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Subsurface Transport Beneath MDA G: A Conceptual Model

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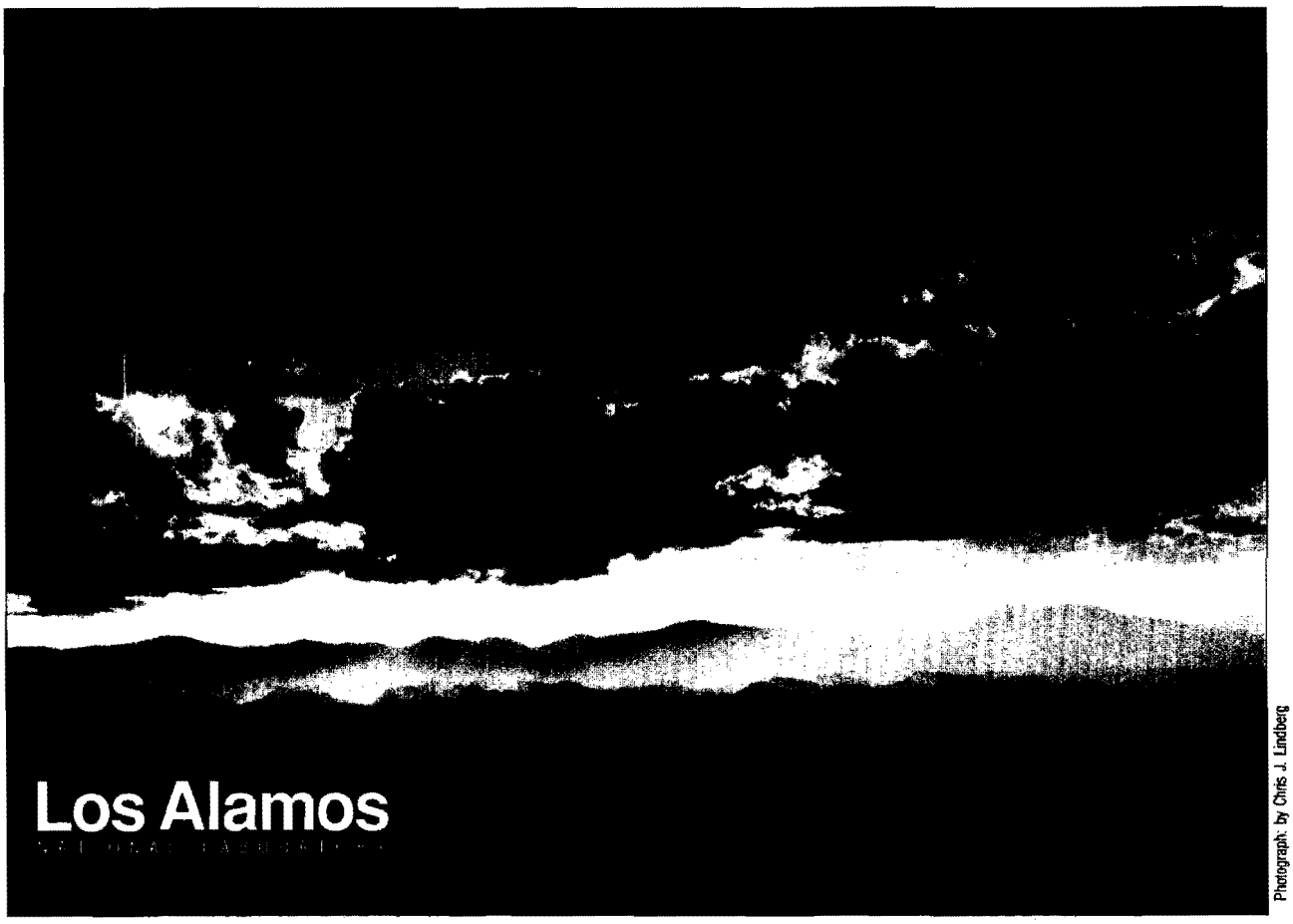

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Executive Summary

The Los Alamos National Laboratory Solid Radioactive Waste Management Group (CST-14) is currently preparing a Radiological Performance Assessment (PA) for Material Disposal Area (MDA) G, located at the Laboratory's Technical Area 54. This PA is being prepared in compliance with DOE Order 5820.2A. The overall goal of the PA process is to evaluate the long-term radiological risk posed to humans and the environment by disposal activities at MDA G.

The Geoanalysis Group (EES-5) has been asked to assist in determining long-term radiological exposure via pathways involving subsurface aqueous-phase transport. The determination will follow a two-stage approach: development of a conceptual model for subsurface transport, followed by implementation of a numerical model for transport calculations and concentration predictions. This report addresses the first of these stages.

Chapter 1 of the report introduces the PA process and the role that conceptual models play. Chapter 2 briefly describes key field observations that helped shape the conceptual model. Many of these observations have been conducted as part of the Laboratory's Environmental Restoration project and have not yet been formally published. Finally, a unified conceptual model for subsurface flow and transport beneath MDA G is presented in chapter 3. The model posits an alternation between two fundamentally different states: an episodic infiltration state contrasting with normal drying conditions. Episodic infiltration can occur either during spring snowmelts or during the intense summer thunderstorm season, when the fracture system is activated and infiltration increases moisture contents both near the surface and deeper within the mesa. In between these events, the system reverts to a more typical drying cycle. Evapotranspiration removes moisture from the surface of the mesa, while the three-dimensional network of fractures and surge beds dries out the mesa from within. Superimposed on both states is the continuous leakage down from the alluvial aquifer system in Pajarito Canyon, which accelerates the downward transport of any contaminants that are entrained in this flow.

According to this model, the system is dominated by transient events, and conditions within Mesita del Buey beneath MDA G are strongly influenced both by the geometry of the mesa and the fractures within the tuff bedrock. Evaporation, both on the surface and perhaps within the mesa, plays a major role in driving moisture movement. These four characteristics of the system contribute much of the uncertainty in our ability to predict subsurface transport, and impose specific requirements on attempts at numerical modeling of flow and transport.

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1. Introduction

This document has been prepared in support of the Radiological Performance Assessment (PA) at Material Disposal Area (MDA) G, located at Technical Area (TA) 54 at Los Alamos National Laboratory (LANL). This PA is being prepared by LANL in compliance with DOE Order 5820.2A.

The overall goal of the PA process is to evaluate the long-term radiological risk posed to humans and the environment by disposal activities at MDA G. This evaluation consists of first identifying potential exposure pathways and then quantifying exposure along those pathways. LANL's Geoanalysis Group (EES-5) has been asked to assist in this effort for those pathways involving subsurface aqueous-phase transport. This report represents the first portion of the EES-5 contribution; a second report, detailing transport calculations and predictions, will follow.

The remainder of this chapter features a discussion of the role of models in general and of conceptual models in particular, with special emphasis on the PA process. Chapter 2 consists of a review and brief discussion of the primary field observations that support our conceptual model of subsurface transport beneath MDA G. This report concludes with chapter 3, a concise description of the model as it now stands. This conceptual model is very much a product of available data, and is subject to modification as additional information becomes available, both from ongoing field work at MDA G and from new research results in the field of vadose-zone hydrology.

1.1. Role of Modeling in Radiological Performance Assessment

To quantify radiological exposures to humans and the environment, it is necessary to determine the concentration of radionuclides at appropriate receptor locations. These locations may include the ground surface for direct radiation and resuspended airborne radioactivity, foodstuffs for ingested radioactivity, and surface streams or wells for water-borne radioactivity. The receptor sites are formalized as "compliance points" by the PA team, because they are chosen on the basis of the performance objectives against which facility compliance is judged.

While present-day radionuclide concentrations at the compliance points are routinely measured as part of LANL's Environmental Surveillance activities, the PA must estimate future concentrations and associated potential exposures.

Any prediction of the future requires a model. Predictions of future radionuclide concentrations around MDA G due to contaminant migration will require a complex model, beginning with conceptualization of the system, evolving into a predictive mathematical tool.

For the first step, we will combine knowledge of vadose-zone flow and transport in general with site-specific observations and measurements to identify those processes that control transport of radionuclides from the MDA to the compliance points. We will develop a conceptualization, a picture, of how the mesa works. For the second step, we will combine that conceptualization with appropriate mathematical formulations to produce a numerical model of subsurface conditions beneath MDA G consistent with the conceptual model. This numerical model will then serve as a predictive tool, which we will use to assess subsurface contaminant transport based on various scenarios of future environmental conditions at the site.

This report describes the results of the first part of the modeling process: conceptualization of subsurface aqueous-phase transport at MDA G. The end product of

this effort is a "conceptual model" identifying and describing those conditions and processes judged significant.

1.2. Uncertainty in Conceptual Models

Uncertainty enters into the final product of our modeling effort, the prediction, from many sources. The most obvious source is uncertainty or error associated with measurements of model parameters, such as infiltration rate or hydraulic conductivity. This uncertainty is relatively easy to quantify, and most modeling efforts include some sort of sensitivity or uncertainty analysis to provide an estimate or bound on the magnitude of uncertainty in the final prediction that comes from the parameters.

Far more difficult to quantify is uncertainty introduced in conceptualization. Major flaws in conceptualization may lead to incorrect predictions and conclusions. Unfortunately, it is difficult or impossible to quantify the probabilities associated with such flaws. The conceptual model can and should be tested by comparing model predictions with field observations. Every agreement decreases our uncertainty in the model; every disagreement is an opportunity to modify and improve the model. The model outlined in this report is based on existing and available observations, many of which are unpublished and perhaps unconfirmed. The model is in the early stages of numerical implementation, and has not produced quantitative predictions of field behavior. At this point in time, therefore, the uncertainty associated with this model is relatively high. Continued field observations and numerical implementation and experimentation will serve to decrease this uncertainty and improve the model.

2. Major Observations

This chapter describes those field conditions observed in the vicinity of MDA G and elsewhere on the Pajarito Plateau that have been most influential in the development of our conceptual model. These descriptions are intended to be concise and brief; we assume the reader is familiar both with the Pajarito Plateau and with principles of vadose-zone hydrology. Many of these observations were carried out as part of the Laboratory's Environmental Restoration (ER) Program or ongoing Environmental Surveillance activities. In both cases, data communication is slow and difficult, and many observations are referenced only to personal communications or unpublished memos and manuscripts. Some of these observations are described in more detail in an MDA G PA Data Compilation memo (Krier 1995). For further details, the reader should consult that document, previous MDA G data compilations (e.g. Los Alamos National Laboratory 1992; Rosenberg and Turin 1993), other primary sources cited in the text, and more general descriptions of the Pajarito Plateau environmental setting, such as that found in the latest edition of the LANL Environmental Restoration Project's Installation Work Plan (Los Alamos National Laboratory 1993).

As new data are collected or made available, it is likely that our conceptualization of flow and transport processes beneath MDA G will be refined or even drastically altered. This conceptual model must therefore be considered a "work in progress," subject to future revision.

2.1. Surface Water Balance

2.1.1. Data and Documentation

In support of the MDA G PA, EES-15 staff have conducted a series of precipitation/runoff/evapotranspiration simulations for MDA G, using the CREAMS computer code (Knisel 1980). Simulation results show that for a 40' deep disposal pit filled with dry crushed tuff and a typical local vegetation cover, no deep (>16.2 m) infiltration occurred over 100,000 years. In other words, under the conditions of their simulation, there is less than a 1 in 100,000 probability of any deep infiltration occurring in any given year (Everett Springer, pers. comm., 1995). A second simulation, with no vegetation cover, resulted in some slight infiltration, suggesting that vegetation-induced evapotranspiration (ET) plays a critical role in preventing deep infiltration. A third simulation was performed, with a realistic vegetation cover and an initial moisture content in the crushed tuff of 8%, close to measured values in active pits (see section 2.3). This run produced an average annual deep infiltration of 0.15" (4 mm). This is the "base case" infiltration rate used in further modeling.

A series of field experiments was performed in 1981 and 1982 at TA-51, on Mesita del Buey a few miles west of MDA G (Perkins and DePoorter 1985). In these experiments, chemical tracers were introduced at depths of 38 cm or 68 cm into 1.5 m long caissons packed with crushed tuff. The caissons had bottom plates welded in place, preventing any deep (>1.5 m) moisture movement. A vegetation cover was established on some caissons, and the experiment was exposed to natural meteorological conditions and supplemental watering for a period of 15 months. At the end of the experiment, the caissons were sampled and tracer profiles determined. No tracer movement was observed in the vegetated caissons, while a strontium tracer did move downward in the bare-soil caissons. This suggests that vegetation-induced ET dominated the system.

More recent experiments on surface water hydrology and fluxes have been performed at various sites around the Pajarito Plateau by Brad Wilcox / EES-15. He has

shown that beneath the Ponderosa Pine forests of the western part of the Plateau that interflow (saturated flow moving laterally through subsurface soil, above the soil/tuff interface) plays a major role in the overall water budget. Performance assessments or other hydrogeologic investigations in that part of the Plateau would need to consider the effects of interflow on contaminant transport. Other studies by Wilcox and his coworkers have demonstrated that interflow is not significant beneath the Piñon/Juniper woodlands characteristic of the eastern parts of the Plateau, including Mesita del Buey and MDA G (Brad Wilcox, pers. comm., 1995).

2.1.2. Relevance to Conceptual Model

The TA-51 field experiments and the initial CREAMS simulations both suggested that there would be minimal downward transport from vegetated pits. Simulations with more realistic moisture contents predicted significant deep infiltration, in contrast to the caisson experiments. This apparent contradiction is due to the 40' depth of the CREAMS simulation, compared to the 1.5 m depth of the caissons. At this shallow depth, roots are plentiful and ET is extremely effective at halting moisture flow. Furthermore, the sealed bottom ends of the caissons effectively eliminated any opportunity for preferential pathways for accelerated transport to move moisture beneath the active rooting zone. At the deeper depths of the disposal pits, the CREAMS simulation suggests that some moisture escapes ET to become deep infiltration.

2.2. Observed Moisture Profiles in Tuff

2.2.1. Data and Documentation

Moisture profiles measured in the Bandelier Tuff beneath undisturbed mesa tops, both at Mesita del Buey (MDAs G & L) and elsewhere at LANL, show a typical pattern of near-surface moisture fluctuations and deeper stable conditions (e.g. IT Corporation 1987). The shallow fluctuations, typically down to a depth of 2-4 m reflect episodic or seasonal infiltration events, followed by ET-driven drying.

Deep moisture profiles generally reveal relatively dry conditions, uniform both in time and space. Wetter profiles have been observed near water sources, such as outfalls, and in areas where surface evapotranspiration has been disturbed, such as paved areas. At Mesita del Buey, the most pronounced spatial exceptions occur at specific stratigraphic horizons, and will be discussed below.

2.2.2. Relevance to Conceptual Model

The shallow moisture fluctuations demonstrate the action of the ET trap discussed above, and suggest that its depth of influence is limited to the top few meters. Contaminants buried beneath this depth are basically in a steady-state environment, and are not subject to transient hydraulic processes.

What can be learned from the deep moisture profiles? Others have attempted to calculate *in-situ* matric potential or hydraulic conductivity from moisture content measurements, using the van Genuchten or related relationships. Theoretically, a flux estimate could then be calculated. While a worthwhile exercise, the uncertainties associated with these calculations must be considered; unfortunately, they are large. There are three major sources of uncertainty in these calculations. First and foremost is the uncertainty introduced by extrapolating the van Genuchten relationships far beyond their original range of applicability. These relationships are based on empirical fits to data measured for agricultural soils under typical agricultural conditions, and there is no intrinsic reason to expect them to apply to intact rock under very dry conditions. The fact that some data

appear to follow the van Genuchten curves is encouraging, but should not be interpreted as guaranteeing some sort of universal applicability into ever dryer conditions. A second source of uncertainty is the extreme sensitivity of unsaturated conductivity to measurement and parameter estimation errors. In the dry region, hydraulic conductivity drops off very rapidly with decreasing effective saturation (figure 2-1), and a small error in either the saturation estimate or the curve-fitting parameters can lead to an order-of-magnitude error in the predicted conductivity value. The final major source of uncertainty is that the van Genuchten relationships are based on effective saturation. While gravimetric and volumetric moisture content are real parameters that can both be measured directly on a carefully collected core sample or estimated from a well-calibrated neutron probe measurement, effective saturation is an artificial idea, incorporating estimates of both "residual" and "saturated" moisture content, quantities that are ill-defined at best, and may be nothing more than additional curve-fitting parameters. To summarize, although calculations of *in-situ* properties based on van Genuchten or other idealized relationships are intuitively appealing, practical considerations indicate that resulting flux estimates have high associated uncertainties.

A separate issue raised by of observed moisture profiles is the lack of temporal variability beneath a few meters depth. This observation has been widely and erroneously cited as evidence of the absence of any deep infiltration (e.g. IT Corporation 1987); a non-changing moisture profile could just as easily indicate steady-state downward (or upward) flow as no flow.

2.3. Initial Moisture Content of Fill

2.3.1. Data and Documentation

Neutron probe measurements within disposal pits at MDA G demonstrate that moisture contents within active Pit 37 are significantly higher than in nearby intact tuff (figure 2-2) (Loaiza and Vold 1995). This additional moisture may be due in part to moisture coming in with waste for disposal, but is more likely attributable to local precipitation, run-on, and ponding during the active lifetime of the pit. Pit activities destroy the natural surface slope of the mesa and may lead to channeling of runoff into the pit, and also effectively eliminate all vegetation from the pit area. As explained above, ET driven by vegetation is a major drying force on the Pajarito Plateau.

These data (Loaiza and Vold 1995) clearly indicate elevated moisture levels within an active pit. The question remains, what happens to this excess moisture after a pit is closed, covered, and allowed to revegetate? One possibility is that the pits will gradually revert towards their natural, pre-existing condition (an unlikely suggestion, given the major disturbance of the tuff by crushing and backfilling). The excess moisture might be extracted by ET as vegetation takes hold, or might infiltrate downward, possibly carrying contaminants. The only available field measurements, described below, indicate that some downward infiltration takes place.

To investigate the long-term behavior of MDA G disposal pits, in 1976 Purtymun drilled 5 horizontal boreholes a few meters beneath Pit 3, a disposal pit active from 1963 to 1966 (Purtymun et al. 1978). Although no clear evidence of migration of radionuclides from the pit was observed in 1976 (Purtymun et al. 1980), recent unpublished neutron probe data show a clear zone of increased moisture (4% - 8% volumetric moisture content, compared to background values of <2%) at depths of 0 to 4.4 m beneath Pit 3 (McLin 1994).

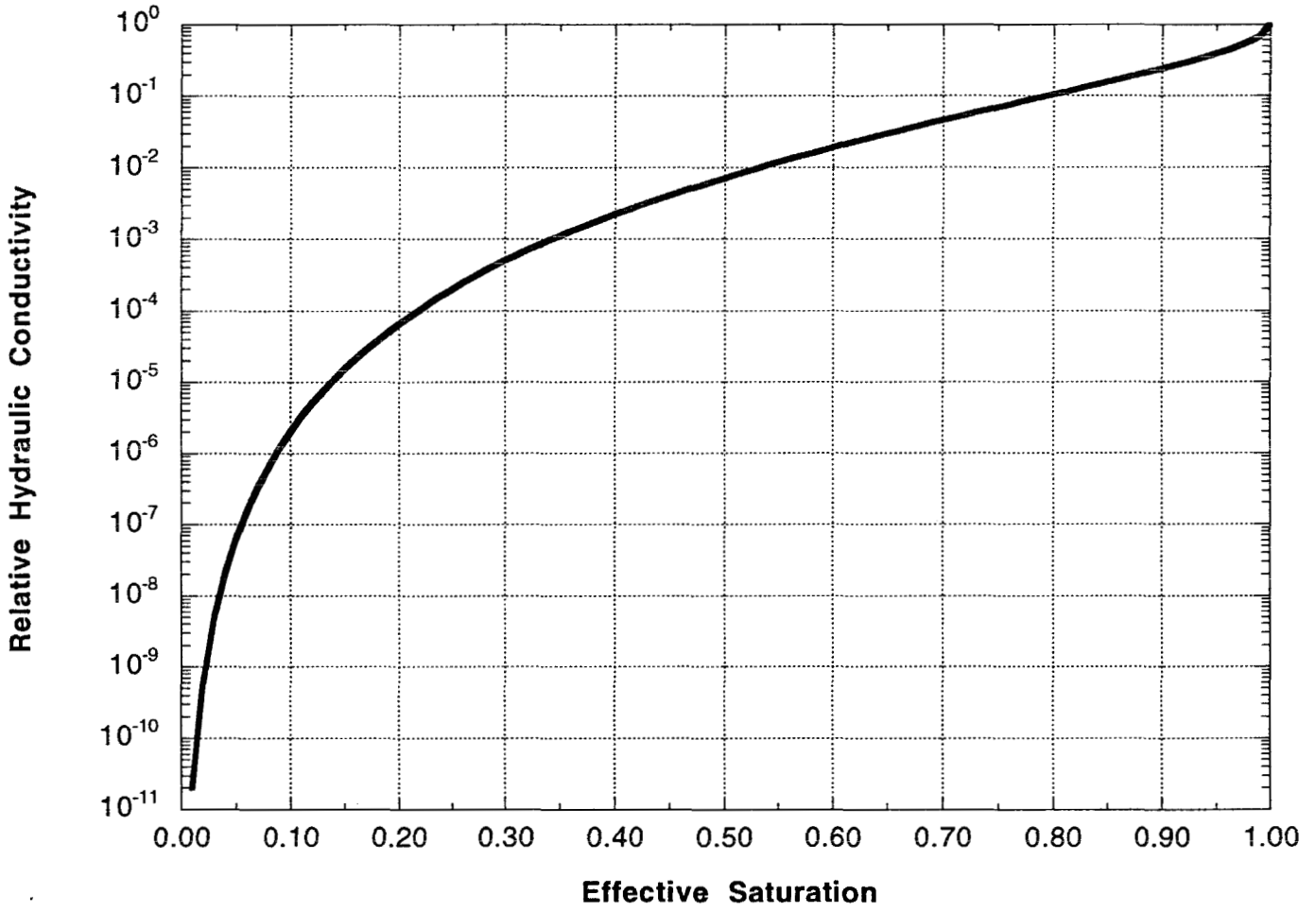

Figure 2-1. Relative hydraulic conductivity as a function of effective saturation, according to the van Genuchten relationship. Curve shown is for an n value of 1.8, typical of the Tshirege member of the Bandelier Tuff (Rogers, 1995).

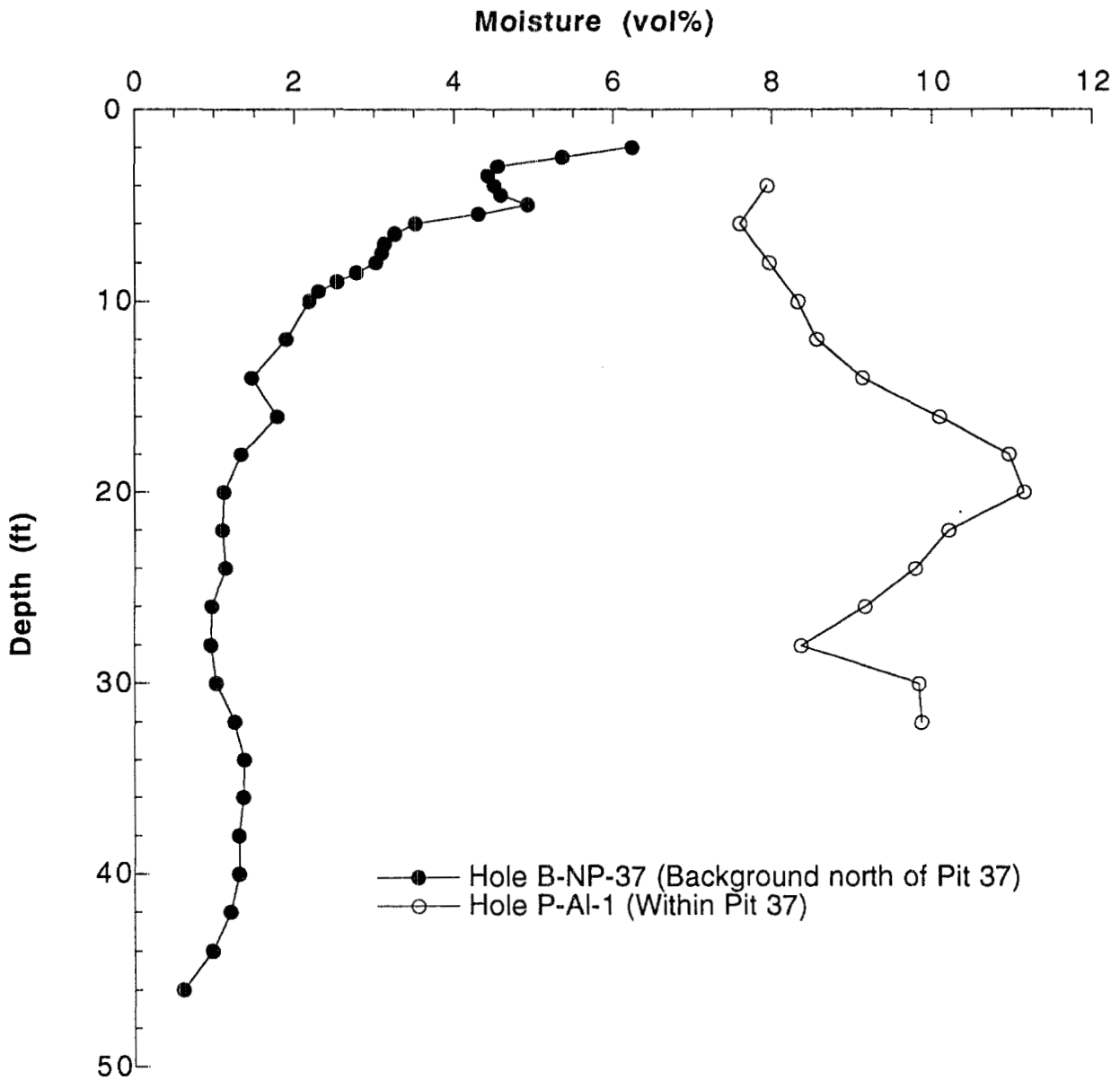

Figure 2-2. Comparison of moisture profiles within and adjacent to MDA G Pit 37. Data from Loaiza and Vold (1995).

2.3.2. Relevance to Conceptual Model

The moisture content data from below Pit 3 provide clear evidence that there can be significant infiltration of water downward from the MDA G disposal pits, in agreement with the CREAMS base case simulation. This infiltrating moisture thus enables potential leaching of contaminants from the disposal pits into the undisturbed fractured tuff below.

2.4. Occurrence of Fractures

2.4.1. Data and Documentation

Fractures are one of the most obvious and ubiquitous features of the Bandelier Tuff, easily visible in outcrop. They are also an obvious potential pathway to transport, and have recently been increasingly studied. While early reports indicated fractured and unfractured units within the tuff, more careful observations have shown that although the degree of fracturing varies widely from unit to unit, all of the units within the tuff are observed to be fractured to some extent, including the Otowi member.

While formal fracture studies on the Pajarito Plateau have thus far been limited to the Bandelier Tuff, observations of outcrops indicate the Cerros del Rio Basalt is intensely fractured in places. Unconsolidated to weakly consolidated sediments of the Puye and Santa Fe Formations are less capable of fracturing, and may be expected to behave more like a porous medium.

2.4.2. Relevance to Conceptual Model

Fractures are a particularly problematic feature for a conceptual model of vadose-zone transport at Mesita del Buey or elsewhere. While great advances have been achieved in recent years in the hydrology of saturated fractured rock aquifers, unsaturated fractured systems continue to pose immense conceptual and analytic challenges (Evans and Nicholson 1987). In fact, the presence of unsaturated fractures at Yucca Mountain, Nevada (location of a proposed high-level radioactive waste repository) has proven to be one of the major stumbling blocks in predicting contaminant transport at that site (Narasimhan and Wang 1992; Wang and Narasimhan 1993).

The primary problem with predicting transport through an unsaturated fractured system is the strongly nonlinear behavior of the system. Unsaturated flow is inherently nonlinear due to the dependence of hydraulic conductivity on moisture content, but in an fractured system, this nonlinearity is exaggerated by the interaction between two alternate flow systems with radically different hydraulic properties: the matrix and the fracture network. At any given point in time and space, one system is likely to dominate flow and transport, depending on local properties and conditions. Transient water flow may change local moisture contents and alter the balance between matrix and fracture dominance.

The effects of fracture fillings and coatings add even more complexity to the system, and will be discussed below.

2.5. Fracture Fill Characteristics

2.5.1. Data and Documentation

Fracture fillings and linings are another subject that has received increased attention recently. While older reports (Baltz et al. 1963; Purtymun and Kennedy 1971) suggested

that shallow fractures are filled and some deeper ones open, more careful field observations have revealed many exceptions to this pattern. In particular, some near surface fractures are wide open, while filled fractures can be observed throughout the Bandelier Tuff.

In a recent Ph.D. dissertation on fractures exposed in a pit at MDA J, two miles northwest of MDA G, Davenport (Davenport 1993) observed fractures containing clay, calcite, or both. He concluded that clay fracture fills were transported downward into the fractures by water movement (rather than being formed by *in-situ* weathering) and that the presence of calcite indicates alternating sequences of wetting (bringing in carbonate ions in solution) and drying (precipitating calcite). The presence of calcite within clay fillings suggests that "clay fill alone does not completely seal the fractures or preclude water movement through them" (Davenport 1993). Both materials are clear evidence of past liquid flow in the fractures. The timing of this flow is not clear; some observers have suggested it was long ago, and is no longer occurring.

At TA-67, 3 miles west of MDA G, EES-1 geologists have reported encountering fracture coatings of evaporite minerals, including gypsum and halite (Vaniman and Chipera 1994). This unexpected observation indicates that the fractures were the site of extensive evaporation; local waters must be concentrated by orders of magnitude before these minerals will precipitate. This much evaporation obviously also requires a great deal of liquid water flow, but again, the timing is uncertain. In addition, without further information on these evaporite fillings, it is impossible to determine whether the solutions that brought the salts to the fractures traveled through the tuff matrix or the fractures themselves.

2.5.2. Relevance to Conceptual Model

The presence of fracture fillings and linings has various implications for the PA at MDA G, some seemingly contradictory. On the one hand, they provide clear evidence of past downward liquid flow along fractures. On the other hand, by their very presence, fracture fillings can greatly affect liquid flow along the fractures in complex ways (Thoma et al. 1992). If a fracture is completely filled with clay, it will not function as an open conduit to flow; but if the fracture walls are simply clay-coated and an open path remains, the clay coating may seal the fracture off from the matrix, resulting in deeper penetration of water and any dissolved contaminants. All of these effects need to be considered in the subsurface conceptual model.

2.6. Moist Zones Associated with Fractures

2.6.1. Data and Documentation

Recent ER activities at TA-73 have included the most detailed and thorough vadose-zone characterization efforts ever conducted at LANL. Unfortunately, no formal results have yet been published, but personal communications with the consultant's project manager at the site have indicated that important new observations will be forthcoming. One of the more striking observations has been a consistent local increase in moisture content associated with some, but not all, fractures at depth in intact tuff (Rolf Schmidt-Petersen, pers. comm., 1995). Kearl et al. (Kearl et al. 1986) made very similar observations at MDA G, where they encountered moisture spikes associated with some fracture zones.

2.6.2. Relevance to Conceptual Model

As mentioned above, fracture fills demonstrate that the fractures acted as conduits for liquid water movement at sometime in the past. It has been suggested that this period

of activity was limited to the geologic past, either associated with the early post-emplacement history of the tuff, or perhaps to a wetter period associated with Pleistocene glaciations (Wayne Hansen, pers. comm., 1995). These new observations of moisture associated with fractures, if confirmed, indicate that some of the fractures are acting as present-day conduits for water movement. These data, by themselves, do not indicate the direction of water movement -- water moving up into the mesa from lower moist regions by capillary action will wet the fractures just as well as water moving down from the land surface, but these two scenarios have drastically different implications for the PA. Recent observations of deep moisture movement associated with snowmelt (see section 2.8) suggest that at least some water is moving down from the mesa tops. Perhaps future chemical or isotopic investigations will provide further information on the source of this fracture-associated moisture.

It should be noted that Kearl et al. (Kearl et al. 1986) attributed the moisture associated with fractures to water vapor absorbing onto the tuff from the fracture, rather than liquid water. They offer no evidence for this theory, which is unconvincing considering the high equilibrium humidity associated with even very dry tuff. This statement is probably a product of their assumption that liquid flow was impossible under *in-situ* conditions, based on inaccurate residual saturation measurements (see discussion by Rogers and Gallaher 1994b).

2.7. Deep Roots

2.7.1. Data and Documentation

Living roots have been observed at depth in fractures both at MDA G and elsewhere at LANL. At MDA G, living roots are currently visible at the bottom of Pit 38, at a depth of 60', and Reneau and Vaniman (Reneau and Vaniman 1994) observed living roots at the bottom of Pit 39, at a depth of 45'. Elsewhere at LANL, reports have mentioned roots as deep as 67' (at TA-33, Bill Laughlin, pers. comm., 1995).

2.7.2. Relevance to Conceptual Model

These observations, like the previous observations of moist zones around fractures, are clear evidence of present-day water movement at depth. While the moisture data were limited to TA-73, these root observations are from MDA G, and the anecdotal reports elsewhere at LANL suggest that deep roots and therefore deep water movement are the rule rather than the exception on the Pajarito Plateau.

It is important to evaluate what the presence of living roots in deep fractures indicates. One obvious conclusion might be that these deep fractures are active conduits for liquid water, and that the roots are following this water. I do not believe this conclusion is justified.

Plants are extremely efficient at extracting water from unsaturated media, even water that is tightly bound by matric forces. A typical value for the permanent wilting point for soil, i.e. the matric potential that finally blocks plant uptake, is 15 bars (Hillel 1980), equivalent to an effective saturation of only 1.7% in Tshirege Unit 2b (similar for other units, as high as 6.2% for 1b). This implies that tuff wetter than this is a viable source of moisture for plants. (This value for the permanent wilting point is taken from the agronomy literature, and is appropriate for typical crops; the drought-adapted trees and bushes of the Pajarito Plateau are probably even more efficient at water collection.) Therefore, the fractures that host living roots need not be water-filled and serve as the roots' water supply; they may simply be zones of weakness in the rock, enabling roots to grow downward, extracting water from the unsaturated tuff matrix.

Either way, the presence of living roots indicates that there is sufficient water available to the roots at depth. More importantly, since plants wouldn't survive long on Pleistocene water in storage, this deep water must be actively replenished. Once again, however, this finding does not indicate the location of the replenishment source.

2.8. Deep Infiltration of Snowmelt

2.8.1. Data and Documentation

In addition to the drilling at TA-73 that revealed increased moisture associated with fractures, ER activities included installation of an extensive array of wide variety of vadose-zone monitoring equipment, including neutron probe access tubes, suction lysimeters, and heat dissipation sensors. This array was installed and operational for a major snowmelt event in February 1995. Preliminary data indicated a major pulse of water moving down through the tuff, to depths of 50'-100' (Rolf Schmidt-Petersen, pers. comm., 1995). In some horizons, moisture contents approached saturation, and enabled relatively large volume samples (500 mL) to be collected by suction lysimeters. Additional details must await further analysis and dissemination of the data.

2.8.2. Relevance to Conceptual Model

This information, which once again is not yet published, clearly points at episodic surface events (in this case snowmelt) as at least one source of renewal for the deep moisture indicated by fracture moisture and living roots. This is the first indisputable evidence that snowmelt can induce downward moisture movement of 50' - 100' beneath a mesa top. This moisture pulse was observed in intact tuff (as opposed to crushed tuff or fill material), but was in the vicinity of the TA-73 landfill. The potential effects of the landfill, nearby surface treatments (the asphalt-paved runway may increase local ponding and thus infiltration), and fractures need to be evaluated before this finding can be directly applied at MDA G, but in the meantime, any conceptual model must include the potential for deep infiltration.

One question that requires immediate attention is why these observations of increased moisture associated with fractures and a deep moisture pulse triggered by snowmelt have not been observed elsewhere at LANL. Perhaps these phenomena are in some way unique to TA-73, and therefore of little relevance to MDA G. This may have some truth to it; as mentioned above, the effects of the landfill and the paved runway need to be further investigated. On the other hand, most of MDA G is either disposal pits, which are basically landfills, or asphalt paving, so that even if TA-73 conditions are artificial, they may be quite similar to conditions at MDA G.

I believe, however, that these special conditions represent only part of the explanation for the new results. The contractor working at TA-73 is a specialist in vadose-zone hydrology, and has applied state-of-the-art vadose-zone characterization and monitoring techniques. Vadose-zone hydrology is a distinct and complex specialty, and unfortunately much of the previous environmental characterization work has not been geared towards vadose-zone problems.

2.9. Lack of Springs and Seeps

2.9.1. Data and Documentation

Numerous workers have spent weeks of field time around Mesita del Buey, involved with drilling, geologic mapping, environmental monitoring, and archeological and biological surveys. None have reported finding any springs or seeps on the canyon walls

below MDA G, or elsewhere in the immediate vicinity. (Numerous springs and seeps have been located elsewhere at LANL, primarily in tuff settings in the western part of the Laboratory, and in pre-Bandelier outcrops near and within White Rock Canyon.)

2.9.2. Relevance to Conceptual Model

The lack of springs and seeps indicates that there is no extensive perched water body within the mesa, which in turn indicates that downward liquid flow does not exceed the saturated conductivity of the least conductive unit within the mesa. Available conductivity measurements for the tuff within Mesita del Buey indicate that the lowest conductivity unit is Tshirege unit 1b, with a geometric mean conductivity of roughly 7×10^{-5} cm/sec (Krier 1995). This provides an upper bound on the infiltration rate of 22 m/year, not a particularly helpful contribution to our problem. This result demonstrates the problem in using *in-situ* hydraulic properties to estimate infiltration rates -- these conductivity measurements are probably typical for at least the central part of the Pajarito Plateau, and would seem to indicate that anywhere perched water and seeps exist that infiltration must be in excess of 22 m/year. This is clearly not consistent with the annual precipitation on the plateau. The problem with this argument is that observed seeps are most likely perched on thin low-conductivity layers, not represented in geometric mean conductivity values.

A simple water budget, coupled with conservation of mass, requires that in the long-term (to eliminate changes in storage) the water entering the mesa from above via precipitation, or below via capillary forces, must be balanced by water leaving the mesa. Possible escape routes include deep infiltration, surface evapotranspiration, enhanced evaporation from within the mesa (via fractures, surge beds, and mesa sides), and surface discharge. The lack of springs and seeps eliminates surface discharge as a potential sink.

The question of springs and seeps is also critical to the contaminant pathway analysis. Springs or seeps on the canyon walls below MDA G could provide pathways for contaminants leached out of pits or shafts to reach the accessible environment. The lack thereof suggests that there is no subsurface pathway from the pits and shafts at MDA G directly to the ground surface. Surface erosion pathways are outside the scope of the EES-5 effort for the PA; the EES-15 team is analyzing that pathway. Subsurface interactions with alluvial aquifers in the canyons will be discussed below.

2.10. Evaporation and Water Vapor Movement

2.10.1. Data and Documentation

In the semiarid climate of northern New Mexico, evaporation and vapor-phase moisture flux may play critical roles in subsurface flow and transport. Two broad categories of effects include subsurface liquid flow driven by surface evaporation, and subsurface evaporation and subsequent vapor-phase transport.

High summer temperatures, strong winds, and extensive bare rock outcrops along canyon walls all combine to intensify surface evaporation in the vicinity of MDA G. Drying of the surface materials induces strong capillary gradients towards the surface, which will drive both liquid and vapor-phase water flow out from the mesa. Whether liquid or vapor dominates will depend on the local relative permeabilities of the tuff. Under dry conditions near the mesa surface, the vapor-phase permeability will be higher than the liquid-phase permeability and vapor flow will dominate, while moister conditions deeper within the mesa will lead to the opposite result.

Evaporation can also occur within the mesa, in areas of high air flow. The resulting water vapor will then move along high-permeability paths in response to vapor-phase driving forces. Although much research has been conducted at Mesita del Buey into air permeability and driving forces, no recent data have been made available for this conceptual modeling effort. Therefore, this discussion must be limited to older data and theoretical generalizations.

Open fractures are obviously extremely high permeability pathways to gas-phase movement. Volcanic surge beds between Units within the Tshirege member have been shown to be a preferential pathway for vapor-phase tritium migration at MDA G (Purtymun 1973). Recent ER-funded air pressure measurements at TA-73 revealed horizons at depth that reflected atmospheric pressure fluctuations with no appreciable lag or damping, suggesting extremely high air permeability (Rolf Schmidt-Petersen, pers. comm., 1995). On the other hand, unpublished *in-situ* air permeability measurements at MDA G do not seem to show high permeabilities associated with the prevalent surge bed at the base of Tshirege Unit 2b (Don Krier, Don Neeper, pers. comm., 1995). This inconsistency is problematic, and requires further investigation. Based on the MDA G tritium data and TA-73 pressure data, however, it appears that the horizontal high-permeability horizons and the predominantly vertical fracture sets together may form an effective three-dimensional network of interconnected pathways to vapor-phase flow.

While transport analyses for vapor-phase contaminants are outside the scope of the EES-5 contribution to the PA, vapor-phase movement of air and water vapor may play a critical role in the overall water budget of the mesa. At the relatively low moisture contents encountered within the mesa, most of the pore space in the tuff is filled with air. This air, in equilibrium with the tuff, has a very high relative humidity. (Air in equilibrium with Tshirege Unit 2b at 5% effective saturation has a relative humidity of 99.7%.) If this humid air within the mesa can exchange with the relatively dry atmospheric air outside the mesa (typical relative humidity in Los Alamos is 40-60%, Bowen 1989), this exchange may provide an efficient means of removing water from the mesa. The surge bed / fracture network described above may provide the avenue for this air exchange; what is needed is a driving force.

Three potential driving forces for vapor-phase transport exist: advective winds, barometric pumping, and water vapor diffusion. The relatively narrow, finger-like shape and crenelated canyon rims of the mesas makes them particularly susceptible to all three forces; no point within the mesa is more than a few hundred feet from atmospheric boundaries at the mesa top and the canyon walls.

The Pajarito Plateau is subject to strong winds, particularly in the spring, after snowmelt. These winds may directly induce advective air motion through the mesas, or induce air movement in wells or fractures by barometric or topographic effects (Weeks 1987). Natural barometric variations can also result in significant air exchange within the mesas with no wind, especially in the presence of the fracture/surge bed network. Both of these processes will induce drying, as relatively dry atmospheric air replaces humid air in the mesa. Finally, even in the absence of these air-flow driven effects, simple gas-phase diffusion of water vapor will drive moisture from the relatively humid mesa interiors towards the atmospheric boundaries.

2.10.2. Relevance to Conceptual Model

I have outlined a plausible mechanism for drying out the mesa via air exchange and gas-phase removal of water vapor. This may be a significant component of the mesa water budget, and if so, may limit the water available for deep infiltration. Until more of the MDA G field data become available, we can only speculate as to the importance of this mechanism. There are, however, some independent field observations described in the

next section that provide some circumstantial evidence that gas-phase dry-out may be very important indeed.

2.11. Observed Tension Profiles in Tuff

2.11.1. Data and Documentation

In conjunction with environmental monitoring drilling activities at MDA G in 1994, ESH-18 personnel measured *in-situ* matric potential profiles, using a chilled-mirror psychrometer (Rogers and Gallaher 1994a). This is a relatively new technique, recently borrowed from the food-processing industry by vadose-zone hydrologists. Although the method has been adopted by the USGS for investigations at Yucca Mountain (Jerry Boak, pers. comm., 1995), no rigorous quality assurance evaluation or standard procedures have been instituted at LANL, so these results are subject to some uncertainty. Nevertheless, the reproducibility and internal consistency of the data suggest that the results are worth considering.

The striking result, encountered in almost every measured profile, was an extremely strong peak in matric potential at a depth of 40'-60', corresponding to the surge beds at the base of Tshirege Unit 2b. The magnitude of the matric potential peak completely overwhelmed the effects of gravitational potential; the same pattern appears regardless of whether matric potential or total head is plotted. These data, if valid, indicate that moisture both above and below the surge bed horizon is moving towards that horizon.

Obviously, if this condition is to persist in time, there must be a separate process underway that is continually removing water from the surge bed horizon. These matric tension profiles could be the field evidence that demonstrates the importance of vapor-phase dry-out along the surge bed horizon.

2.11.2. Relevance to Conceptual Model

These profiles suggest that air-flow dry-out of the mesas may exert a significant influence on the overall moisture budget within the mesas. They may also help explain the apparent discrepancy between the low estimates of infiltration produced by the CREAMS simulations described in section 2.1, and the observations of significant deep moisture movement associated with snowmelt events, as described in section 2.8. Furthermore, these matric potential and head profiles, if correct, indicate that the surge beds form a "dry barrier" to downward water flow. The implications for the MDA G PA are profound, if this barrier is complete. However, as will be demonstrated, it is unlikely that the barrier is complete.

The presence of gradients towards the surge beds both above them and below them implies two things. First, as mentioned above, there must be a mechanism to remove moisture from the surge bed horizon; e.g. air-flow dry-out. Secondly, there must be an ongoing source of water to the gradients, both above and below the surge beds. Surface infiltration can provide the upper source, but the lower source of water must be either water moving up through the mesa from some deep source, or surface infiltration water that has somehow gotten past the surge bed "dry barrier," only to be caught and drawn back up to the surge beds, by the matric potential gradient induced by airflow through the surge beds. I will address the possibility of a deeper water source below; for now, let us consider possible routes for surface infiltration water to bypass the dry barrier.

Fractures may provide just such a bypass. We have some independent circumstantial evidence (discussed in section 2.8) from TA-73 that fractures can provide conduits for deep water flow in episodic events, such as snowmelt. The matric potential profiles measured at MDA G in tuff matrix represent a single point in time, and should not

be expected to reflect transient events. These profiles more likely approximate long-term average conditions. Water rapidly flowing down an open fracture in a snowmelt or monsoon event will not have time to equilibrate with the tuff every step of the way. The dry tuff will gradually absorb the water from the fracture, but some water may pass through and penetrate deeper than the surge beds before being absorbed. After the transient infiltration event ends, the fracture will drain, and once again serve as a pathway for air flow, air that can pick up moisture from the tuff, carry it to the surge beds, and then out to the canyon walls. (Unlike the mesa tops, the canyon walls have little or no soil cover to close the fractures off from the atmosphere.) Thus, in a system subject to transient events, the same fractures that move liquid water down past the "dry barrier" during episodic infiltration events, will then bring water vapor back up and out during normal conditions. When considering this scenario, it is important to bear in mind that for non-volatile contaminants (such as most radionuclides of concern), vapor-phase drying that may imply no net water movement does not imply no net contaminant transport.

2.12. Vapor-Phase Notch

2.12.1. Data and Documentation

Most moisture profiles from Mesita del Buey (and elsewhere on the Pajarito Plateau) show a pronounced increase in moisture content at and above the Tshirege 1a/1b contact, a horizon known as the "vapor-phase notch" (VPN). The VPN represents a transitional zone from vitric tuffs below to devitrified tuffs above (Broxton et al. 1995a), and forms a prominent erosional notch in outcrop. Any valid subsurface conceptual model must offer an explanation for the moisture anomaly associated with the VPN.

Possible explanations at Mesita del Buey are complicated by the coincidental correspondence between the elevation of the VPN and the floor of Pajarito Canyon, a major canyon with its own alluvial aquifer system, south of Mesita del Buey. (In reality, this correspondence is probably only coincidental from a modern hydrology point of view. Geomorphologically, the VPN likely exerts some control on downcutting of the canyon. Cañada del Buey, north of Mesita del Buey, is stratigraphically deeper than Pajarito Canyon and the VPN is well-exposed along its canyon walls). However, at other locations at the Laboratory where the VPN and adjacent canyon floors do not coincide, the VPN still shows increased moisture contents (TA-21, Broxton et al. 1995b; TA-49, Dave Broxton, pers. comm., 1994).

2.12.2. Relevance to Conceptual Model

There seem to be two primary possible explanations for increased moisture content at the VPN: a change in hydraulic properties at that location in the profile, or a lateral input of water from the alluvial system in Pajarito Canyon.

In the first case, the observed profiles may well reflect a steady-state one-dimensional flow system. In the vadose zone such a system will tend towards a uniform downward unit gradient due to gravity, with moisture contents in various layers adjusting themselves to ensure a uniform unsaturated hydraulic conductivity and head gradient, despite variations in the layers' saturated hydraulic conductivity. In this situation, the exact nature of the moisture profile and conductivity relationships may provide valuable information on downward fluxes from the mesa surface.

In the second case, the flow system is inherently multidimensional, with lateral flow from the canyon playing an important role. In this situation, the water source at the canyon-floor level should be associated with an increase in total head at that horizon, and the details of the anomaly may have little bearing on deep fluxes from the mesa top.

There are three lines of argument that all suggest that the primary explanation for the observed moisture spike at the VPN is a change in hydraulic properties, and that the coincidental alignment with the Pajarito Canyon alluvial system plays little if any role. First, as already mentioned, the VPN is associated with moisture spikes at other locations on the Pajarito Plateau where there is no coincidental saturated alluvial system. Second, chilled-mirror psychrometer profiles measures at MDA G do not show a strong signal at the VPN (Rogers and Gallaher 1994a) (subject to the caveats on the chilled-mirror method described above), suggesting that a unit gradient one-dimensional flow system is present. Finally, preliminary field infiltrometer measurements performed in Cañada del Buey north of MDA G suggest that there is indeed a low conductivity zone extending upward from the VPN a few meters (Benton et al. 1994). The infiltrometer measurements yield estimates of both saturated and unsaturated hydraulic conductivity, but are limited to the wet end of a moisture curve.

If, as these data suggest, the VPN moisture anomaly does represent the effects of property changes on a one-dimensional flow system, the details of the anomaly might provide useful insight into the nature of that system, and therefore into the long-term potential for downward migration from the ground surface at Mesita del Buey. This hypothesis might be tested by detailed chemical and isotopic analyses which ought to be able to distinguish between local precipitation and Pajarito Canyon stream flow from farther to the west.

2.13. Presence of Alluvial Systems in Canyons

2.13.1. Data and Documentation

The two canyons that bound Mesita del Buey are Cañada del Buey on the north, and Pajarito Canyon on the south. The floors of both canyons are blanketed with a layer of alluvium of varying thickness. In Pajarito Canyon, this alluvium is partially saturated, forming a perennial perched alluvial aquifer above unsaturated Bandelier Tuff. This aquifer has been characterized by the LANL Environmental Surveillance Group (Devaurs and Purtymun 1985). Recent ER activities have led to increased monitoring of the alluvial aquifer (Merlin Wheeler, pers. comm., 1994), including some slug tests to determine hydraulic properties of the alluvium (Los Alamos Technical Associates 1991). The alluvial aquifer is a direct consequence of the surface stream in Pajarito Canyon, one of the main drainages of the Pajarito Plateau. The alluvial aquifer and the stream are in direct hydraulic contact, and there is likely free exchange between the two. Although not capable of supplying a municipal or industrial water-supply well, the permanence and shallowness of the alluvial aquifer suggests it could supply water to an individual homestead via a shallow drilled or dug well.

Despite extensive drilling programs by the Environmental Surveillance Group, no similar perennial aquifer has been located in Cañada del Buey. There is an intermittent stream in Cañada del Buey, and the sketchy data available indicate that some monitoring wells occasionally show some saturated alluvium, but no perennial aquifer (Gallaher 1993). No further details on this system are yet available.

2.13.2. Relevance to Conceptual Model

Basic hydrologic theory and some recent field observations suggest that the perennial alluvial aquifer systems found in some of the canyons of the Pajarito Plateau provide significant recharge to the main aquifer. Perfectly impermeable materials are rare to nonexistent in the real world; it is inconceivable that there is no downward leakage from the perched systems, especially considering that they are resting in fractured tuff. While unsaturated tuff at typical field moisture contents has a low conductivity, the saturated

conductivity values, which would apply in the ponded situation below perched systems, are on the order of 10^{-4} cm/sec, not particularly low. (These are hydraulic conductivities typical of silt or silty sand.) Therefore, in this setting, it would be more difficult to explain a lack of recharge than significant recharge.

Los Alamos Canyon is another major canyon that cuts across the Pajarito Plateau, north of Pajarito Canyon. Like Pajarito Canyon, Los Alamos Canyon contains a perennial alluvial aquifer. Recent ER activities in Los Alamos Canyon have yielded new evidence for active deep infiltration downward from the alluvial aquifer there. Drilling encountered a deep perched system in the Guaje Pumice at a depth of 325', well below the canyon floor (Broxton et al. 1995b). Water from this depth showed a distinct tritium and sodium chloride signature of modern Laboratory activities. The presence of a deep perched zone beneath Los Alamos Canyon suggests downward infiltration from the alluvium, and the modern chemical signature demonstrates that this infiltration is currently active and relatively rapid (reaching a depth of 325' in at most 50 years, indicating a infiltration velocity in excess of 6 ft/yr). At present, there are no similar data for the Pajarito Canyon, but there is no reason to doubt that the two system behave similarly.

A working model for alluvium systems on the Pajarito Plateau envisions the canyon alluvium as a line source of deep recharge. Major structural features such as fault zones may focus this recharge to some extent. Ponded water in the alluvium infiltrates down through unsaturated tuff, and to some extent laterally beneath the adjoining mesas, drawn by matric forces. The saturated alluvium acts as an unlimited supply of water and as such will increase moisture contents, hydraulic conductivities, and flow rates in the vicinity. In particular, if the wetter region influenced by the alluvium extends beneath the mesa, it would cause higher downward flow velocities than would be predicted based on mesa-top infiltration rates. Any contaminants that leach down from the pits and shafts at MDA G and enter this wetter region would then be entrained in the rapid flow path, and could reach the main aquifer faster than might otherwise be expected.

2.14. Moist Zones at Depth

2.14.1. Data and Documentation

Recent ER drilling below MDA L (just west of MDA G) encountered numerous "moist" zones in the Puye Conglomerate and Cerros del Rio basalts at depth beneath Mesita del Buey (Don Krier, pers. comm., 1995, no details yet available). Earlier drilling in Pajarito Canyon west of MDA G also encountered wet conditions at depth, near the Tshirege/Otowi contact (Gardner et al. 1993). These are qualitative observations based on wet cuttings and drilling tools, rather than quantitative data (hopefully, formal ER data will be available at some point). There is no conclusive evidence of perched water beneath Mesita del Buey.

2.14.2. Relevance to Conceptual Model

The source of this deep moisture may be either infiltrating surface water that has moved down through the mesa, possibly carrying contaminants from MDA G, or alluvial water from the Pajarito Canyon aquifer. It is possible that these two sources could be distinguished chemically or isotopically, but collecting an adequate volume for analysis might prove challenging. Without any conclusive data, the subsurface conceptual model is unconstrained as to the source of this water, but must acknowledge its existence.

2.15. Pre-Bandelier Units at Depth below MDA G

2.15.1. Data and Documentation

Almost all of the hydrologic characterization on Mesita del Buey has focused on the Bandelier Tuff. The tuff is the shallowest formation, and is the host rock for all waste disposal activities. It is the easiest to access, and might be expected to control downward migration. Unfortunately, the deeper pre-Bandelier formations are not at all well-characterized, or even identified. No deep boreholes yet exist near MDA G, and the predictions of the pre-Bandelier stratigraphy are based on correlations with water-supply wells PM-2, PM-4, and PM-5, located 1½ - 2 miles northwest of the site (Los Alamos National Laboratory 1992). While these correlations may be reliable in other geologic settings (e.g., "layer-cake" stratigraphy), in this portion of the Pajarito Plateau, the Cerros del Rio Basalts (from eruptive centers east of the Rio Grande) are interfingering with Puye Conglomerate (shed from the Jemez Mountains to the west) in an unpredictable fashion.

Recent ER drilling has produced the first definitive pre-Bandelier data, showing a thin layer (<10') of Puye-like sediments between the base of the Bandelier Tuff and Cerros del Rio basalts. The deepest borehole thus far has reached a depth of 448' beneath a tributary of Cañada del Buey at MDA L (about ¾ mile west of MDA G), and has not completely penetrated the basalts (Don Krier, pers. comm., 1995). Future drilling will better define the deep stratigraphy in the area.

Basalt samples collected so far beneath Mesita del Buey display enormous variability. Some core samples are extremely dense, with no apparent porosity, others are fractured to the point of appearing shattered, while still others are so vesicular as to appear foamy. Drillers report major losses of circulation at various locations in the basalt, and in one case, two boreholes 350' apart exhibited a direct and rapid air connection (Don Krier, pers. comm., 1995). Variability in the basalt occurs over distances of tens of feet, and appears quite random; no study of the spatial distribution or even relative prevalence of these different zones has been conducted. Obviously these variations are not truly random, but represent volcanic flow processes that could theoretically be characterized and mapped, but given the cost of drilling, it is unlikely that this degree of characterization will be undertaken. In the meantime, it is clear that these different basalt lithologies will exhibit radically different hydraulic properties.

2.15.2. Relevance to Conceptual Model

At the present time, it is difficult to imagine a method of modeling flow and transport through the Cerros del Rio Basalts underlying MDA G, due to the extreme lithologic and hydrologic variability encountered therein. Not only are effective hydraulic parameters practically impossible to estimate, the very style of flow varies. In intensely fractured rubble zones, the scale of the fracturing is such that the material may behave like a coarse porous medium, while in more intact zones, any flow is likely to follow individual fractures. Our only hope of estimating bulk effective properties of the basalt seems to be examination of natural or artificial tracer profiles. No such study has yet been undertaken. Therefore, I believe that it is impossible at this point to produce a <u>defensible</u> conceptual or numerical model of flow and transport through the basalt.

Presumably, the Puye Formation underlies the Cerros del Rio Basalt at depth beneath MDA G. Although not adequately characterized for detailed flow and transport modeling, the geology of the Puye suggests that it is less variable hydrologically than the basalts, and some bounding calculations on travel times might be possible. Unfortunately, without knowledge of the deep subsurface stratigraphy beneath MDA G, we do not know enough about the thickness or saturation of the Puye to even perform these bounding

calculations at this point in time. Given the present lack of knowledge, the only defensible approach seems to be to neglect the existence of the pre-Bandelier formations beneath MDA G, and effectively move the point of compliance to the base of the Bandelier Tuff.

2.16. Effects of Paving

2.16.1. Data and Documentation

In a possibly misguided attempt to decrease infiltration and potential contaminant transport, large areas of MDA G have been or are being paved with asphalt. In addition to these intentional hydrologic alterations, operational requirements have led to wide-scale surface disturbances, including road paving and large spoil piles.

ER investigations of MDAs at TA-49 have demonstrated marked increases in moisture content beneath asphalt pads. In some cases, moisture contents beneath the pads may approach saturation, producing perched zones subject to saturated flow and transport (Bennie Martinez, pers. comm. 1994).

2.16.2. Relevance to Conceptual Model

This issue is important both for the conceptual modeling task of the PA and for future operational decisions at MDA G and elsewhere at the Laboratory. As discussed above, vegetation-driven ET, possibly in combination with barometric pumping, appears to be very effective at drying out the tuff within the mesas. Asphalt paving eliminates or greatly decreases both processes; large piles of crushed tuff spoil might be expected to have a similar effect.

Eliminating ET and barometric pumping from a site would not necessarily be bad, if one could also eliminate all inflow of moisture. Asphalt paving does not do this; asphalt at the Laboratory rapidly deteriorates and cracks (perhaps accelerated by the intense sunshine and temperature extremes at the Laboratory's elevation), permitting infiltration. Even in the absence of cracking, lateral movement of water in from soil adjacent to the asphalt during wet periods can contribute substantial moisture to the paved system. Potential for lateral movement may be increased by focused surface runoff from the paved surface. One way or another, water does find its way beneath the asphalt. In the absence of effective drying mechanisms, it tends to accumulate there, resulting in the observed high moisture content conditions.

These wet conditions have three major effects, all negative from a waste management point of view. First, the high moisture will tend to increase physical, chemical, and microbiological activity within the waste. This activity may directly or indirectly increase the availability of contaminants within the waste and their rate of release. Second, in an unsaturated setting hydraulic conductivity is a strong function of moisture content. Increased moisture will dramatically increase the hydraulic conductivity of the medium and the potential for transport. Finally, the increased moisture creates a moisture gradient away from the waste by increasing saturation and decreasing matric potential. In summary, by increasing moisture contents within the waste, paving an MDA can increase the availability of contaminants from the waste, increase the conductivity of the material surrounding the waste, and increase the gradient forcing contaminants away. These effects should be considered for the PA at MDA G, but the issue clearly goes beyond just PA concerns, and should be further investigated. A combination of detailed field observations and numerical experiments could provide information critical to a more complete understanding of the effects of paving in the vicinity of MDAs.

3. Conceptual Model for Subsurface Transport at MDA G

3.1. Model Description

The observations described in the previous chapter paint a unified picture of how flow and transport beneath MDA G may occur. I say "may" because this is not the only possible interpretation, nor is it cast in stone. As new observations become available, and as other investigators provide original insights, this model is sure to change, or perhaps even be completely discarded. In the meantime, it provides a conceptual model consistent with available observations, a starting point for numerical modeling, and a basis for future field studies.

This conceptual model for subsurface flow and transport posits an alternation between infiltration episodes (figure 3-1) and normal drying conditions (figure 3-2). Episodic infiltration can occur either during spring snowmelts or during the intense summer thunderstorm season, when the fracture system is activated and infiltration increases moisture contents both near the surface and deeper within the mesa. In between these events, the system reverts to a more typical drying cycle. ET removes moisture from the surface of the mesa, while the three-dimensional network of fractures and surge beds dries out the mesa from within. Superimposed on both states is the continuous leakage down from the alluvial aquifer system in Pajarito Canyon, which would accelerate the downward transport of any contaminants that are entrained in this flow.

Figure 3-1 schematically portrays the processes of the infiltration state. The mesa top soils are becoming saturated, and water is soaking into the top few meters of tuff. Some fractures are acting as preferential pathways, carrying water deep inside the mesa. Cool temperatures and high atmospheric relative humidity minimizes ET from the mesa top, while internal drying of the mesa is low, because the wet fractures cannot carry much air, and what air is circulating through the mesa is relatively humid to start with. Precipitation is running off the mesa top, and the streams in both Pajarito Canyon and Cañada del Buey are flowing. The increased ponding in Pajarito Canyon accelerates the leakage into the underlying tuff, while the presence of any standing water in Cañada del Buey has activated otherwise dormant recharge paths down into the fractured tuff beneath the stream bed.

Contaminants that have slowly been leached through the crushed tuff backfill of the disposal pits and shafts may find themselves in an active fracture transport system, and may be carried down a few cm or a few tens of meters, before the water is absorbed into the matrix. Depending on the chemical nature of the contaminant, it may be sorbed on a thin clay film on the fracture wall, where it will be ready to be picked up by the next wave of water, the next week or the next century.

Eventually, the infiltration event comes to an end. As figure 3-2 shows, the sun comes out and streamflow decreases in Pajarito Canyon and ceases altogether in Cañada del Buey. As air temperature and plant activity increase, much of the newly infiltrated water in the soil and the top few meters of tuff on the mesa top will be drawn out by ET. Without a steady source of water, the active fractures can no longer support flow, and rapidly drain. The open fractures that were preferential pathways for water movement now become conduits to air flow, induced by wind against the canyon walls and by natural barometric fluctuations. Air coming in from the northern New Mexico atmosphere is quite dry, but rapidly becomes saturated by evaporating water from the fracture walls. This drying of the fracture walls draws water from deeper in the matrix towards the fracture, and if the fracture density is high enough, may effectively dry out the whole mesa.

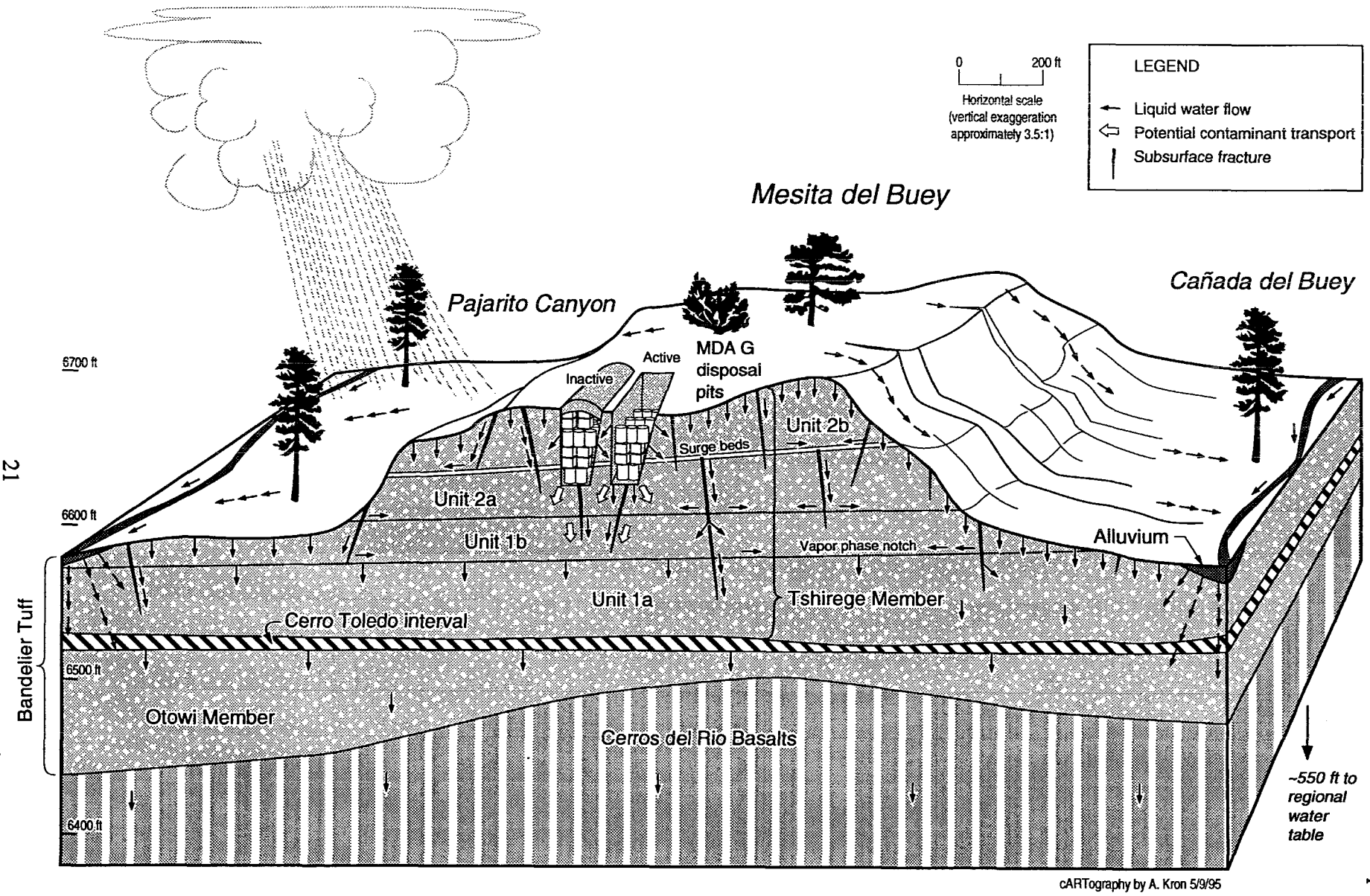

Figure 3-1. Conceptual model of flow and transport beneath MDA G during an infiltration episode. Subsurface features are schematic; processes are hypothetical (stratigraphy from Krier 1995).

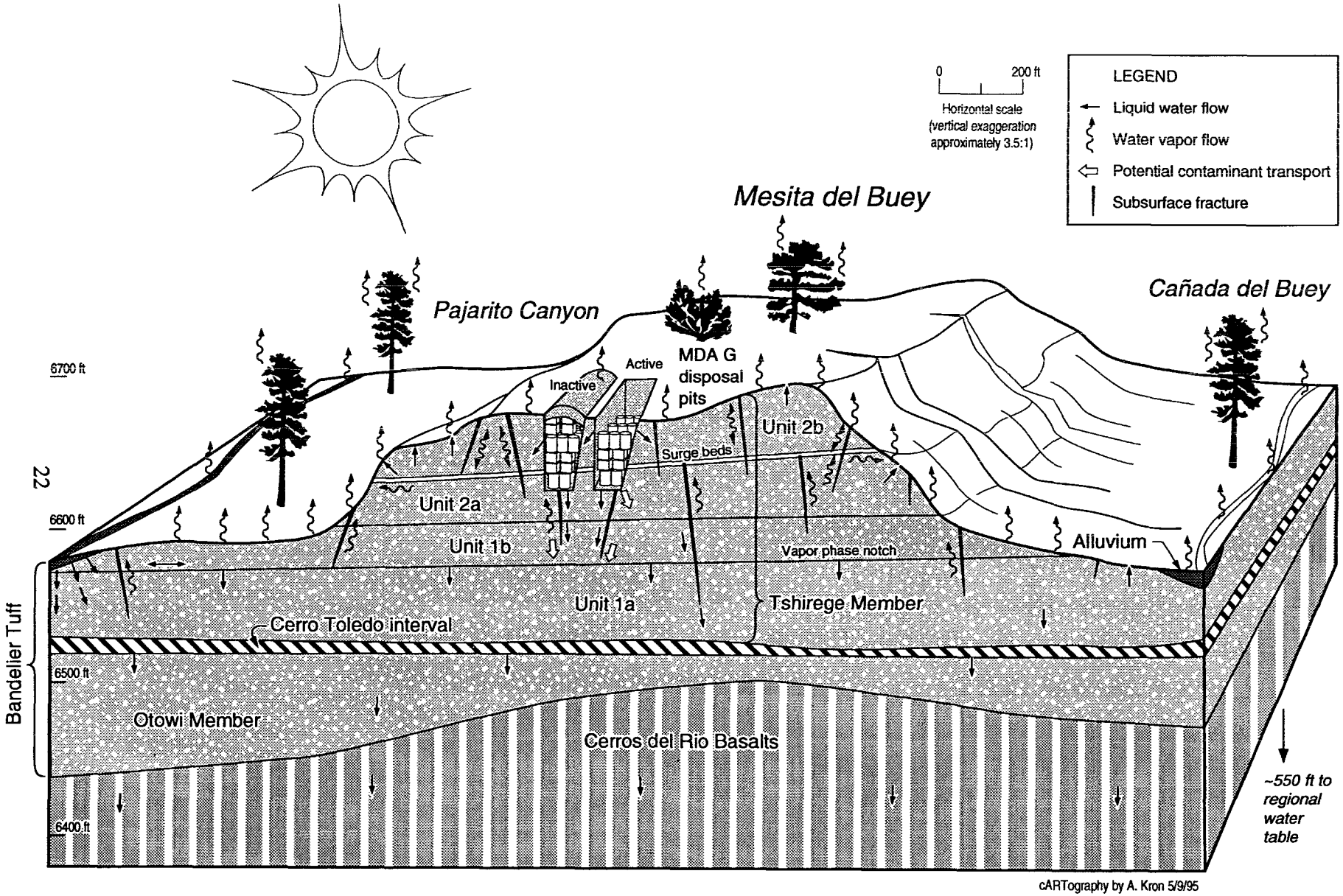

Figure 3-2. Conceptual model of flow and transport beneath MDA G during normal drying conditions. Subsurface features are schematic; processes are hypothetical (stratigraphy from Krier 1995).

Meanwhile, enhanced airflow through permeable surge beds may have the same drying effect throughout the mesa in this laterally continuous horizon.

Cañada del Buey has run dry, but Pajarito Canyon continues to function as an active recharge source to the relatively dry tuff below, and laterally, beneath Mesita del Buey. Eventually, some contaminants leached out of the pits or shafts may work their way all the way down to the vapor-phase notch. From here on down, the tuff is less fractured, and there is less opportunity for preferential flow paths, but this is offset to some degree by an influx of water from the stream and perennial aquifer in Pajarito Canyon. This increased moisture means higher hydraulic conductivities and faster flow rates, while the location beneath the canyon floor practically eliminates the possibility of air movements drying out the tuff. With the increased flux and decreased opportunity for dry-out, any contaminants that reach this point have only one way to go, and it is only a matter of time before they reach the main aquifer.

3.2. Uncertainties and Recommendations for Future Work

The conceptual model presented here is generally consistent both with the science of hydrogeology and with the local field observations of which I'm aware. The interpretation is obviously only as good as the observations, and future (or existing but unavailable) field data may alter parts or all of this model. The ultimate test of the model is its ability to accurately predict field behavior. To this end, I recommend pursuing numerical implementation of this conceptualization, to produce a practical tool that can be directly compared to field observations. These field observations should ideally include both natural mesa-top conditions and perturbed conditions (e.g., near a disposal pit, beneath asphalt paving, or an increased recharge tracer test).

At this point, a few obvious sources of uncertainty can be identified for particular attention:

- The source of moisture above the vapor-phase notch.
- The air-flow characteristics and continuity of the fractures and surge beds.
- Short-term fluctuations in hydraulic gradient, and the effectiveness of the ET trap.
- Response of deep fractures to surface infiltration events (compare with TA-73 observations).

Finally, I'd like to stress that the best way to predict solute transport is to observe solute transport. Long-term field-scale tracer tests will provide the most reliable and defensible data on the behavior of contaminants in the subsurface beneath MDA G and the rest of the Pajarito Plateau, and should be initiated as soon as possible.

3.3. Implications for Numerical Modeling

Based on the conceptual model presented above, it is clear that a corresponding numerical model should:

- Be at least two-dimensional, to account for the geometry of the mesa/canyon system;
- Be transient, to account for the alternative infiltration/drying states;
- Be capable of multiphase transport, to account for water and air/water vapor movement through the tuff;

- Include fractures, which seem to play a major role in deep infiltration of water during episodic events;
- Account for ET, which dries the mesa out between episodic events; and
- Include the alluvial system in Pajarito Canyon, which may provide a driving force for deep recharge.

Sources of Unpublished Data

Much of the data discussed in this report has not been formally published, and was made available to the author in the form of personal communications. Without these data, development of the conceptual model would have been impossible. The assistance of the following scientists and engineers is gratefully acknowledged.

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ER Contractor

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