtel SAIC Company, LLC. "Hydrogeologic Framework Model for the Saturated Zone Site-Scale Flow and Transport Model." MDL–NBS–HS–000024. Rev. 00. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004a.

———. "Saturated Zone Site-Scale Flow Model." MDL–NBS–HS–000011. Rev. 02. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004b.

———. "Site-Scale Saturated Zone Transport." MDL–NBS–HS–000010. Rev. 02. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2004c.

———. "Saturated Zone Flow and Transport Model Abstraction." MDL–NBS–HS–000021. Rev. 00. Las Vegas, Nevada: Bechtel SAIC Company, LLC. 2003.

Bertetti, P.F. and B. Werling. "Sorption of Neptunium-237 on Alluvium Collected from Fortymile Wash, Nye County, Nevada." San Antonio, Texas: CNWRA. 2005.

Carle, S.F. "T-PROGS: Transitional Probability Geostatistical Software." User's Guide. Davis, California: University of California. 1999.

Carle, S.F. and G.E. Fogg. "Modeling Spatial Variability With One- and Multi-Dimensional Continuous Markov Chains." *Mathematical Geology*. Vol. 29, No. 7. pp. 891–918. 1997.

———. "Transition Probability-Based Indicator Geostatistics." *Mathematical Geology*. Vol. 28, No. 4. pp. 453–476. 1996.

Carle, S.F., E.M. LaBolle, G.S. Weissmann, D. VanBrocklin, and G.E. Fogg. "Conditional Simulation of Hydrofacies Architecture: A Transition Probability/Markov Approach—Vol. 1: Environmental Geology." *Hydrogeologic Models of Sedimentary Aquifers, SEPM Concepts in Hydrolgeology.* G.S. Fraser and J.M. Davis, eds. Tulsa, Oklahoma: Society for Sediment Geology. pp. 147–170. 1998.

Dagan, G. *Flow and Transport in Porous Formations*. Berlin, Germany: Springer-Verlag. 1989.

Dai, Z., R.W. Ritzi, and D.F. Dominic. "Improving Permeability Semivariograms with Transition Probability Models of Hierarchical Sedimentary Architecture Derived from Outcrop-Analog Studies." *Water Resources Research.* Vol. 41. doi:10.1029/2004WR002515. 2005.

Davis, M. *Statistics and Data Analysis in Geology*. San Diego, California: Academic Press. 1986.

de Marsily, G., F. Delay, J. Gonçalvès, P. Renard, V. Teles, and S. Violette. "Dealing with Spatial Heterogeneity." *Hydrogeology Journal.* Vol. 13. pp. 161–183. 2005.

Deutsch, C.V. and A.J. Journel. *Geostatistical Software Library and User's Guide*. New York, New York: Oxford University Press. 1992.

Desbarats, A.J. "Macrodispersion in Sand-Shale Sequences." *Water Resources Research*. Vol. 26, No. 5. pp. 153–163. 1990.

Dictionary of Geological Terms. 3rd Edition. New York, New York: Anchor Press. 1984.

Doveton, J.H. "Theory and Applications of Vertical Variability Measures from Markov Chain Analysis." *Stochastic Modeling and Geostatistics—Principles, Methods and Case Studies*. J.M. Yarus and R.L. Chambers, eds. American Association of Petroleum Geologists. Computer Methods in Geology. Vol. 3. pp. 55–64. 1994.

Durlofsky, L.J., R.C. Jones, and W.J. Milliken. "A Nonuniform Coarsening Approach for the Scale up of Displacement Processes in Heterogeneous Pouous Media." *Advances in Water Resources.* Vol. 20. pp. 335–347. 1997.

Durlofsky, L.J., R.A Behrens, R.C. Jones, and A. Bernath. "Scale up of Heterogeneous Three-Dimensional Reservoir Descriptions." *SPE Journal.* Vol. 1. pp. 313–326. 1996.

Farmer, C.L. "Upscaling: A Review." *International Journal for Numerical Methods in Fluids*. Vol. 40. pp. 63–78. 2002.

Greenhaus, M.R. and C.J. Zablocki. "A Schlumberger Resistivity Survey of the Amargosa Desert, Southern Nevada." U.S. Geological Survey Open-File Report 82–897. 1982.

Guertal, W.R., A.L. Flint, L.L. Hofmann, and D.B. Hudson. "Characterization of a Desert Soil Sequence at Yucca Mountain, NV." Proceedings of the 5th Annual International Conference on High-Level Radioactive Waste Management, Las Vegas, Nevada, May 22–26, 1994. Vol. 4. pp. 2,755–2,763. 1994.

Isaaks, E.H. and R.M. Srivastava. *Applied Geostatistics*. New York, New York: Oxford University Press. 1989.

Koltermann, C. and S.M. Gorelick. "Heterogeneity in Sedimentary Deposits: A Review of Structure-Imitating, Process-Imitating, and Descriptive Approaches." *Water Resources Research*. Vol. 32, No. 9. pp. 2,617–2,657. 1996.

Lunt, I.A., J.S. Bridge, and R.S. Tye. "A Quantitative, Three-Dimensional Depositional Model of Gravely-Braided Rivers." *Sedimentology*. Vol. 51. pp. 377–414. 2004.

Murray, D.A., J.A. Stamatakos, and K.D. Ridgway. "Regional Stratigraphy of Oligocene and Lower Miocene Strata in the Yucca Mountain Region." San Antonio, Texas: CNWRA. 2002.

Nye County Nuclear Waste Repository Project Office. "Nye County Early Warning Drilling Program Phase IV Drilling Report." Nye County, Nevada: Nye County Nuclear Waste Repository Project Office. 2005.

Painter, S. "Statistical Characterization of Spatial Variability in Sedimentary Rock." *Heterogeneity in the Crust and Upper Mantle*. J. Goff and K. Helliger, eds. New York City, New York: Kluwer Academic/Plenum Publishers. 2003.

Painter, S., V. Cvetkovic, and D. Turner. "Effect of Heterogeneity on Radionuclide Transport in the Alluvium Aquifer Near Yucca Mountain, Nevada." *Ground Water*. Vol. 39, No. 3. pp. 326–338. 2001.

Potter, C.J.; R.P. Dickerson; D.S. Sweetkind; R.M. Drake, II; E.M. Taylor; C.J. Fridrich; C.A. San Juan; and W.C. Day. "Geologic Map of the Yucca Mountain Region, Nye County, Nevada." Pamphlet Accompanying U.S. Geological Survey Investigation Series I–2755. 2002.

Proce, C.J., R.W. Ritzi, D.F. Dominic, and Z. Dai. "Modeling Multiscale Heterogeneity and Aquifer Interconnectivity." *Ground Water.* Vol. 42, No. 5. pp. 658–670. 2004.

Prothero, D.R. "Interpreting the Stratigraphic Record." New York, New York: W. H. Freeman and Company. 1990.

Renard, P.H. and G. de Marsily. "Calculating Effective Permeability: A Review." *Advances in Water Resources*. Vol. 20. pp. 253–278. 1997.

Ressler, T.R., J.A. Stamatakos, K.D. Ridgeway, and J. Winterle. "Preliminary Hydrostratigraphy of the Valley-Fill Aquifer in Fortymile Wash and the Amargosa Desert." San Antonio, Texas: CNWRA. 2000.

Ritzi, R.W. "Behavior of Indicator Variograms and Transition Probabilities in Relation to the Variance in Lengths of Hydrofacies." *Water Resources Research*. Vol. 36, No. 11. pp. 3,375–3,381. 2000.

Ritzi, R.W., D.F. Dominic, A.J. Slesers, C.B. Greer, E.C. Reboulet, J.A. Telford, R.W. Masters, C.A. Klohe, J.L. Bogle, and B.P. Means. "Comparing Statistical Models of Physical Heterogeneity in Buried-Valley Aquifers." *Water Resources Research*. Vol. 36, No. 11. pp. 3,179–3,192. 2000.

Scheibe, T.D. and C.J. Murray. "Simulation of Geologic Patterns: a Comparison of Stochastic Simulation Techniques for Groundwater Transport Modeling." *Hydrogeologic Models of Sedimentary Aquifers, Concepts in Hydrogeology and Environmental Geology No. 1*. Tulsa, Oklahoma: Society of Sedimentary Geology. pp. 137–145. 1998.

Walker, R.G. "Facies Models." 2nd Edition. Geoscience Canada Reprint Series 1. Toronto, Canada: Geologic Association Canada. pp. 1–9. 1984

Weissmann, G.S. and G.E. Fogg. "Multiple-scale Alluvial Fan Heterogeneity Modeled with Transition Probability Geostatistics in a Sequence Stratigraphic Framework." *Journal of Hydrology.* Vol. 226. pp. 45–48. 1999.

Weissmann, G.S., S.F. Carle, and G.E. Fogg. "Three-Dimensional Hydrofacies Modeling Based on Soil Surveys and Transition Probability Geostatistics." *Water Resources Research*. Vol. 35, No. 6. pp. 1,761–1,770. 1999.

Wen, X.H. and J.J. Gómez-Hernández. "Upscaling Hydraulic Conductivities in Heterogeneous Media: An Overview." *Journal of Hydrology*. Vol. 183. pp. ix–xxxii. 1996.

Winterle, J.R. and D.A. Farrell. "Hydrogeologic Properties of the Alluvial Basic Beneath Fortymile Wash and Northern Amargosa Valley, Southern Nevada." San Antonio, Texas: CNWRA. 2002.

Zinn, B. and C.F. Harvey. "When Good Statistical Models of Aquifer Heterogeneity Go Bad: A Comparison of Flow, Dispersion, and Mass Transfer in Connected and Multivariate Gaussian Hydraulic Conductivity Fields." *Water Resources Research*. Vol. 39, No. 3. 1051, doi:10.1029/2001WR001146. 2003.

Zyvoloski, G., E. Kwicklis, A.A. Eddebbarh, B. Arnold, C. Faunt, and B.A. Robinson. "The Site-Scale Saturated Zone Flow Model for Yucca Mountain: Calibration of Different Conceptual Models and Their Impact on Flow Paths." *Journal of Contaminant Hydrology*. Vol. 62/63. pp. 731–750. 2003.