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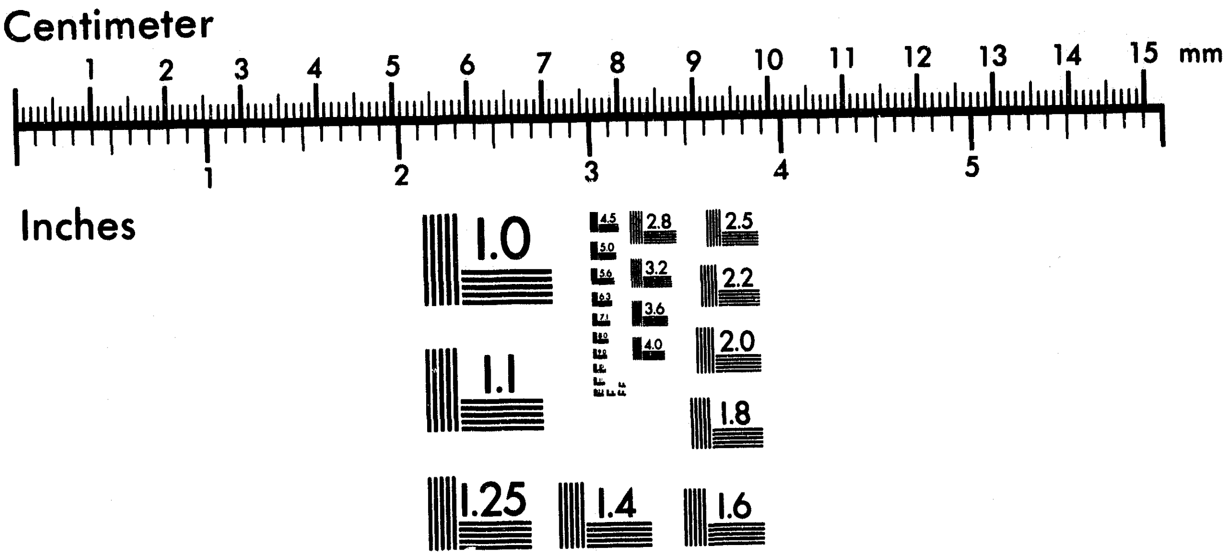

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HYDROGEOLOGIC CHARACTERIZATION OF AN ARID ZONE RADIOACTIVE WASTE MANAGEMENT SITE

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ABSTRACT

An in-depth subsurface site characterization and monitoring program for the soil water migration pathway has been planned, implemented, and completed to satisfy data requirements for a waiver from groundwater monitoring, for an exemption from liner leachate collections systems, and for different regulatory driven performance assessments.

A traditional scientific approach has been taken to focus characterization and monitoring efforts. This involved developing a conceptual model of the hydrogeologic system and defining and testing hypotheses about this model. Specific hypotheses tested included: that the system was hydrologically heterogenous and anisotropic, and that recharge was very low or negligible.

Mineralogical, physical, and hydrologic data collected to test hypotheses has shown the hydrologic system to be remarkably homogenous and isotropic rather than heterogenous and anisotropic. Both hydrodynamic and environmental tracer approaches for estimating recharge have led to the conclusion that recharge from the Area 5 RWMS is not occurring in the upper region of the vadose zone, and that recharge at depth is extremely small or negligible. Thus the potential for the migration of hazardous constituents through soil water pathway to the uppermost aquifer should be judged to be negligible. This demonstration of "no migration of hazardous constituents to the water table satisfies a key requirement for both the groundwater monitoring waiver and the exemption from liner leachate collection systems.

Data obtained from testing hypotheses concerning the soil water migration pathway have been used to refine the conceptual model of the hydrogeologic system of the site. These data suggest that the soil gas and atmospheric air pathways may be more important for transporting contaminants to the accessible environment than the soil water pathway. New hypotheses have been developed about these pathways, and characterization and monitoring activities designed to collect data to test these hypotheses.

MASTER

INTRODUCTION

The U.S. Department of Energy Nevada Operations Office Waste Management Division (DOE/NV WMD) has developed a long-term comprehensive strategy for management of low-level radioactive, mixed, transuranic (TRU), and orphan waste at the Area 5 Radioactive Waste Management Site (RWMS) at the Nevada Test Site, Nye County, Nevada. This strategy includes meeting regulatory requirements for the land disposal of different waste types. Some of the applicable regulations as determined by DOE/NV WMD which specify site characterization and baseline monitoring (subject of this report) are presented in Table 1.

Since 1987, two of the long-term goals for the management of mixed waste at this arid alluvial basin site have included obtaining a waiver from the RCRA requirement for groundwater monitoring (40 CFR 265.90(b)) and an exemption from liner leachate collection systems (40 CFR 265.301(b)). Groundwater monitoring is considered impractical because the great depth to the uppermost aquifer (approximately 240 m) precludes early detection of contaminant migration, and liner leachate collection systems are not considered to be "best available technology" for an arid site where evapotranspiration far exceeds precipitation.

Both of the above-mentioned waiver and exemption require a demonstration that "no migration" of hazardous constituents occurs to the water table. Beginning in FY88 an in-depth site characterization and baseline monitoring program was designed and implemented to make this demonstration, as well as to satisfy data requirements for the soil water pathway for a number of other regulatory drivers, including performance assessments for low level radioactive waste (DOE Order 5820.2a) and TRU and orphan waste (40 CFR 191). This program was designed and implemented following the traditional scientific approach to problem solving. For site characterization, this approach involves developing a conceptual model about the hydrogeologic system, identifying and testing hypotheses about this conceptual model, refining this conceptual model based on these tests, and repeating the steps of hypothesis testing and refinement of the conceptual model until the model is technically defensible and can be used to satisfy regulatory requirements.

Table 1. Regulatory Requirements Specifying Site Characterization and Baseline Monitoring for Different RWMS Waste Types and Facility Categories

Requirement	Waste and Facility Category					
	Low Level Waste	Mixed Waste (new cells)	Mixed Waste (existing cells)	LDR Mixed Waste (no treatment available)	TRU & Orphan Mixed Waste (new GCD[7] cells)	TRU & Orphan Mixed Waste (existing GCD cells)
DOE Order 5820.2a						
Performance assessment	Characterization & Monitoring	Characterization & Monitoring	Characterization & Monitoring	Characterization & Monitoring	Characterization & Monitoring	Characterization & Monitoring
RCRA (Part B Permit)						
Releases from solid waste management unit (40 CFR 264.90-.101)[1]	N/A	Monitoring	N/A	N/A	Monitoring	N/A
Groundwater monitoring waiver (40 CFR 265.9)[2]	N/A	Characterization	Characterization	N/A	N/A	Monitoring
No migration variance (40 CFR 268.6(a))[3]	N/A	N/A	N/A	Characterization & Monitoring	Characterization & Monitoring	Characterization & Monitoring
Exemption for liner and LCRS/LDCRS[4] (40 CFR 264.301 (b,d))[1]	N/A	Characterization	N/A	N/A	N/A	N/A
Proposed 40 CFR 193[5]						
Groundwater Protection	Characterization & Monitoring	N/A	N/A	N/A	N/A	N/A
40 CFR 191[6] (vacated and remanded)						
Performance Assessment	N/A	N/A	N/A	N/A	Characterization & Monitoring	Characterization & Monitoring

[1] CFR 264-Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities
[2] CFR 265-Interim Status Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities
[3] CFR 268-Land Disposal Restrictions
[4] Leachate Collection and Removal System/Leachate Detection, Collection, and Removal System
[5] Environmental Standards for the Management, Storage, and Land Disposal of Low-Level Radioactive Waste and Naturally-occurring and Accelerator-produced Waste
[6] Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High Level, and Transuranic Radioactive Wastes
[7] Greater Confinement Disposal

The purpose of this present report is first to describe the major components of this successful subsurface site characterization and monitoring program based on the traditional scientific approach of developing, testing, and refining a conceptual model of the hydrogeologic system; second, to present results of hypothesis testing which have provided conclusive and defensible evidence that the Area 5 RWMS is located in an extremely favorable hydrogeologic setting with no recharge occurring to the water table under the present climatic conditions; and third, to describe the refined conceptual hydrologic model of the site and new hypotheses which are currently being tested.

This report is limited to considering only one migration pathway (soil water pathway) in the hydrogeologic conceptual model of the Area 5 RWMS. This focus will permit an illustration of the scientific approach that has been applied to successfully demonstrate "no migration" to the water table, which is required both for a groundwater monitoring waiver and an exemption from liner leachate collection systems. The following section will provide further detail on the scope of this report.

SCOPE

Early in the planning stages of this program it was determined that the data needs associated with making the "no migration" to the water table demonstration (called NM-WT demonstration in the following) are very extensive and encompass data requirements of other applicable regulatory drivers for the soil water pathway. For this reason the NM-WT demonstration was used to focus the subsurface characterization program and provide a definitive list of data needs for the soil water pathway. Data needs and characterization activities for other pathways will only be discussed briefly in light of findings concerning migration via the soil water pathway.

The actual plans developed for characterizing and monitoring the soil water migration pathway focused on collecting data to quantify the amount of recharge occurring to the water table, rather than on the more difficult task of attempting to measure the migration or transport of contaminants. Contaminants generally move much more slowly than water because of the numerous potential chemical, physical, and biological changes and interactions which they can undergo in a porous media environment. Therefore, if recharge was found to be negligible, migration of contaminants via the soil water pathway would also be negligible.

The demonstration to obtain the above-mentioned waiver and exemption also requires an alternative "design and operation" to replace liner leachate collection systems and groundwater monitoring. DOE/NV WMD has developed detailed plans and conducted prototype tests of an alternative shallow vadose zone monitoring system to provide early detection monitoring and to take full advantage of natural evapotranspiration processes which provide a natural barrier to downward liquid migration. The design and operation of this alternative monitoring system will be the subject of a future report.

DOE/NV plans to submit to the State of Nevada (RCRA Authority) a formal petition for a groundwater monitoring waiver and an exemption from liner leachate collection systems in FY94. The petition will be included in a revision to the Part B Permit application for new mixed waste cells at the Area 5 RWMS. This submittal will include both a complete demonstration of NM-WT and details of the design and operation of an alternative shallow vadose zone monitoring system.

In the middle of FY92, DOE/NV WMD added the goal of obtaining a "no migration" waiver, as described in 40 CFR 268.6(a) for disposing land disposal restricted (LDR) waste that does not meet treatment standards, to their long-term strategy for managing mixed waste at the Area 5 RWMS (O'Neill et al.)[1]. "No migration" in this waiver (called LDR-NM in the following) is much more restrictive than in the NM-WT demonstration mentioned above, and is defined as "...no migration of hazardous constituents from the disposal unit zone as long as the waste remains hazardous." LDR-NM differs from NM-WT in that the former includes all pathways, and the distance to the point of compliance in the former is far less than in the latter.

To meet these restrictive migration requirements it is not surprising that formal guidance for the LDR-NM demonstration (EPA)[2] recommends the most detailed and comprehensive list of site characterization and monitoring data needs of all known applicable regulations and guidance, including data needs required for the NM-WT demonstration. The Area 5 RWMS site characterization and monitoring program was expanded in late FY92 to meet the more extensive LDR-NM data needs. The same scientific approach to site characterization as described in this present report has been followed in this expanded characterization and baseline monitoring program. The reader is referred to O'Neill et al.[1] for a detailed description of this expanded program.

In summary, the scope of this present report is limited to summarizing portions of the site characterization and monitoring program which successfully demonstrates that downward liquid flow through alluvial basin fill to the water table is not a pathway of concern at this arid site. In the following sections this report will first describe the traditional scientific approach to define critical data needs for the subsurface hydrogeologic site characterization program. This approach involves conceptual model development and hypothesis testing to refine the conceptual model. Second, site characterization activities designed to test hypotheses and to satisfy these data needs will be discussed. Third, selected results from hypothesis tests which illustrate the low potential for migration to the uppermost aquifer will be discussed. And finally, a brief summary will be given of additional work required based on new hypotheses concerning the revised conceptual model of the hydrogeologic system.

GENERAL APPROACH TO SITE CHARACTERIZATION AND MONITORING

A traditional scientific approach has been taken to focus subsurface hydrogeologic characterization and monitoring activities of the soil-water pathway at the Area 5 RWMS. This approach is illustrated in Figure 1 and includes the relationship between these activities and performance assessment. A central element of this approach is the development of a preliminary conceptual model of the hydrogeologic system based on a thorough review of historical data, sound professional judgement, and preliminary modeling including performance assessment. This conceptual model contains a number of hypotheses about important processes and site conditions. Data needs required to test these hypotheses are then identified. Additional data needs specified by regulatory requirements are also identified, and a site characterization and monitoring program is designed and implemented to meet all data needs. Based on data obtained from this program, hypotheses and the overall conceptual model are modified as appropriate; and modeling, including performance assessment, is updated to reflect the new data.

A decision point is then reached to determine if additional site characterization and monitoring work is required. The following questions should be asked:

- Is the conceptual model defensible?
- Are regulations satisfied?
- Have DOE goals been met?

If the answer is yes to all these questions, then characterization is concluded. If the answer is no to any of the questions, additional data needs are identified and additional characterization is planned and implemented. Clearly, these are difficult questions. Guidelines are required to determine who should ask these questions and what criteria are needed to answer them. These guidelines are beyond the scope of the present report and will be the topic of a future publication.

A preliminary conceptual model of the hydrogeology of the site was developed based on historical site and regional characterization data, and that took into account an arid climate with low precipitation and high evapotranspiration and a thick alluvial vadose zone. Preliminary performance assessment sensitivity modeling (Price et al.)[3], primarily using regional historical data, identified recharge flux as one of the key parameters affecting the outcome of performance assessment calculations. A conceptual model of subsurface water flux was then developed that hypothesized low recharge. In addition it was hypothesized that the alluvial basin fill materials would exhibit considerable heterogeneity and anisotropy with respect to mineralogical, physical, and hydrologic parameters.

Additional hypotheses about other important pathways in the hydrogeologic system were also developed and tested. For example, it was hypothesized that the groundwater pathway was characterized by a horizontal gradient, and deep boreholes were located to test this hypothesis. Further, it was hypothesized that near surface processes such as evapotranspiration and hydrologic conditions would be most variable in the upper 10 to 30 m of the vadose zone, and sampling and analysis plans were designed with this in mind. These and many other hypotheses concerning the conceptual model of the hydrogeologic system are outside the scope of this report and will be discussed elsewhere.

To test the hypotheses concerning recharge, two independent approaches were followed. The first, termed the hydrodynamic approach, estimates present day flux as a function of depth from hydrologic conditions and properties. The second, termed the environmental tracer approach, infers recharge from the present day vertical concentration profiles of natural environmental tracers. This latter approach integrates precipitation, infiltration, and evapotranspiration processes over many thousands of years. Required data needs (parameters) were identified for each approach, and sampling and analysis plans were developed taking into account the hypothesized heterogeneity and anisotropy of these parameters.

The sampling and analysis plans developed for the Area 5 RWMS specified collecting a large number of geologic samples throughout the vadose zone for an extensive set of laboratory tests to meet data requirements to statistically test hypotheses where possible. Statistical testing was considered essential to generate a technically defensible hydrogeologic conceptual model of the soil water migration pathway. Further, care was taken to measure a sufficient number of different types of physical, hydrologic, and environmental tracer parameters to provide a number of lines of evidence for testing the hypotheses, and to help develop an acceptable level of confidence in the outcome of the tests.

DESCRIPTION OF SUBSURFACE INVESTIGATIONS

Subsurface characterization of the alluvial basin fill materials beneath the Area 5 RWMS to date has involved three investigations designed to produce data to test the hypotheses included in the conceptual model of the soil water migration pathway. These investigations have been conducted in order of increasing complexity and cost beginning with the Existing Excavations Project (REECo)[4], followed by the Science Trench Boreholes Project (REECo)[5], and ending with the

Pilot Wells Project (REECo)[6]. Information obtained from earlier investigations was used to design and focus sampling and testing in later investigations. Sampling, in situ testing, and laboratory analysis programs for all investigations were designed to test conceptual model hypotheses described previously, and to provide representative input data into performance assessment modeling, given the budget and schedule constraints of the program.

The locations of the three investigations with respect to the Area 5 RWMS are shown in Figure 2. The relative lateral and vertical spatial coverage of the sampling transects in each of these investigations, as well as some of the major differences between investigations is summarized in Table 2.

Table 2. Summary of Subsurface Site Characterization Investigations

Step No.	Task	Location	Cost	Ease of Sampling	Sample Disturbance	Spatial Coverage	
						Vertical	Moderate
1.	Existing Evacuations	Onsite Trench 8 & Pit 3	Low	Easy	Low To Moderate	Poor	Good
2.	Science Trench Boreholes	Offsite SE Corner	Moderate	Difficult	Very Low	Moderate	Moderate
3.	Pilot Wells Corners	Offsite SE, NE, & NW Corners	High	Very Difficult	Very Low to Low	Good	Poor

The first investigation, Existing Excavations Project, focused on characterizing the spatial variability of important physical and hydrologic properties of two major allostratigraphic alluvial units (Snyder et al.)[7] exposed along lateral transects in two approximately 8 m deep waste disposal trenches within the Area 5 RWMS. These data requirements were necessary to help test the hypotheses of heterogenei'y and anisotropy of hydrologic and related parameters in the near surface. Core samples were collected and in situ measurements made at sampling locations along four 183 m transects established along the exposed face of two existing disposal excavations.

The transects were aligned approximately parallel (Trench 8, recently renamed as Pit 6) and perpendicular (Pit 3) to the principal direction of sediment transport. The thick black lines in Figure 2 represent the approximate locations of lateral transects in Pit 3 and Trench 8. One transect in each excavation was located within a clearly identified fine-grained layer and the other within an underlying coarse-grained layer. Forty-nine sampling points within each lateral transect were located according to a "clustered line" experimental design (Russo)[8] to aid in the statistical analysis of the data.

The second investigation, Science Trench Boreholes Project, consisted of a drilling, coring, and completion program involving 10 boreholes designed to characterize the lateral and vertical spatial variability of flow and transport related parameters in the upper approximately 37 m of alluvium primarily along a 61 m lateral transect near the southwest corner of the Area 5 RWMS. This spatial variability data was required primarily to test the hypothesis that the system was heterogenous with respect to hydrologic and related parameters.

A plan view of Science Trench borehole locations is shown in Figure 3; a summary of borehole depths, drilling methods, and completion methods are presented in Table 3. Seven of the 10 boreholes were located along a lateral sampling transect that was approximately aligned with the principal sediment transport direction (northeast to southwest) of the Scarp Canyon Fan, the principal alluvial fan at the site. The spacing of these boreholes (approximately 15 m) was based on spatial variability data obtained from existing excavations. The remaining boreholes were located between 9 and 30 m southeast of this transect in nearby surface channel deposits. Moreover, four of the approximately 37-m deep boreholes were completed with 0.6-m long well screens spaced 6 m apart to permit in situ air permeability testing and gas sampling using packer systems.

Table 3. Description of Science Trench Boreholes				
Borehole	Drilling Method	Borehole Diameters (m)	Total Depth (m)	Completion Method
UE5ST-1	CAU[1]	0.187	35.8	SS[3]
UE5ST-2	HSA[2]	0.178	37.7	BF[4]
UE5ST-2A	CAU	0.187	36.6	SS
UE5ST-3	HSA	0.178	4.4	BF
UE5ST-4	HSA	0.178	34.7	BF
UE5ST-4A	CAU	0.187	36.6	SS
UE5ST-5	HSA	0.178	11.4	BF
UE5ST-6	HSA	0.178	35.4	BF
UE5ST-6A	CAU	0.187	36.6	SS
UE5ST-7	HSA	0.178	10.7	BF

[1] Casing Advance Under-reaming Drilling System
[2] Hollow-stem auger
[3] Screened and stemmed
[4] Backfilled

The third investigation, Pilot Wells Project, included drilling, sampling, logging, instrumentation, and in situ testing activities in three deep boreholes which were completed through the thick vadose zone and into the uppermost aquifer. The locations of the approximately 275 m deep Pilot Wells (Figure 2) were chosen to be outside of past, current, and future waste disposal areas; and to be at the apexes of a triangular array and separated by approximately 1.6 km to help test the hypothesis of a virtually horizontal water table mentioned previously. UE5PW-1 and UE5PW-2 were both located on older pediment surfaces where early stages of desert pavement have developed. UE5PW-3 is located closer to the Massachusetts Mountains on a much younger pediment surface.

These Pilot Wells were designed to provide detailed vertical spatial coverage of hydrologic and related parameters from the ground surface to 15 m below the uppermost level of groundwater to test hypotheses concerning both heterogeneity and recharge described in previous sections. In addition to completing these wells as RCRA-type monitor wells, instrumentation was installed throughout the vadose zone to monitor hydrologic parameters over time and provide access to collect subsurface gas samples and conduct in situ testing. A summary of Pilot Well depths and borehole diameters is given in Table 4.

Table 4. Description of Diameters and Depths of Pilot Wells				
Borehole	Drilling Method	Borehole Diameters (m)	Depth (m)	Total Depth (m)**
UE5PW-1	CAU*	0.306 0.237	0 - 115.9 115.9 - 255.7	255.73
UE5PW-2	CAU	0.306 0.237	0 - 122.0 122.0 - 280.4	280.4
UE5PW-3	CAU	0.306 0.237 0.212 0.200	0 - 137.3 137.3 - 234.9 234.9 - 250.9 250.9 - 291.3	291.3

* Casing Advance Under-reaming Drilling System
**Measured from the ground surface

Site Characterization Methods

Industry standard methods were followed (where possible) for field and laboratory site characterization activities. Methods related to sample collection will be described in this report because the methods are relatively new and the reader may not be familiar with them. Other methods which may have an equal impact on data validity, including sample handling, laboratory testing, in situ testing, and borehole instrumentation and completion are described in detail elsewhere (REECo)[4,5,6].

Core Sampling

In each of the previously mentioned investigations (Existing Excavations, Science Trench Boreholes, and Pilot Wells) large numbers of representative geologic core samples were collected for laboratory testing to provide information about important parameters which influence recharge and migration beneath the Area 5 RWMS. The primary method used to obtain representative core samples involved using an air-percussion hammer to drive a sample tube containing segmented polycarbonate or stainless steel liners. This drive-core sampling method was selected based on its capability to collect representative core samples from relatively dry coarse-grained alluvial deposits for laboratory testing of important physical and hydrologic parameters (Hammermeister et al.)[9].

Drill Cuttings Sampling

Drilling methods were selected for the borehole investigations (Science Trench Boreholes and Pilot Wells) to minimize the disturbance of the formation and drill cuttings. The Pilot Wells and four of the Science Trench Boreholes were drilled with different diameter casing-advance under-reaming (CAU) systems using air as the drilling fluid. The remaining Science Trench Boreholes were drilled with hollow-stem auger systems. The CAU drill cuttings samples were collected from both Science Trench Boreholes and Pilot Wells at 0.76 m depth intervals in a cyclone separator. Auger cuttings were not collected from the hollow-stem auger holes because of the poor return of cuttings to the ground surface.

The CAU drilling systems, when operated as designed, rapidly and nearly completely move drill cuttings to the ground surface from the interval being drilled, ensuring that drill cuttings samples collected at the ground surface are from the interval being drilled. Further, the rapid transport of drill cuttings to the ground surface minimizes the disturbance of the water content of the samples. Moreover, these systems case-off (seal) the formation as it is being drilled and minimize the disturbance of the formation from the compressed air drilling fluid. Minimizing the disturbance of the hydrologic parameters in the formation is necessary to obtain meaningful vadose zone monitoring data in a timely manner.

Drill cutting samples were especially important in the Pilot Wells investigations because they could be used to supplement the information obtained between often widely spaced core intervals.

SELECTED CHARACTERIZATION LABORATORY ANALYSES AND RESULTS

Only selected results from the laboratory analysis of geologic core and drill cutting samples that helped test hypotheses concerning the soil water migration pathway will be presented in this section. A large body of related data, not included in the following, from all three investigations fully supports results of hypothesis tests described below. The reader is referred elsewhere (REECo)[4,5,6] for a complete discussion of this comprehensive data set.

Both data requirements and methods of obtaining these data have been defined to test specific hypotheses. In order to test the hypothesis of heterogeneity and anisotropy in the near surface, laboratory measurements of particle size distribution, bulk density, and hydraulic conductivity were conducted on all vertically and horizontally oriented core specimens collected from two major allostratigraphic units in the Existing Excavations. In addition, moisture retention relations and unsaturated hydraulic conductivity were determined on selected horizontal and vertical core.

The same parameters were measured in the laboratory on vertically oriented core samples from both the Pilot Wells and Science Trench Boreholes to test the hypothesis of heterogeneity throughout the thick alluvial vadose zone. Since it was not possible to collect horizontally oriented core samples from these boreholes, the hypothesis of anisotropy could not be tested with depth.

In order to test the hypothesis of negligible recharge, laboratory measurements of water content and water potential as well as environmental tracers were also measured on the vertically oriented core samples from both Science Trench and Pilot Well Boreholes.

Finally, borehole drill cuttings samples were tested to supplement core sample data for parameters not affected by the arrangement and orientation of alluvial particles and by small changes in water content from in situ conditions. These parameters included inorganic and organic carbon, chloride (environmental tracer), and particle size distribution.

Heterogeneity and Anisotropy Hypothesis Testing

Inorganic and Organic Carbon

Inorganic and organic carbon concentration profiles are useful in identifying soil layers that have the potential for retarding the movement or altering the chemical behavior of contaminants (Domenico and Schwartz)[10]. For example, organic carbon measurements help to identify soil layers with elevated humus concentrations which have the potential to strongly sorb most hydrophobic contaminants. Moreover, inorganic carbon measurements can help to identify caliche (carbonate cemented) layers. Caliche layers can exhibit very low porosities and hydraulic conductivities and thus can greatly influence hydrologic processes of infiltration, evapotranspiration, redistribution, and recharge.

Depth profiles of inorganic carbon in alluvial drill cuttings samples from all three Pilot Wells are illustrated in Figure 6. Inorganic carbon data from core samples (not shown here) are very similar to the drill cuttings data. Moreover, data from the upper approximately 37 m of the Pilot Wells are typical of data from the Science Trench Boreholes. These data show that inorganic carbon concentrations are very low (mean values are less than one percent by weight) and nearly constant throughout the entire thickness of alluvium penetrated. Clearly caliche layering will not be responsible for significant heterogeneity in hydrologic parameters.

Organic carbon values are generally an order of magnitude lower and equally as constant, demonstrating the absence of humus accumulation and layering which may cause heterogeneity in hydrologic and geochemical parameters.

Physical Properties

Several physical properties are relatively easy and inexpensive to measure and are indicators of heterogeneity and anisotropy of hydrologic parameters in the hydrologic system beneath the Area 5 RWMS. These physical properties include particle size distribution, bulk density, and porosity. Particle size distribution together with bulk density (and porosity) can provide a rough estimate of hydrologic flow properties (eg. hydraulic conductivity and moisture retention characteristics). In addition they provide insight into the depositional environment.

Particle Size Distribution. Plots of selected particle size distribution parameters of core samples from representative transects in Existing Excavations, Science Trench Boreholes, and Pilot Wells are shown in Figures 5, 6, and 7 respectively. Data from the No. 4 and No. 200 sieve analyses (percent of material passing) are presented in these figures. Particles larger than the No. 4 sieve (4.75 mm) are classified as gravel and particles smaller than the No. 200 sieve (0.075 mm) are classified as fines (silt and clay). These figures illustrate the relative percent of materials falling into the gravel, sand, and silt/clay fractions along sampling transects; and show that the particle size distribution of alluvial materials is remarkably similar both in the lateral and vertical direction. These materials are predominantly composed of sand-sized particles with considerable amounts of gravel and usually contain less than 10 percent silt/clay. Hydrometer analyses performed on selected samples indicated that the fine fraction (silt/clay) consisted primarily of silt for all transects.

Similar plots of particle size data from drill cuttings samples collected from the first Pilot Well (Figure 7) indicate only a small difference between core and drill cuttings profiles. These relative small differences may be due to a number of drilling and sampling related factors. Regardless it is important to note that the drill cuttings data (collected and measured on 0.76 m sampling depth intervals) indicate that the relatively uniform particle size distribution profiles obtained from widely separated core samples are typical of the entire vadose zone.

Using particle size distribution data, core and drill cuttings samples were classified into different textural classes based on the Unified Soil Classification System (USCS) for vertical transects. Preliminary stratigraphic columns (REECo)[5,6] were prepared for each Pilot Well and Science Borehole using USCS data. Little if any correlation of textural units was noted between boreholes, even the Science Trench Boreholes separated by only 1.5 m. This lack of correlation is not surprising because the depositional processes that combine to form alluvial fans often interact to produce highly variable and discontinuous stratigraphies both in the lateral and vertical directions.

Particle size distribution data from all three investigations show little variability in both the vertical and horizontal directions, and no evidence of trend was noted in either direction. In short, the alluvial system is remarkably homogeneous rather than heterogeneous in terms of particle size distribution. If this parameter is an indicator of hydrologic parameters, it is likely that hydrologic parameters will also exhibit homogeneity rather than heterogeneity.

Bulk Density and Porosity. Porosities were calculated for core samples assuming a particle density of 2.65 g/cm^3. These data indicate that bulk densities (and porosities) are relatively constant in all transects, and especially so in the lateral transects in the Existing Excavations. This uniformity may be due in part to the similarity of the particle size distribution, consistency in mineralogy and lithology, and the near absence of secondary mineral cementing agents. The only trend appears to be a slight increase in bulk density and decrease in porosity with depth in the upper portion of Science Trench Boreholes. In summary these data suggest no evidence of layering which could in turn cause heterogeneity in hydrologic properties.

Hydrologic Properties

Hydrologic properties are required, together with hydrologic conditions (see following section), to estimate rates of water movement, potential travel times, and recharge. Hydrologic property measurements include saturated and unsaturated hydraulic conductivities and moisture retention relations. Unsaturated hydraulic conductivities were calculated from the above-mentioned parameters in this study because they are very difficult, if not impossible, to measure in the laboratory or in the field at the very dry in situ water contents found in the vadose zone beneath the Area 5 RWMS.

Saturated Hydraulic Conductivity. Saturated hydraulic conductivities of core samples from representative vertical and lateral transects (Figures 8, 9, and 10) are remarkably uniform in value and are typical of values for silty sand alluvial deposits reported in the literature (Freeze and Cherry)[11]. Probably the most convincing demonstration of uniformity of saturated hydraulic conductivity values was found in the coarse and fine transects corresponding to different allostratigraphic units in the Existing Excavations. Statistically significant differences in saturated hydraulic conductivity (log K_s) were found to exist between coarse and fine layers for Trench 8 but not for Pit 3. The lack of significant differences in log K_s between coarse and fine layers in Pit 3 was unexpected given apparent differences in particle size distribution for these materials. Further, differences between core orientation (horizontal vs. vertical) were not significant for Trench 8 or Pit 3. The lack of vertical vs. horizontal anisotropy for log K_s in the coarse layers was unexpected given the presence of cross-bedding in these materials. In summary, there appear to be very little heterogeneity and anisotropy with respect to this important hydrologic property, even in layers with contrasting particle size distributions.

Moisture Retention Relations. Moisture retention curves measured on core samples from the first Pilot Well are presented in Figure 11. These curves are typical of data obtained from core samples from vertical and horizontal transects in all investigations. Core sample depths for each curve are not identified in these plots. The general shape of these moisture retention curves is, without exception, typical of coarse-grained deposits (Koorevaar et al.)[12]. Again, this data demonstrates homogeneity rather than heterogeneity.

Moisture retention data were fit to the van Genuchten[13,14] parameterization of the water retention relation described by:

$$\Theta = \Theta_r + (\Theta_s - \Theta_r)[1+(-\alpha h)^n]^{-m} \qquad \text{Eq. (1)}$$

where Θ is volumetric water content (cm^3/cm^3), Θ_s is the saturated volumetric water content, Θ_r is the residual volumetric water content, h is matric potential (cm), α (cm^{-1}), and m and n (dimensionless) are curve fitting parameters, where m is (1-1/n).

A nonlinear least squares computer code (van Genuchten)[13] was used to calculate the curve-fitting parameters α,n, and the residual saturation Θ_r. These parameters were tabulated for core samples from different investigations, and summary descriptive statistics were calculated (REECo)[4,5,6] assuming each parameter was normally distributed. The values of these parameters are consistent with values calculated for a number of coarse-grained soils (van Genuchten)[13]. Curves obtained from mean values of these parameters for different vertical and lateral transects are plotted in Figure 12. These curves are remarkably similar and are consistent with the very similar particle size distributions and porosities measured for these materials, indicating homogeneity rather than heterogeneity in the unsaturated flow properties of the alluvium at the Area 5 RWMS.

Unsaturated Hydraulic Conductivity. Unsaturated hydraulic conductivity relationships were obtained by combining the van Genuchten moisture retention relations (van Genuchten)[13,14] with the hydraulic conductivity model of Mualem[15] to obtain:

$$K(S) = K_s S^{1/2}[1-(1-S^{1/m})^m]^2 \qquad \text{Eq. (2)}$$

where K_s is the saturated hydraulic conductivity and S is effective saturation as defined by:

$$S = (\Theta-\Theta_r)(\Theta_s-\Theta_r)^{-1}. \qquad \text{Eq.(3)}$$

The resulting K(S) data, which has been converted to K(Θ) data through Equation 3, is illustrated for core samples from the first Pilot Well in Figure 13. Figure 14 shows curves calculated from mean van Genucthen parameters and mean K_s values for core samples from representative transects from all investigations. These curves illustrate that unsaturated hydraulic conductivities decrease rapidly with decreasing water contents. At the low water contents found in the unsaturated zone at the Area 5 RWMS, the unsaturated hydraulic conductivities are many orders of magnitude less than the saturated hydraulic conductivities. Finally, these curves are remarkably uniform indicating homogeneity rather than heterogeneity with respect to unsaturated flow properties throughout the vadose zone.

Hydrodynamic Approach To Testing the Hypothesis of Negligible Recharge

The hydrodynamic approach relies on hydrologic conditions in combination with hydrologic properties to estimate rates of water movement, potential travel times, and recharge. The actual calculation of rates of water movement presented in the following require the assumption of homogeneity and isotropy that have been demonstrated in the previous sections.

Hydrologic Conditions

Hydrologic conditions are properties of the formation that vary over time. These include water content and water potential, where the latter is dependent on the former. The gradient of water potential values (i.e., the difference in value between two points divided by the distance separating these points) is one of the primary forces that drive the movement of liquid water.

Water Content. A comparison of the alluvial volumetric water content profiles from all three Pilot Wells (Figure 15) illustrates that water content values are remarkably low and constant throughout the entire zone of unsaturated alluvium. Plots of similar data from Science Trench Boreholes (REECo)[5] confirms these trends in the upper approximately 37 m. The only noticeable trend in these profiles is a possibly a slight increase in water content from the ground surface to a depth of approximately 30 m. The mean water contents of these plots correspond to the steeply sloping portion of the moisture retention relations shown in Figure 12, indicating that in situ alluvial materials exist in a very dry state. Clearly, little if any water is presently draining from the system. Both unsaturated hydraulic conductivity data discussed previously and water potential data discussed below support this picture of the system.

Water Potential. Water potential depth profile data (Figure 16) show a positive gradient (upward flow) to at least a depth of 30 m in each Pilot Well. Similarly, water potential data from representative Science Trench Boreholes (Figure 17) show a positive gradient throughout the upper 37 m of alluvium, with the largest gradient in the upper 9 m. This data suggests that water is moving upward in the upper 30 m, because other potential gradients affecting water movement (eg. gravitational potential) are small compared to the water potential gradient.

Water potentials are actually the sum of the matric and osmotic potentials. Matric potentials result from capillary forces and osmotic potentials from dissolved salts. The osmotic component for the alluvium at the Area 5 RWMS is estimated to be no more than -10 bars in the near surface and trends monotonically with depth to a value near zero in cores below 100 m. Considering the relative magnitudes of the water potential and the osmotic potential in the upper

100 m in both Pilot Wells and Science Trench Boreholes (Figures 16 and 17), the contribution of the osmotic potential to the water potential is considered to be negligible.

The direction of water flux in alluvium throughout the entire vadose zone can be identified by plotting the matric potential against the height above the water table (Koorevaar et al.)[12]. Since in the Science Trench Boreholes and Pilot Wells Projects water potential measurements are approximately equal to matric potentials, a plot of water potentials against height above the water table (Figure 18) can provide insight into the direction water is moving.

When there is no movement of water (equilibrium condition) the relationship between matric potential and height will follow a 1:1 line. For a recharging condition (downward flux), the matric potential will be larger (less negative) than the equilibrium value and plot to the right of the 1:1 line. An upward flux would be characterized by more negative matric potentials which would plot to the left of the 1:1 line.

The data in Figure 18 show an upward flux to be present between 200 m and 230 m above the water table (upper 30 m of the vadose zone), indicative of a profile undergoing long term evaporation and drying. Between approximately 80 m to 200 m above the water table, the potential data suggest downward flow. From 80 m above the water table (150 m below land surface) to the water table, the soil water is in equilibrium with the water table and there is no potential for movement.

In summary, analysis of water potential profiles at the Area 5 RWMS indicates that the hydrologic regime of the vadose zone consists of an upper region where infiltrating precipitation redistributes and then leaves the upper profile via evapotranspiration, a middle region characterized by low water contents and a small downward gradient (see next Section) resulting in extremely small downward fluxes, and a lower region which is in equilibrium with the uppermost aquifer which means there is zero potential and zero rate of soil water movement to the water table. These data provide strong evidence that recharge under present day climatic conditions is negligible and therefore the hypothesis concerning recharge is correct.

Rate of Flow

Darcy's law describes one-dimensional flow in an isotropic homogeneous medium by:

$$q = -K(\theta)\frac{\Delta H}{\Delta z} \qquad \text{Eq. (4)}$$

where q is the flux or the volume of water passing a unit area of sediment per time, K is the hydraulic conductivity which is a function of the water content θ, Δz is the difference in height between two points in the vadose zone, and ΔH is the difference in total potential between those two points. The total potential is approximately equal to the sum of the matric potential (assumed equal to the water potential in these investigations) and the gravitational potential, where the gravitational potential is simply equal to the height above some reference datum such as the water table.

Since the water potential gradient ($\Delta H/\Delta z$) in the middle region of the vadose zone is approximately zero (Figure 18), the total potential gradient becomes equal simply to the gravitation gradient, which by definition (see above paragraph) is equal to one. Darcy's law then simplifies to flux being equal to the unsaturated hydraulic conductivity. A rate of flow can be calculated by dividing the flux by the water filled porosity.

Using appropriate representative values for unsaturated hydraulic conductivity and water filled porosity, the rate of flow has been previously calculated to be approximately 3 m/1000 yr (O'Neill et al.)[1]. If this were the rate of flow near the water table, recharge would be considered negligible and the original hypothesis concerning recharge would be considered correct. As shown above in the discussion of water potentials, the liquid soil water near the water table appears to be in static equilibrium and rate of flow at the water table is actually estimated to be zero.

Environmental Tracer Approach To Testing the Hypothesis of Negligible Recharge

Environmental tracers provide another method, independent of the hydraulic parameters described above for estimating recharge. The basic premise of this method is that infiltrating water (from precipitation and run-off) contains dissolved natural and man-made tracers that travel with the water as it moves into and through the vadose zone. It is assumed that formation materials do not contribute to the concentrations of these tracers. The concentrations of these tracers are measured with depth, and the analysis of the profile data yields information concerning the history of water movement through the unsaturated zone.

Chloride Profiles

Chloride ions move readily with water in geologic formations because their negative charge discourages sorption with negatively charged mineral surfaces at solution pH values commonly found in soils and alluvium. Chloride enters the soil profile dissolved (in relatively constant concentrations) in precipitation and also as wind blown dust (more variable concentrations). As water evaporates from the soil, leaving this ion behind, the concentration of chloride increases in the soil water. Thus zones of high chloride concentration in the vertical transects suggest that evaporation has predominated over infiltration. Zones of lower chloride concentration suggest that the opposite is true.

Depth profiles of chloride concentrations (per unit dry weight of soil) for core samples from the Pilot Wells and the Science Trench Boreholes are presented in Figures 19 and 20, respectively. These concentration data are converted to a per unit volume basis when quantitative analysis of the data is conducted.

The large differences in the shapes of the chloride profiles in the upper portions of the Pilot Wells (Figure 19) may be due to a number of factors. Differences in the amount of surface water run-off at the Pilot Well sites (which is in turn related to proximity to upland mountains and to the size of the drainage basin) will affect the amount of infiltration, and ultimately, the accumulation of chloride. Variations in plant communities and their rooting habits affect the relative amounts of evapotranspiration and infiltration, and therefore chloride concentrations. Finally, the relative rates of aggradation and erosion may play an important role in affecting the concentration profiles.

Despite the variations found in the concentration profiles, the relatively high concentrations of chloride in the shallow subsurface of all boreholes (vertical transects) suggest that evaporation rates are high compared to the downward movement of water under the present climate. The very low concentrations of chloride at depth suggest that this water entered the system under a much wetter climate where recharge rates compared to evaporation rates were much higher than present rates (Conrad)[16].

These data support the general conclusion made previously from hydraulic data; that is there is a net upward movement of water in the upper region of the vadose zone and there is no net infiltration under present climatic conditions. Stable isotope data discussed below also supports this conceptual model of the upper portion of the hydrologic system. Zero net infiltration under the present climate implies negligible recharge at the water table. Estimates of recharge rates based on chloride data will be presented in the following.

Estimated Recharge Rates From Chloride Data

The very high concentrations of chloride near the surface are characteristic of many soil profiles in arid portions of North America (Phillips)[17]. This distinct "bulge" of chloride near the surface has been interpreted by Phillips[17] to result from the dry climatic conditions which have limited downward flux over approximately the last 12,000 years. This implies that water and chloride have moved approximately a total of 100 m (bottom of chloride bulge) over a period of 12,000 years. This rate of water movement is considered negligible.

Using a chloride mass balance approach, Conrad[16] has made preliminary calculations of the rate of water movement in the first Science Trench Borehole (UE5ST-1). He estimated the rate of water movement in the profile to be approximately 0.04 m/1,000 yr and water to be over 100,000 years old at the bottom of the profile. Conrad[16] emphasizes that this calculation approach makes a number of assumptions. However, despite the assumptions and uncertainties in the chloride mass balance method, these data clearly show that downward soil water flux has been very limited for at least several thousand years (and probably longer) to allow a significant accumulation of chloride. These data strongly support the negligible recharge hypothesis.

Stable Isotope Profiles

The stable isotopes of hydrogen (D and H) and oxygen (^{16}O and ^{18}O) are excellent tracers of water movement because they are a component of the water molecule itself. Stable isotopes are used in unsaturated zone studies to infer the source of soil water and determine if evaporation has occurred. Data are reported as a ratio of heavy to light isotopes (D/^{1}H and $^{18}O/^{16}O$) in delta notation (δ) relative to Standard Mean Ocean Water. Fractionation (a change in the ratio) occurs during phase change processes. Therefore, condensation and evaporation processes are both reflected in the isotopic ratios. The condensation of precipitation from the atmosphere occurs under very nearly thermodynamic equilibrium conditions, resulting in a linear relationship between hydrogen and oxygen isotopes in worldwide precipitation known as the meteoric water line (MWL). Evaporation of water generally occurs under non-equilibrium conditions and fractionation of the oxygen isotopes is greater than that of hydrogen isotopes. The water remaining behind in the evaporation process thus develops an isotopic composition that plots to the right of the MWL.

Stable isotope data from selected core samples from all Pilot Wells and three Science Trench Boreholes (UE5ST-1, UE5ST-2, and UE5ST-4) are presented in Figures 21 and 22. In general, these profiles show more enrichment of heavy isotopes in the upper vadose zone, suggesting that shallow water has been subjected to more evaporation. A plot of normalized hydrogen isotopic ratios vs. oxygen isotopic ratios from selected core samples, with the MWL for reference, is shown in Figure 23. The shallow samples plot to the right of the MWL on a line with a slope between 3.5 and 4. This slope is consistent with the range found by Allison and Hughes[18] in experiments of water evaporating from sand columns, and strongly supports the hypothesis that evaporation rates are high relative to the downward rate of water movement in the upper vadose zone under the present climate. These data, like the chloride data, support the hypothesis of negligible recharge.

ADDITIONAL WORK REQUIRED

The above-mentioned mineralogical, physical, and hydrologic parameter data have demonstrated that the hypothesis of heterogeneity and anisotropy with respect to hydrologic parameters was incorrect. In fact, the system appears to be remarkably homogenous and isotropic and the conceptual model of the hydrogeologic system has been revised accordingly. This homogeneity and isotropy in hydrologic parameters greatly simplifies modeling efforts to simulate flow and transport processes under different possible climatic conditions and simplifies the interpretation of environmental tracer data.

The above-mentioned data from both the hydrodynamic and environmental tracer approaches to estimating recharge have strongly supported the hypothesis of negligible recharge. In addition, these data have provided new information about infiltration and evapotranspiration processes in the upper approximately 30 m of the profile. Based on this new information the conceptual model of the near surface hydrogeologic system has been refined to emphasize the importance of the soil gas pathway and the atmospheric air pathway for the potential transport of contaminants from buried waste.

A number of new hypotheses have been developed concerning this soil gas pathway, the atmospheric air pathway, and their interaction. Site characterization and monitoring activities have been designed to produce data to test these new hypotheses. Some of the new hypotheses and corresponding testing activities are summarize in the following.

- It is hypothesized that the liquid zero flux plane is located between 10 and 30 m and its position varies between summer and winter conditions. Boreholes approximately 50 m deep are currently being instrumented with sensors at different depths to monitor water potentials over a period of time and to characterize the zero flux plane.

- It is hypothesized that porous media is homogenous and isotropic with respect to gas permeabilities. In situ measurements of the spatial variability of gas permeabilities are being made in the near surface using a portable hydraulically driven probe system and at depth within and between boreholes using packer systems.

- It is hypothesized that the advective flow of gas plays an important role in gas transport under certain barometric pressure conditions. Experiments have been designed to determine the relative importance of the effects of diffusion and advection on the transport of naturally occurring radon gas during large changes in atmospheric barometric pressure.

- It is hypothesized that both average evapotranspiration and evaporation rates significantly exceed average precipitation rates even during the winter season. Several independent measures of evaporation and evapotranspiration are being made over time on vegetated and unvegetated sites using micrometeorological data and weighing lysimeters.

SUMMARY

An in-depth subsurface site characterization and monitoring program for the soil water migration pathway has been planned, implemented, and completed to satisfy data requirements for a waiver from groundwater monitoring, for an exemption from liner leachate collections systems, and for different regulatory driven performance assessments. A traditional scientific approach has been taken to focus characterization and monitoring efforts. This involved developing a conceptual model of the hydrogeologic system, and defining and testing hypotheses about this model. Specific hypotheses tested included: that the system is hydrologically heterogenous and anisotropic, and that recharge is very low or negligible.

Extensive sampling, laboratory testing, and analysis have demonstrated conclusively that the alluvial deposits in the vicinity of the Area 5 RWMS are virtually homogeneous with respect to hydrologic properties with no evidence of significant layering or preferential flow pathways. For example, properties which influence the flow of water such as hydraulic conductivity, moisture retention relations, and the relationship between hydraulic conductivity and moisture content were

not highly variable or characterized by trends, but were consistently typical of coarse grained materials. In addition, hydrologic property data from oriented core samples collected from two major near surface layers of contrasting particle size distribution indicate isotropic conditions rather than anisotropic conditions. In summary, hypothesis tests have shown the hydrologic system to be remarkably homogenous and isotropic rather than heterogenous and anisotropic.

Analysis of water potential profiles at the Area 5 RWMS indicate that the hydrologic regime of the vadose zone consists of an upper region where infiltrating precipitation redistributes and then leaves the upper profile via evapotranspiration, a middle region characterized by low water contents and a unit gradient resulting in extremely small downward fluxes, and a lower region which is in equilibrium with the uppermost aquifer. Both chloride and stable isotope concentration profiles provide further support for this flow regime. In addition, chloride ages of pore water indicate that the evaporation regime in the upper portion of the profile has persisted at least for several thousands of years.

Both hydrodynamic and environmental tracer approaches to estimating recharge lead to the same conclusion: that recharge from the Area 5 RWMS is not occurring in the upper region of the vadose zone, and that recharge at depth is extremely small. Thus the potential for the migration of hazardous constituents through the thick vadose zone to the uppermost aquifer should be judged to be negligible. This demonstration of "no migration of hazardous constituents to the water table satisfies a key requirement for both the groundwater monitoring waiver and the exemption from liner leachate collection systems.

Finally, the data obtained from testing hypotheses of heterogeneity, anisotropy, and negligible recharge in the soil water pathway have been used to refine the conceptual model of the hydrogeologic system at the site. These data suggest that the soil gas and atmospheric air pathways may be more important in transporting contaminants to the accessible environment than the soil water pathway. New hypotheses have been developed about these pathways and characterization and monitoring activities designed to test these new hypotheses.

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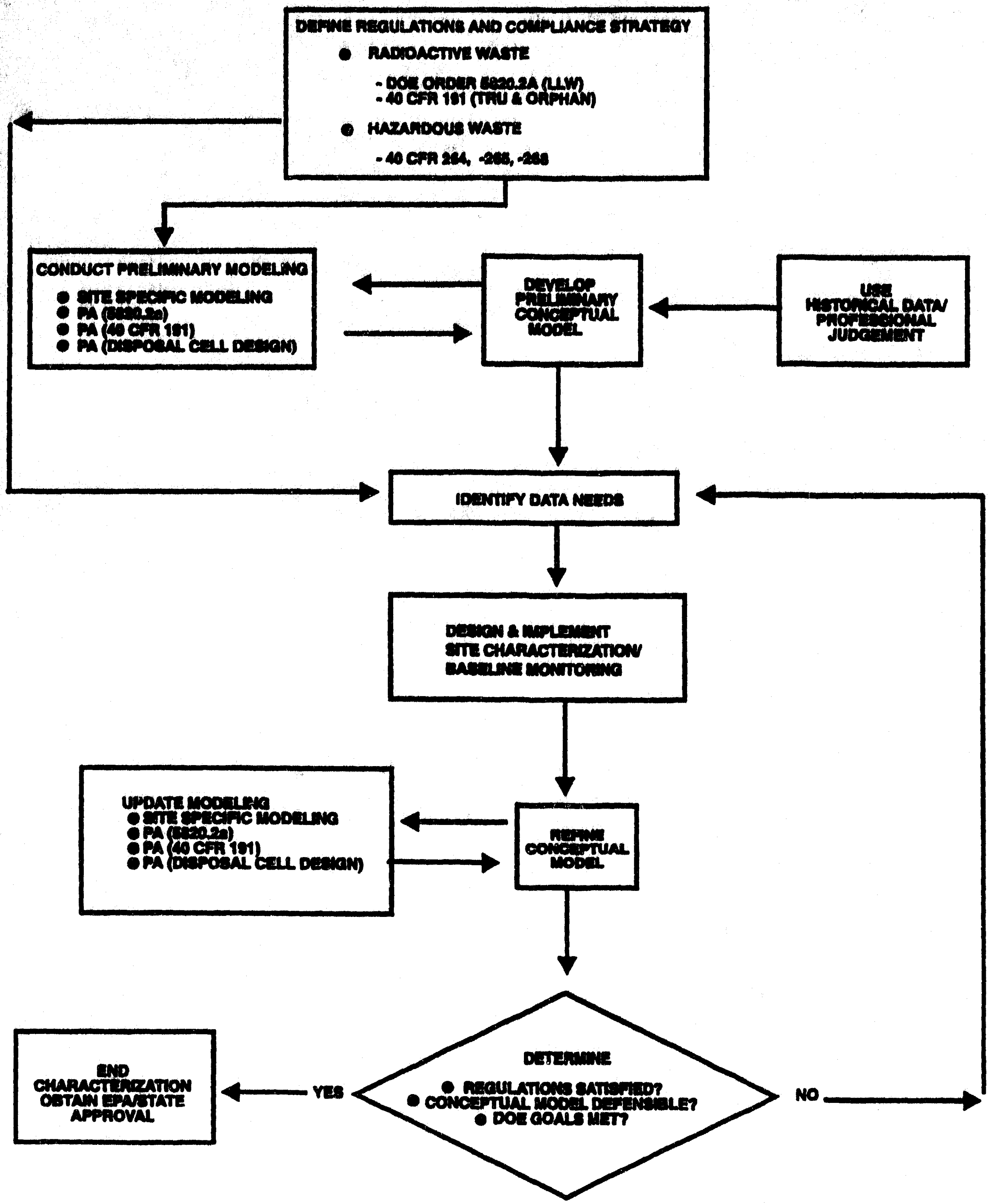

Figure 1. General approach to Site Characterization

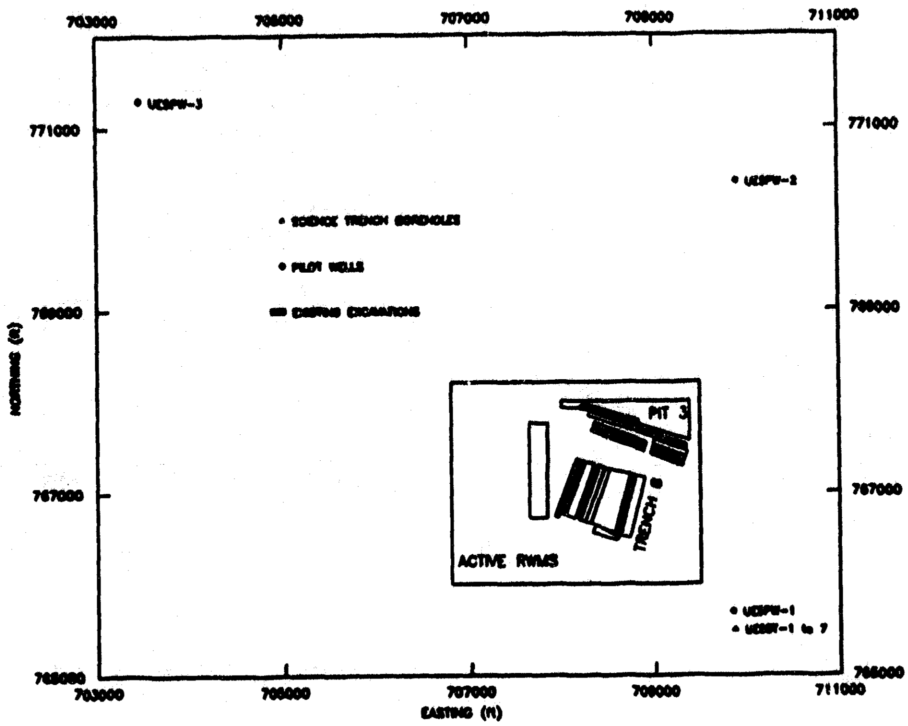

Figure 2. Location map of Area 5 RWMS subsurface characterization activities.

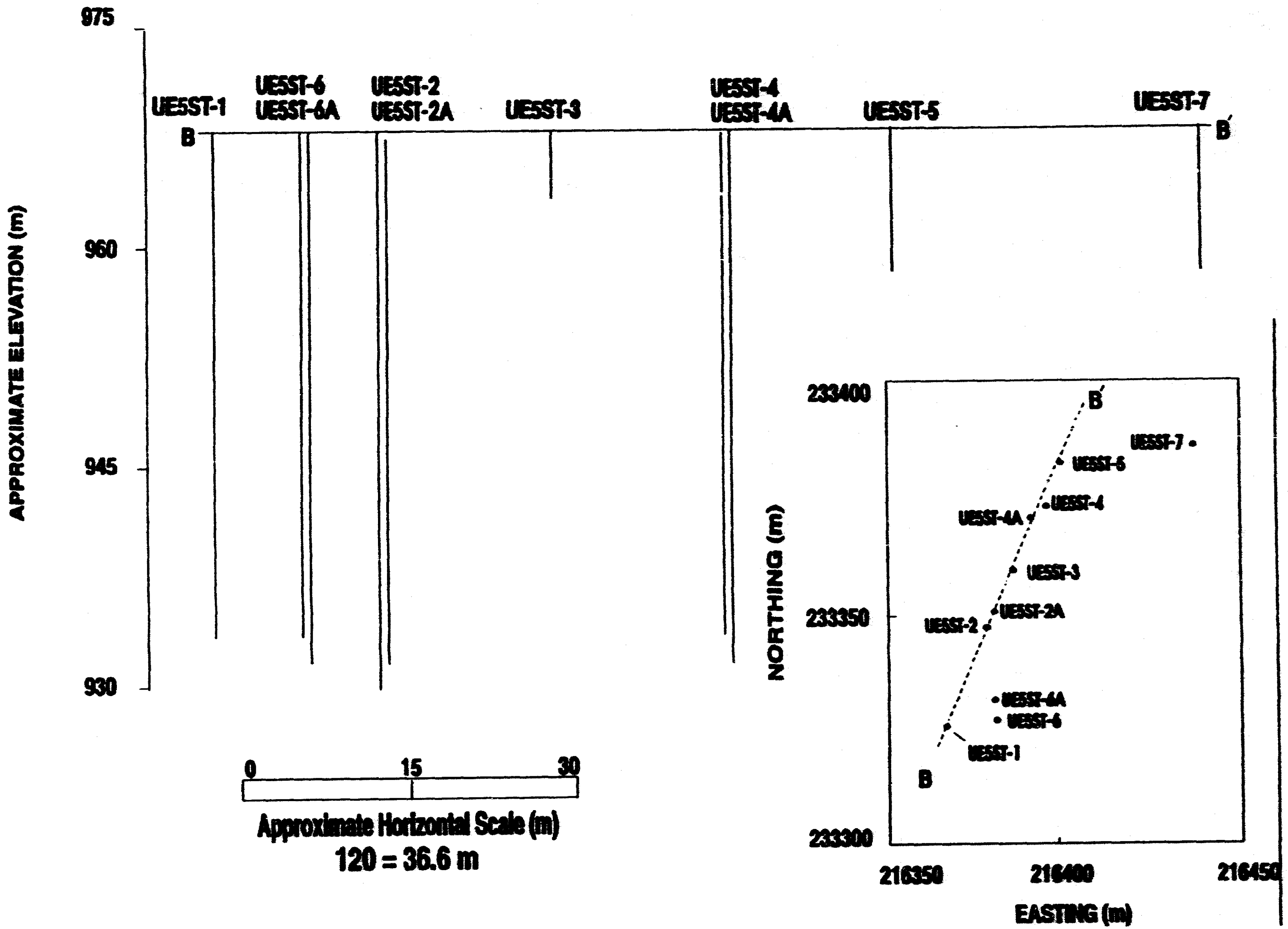

Figure 3. Cross-section along main sampling transect showing Science Trench Borehole locations and depths. Note boreholes UE5ST-6, 6A, and 7 are projected into cross-section. Inset shows plan view of borehole locations at Area 5 RWMS, Nevada Test Site.

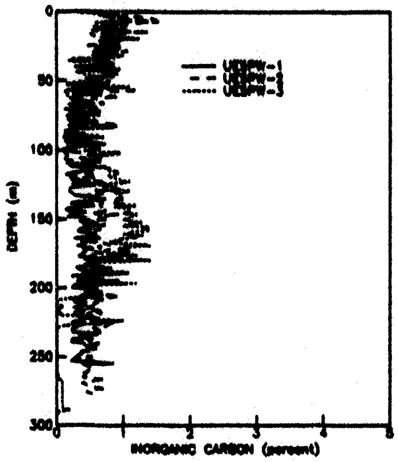

Figure 4. Depth profiles of inorganic carbon for drill cuttings samples from the Pilot Wells.

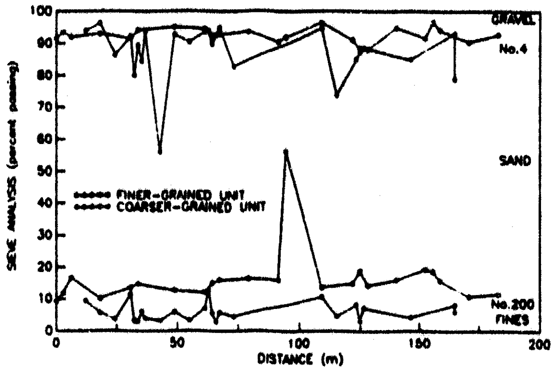

Figure 5. Lateral transect of dry sieve analyses (percent passing No. 4 and No. 200 mesh screens) of vertical core samples from major coarse-grained and fine-grained layers in Pit 3.

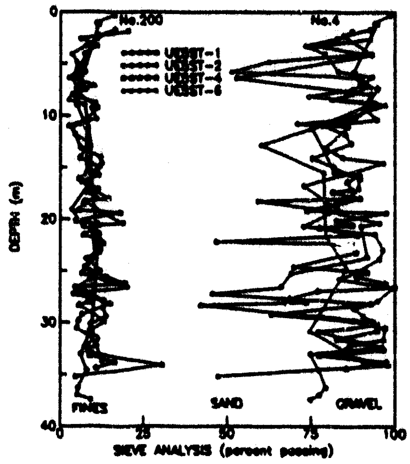

Figure 6. Depth profiles of dry sieve analyses (percent passing No. 4 and No. 200 mesh screens) for core samples from the Science Trench Boreholes.

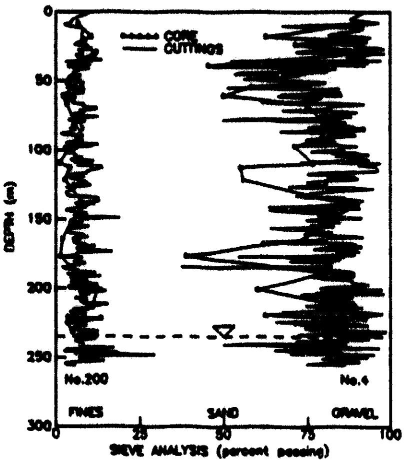

Figure 7. Depth profiles of dry sieve analyses (percent passing No. 4 and No. 200 mesh screens) for core and drill cuttings samples from UE5PW-1.

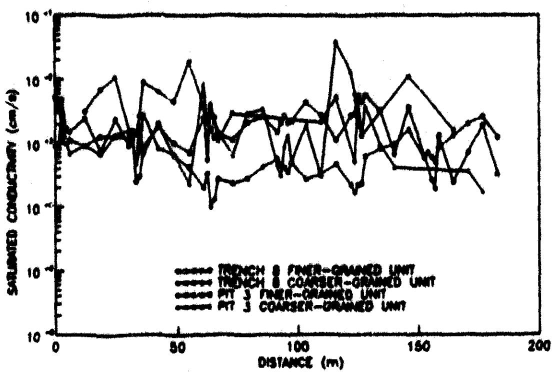

Figure 8. Lateral transect of saturated hydraulic conductivities of vertical core samples from major coarse-grained and fine-grained layers in Trench 8 and Pit 3.

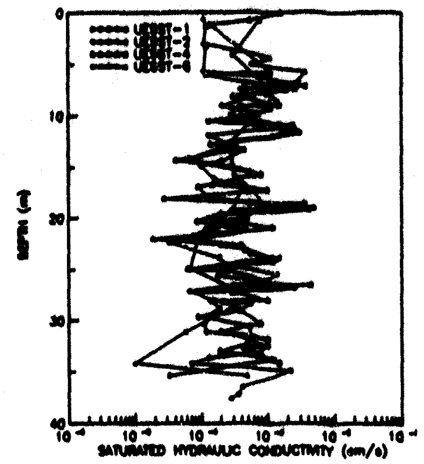

Figure 9. Depth profiles of saturated hydraulic conductivities for core samples from the Science Trench Boreholes.

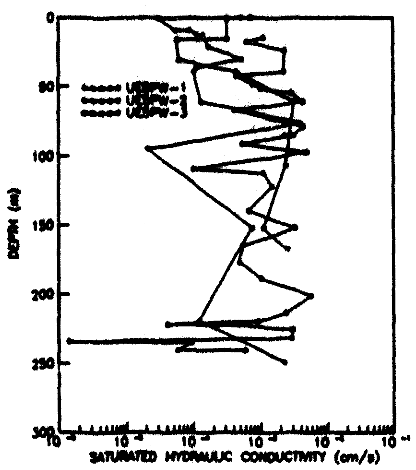

Figure 10. Depth profiles of saturated hydraulic conductivities for core samples from the Pilot Wells.

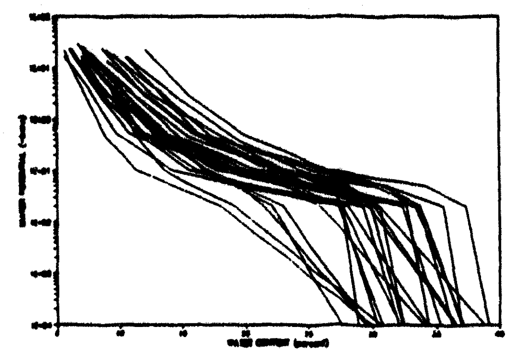

Figure 11. Composite moisture retention data for core samples from UE5PW-1.

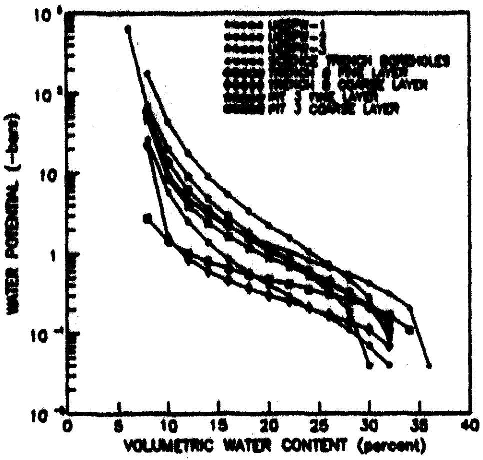

Figure 12. Calculated moisture retention curves for core samples from the Existing Excavations, Science Trench Boreholes, and Pilot Wells using the mean van Genuchten curve fitting parameters determined from laboratory measured moisture retention curves.

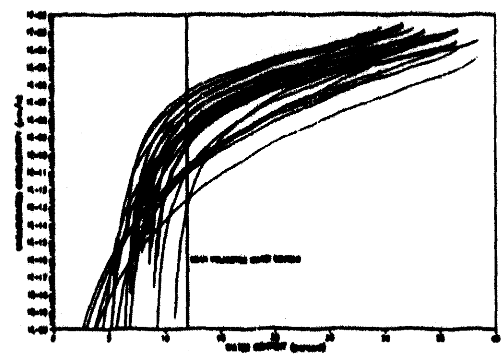

Figure 13. Fitted unsaturated hydraulic conductivity functions for core samples from UE5PW-1.

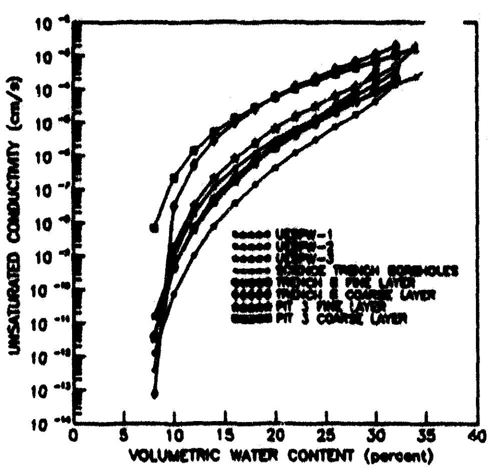

Figure 14. Calculated unsaturated hydraulic conductivity curves for core samples from the Existing Excavations, Science Trench Boreholes, and Pilot Wells using the mean van Genuchten curve fitting parameters determined from laboratory measured moisture retention curves.

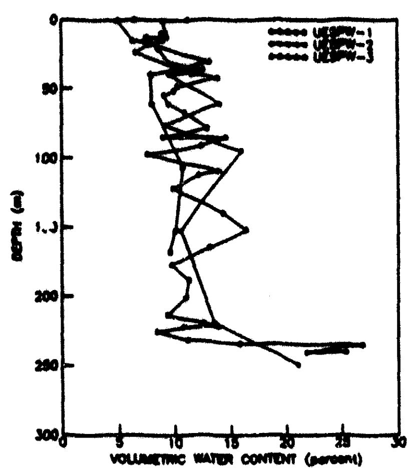

Figure 15. Depth profiles of volumetric water content for core samples from the Pilot Wells.

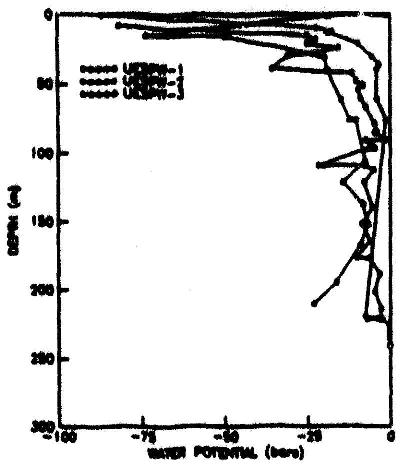

Figure 16. Depth profiles of water potential for core samples from the Pilot Wells.

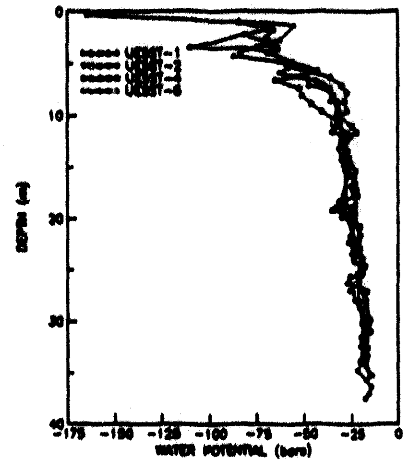

Figure 17. Depth profiles of water potential for core samples from the Science Trench Boreholes.

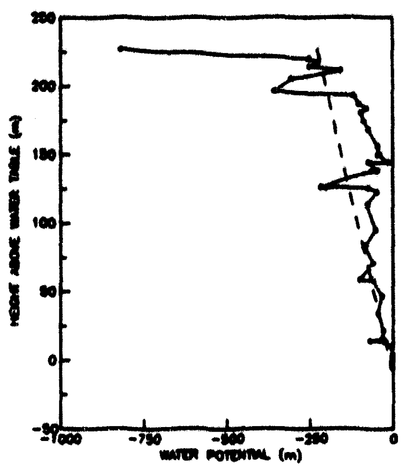

Figure 18. Water potential data for core samples from UE5PW-1. Data to the right of the 1:1 line indicate upward liquid flow.

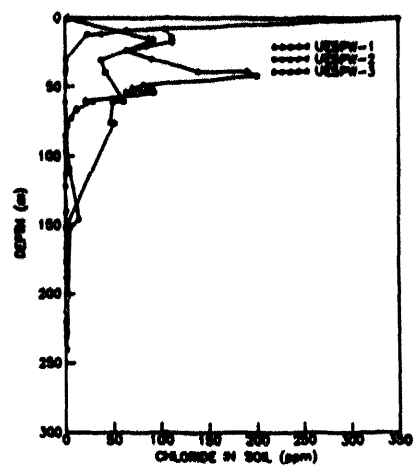

Figure 19. Depth profiles of dry soil chloride concentrations for core samples from the Pilot Wells.

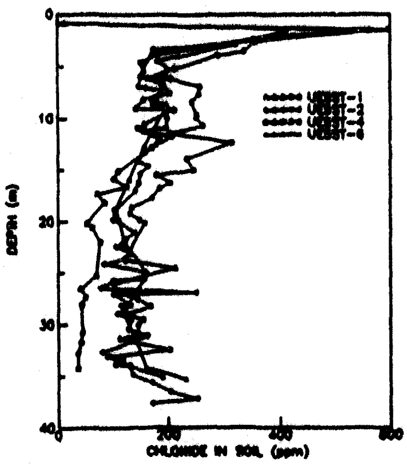

Figure 20. Depth profiles of dry soil chloride concentrations for core samples from the Science Trench Boreholes.

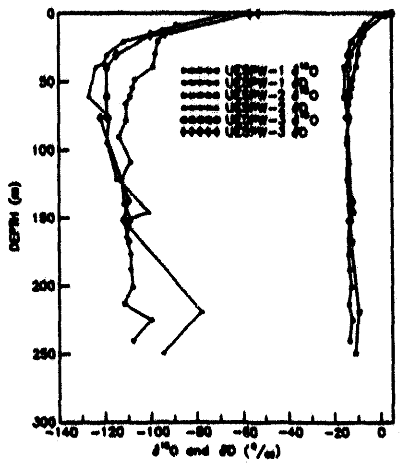

Figure 21. Depth profiles of stable isotope data for core samples from the Pilot Wells.

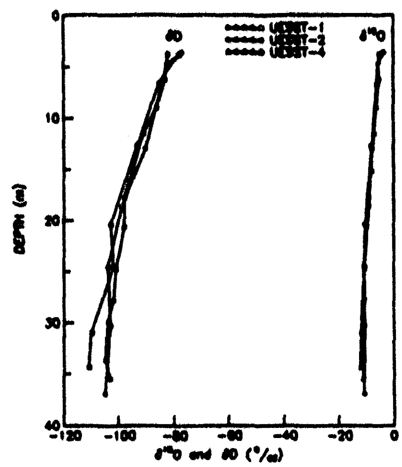

Figure 22. Depth profiles of stable isotope data for core samples from the Science Trench Boreholes.

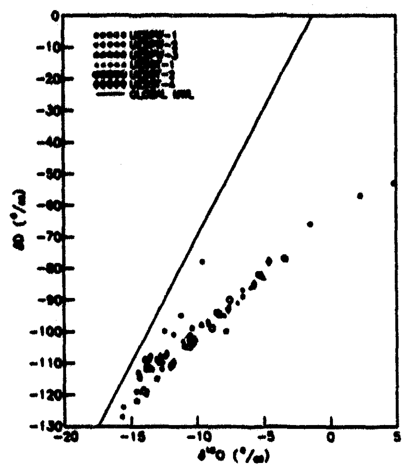

Figure 23. Comparison of measured stable isotopes for core samples from the Science Trench Boreholes and Pilot Wells with stable isotope data for the global Meteoric Water Line (MWL).

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