**YUCCA MOUNTAIN PROGRAM
SUMMARY OF RESEARCH
AND TECHNICAL REVIEW ACTIVITIES
(July 1988 - June 1989)**

DISCLAIMER

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Las Vegas and Reno*

*for
Nuclear Waste Projects Office
Agency for Nuclear Projects
State of Nevada*

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The Nevada Agency for Nuclear Projects/Nuclear Waste Project Office was created by the Nevada Legislature to oversee federal high-level nuclear waste activities in the state. Since 1985, it has dealt largely with the U.S. Department of Energy's siting of a high-level nuclear waste repository at Yucca Mountain in southern Nevada. As part of its oversight role, NWPO has contracted for studies of various technical questions at Yucca Mountain.

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SECTION I

Introduction

INTRODUCTION

The Desert Research Institute (DRI), through its Water Resources Center (WRC), since 1984 has supported the State of Nevada Nuclear Waste Project Office's activities related to the proposed high-level radioactive waste repository at Yucca Mountain on the Nevada Test Site (NTS). This effort is directed at providing the State Office with an unbiased evaluation of the Yucca Mountain Project (YMP) investigations performed by the U.S. Department of Energy (DOE) and the Nuclear Regulatory Commission (NRC). The overall objective is to determine independently whether or not the site meets the performance criteria defined by the Nuclear Waste Policy Act of 1982 and amendments for isolating and containing the wastes during emplacement and the proposed life of the repository.

A particularly important area of concern with the proposed repository is the site's hydrology. Over the thousands of years that the repository must successfully contain the radioactivity, it is water that is most likely to come into contact with the wastes and move radionuclides from the repository to man's accessible environment. Recognizing that the hydrogeologic and closely-related investigations of the proposed repository are of paramount importance, the DRI program has focused on these concerns.

The faculty of the DRI have long been involved with research throughout the State and have particular expertise in groundwater studies related to radionuclide migration and hydrologic safety of underground nuclear testing by DOE and predecessor agencies. This experience gives a substantial background upon which to call when evaluating physical parameters of the Yucca Mountain site and its ability to meet performance criteria. Research and support personnel working on the various efforts under this Nevada Waste Project Office program are listed in Table I-1.

In addition, we utilize laboratory personnel for chemical and isotopic analyses in both of the DRI-WRC water chemistry laboratories.

The State-supported DRI Yucca Mountain program consists of: 1) selected independent research projects to complement those undertaken by the DOE; 2) on-site monitoring of DOE-sponsored field activities; and 3) in-depth technical review of key investigations and repository reliability issues.

The DRI has developed an independent research component to the program related to hydrologic aspects of the potential repository. The objective of this component is to perform research independent of DOE that is directed at resolving key hydrologic issues related to site characterization and repository performance. Each of the research projects, which use alternative approaches and analyses, is recognized as an important supplementary effort to those of DOE and its contractors. These efforts should produce results of significant value in terms of repository asses-

sment. The specific areas presently under study relate to flow in both the saturated and unsaturated zones, the influence of present climate on recharge, an investigation of past climates, and a study related to possible historic groundwater discharge in the immediate vicinity of Yucca Mountain.

Each of these major research efforts, conducted during the period of July 1988 through June 1989, is further discussed in the remainder of this report.

In addition to the specific research projects described in Section II, the WRC provides on-site monitors to observe relevant YMP field activities where key hydrogeologic data are being collected or testing is being conducted. This activity provides first-hand, in-depth knowledge of data collection and testing activities allowing the State Office and other State contractors to remain current as to the progress, methodologies and implementation of DOE-sponsored hydrologic investigations of the site. Monitoring activities, coordinated with DOE and its contractors, also include review of drilling procedures, sampling methods and sample handling, testing procedures, and other field aspects which may influence the quality and reliability of the data collected. These observations are valuable to those evaluating the use of, and conclusions drawn from, the site characterization activities.

The project staff also perform in-depth reviews of released reports and position papers on hydrologic, hydrogeologic, hydrogeochemical, and geostatistical investigations related to the DOE study of Yucca Mountain. NRC reports on nuclear waste activities are also reviewed. The review of technical areas varies in scope depending upon the assessment made by faculty, which forms a basis for categorization as to potential importance to technical issues, quality of work, and unanswered questions. Whether the document content bears directly on key issues that are related to site suitability and licensing criteria is also determined. Areas that relate to key issues are thoroughly considered, including background research into the body of literature pertaining to that particular issue.

TABLE I-1. YUCCA MOUNTAIN PROJECT PERSONNEL
(June 30, 1989)

Individual Activity

Research Faculty

Dr. Thomas Brikowski - Principal Investigator: Thermal Phenomena Project
Dr. Michael E. Campana - Principal Investigator: Isotope Modeling Project
Dr. Gilbert F. Cochran - Principal Investigator: Short-Term Climate Project
Dr. Richard Craig (Kent State University) - Short-Term Climate Project
Dr. Jonathan O. Davis - Principal Investigator: Trench-14 Project
Mr. John W. Fordham - Program Manager, and Short-Term Climate Project
Dr. John W. Hess - Regional Geochemistry
Dr. Elizabeth Jacobson - Isotope Modeling Project
Mr. Fred L. Nials - Trench 14 Project
Dr. Martin Rose - Principal Investigator: Paleoenvironments Project
Dr. Stanley D. Smith (UNLV) - Short-Term Climate Project
Mr. Scott W. Tyler - Principal Investigator: Fractal Geometry Project
Dr. Stephen W. Wheatcraft - Principal Investigator: Fractal Geometry Project
Dr. Peter E. Wigand - Principal Investigator: Paleoenvironments Project

Graduate Research Fellows

Mr. Andy Berzins (Kent State) - Short-Term Climate; Runoff/Recharge
Mr. Robert Byer (UNR) - Isotope Modeling
Mr. Clay Cooper (UNR) - Numerical Modeling Vapor/Air Movement
Ms. Sandra Haws (UNLV) - Thermal Phenomena Modeling
Ms. Connie Herr (UNLV) - Short-Term Climate; Plant Ecology
Mr. Kevin Leary (UNR) - Short-Term Climate; Plant Transpiration
Mr. Peter Leffler (UNR) - Short-Term Climate; Precipitation Analysis
Ms. Nancy Matuska (UNLV) - Regional Geochemistry
Ms. Kathy Murphy (Kent State) - Short-Term Climate; Runoff/Recharge
Mr. Michael Nicholl (UNR) - Fractal Geometry
Mr. Rik Orndorf (Kent State) - Short-Term Climate; Runoff/Recharge
Mr. Barry Roberts (Kent State) - Short-Term Climate; Code Conversions
Mr. John Stamm (Kent State) - Short-Term Climate; Code Conversions
Mr. Peter K. Van de Water (University of Arizona) - Paleoenvironments Project;
Paleocologist

Support

Mr. Craig Biggart - Paleoenvironments Project; Plant Taxonomy
Ms. Martha L. Hemphill - Paleoenvironments Project; Palynologist
Mr. Samuel L. Hokett - Site Monitoring; Field Hydrogeology
Ms. Marjory A. Jones - Program Management
Dr. Robert R. Kinnison - Quality Assurance
Mr. Randy Nicholson - Site Monitoring; Field Hydrogeology
Ms. Cheryl K. Nowak - Paleoenvironments Project; Plant Taxonomist
Ms. Becky A. Peters - Paleoenvironments Project; Zoologist

SECTION II
Research Project Summaries

ANALYSIS OF SHORT-TERM CLIMATE AND WEATHER INFLUENCE ON SURFACE WATER HYDROLOGY AND POTENTIAL RECHARGE

G. Cochran, J. Fordham, S. Smith, S. Hokett, P. Leffler, and K. Leary

INTRODUCTION

This project was undertaken to define how weather and climatic change affect surface-water runoff and the amount of moisture potentially available for recharge. "Climate" is a description used to classify the normal (or average) seasonal and/or annual weather regime. It encompasses not only the meteorological processes, but also the environmental response to that "average" weather regime in terms of vegetation distribution, density, and diversity. Hydrologically, the weather or climate connection is made through the process of infiltration, which determines the partitioning of a precipitation event between direct surface runoff and accretions to soil moisture. Subsequent disposition of soil moisture then determines how much of the precipitation eventually becomes groundwater recharge (water actually reaching the water table or zone of saturation). That disposition is strongly effected by vegetation through the process of transpiration and by soil-water evaporation. These latter processes reflect a climatic feedback. The greater the annual precipitation, the greater is the distribution, diversity, and density of vegetation, but with greater precipitation the driving forces of evapotranspiration are reduced, e.g., less solar input, higher relative humidity. Seasonal distribution of precipitation is also a strong determinant of the relative importance of hydrologic-climatic processes.

Specific objectives of this research are to: 1) explore climate patterns within existing meteorologic records for extreme year (high and low) and "average" year precipitation conditions; 2) examine the infiltration process in terms of efficiency with respect to frequency, duration, intensity, and seasonality of precipitation events; 3) study the distribution of the infiltration characteristics of soils in the Yucca Mountain environment; 4) study the vegetation distribution in the Yucca Mountain environment and the transpirative characteristics of various species in relation to the meteorologic/hydrologic environment; and 5) integrate the results of the foregoing to derive rational estimates of the runoff/recharge effects of a climatic change.

These objectives are being met through a combination of field studies/experiments, literature review, and computer manipulation of data bases (statistical analysis and modeling).

ACTIVITIES

Field aspects of this study have been implemented at a location approximately 2 miles northwest of Yucca Mountain. In 1987, this location was selected because the three major geomorphic landforms of the Yucca Mountain environment are all repre-

sented in a small area (ephemeral stream channel with deep stream sediments, steep-sloped fractured tuff with thin soil mantle, and dissected alluvial fan remnant). After the area had been selected, several soil pits were excavated to depths up to 8 ft and soil descriptions were prepared. Also, vegetation was mapped and dominant species on each landform were identified. On each landform, young, mature, and old individuals of each dominant plant species were identified for monitoring. Time domain reflectometers (TDR), soil moisture probes, were installed at each of the selected individual plants, in unvegetated (bare) areas and in the excavated soil pits.

All field activities for the current reporting period were carried out in this study area. Field activities included: 1) implementation of a vegetation/soil moisture climate change response investigation; and 2) monitoring of the existing soil moisture/plant network. Office-based activities included: 1) development of a preliminary water balance for the field study area; 2) analysis of this historical climate data for a network of stations within 150 miles of Yucca Mountain; and 3) refinement of the Kent State regional climate model.

Field Study Area Water Balance

Plant transpiration, soil moisture, and precipitation data collected from November 1987 through November 1988 were analyzed to develop a water balance for the study area. Transpiration rates for the dominant species on each landform were examined as function of time and correlated with observed soil moisture changes. These analyses form the basis for a Master of Science thesis in Hydrology by Kevin Leary. The thesis draft was in review as of 6/30/89.

Results

Annual soil evaporation losses ranged from 4.3 to 5.1 inches, but were significantly reduced by vegetation shading. For the dominant plant species, most transpiration occurred in a four- to five-month period. Plant community transpiration accounted for approximately one-third of the observed precipitation. Transpiration losses appeared to vary linearly with increases in precipitation. During the analysis study period, little, if any, moisture moved below the plant root zone to potentially become recharge.

Vegetation and Soil Moisture Response

Experimental Plot Development

A series of eight experimental plots were established in 1989 in the wash site in order to simulate a "pluvial maximum" climate at Yucca Mountain and then follow the responses of soil moisture content, depth of wetting front, vegetation water potential and transpiration rate, and total site evapotranspiration to the simulated climate.

Other plots were maintained in the wash site in order to provide a control (i.e., current climatic conditions).

Plots were initially established by trenching four paired plots with a backhoe. Plots were 4 m² (2 m on a side) (Figure 1), and were trenched on each side down to 1.2 m. TDR probes were placed horizontally at 0.15 m intervals in each plot, and the plots were then wrapped in two layers of plastic to prevent lateral water transport; the trenches were then back-filled. Additionally, vertical TDR probes of differing depth were placed near the center of each plot. Plots were chosen at four characteristic locations in the wash, and were replicated in a paired fashion at each location. For each set of paired plots, one plot was left in its normal vegetated condition, while the immediately adjacent plot was completely cleared of all above-ground vegetation. These cleared plots were then routinely maintained without vegetation throughout the study. In this way, soil evaporation could be estimated from the cleared plots, whereas total evapotranspiration was estimated from the vegetated plots. The difference between the two plots would then give a reasonable estimate of water loss via plant transpiration.

Plots were initially chosen in a non-random fashion in order to obtain plots with moderately high plant cover, since this type of vegetation would be expected in a pluvial setting. Two plots at the upper part of the wash contained only blackbrush (*Coleogyne ramosissima*), the dominant shrub of the wash community, whereas the lower plots each contained a mixture of three to four species. Therefore, further comparative response of a monospecific shrub community versus a mixed shrub community can be obtained.

All plots are irrigated twice per month with the drip line irrigation system. TDR readings are taken before and after each irrigation. Horizontal TDR probe data provide depth to wetting front information and volumetric moisture content at discrete depths. A weighted average of vertical TDR readings provides a measure of total plot water use. Comparison of data from vegetated and bare plots yields estimate of plant transpiration.

Paleoclimate Precipitation Regime

The pluvial climate simulated in this experiment is based on a pluvial climate model proposed by Spaulding (1983). Using this model, all plots (both vegetated and cleared) were irrigated using a trickle irrigation system with monthly amounts of water that would result in similar levels of soil moisture recharge and storage as occurred during the pluvial maximum. These amounts take into account not only the higher precipitation that occurred in pluvial times, but also the lower temperatures and higher humidities that occurred at that time, thus lowering the evaporative power

FIGURE 1. Generalized Sketch of a Typical Field Irrigation Plot Showing the Arrangement of Vertical and Horizontal TDR Probes. See page 6 for Exact Probe Depths.

of the atmosphere. Thus, the irrigation amounts are greater than actual precipitation during the pluvial maximum.

The monthly irrigation amounts used in this study are given below:

<u>Month</u>	<u>Amount of Water Added</u>	
	<u>Millimeters</u>	<u>Inches</u>
January	30.5	1.20
February	32.5	1.28
March	33.8	1.33
April	32.3	1.27
May	27.4	1.08
June	26.2	1.03
July	25.9	1.02
August	13.6	0.93
September	20.3	0.80
October	21.8	0.86
November	26.9	1.06
December	<u>27.9</u>	<u>1.10</u>
YEARLY TOTAL	329.2	12.96

The total yearly amount is approximately three times the present site precipitation. Also, the variability between monthly amounts is considerably lower than occurs under the present climate. Highest simulated precipitation occurs in the winter-spring period, a majority of which passed prior to the establishment of our plots in 1989. Thus, continuation of the study through 1990 will enable us to assess the response of the experimental plots to this high winter potential recharge period.

Soil Moisture Monitoring

Background soil moisture has been monitored at each of the three geomorphic landforms since the fall of 1987. Six soil pits ranging in depth from 0.6 to 3 m have been instrumented with horizontally placed 0.46 m long TDR probes. Soil moisture readings are taken on a monthly basis and following significant precipitation events. From this data, depth to wetting fronts and moisture content at discrete depths can be measured. This allows determination of the final fate of precipitation relative to the depth of the deepest sets of TDR probes.

In addition, dominate plant species have been instrumented with TDR probes driven vertically to depths of 0.15, 0.30, and 0.46 m. Similar probe arrangements have been installed in "bare soil" areas of each site. Comparison of this data provides a good estimate of plant water usage.

Results

Plot irrigation began March 17, 1989 and was conducted utilizing the Spaulding (1983) water deficit model for the last pluvial maximum. Irrigation waters have infiltrated to a maximum depth of 1.06 m in bare plots. Cumulative evapotranspiration in vegetated plots average 160 mm, while bare plot evaporation averaged 82 mm. Average initial volumetric moisture content for vegetated plots increased from 3.54 percent in March to 6.44 percent in September. Bare plots for the same time period experienced a volumetric moisture content increase from an initial 3.71 to 10.45 percent.

From November 1988 to present, 7.72 cm of precipitation has been recorded at the Yucca Mountain field site. The majority of this occurred in two events, 3.81 cm in August and 1.02 cm in December. The August event has infiltrated (as of September 14, 1989) to a depth range of 0.42 to 0.55 m in the ephemeral streambed. All but the August event has been lost to evaporation, as measured by the 1.2 m vertical probes in an unvegetated background plot (no irrigation applied) located in the ephemeral streambed. TDR vertical probe data from background vegetated sites within the ephemeral stream channel suggest that all of this event has been lost to evapotranspiration.

Vegetation Monitoring

A variety of vegetation measurements were made on the experimental plots and on control plants in the wash site. We visited the site twice per month throughout the study in order to monitor plant water potential (a thermodynamic measure of water status), stomatal conductance (a measure of stomatal aperture), and plant transpiration at the leaf level. Water potentials were measured with a pressure chamber at dawn and midday, when they are at maximum and minimum values, respectively. Stomatal conductance and transpiration were measured at several intervals during the day with a steady-state porometer. These data can then be compared with TDR readings, which integrate soil moisture additions (via irrigation) and losses (via evapotranspiration) to determine overall water budgets for the plots. For the two blackbrush plots, four to five readings were made of the blackbrush shrubs at each time interval for each plot. For the mixed shrub plots, the three dominant shrubs were each monitored with four measurements made per shrub species per plot. The three shrubs monitored in the mixed plots were: Ephedra nevadensis; Eriogonum fasciculatum; and Salazaria mexicana. A similar number of measurements were made of each species on control plants that were permanently tagged in the adjacent wash site.

Results

The 1989 data set has yet to be synthesized completely, but several trends are already apparent. 1989 was a very dry year, and the control vegetation became dormant much earlier than in 1988. This varied from late May to early June in each of the species. Basically, the control vegetation was active for only a brief "window" of about 30 to 60 days between winter dormancy and drought-induced summer dormancy. By the end of May, all species of control vegetation exhibited a midday water potential of below -7.0 MPa (-70 bars). There was a second brief "window" of activity of control shrubs in response to the late summer rainfall event of 40 mm (1.5 inches). Each of the shrubs, with the exception of *Eriogonum*, rehydrated up to -3 to -4 MPa (-30 to -40 bars), and exhibited an increase in transpiration. This period of activity lasted less than 30 days, after which all control shrubs again ceased transpirational water loss and dropped back to water potential of -7 MPa or less.

In contrast to the control plants, shrubs on the experimental plots maintained a high level of activity and transpirational water loss throughout the year. All shrubs responded within two to three weeks after irrigation began in March with a vigorous cohort of new leaves. Plant water potentials were maintained above control shrubs throughout the Spring, and transpiration rates were several-fold higher, even prior to the control shrubs going into dormancy. Uniformly high water potentials were maintained throughout the year, even in the hot summer months. For example, mean water potentials of all the shrubs on the experimental plots in mid-July averaged -2.6 MPa (-26 bars) at dawn and -4.4 MPa (-44 bars) at midday. Although transpiration remained uniformly high throughout the hot summer months, stomatal conductance did exhibit a decline in July and August, presumably due to the high temperatures and low relative humidities that the plants were exposed to at that time. This contrasting behavior between experimental and control shrubs clearly points to soil moisture as the primary factor inducing summer dormancy in this vegetation type, not high summer temperatures or "atmospheric stress". Under a cooler, moister "pluvial maximum" type climate, one would thus assume that the vegetation would remain physiologically active throughout the summer months, resulting in substantially higher productivity, greater ground cover, and larger stature of the vegetation.

Future Studies and Expectations

This study will continue through the 1990 growth season for two reasons. First, the experimental plots were not established until March of 1989, thus missing the high precipitation winter months that precede the start of the growth season at this high desert site. The winter period is anticipated to be the time of maximum soil recharge because it is the time of lowest potential evaporation and because the vegetation is dormant at that time. By the time this experiment was started in spring of 1989, the soils on the site were already beginning to dry out due to a lack of spring

precipitation. We thus anticipate that the near-surface hydrology and vegetation responses may be significantly different after a full fall-winter period of "pluvial climate" recharge conditions. Second, 1989 was such a dry year that few comparisons could be made between experimental and control plants. If 1990 is a wetter year, then we will be able to obtain a much better comparison of vegetation under a current versus simulated pluvial climate. In the early stages of this study, we had a similar sequence of years, with 1987 being an extremely dry year and 1988 being a more typical year statistically. Not surprisingly, 1988 yielded more interpretable results of moisture flux on the site. Thus, our expectation is that being able to simulate a pluvial climate throughout the 1989-90 winter period, followed by a more typical climatic year in 1990, will yield an ideal data set for assessing vegetation water use and moisture flux characteristics under current versus simulated pluvial climatic conditions.

Analysis of Historical Climate Data

Precipitation and temperature data from the historical climate record were examined for seven stations in the southern Great Basin. These stations define regional climatic characteristics for the Yucca Mountain area. Precipitation and temperature data were grouped on the basis of wet, average, and dry years to compare characteristics under various climatic conditions.

An analogue method was used to construct two wetter climate scenarios for this region. This method uses wet years from the historical record to be representative of average years in a pluvial (wetter) regime. The seasonal and monthly distributions of precipitation were examined and compared for modern and wetter climate scenarios. Wetter climate scenarios were defined using the wettest ($1/3$) and wettest ($1/6$) years from the historical record.

Daily precipitation data were analyzed within a seasonal framework. The frequency of daily precipitation was calculated at five threshold values: 0.01, 0.10, 0.25, 0.50, and 1.00 inches. Average daily storm depths were calculated for days on which at least 0.01 inches of precipitation was recorded. Daily data were also used to calculate the distributions of wet day sequences (storm duration), dry day sequences (storm intervals), and storm depths. Statistical models were applied to the observed distributions. Wet day sequences were modeled with a first-order Markov chain, dry day sequences with a third-order Markov chain, and storm depths with the Weibull distribution.

The primary emphasis in analyzing temperature data was on its relationship to precipitation. Therefore, temperature data were grouped on the basis of the wettest ($1/3$), middle ($1/3$), and driest ($1/3$) years in the historical record. Average temperatures were calculated for wet, middle, and dry years at each station. Daily tempera-

ture data were also grouped on the basis of wet and dry days within each month. Average temperatures were calculated for wet and dry days in each month.

Results

Comparison of the wettest ($1/3$) years with the entire period of record indicates a 50 percent increase in annual precipitation during wet years (as an average of all seven stations). On a seasonal basis, the greatest increase occurs during winter (57 percent) and the smallest increase during summer (36 percent). Overall, precipitation increases most during the months of January, February, and March for wet years in the study area.

Comparison of the wettest ($1/6$) years and the entire period of record indicates a 75 percent increase in annual precipitation. On a seasonal basis, the greatest increases occur during winter and spring (85 and 88 percent, respectively), and the smallest increase during summer (35 percent).

The daily frequency of precipitation is greatest during winter and spring. Average daily storm depths are greatest during winter and fall. Comparison of daily frequency and average depths between the wettest ($1/3$) and middle ($1/3$) show that wet years are characterized by an increase in both frequency and average depths. However, wet years are caused primarily by an increase in frequency of events.

Statistical models, Markov chains and Weibull distribution, were applied to daily precipitation data comprising three different data sets: entire period of record, middle ($1/3$), and wettest ($1/3$). Modeling of observed data provides a basis for writing a computer program to generate synthetic sequences of daily precipitation data.

Analysis of temperature data reveal that annual average temperatures are 1°F cooler for the wettest ($1/3$) years compared to the driest ($1/3$) years. Annual average temperatures for the wettest ($1/3$) and middle ($1/3$) were approximately equal. Comparison of wet and dry-day temperatures show that dry days range from -2 to $+11^{\circ}\text{F}$ warmer depending on the month and station. The greatest temperature differences between wet and dry occur from April to June.

Regional Climate Model

The existing (first generation) climate model and the code for the surface drainage model were converted to 'C' and adapted to the UNIX System on the DRI SUN computers. Training was given to DRI personnel on the use of these models and user's manuals prepared.

A Conceptual Model Report defining methods needed to define a new generation of climate model was prepared. The focus of this model is to allow: 1) incorpora-

tion of climatic influences from the Gulf of Mexico; 2) portability to other areas; 3) a more sophisticated representation of winds at several levels in the atmosphere; and 4) energy balance considerations. Over 600 climate stations were used for calibration and about 100 more for verification. Five-year averages of mean monthly temperature and precipitation were successfully modeled with canonical regression.

Results

Computer code (in 'C') was prepared to solve independent variables representing local controls upon climate. These are solved at each point of a grid at 10 km spacing. Independent variables are computed from boundary conditions (sea surface temperatures, winds, and topography). Calibration of the canonical regression equations was done at 623 climate stations. For temperatures, R^2 values (percent variance explained) are about 80 to 90 percent for precipitation, R^2 ranges from 60 to 70 percent. Records from 96 stations were used for an independent validation. Validation was successful for all months, both temperature and precipitation. Residual standard deviations are about 1°C for temperature and show little, if any, systematic spatial pattern.

Calibration used climate stations from Arizona, California, Colorado, Nevada, New Mexico, and Utah. The 1975-1979 period was chosen. Of the approximately 1,000 available stations, only 719 had usable records because of station moves, missing data, etc. Of these, 623 were applied to calibration and 96 to validation.

In addition to the computer code to solve the independent variables, code was written to solve the canonical regression transfer function equations. This takes as input the values of the independent variables and the coefficients of the canonical regression equations. From these, the climate variables are solved.

A utility code was produced to take angularly-spaced topographic data and create a square grid of data for the requisite digital elevation model. The wind interpolation model is a mass-balance consistent chebyshev polynomial. It uses sparse, irregularly-spaced data to compute values at any point. We use two levels of the atmosphere (500 mb and 800 mb). Code for computing wind trajectories 1,000 km upwind of each grid point has been completed.

The energy balance is computed considering longwave and shortwave radiation separately. Adjustment is made for reflecting and absorbance (such as by CO₂). Both surface and planetary temperatures are computed. Over oceans, surface temperatures are fixed at known sea surface temperatures supplied independently.

IMPLICATIONS

This research project is the result of a NWPO-identified site suitability issue related to the effect climatic variations and resulting changes in the hydrogeologic

regime have on the integrity of the site. This issue relates to NRC licensing criteria (10 CFR Part 60) which considers the potential for changes in hydrologic conditions resulting from reasonably foreseeable climatic changes. Changes in hydrologic conditions may effect the site's ability to meet the EPA standard (40 CFR Part 191) for release of radionuclides from the waste package to the accessible environment.

In determining the viability of Yucca Mountain as a potential waste repository, it is necessary to quantify the moisture potentially available for recharge by defining the response to extreme weather and climate variations. Short-term weather and climatic variations influence the unsaturated zone hydrology. Regional climatic and hydrologic data are being analyzed for wet cycles and classified with respect to depth-duration-frequency, which, when combined with soil characteristics, will define site conditions and responses expected in the future, assuming historical climate data are representative of future climate conditions.

Estimates of potential recharge in the repository site area derived from climate and weather analysis and near-surface soil moisture studies (designed to describe and quantify moisture movement through the unsaturated zone) will provide a basis for estimating future moisture flux, under an assumption of continuation of the present climatic regime as well as under possible future wetter conditions. This research is important in evaluating the long-term performance of the repository with respect to future climatic conditions and variations in flux.

REFERENCES

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CARBONATE/SILICATE DEPOSITION AND ROCK ALTERATION ALONG FAULTS EXPOSED IN TRENCH 14, YUCCA MOUNTAIN

Fred L. Nials and Jonathan O. Davis

INTRODUCTION

As a part of the process of evaluating the feasibility of the proposed Yucca Mountain repository, a series of trenches was excavated across observed or inferred faults in the Yucca Mountain vicinity to evaluate the character and timing of displacement along the faults. Trench 14, on the west slope of Exile Hill at Yucca Mountain, exposed subvertical laminated carbonate and silicate deposits filling fault-related fractures. These deposits are localized, seemingly unique to the Trench 14 area, and are extensively developed only in the original Trench 14 excavation (Trench 14A). Although numerous explanations for the origin of these deposits have been suggested, most rely on processes related to either groundwater or pedogenic phenomena.

Trench 14 is near the proposed repository portal, and evidence of groundwater discharge would suggest that, at some time in the past, groundwater levels were sufficiently high to flood the proposed repository. This would be especially disquieting because of the reactive nature of hydrothermal waters, and the possibility that future hydrothermal waters might come in contact with waste packages. A demonstration is required by 10 CFR Part 60 (Section 60.112) that the site will not undergo changes in hydrologic conditions or volcanic activity which might lead to the reduction in containment and the migration of radionuclides to the accessible environment. Consequently, it is imperative that the origin of the deposits be ascertained, and subsequent geologic studies at and near Trench 14 have focused on the possibility that groundwater discharge may have occurred.

Five possible analogues for the Yucca Mountain fault fillings were envisioned by Vaniman et al. (1988): 1) near-surface exposures of hydrothermal vein deposits; 2) warm- or hot-spring deposits; 3) cold-spring or seep deposits; 4) soil deposits; and 5) aeolian "sand ramp" deposits. Although soil and "sand ramp" deposits are differentiated, both are of pedogenic origin and differ only in the nature of surface runoff and soil parent material. Each of these analogues has geochemical, mineralogic, morphologic or other characteristics that may serve to characterize specific environments.

Literally hundreds of sources of hydrothermal deposits are known in Nevada alone (Horton, 1964; Garside and Schilling, 1979), and the formation of sinter and shallow veins around warm springs in Nevada was the subject of investigation more than a century ago (LeConte, 1883). Spring deposits have been the subject of vigorous debate recently in Nevada, and analyses of sinter and vein deposits have shown

that mineralogic, petrographic, and chemical characteristics vary widely from one spring type and system to another (Hay et al., 1986; Vaniman et al., 1988), and with depth (Ross et al., 1982). These preliminary tests suggest that it may be possible to characterize deposits from a single fault system in some cases, or from a single hydrologic basin.

Spring deposits are highly variable. Siliceous material (sinter) is deposited as a hard incrustation on rocks or on the ground by precipitation from mineral-bearing waters (Gary et al., 1972). This material is typically hydrothermal in origin and quite variable in character. Physical characteristics and mineralogy may be greatly affected by slight differences in water temperature, chromophore content, alteration induced by continuing spring discharge, post-alteration contamination and other aspects of the environment of deposition. Springs may be re-activated over time, with different water character.

It is possible, however, that the laminated carbonate and silica deposits may have been created by pedogenic processes, rather than by groundwater discharge. Vaniman et al. (1988), for example, examined the mineralogic characteristics of the Trench 14 deposits, compared them with samples from the various analogues, and concluded that the Trench 14 deposits were of pedogenic origin. Pedogenic processes are known to form laminated deposits somewhat similar to those in Trench 14. Although the orientation of pedogenic laminated deposits normally is different, Trench 14 deposits share many physical characteristics with pedogenic deposits, including the presence of pisolites, which are not reported from hydrothermal deposits. Morphologic characteristics of the deposits in Trench 14 are not inconsistent with pedogenic deposition in open fractures caused by recurrent faulting. In addition, Nials has observed numerous exposures of petrocalcic horizons in the Ogallala Formation in New Mexico and West Texas. In these localities, the orientation of laminae is predominantly parallel to the ground surface, but both subhorizontal and subvertical orientations have been observed along fracture planes and dissolution features.

ACTIVITIES

The purpose of this study is to evaluate evidence for the origin of the laminated carbonate and silica deposits and when they were formed. It was decided that a variety of documentation was necessary to determine the origin of the laminated deposits in Trench 14. Efforts were concentrated on evaluation of the morphology of the deposits, their geochemical character, and the nature of processes known to produce laminated carbonate/silicate deposits. This involved field and literature evaluations of known groundwater-related deposits as well as pedogenic deposits.

A number of field examinations were made of the Trench 14 area and of other trenches excavated across faults in the general vicinity of Yucca Mountain. The pur-

pose of these visits was to examine the trenches for evidence of recurring faulting, fault-related deposits of pedogenic or groundwater origin, and to examine the general nature of unconsolidated sediments in proximity to geologically young faults. No laminated carbonate/silicate deposits similar to those of Trench 14A were observed in any of the other trenches. Massive carbonate deposits (hand-specimen identification) were observed on fault planes in several of the trenches excavated into unconsolidated deposits, however. These varied in degree of induration from friable "chalky" deposits to true petrocalcic character. In several instances, weakly developed parting was developed parallel to fault planes in the massive deposits, but hand-specimen evaluation revealed no lamination or segregation of minerals. Since these deposits were in basically homogeneous unconsolidated sediments, it was concluded that water would be directed along the conduit provided by the fault plane only until the slightly higher permeability was "sealed" by precipitates. After that, the high porosity and permeability of the sediments surrounding the fault plane allowed an almost uniform facility of infiltration and dispersal of descending water.

In addition, samples were collected from 19 hot-, warm-, and cold-water springs within a 100-mile radius of Yucca Mountain. The rationale for the sampling program was that the geochemical characteristics of the spring deposits should relate to the water chemistry of the spring. Although sample analysis results from these deposits have yet to be returned, preliminary sampling of spring deposits during the previous year suggest that spring deposits are chemically dissimilar to the Trench 14 deposits. Mineralogical analysis of various types of deposits from the five possible analogues by Vaniman et al. (1988) indicates that the mineralogy of spring deposits is also dissimilar to the Trench 14 deposits. Each of the spring deposits was examined for morphological characteristics. Although laminated or bedded deposits were observed in several of these localities, none were morphologically similar to the Trench 14 deposits.

The south wall of Trench 14A was also systematically re-sampled for geochemical analysis. The wall was first cleaned using compressed air, and photographed before, during, and after sampling. A total of 29 sample locations were chosen on the basis of geologic considerations. Although various criteria were used in the selection of any given specific sample, the samples were chosen to allow characterization of the following conditions: a) some samples were chosen from identical locations as those previously selected by USGS personnel, as a cross-check; b) some were chosen as representative of specific morphological conditions, e.g., laminated vs. more massive deposits; c) some were chosen because their topographic and stratigraphic position showed they were unquestionably of pedogenic origin; d) others were chosen because they appeared to be of pedogenic origin, but were downslope from the fault zone and laminated carbonate/silicate deposits; e) some samples were chosen to characterize stratigraphically distinct generations of deposits; and f) others were cho-

sen to characterize surface or near-surface soil horizons. Samples suitable for oriented samples were marked prior to removal. Results of analysis have yet to be returned to the investigators. Photographs were also taken of various features in Trenches 14B, C, D, and E.

An extensive literature search was conducted for information regarding spring deposits and pedogenic deposits. Descriptions of groundwater-related deposits uniformly differ from observed characteristics of the Trench 14 deposits. However, morphologically and mineralogically similar laminated carbonate/silicate deposits are reported from a number of pedogenic deposits, including strongly developed petrocalcic horizons in the Ogallala Formation of the Great Plains.

RESULTS AND IMPLICATIONS

Field, literature, and laboratory research on the Trench 14 deposits have resulted in the following proposed explanation of the origin of the deposits: Initial faulting occurred, with the west side of the fault being downdropped. Footwall materials in Trenches 14A and 14B are the only exposed materials affected by initial faulting. Exile Ridge and the fault-line valley west of the ridge were formed and achieved topographic expression roughly similar to that of the area today over a long period of erosion following initial faulting. Faulting probably recurred during the early-middle Pleistocene. Erosion of the hillslope and upthrown side of the fault subsequently occurred, with eroded sediments being deposited on the downdropped block at the base of the slope and in the valley bottom. Initial erosion and slope adjustment would have been more rapid as the slope adjusted to fault displacement. Deposition would similarly have been more rapid with little time for development of pedogenic horizons, including petrocalcic horizons. If the movement along the fault was confined to a single event, the slope would eventually achieve quasi-equilibrium conditions under a given climate regime, and both erosion and deposition would progressively diminish. As the quasi-equilibrium condition is approached, pedogenesis would intensify, and in an arid climate regime, petrocalcic horizons would eventually develop.

During this process, runoff appears to have been directed along fault-related fractures and separations in the petrocalcic horizon. In the area of Trench 14A, the juxtaposition of bedrock at the surface and recurrent movement along a very narrow fault zone appears to have produced open fractures that provided ready conduits for downward movement of runoff-supplied waters. To either side of Trench 14A, however, later faulting disrupted unconsolidated materials at the surface, materials not conducive to the production of open fractures. Runoff from slopes above would not be diverted into open fractures, but rather would infiltrate into the more homogeneous unconsolidated sediments over a much broader area. In addition, the absence of a single, well-defined, narrow fault zone suggests that the unconsolidated materi-

als absorbed recurring movements along the fault, resulting in a series of small-displacement faults. The net effect is that runoff-supplied precipitates are deposited over a much broader area and lack the concentration necessary to produce the laminated calcareous/silicated deposits in question. Runoff from the slopes above the fault traverses a single tuff unit, and within the limits of variation in airfall-supplied detritus is uniform in chemical composition.

This model explains most observed characteristics of precipitates in the Trench 14 area. Laminated deposits are produced by precipitation in open fractures. The concentration of laminated deposits in a limited area is explained by the distribution of bedrock at and near the surface in Trench 14A and, to a much lesser extent, in Trench 14B. The open fractures necessary for deposition of laminated deposits is explained by recurrent faulting in a narrow fault zone in Trench 14A. Displacement of and cross-cutting relationships in the laminated deposits are explained by recurrent movement along the fault, as are soil materials and volcanic ash in some fractures that could only have originated from above the laminated deposits. Non-laminated, more obviously pedogenic deposits are formed where the substrate is homogeneous, allowing for a more uniform infiltration of runoff waters. Precipitation from infiltrating runoff waters (i.e., pedogenesis) explains the mineralogic characteristics observed by Vaniman et al. (1988). Preliminary chemical analyses indicating a uniform chemical composition consistent with pedogenically derived carbonates and silicates are explained by the origin of, and materials traversed by runoff waters.

In conclusion, although some sample analyses have yet to be returned, morphologic, mineralogic, and geochemical characteristics of the laminated carbonate/silicate deposits in the Trench 14 area seemingly support an origin of precipitation along open fractures of dissolved materials in runoff-derived soil water. It seems apparent from this analysis to date that spring discharge had no part in the formation of the laminated deposits, although the significance of recurrent faulting to the proposed repository cannot be dismissed.

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GEOCHEMICAL MODELING OF GROUNDWATER IN A TUFFACEOUS SYSTEM AT YUCCA MOUNTAIN, NEVADA

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INTRODUCTION

The Yucca Mountain study area is located in southern Nevada, 105 km northwest of Las Vegas, situated on the southwest side of the Nevada Test Site (NTS). The stratigraphy of Yucca Mountain and vicinity consists of Paleozoic carbonate sediments unconformably overlain by Tertiary ash-flow and nonwelded to welded volcanic sequences. Quaternary alluvium blankets the intermontane valleys.

The objective of this study was to determine if there was an upward vertical flow direction between the carbonate and volcanic hydrologic units, based on water chemistry analysis. This was accomplished by simulating a flow path using geochemical computer programs, from recharge in a soil downward through a tuffaceous system, and then mixing this with water from a carbonate system. In addition, isotope analyses were used to verify the computer modeling.

ACTIVITIES

Geochemical data used in this study were collected by the USGS from 14 wells on Yucca Mountain during 1971 to 1983 (Benson and McKinley, 1985), and from six wells in the spring of 1988 by DRI. These latter six water table (WT) wells were drilled in 1983 by the USGS and were sampled to increase the data base of the water chemistry found near the top of the saturated zone. Each well was pumped continuously until at least three well volumes were purged, and the discharge was monitored for pH, temperature, electrical conductivity and dissolved oxygen. Once three well volumes were pumped and these parameters stabilized, samples were collected for major and minor chemistry, and isotopes deuterium, $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, and $\delta^{14}\text{C}$. Sample protocol followed the procedures outlined by the USGS (Wood, 1976).

The geochemical flow path was modeled using geochemical computer models PHREEQE (Parkhurst et al., 1980), WATEQDR (Bohm and Jacobson, 1981), which is a modification of WATEQF (Plummer et al., 1975) and BALANCE (Parkhurst et al., 1982).

Geology and Hydrology of the Site

Yucca Mountain is located in the Great Basin subprovince of the Basin and Range physiographic province. There are two principal hydrologic units within Yucca Mountain: the interlayered tuffaceous aquifers and aquitards, and the lower carbonate aquifer (Table 1).

TABLE 1. STRATIGRAPHIC AND DIAGENETIC MINERAL ZONES OF YUCCA MOUNTAIN, NEVADA.

FORMATION		Member	Diagenetic Mineral Zone		Well
Interlayered Aquifers and Aquitards (TERTIARY)	PAINTERUSH TUFF	Tiva Canyon Yucca Mountain Pah Canyon Topopah Spring	ZONE I Unaltered volcanic glass with minor heulandite and calcic clinoptilolite locally in fractures. Incipient alteration of glass to smectites and opal in groundmass, with calcite present as filling in pumice fragments.	Unsatuated Zone	
	TUFF OF CALICO HILLS (informal)		ZONE II (upper) Vertically discontinuous, forming within nonwelded tops and bases of flows. Upper section has clinoptilolite replacing glass and composing 50 to 75% of the rock. Minor cristobalite, orthoclase and smectites are also present.	J-12 UE25 WT-12 J-13 UE25 WT-14 UE29-a#2 UE25 WT-15 USW WT-7 USW WT-10	
	CRATER FLAT TUFF	Prow Pass Bullfrog Tram	ZONE II (lower) Same as Zone II (upper), except that mordenite replaces clinoptilolite as the dominant mineral.	J-13 USW H-1 UE25 b#1 USW H-3 UE25 c#1 USW H-4 UE25 c#2 USW H-5 UE25 c#3 USW H-6 USW G-4 USW VH-1	
	DACITE FLOW BRECCIA LITHIC RIDGE TUFF		ZONE III Vertically discontinuous in tops and basal layers of the flow members. Analcime replaces clinoptilolite and mordenite. Quartz and calcite present in vugs, and smectites increase in groundmass.	USW H-1 USW H-3	
	OLDER, UNNAMED TUFFS		ZONE IV Analcime replaced by authigenic albite. Groundmass is cryptocrystalline quartz and feldspar; plagioclase phenocrysts are altered to albite, calcite and illite. Calcite and chlorite minerals are minor, but ubiquitous.	UE25 p#1	
Lower Carbonate Aquifer	(CAMBRIAN - SILURIAN) LONE MOUNTAIN DOLOMITE ROBERTS MOUNTAIN ELY SPRINGS DOLOMITE EUREKA QUARTZITE POGONIP GROUP N'PAH BONANZA KING CARRARA		Dolomites, limestones and siltstones, with calcite and chert stringers. Calcite, chert, fluorite, pyrite and iron-magnesium oxides in the fractures.	UE25 p#1 Test Well F Test Well C Army-1 Devils Hole	

The Miocene volcanic tuffs present beneath Yucca Mountain are high silica rhyolites and quartz latites which were predominantly deposited as multiple ash-flow tuff aquitards. Due to secondary mineralization within the nonwelded tuffs, aquifer transmissivity is a function of degree of fracturing and interconnectiveness of the fracture systems in the welded tuffs (Waddell et al., 1984).

Recharge sources to the tuffaceous groundwater are suggested to be long duration winter storms, with minor input from summer thundershowers, subsurface flow from other tuffaceous areas, or upward flow from the regional carbonate aquifer (Kerrisk, 1987). Based upon potentiometric head data, groundwater flow within the tuffs appears to be to the southeast (Robison, 1984).

Near Yucca Mountain, the lower carbonate aquifer is composed of a thick sequence of Silurian to Mississippian dolomites and limestones (Carr et al., 1986). The lower carbonate aquifer underlies a large portion of southern Nevada, and contributes to the majority of regional groundwater flow. Beneath NTS and vicinity, the flow direction is from the north to the southwest, and is thought to eventually discharge into Death Valley, California (Waddell et al., 1984). This aquifer is located directly to the east of Yucca Mountain and is hypothesized to be partly beneath Yucca Mountain, based upon geophysical gravity surveys and inference of nearby carbonate sequences in the Bare Mountains and well UE-25 p#1 (Snyder and Carr, 1982; Carr et al., 1986).

All wells on Yucca Mountain, except UE-25 p#1, are completed within the Tertiary volcanic tuffs. Well UE-25 p#1 is completed in Silurian dolomite and water samples were collected from both volcanic and carbonate intervals. Several wells show evidence of an upward flow gradient, from either temperature measurements (USW H-1, USW H-4, UE-25 b#1, USW G-4) or hydraulic head potentials (USW H-1, UE-25 p#1) (Waddell et al., 1984). However, evidence for upward flow is considered to be conclusive by the USGS only for well UE-25 p#1 at this time.

Controls on Geochemistry

Groundwater chemistry in the volcanic rock on the NTS is thought to be controlled by primary glass and diagenetic minerals (Claassen and White, 1979). Volcanic glass (perlite) is present at Yucca Mountain with a composition of a hydrated high-silica rhyolite with subequal Na_2O and K_2O , plus CaO and H_2O and a silica-to-aluminum ratio of 4.8 to 5.6 (Broxton et al., 1986; Broxton et al., 1987).

Diagenetic alteration has affected most of the volcanic rocks, especially those below the water table. The principal alteration products present are zeolites, smectites and authigenic minerals which replace volcanic glasses, pumice, and primary feldspars. Alteration is best developed in the groundmass and phenocrysts of the

nonwelded sections of the cooling units (Broxton et al., 1986), and as fracture coatings in the welded tuffs (Carlos, 1985). Broxton et al. (1986) applied Iijima's (1980) zeolite zonation to the altered volcanic tuffs of Yucca Mountain, and divided the diagenetic mineral zonation into four zones, based upon zeolite compositions (Table 1). The diagenetic mineral zones grade from incipient alteration in the volcanic glass in the shallowest zone to zeolitic at greater depths which, in turn, grades into epigenetic feldspars and smectites at greatest depths.

Tuffaceous Geochemical Flow Model

The purpose of the geochemical computer modeling was to trace the chemical evolution of a solution as it traveled downward through a tuffaceous aquifer, interacting with the diagenetic minerals. This volcanic water was then mixed with a water from the lower carbonate aquifer, and the results compared to Yucca Mountain wells to determine if the waters are purely from volcanic rock aquifers, or are a mixture of volcanic and carbonate waters.

Geochemical Model Input

The hypothetical groundwater flow path was modeled using the computer program PHREEQE and consisted of six zones. These correlate to initial recharge through the soil and a downward travel path through the diagenetic mineral zones. In each zone, an initial solution interacted with a reaction step that replaced or removed ions. This new solution then interacted with a given suite of minerals, which underwent congruent dissolution, until equilibrium was attained with the first mineral phase listed.

The reaction is an ion suite or phase that was reacted with the solution and subsequent mineral phases. These were the most chemically reactive phases present, such as the volcanic glass or the ion exchange in the zeolites, and in general composed the largest volume percentage of the rock.

The mineral assemblages used in each section are those defined by the diagenetic mineral zones of Broxton et al. (1986), and consisted of zeolites, smectites, epigenetic feldspars, calcite and quartz polymorphs. Primary phenocrysts interbedded within the glass matrix of the volcanic tuffs were considered relatively inert when compared to the secondary minerals, and thus were not used within the model reactions. The secondary minerals were considered to be much more reactive, because of their large quantities (zeolites) or else were located along flow pathways (i.e., calcite and clays in fractures and vugs) and thus may be more influential on water chemistry than their low quantities might otherwise indicate.

Sources of CO₂ in Zone I were considered to be either from recharge from the atmosphere, precipitation or dissolution of carbonate minerals. Deeper than Zone I,

the system was closed to atmospheric CO_2 input, based upon studies by White and Chuma (1987) which suggest that deep groundwater systems are closed. No sources or sinks of the anions Cl^- or SO_4^{2-} were included in the flow path model because the necessary mineral phases were either not identified in the formations or were not discussed in the literature.

Benson and McKinley (1985) did not include Al^{3+} values in their Yucca Mountain analyses; there an Al^{3+} concentration of 0.0037 mmol/L, derived from previous Al^{3+} analyses of wells J-11 and J-12 (Moore, 1961), was set for the Yucca Mountain well solutions. The aluminum values used in the modeled tuffaceous flow path came entirely from the dissolution of the aluminosilicate-rich volcanic glass.

Geochemical Flow Path Model

The following hypothetical flow path (Table 2) was assumed to be the most representative model of groundwater flow through the volcanic tuffs of Yucca Mountain.

The initial recharging water used for this study was taken from an analysis of soil water collected on Shoshone Mountain, 15 km to the northeast of Yucca Mountain (Spencer, 1989). This site has a lithology and elevation similar to conditions at Yucca Mountain, consisting of a thin, sparsely vegetated, volcanic-derived soil overlying the volcanic bedrock. The initial water was high in Ca^{2+} , K^+ and NO_3^- , with a pH of 8.17.

The water travels downward through the unsaturated zone of the Paintbrush Tuff Formation, dissolving volcanic glass, which adds large quantities of Na^+ , K^+ and SiO_2 . The system was left open to atmospheric CO_2 , with a $\log P_{\text{CO}_2}$ set at -2.5. The clay and zeolite minerals present represent the secondary mineralization, and the calcite represents the caliche at the top of the zone and the calcite coatings in the fractures. The model suggests that in the unsaturated zone, calcite and heulandite are forming and that the solution becomes high in Na^+ and K^+ from the volcanic glass dissolution.

As the water travels into the saturated zone, cations are added or removed through ion exchange with zeolites and mineral reactions. The solution remains Na^+ and K^+ -rich, with a pH range from 7.25 to 8.04. The partial pressure of CO_2 remains fairly constant at approximately -2. In general, the quartz polymorph minerals are dissolving and calcite, when present, is precipitating. This suggests that the formation of calcite fracture coatings is an ongoing process. The clay minerals appear to have fairly steady cation exchange occurring between the Na-K-Ca end members, with some formation of clays also occurring. At the deepest diagenetic mineral zone (IV), no zeolites are present and the water chemistry is controlled entirely by the reactions of mineral precipitation and dissolution.

TABLE 2. GEOCHEMICAL MODEL OF GROUNDWATER FLOW THROUGH A TUFFACEOUS SYSTEM, YUCCA MOUNTAIN, NEVADA.

	Description	Reaction (mmoles)	Minerals	Results	Well (mmoles/l)
Initial Soil Water	Water collected from thin, volcanic-derived soil with sparse vegetation.	Soil/water interactions		pH: 8.17 Ca: 0.462 Mg: 0.0112 Na: 0.099 K: 0.463 Cl: 0.014 SO ₄ : 0.022 HCO ₃ : 1.447 SiO ₂ : 0.433	NONE
Zone I	Unsaturated zone of the Paintbrush Tuff Formation. P _{CO2} set at -2.5, and temperature is 25°C.	Dissolution of Volcanic Glass +5.6 Na +4.2 K +0.1 Ca +0.7 Fe +9.6 Al +51.9 SiO ₂	cristobalite calcite Na-beidellite heulandite amorphous silica	pH: 7.76 Ca: 0.101 Mg: 0.112 Na: 5.742 K: 4.663 Cl: 0.014 SO ₄ : 0.022 HCO ₃ : 4.132 SiO ₂ : 0.605 P _{CO2} : -2.39	NONE
Zone II (upper)	Saturated base of Topopah Spring member of the Paintbrush Tuff, and Tuff of the Calico Hills. WT wells screened in this zone. Temperature is 30°C.	Clinoptilolite ion exchange +1.0 Ca +0.2 Mg -1.0 Na -1.0 K	cristobalite adularia K-beidellite Na-beidellite amorphous silica	pH: 8.04 Ca: 1.101 Mg: 0.312 Na: 4.449 K: 0.079 Cl: 0.014 SO ₄ : 0.022 HCO ₃ : 4.132 SiO ₂ : 0.677 P _{CO2} : -2.64	Well J-13 pH: 7.2 Ca: 0.299 Mg: 0.086 Na: 1.827 K: 0.128 Cl: 0.200 SO ₄ : 0.177 HCO ₃ : 2.032 SiO ₂ : 0.949 P _{CO2} : -2.07
Zone II (lower)	Located in the Crater Flat Tuff; most Yucca Mountain wells screened in this zone. Temperature is 35°C.	Mordenite ion exchange +0.1 K -1.0 Na -0.5 Ca -0.25 Mg	cristobalite calcite	pH: 7.25 Ca: 0.139 Mg: 0.062 Na: 3.449 K: 0.179 Cl: 0.014 SO ₄ : 0.022 HCO ₃ : 3.671 SiO ₂ : 0.880 P _{CO2} : -1.88	USW VH-1 pH: 7.50 Ca: 0.247 Mg: 0.062 Na: 3.394 K: 0.046 Cl: 0.282 SO ₄ : 0.458 HCO ₃ : 2.590 SiO ₂ : 0.816 P _{CO2} : -2.24

TABLE 2. GEOCHEMICAL MODEL OF GROUNDWATER FLOW THROUGH A TUFFACEOUS SYSTEM, YUCCA MOUNTAIN, NEVADA (cont.).

	Description	Reaction (mmoles)	Minerals	Results	Well (mmoles/l)
Zone III	Tram member of the Crater Flat Tuff, Lithic Ridge Tuff and older tuffs; few wells screened in this zone. Temperature is 40°C.	Analcime ion exchange +1.0 Na -1.0 Ca -0.5 Mg	quartz calcite Na-beidellite K-beidellite Ca-beidellite	pH: 7.53 Ca: 0.201 Mg: 0.061 Na: 2.159 K: 0.051 Cl: 0.014 SO ₄ : 0.022 HCO ₃ : 3.171 SiO ₂ : 0.815 PCO ₂ : -2.16	USW H-1 pH: 7.5 Ca: 0.155 Mg: 0.004 Na: 2.219 K: 0.041 Cl: 0.164 SO ₄ : 0.198 HCO ₃ : 1.999 SiO ₂ : 0.666 PCO ₂ : -2.35
Zone IV	Deepest diagenetic mineral zone; found in the Lithic Ridge and older tuffs. Only well UE-25 p#1 screened in this zone. Temperature is 45°C.	no reaction step	chalcedony calcite adularia albite illite chlorite amorphous silica	pH: 7.51 Ca: 0.179 Mg: 0.004 Na: 1.936 K: 0.005 Cl: 0.014 SO ₄ : 0.022 HCO ₃ : 3.150 SiO ₂ : 0.896 PCO ₂ : -2.10	UE-25 p#1* pH: 6.8 Ca: 0.623 Mg: 0.308 Na: 2.822 K: 0.062 Cl: 0.162 SO ₄ : 0.334 HCO ₃ : 5.148 SiO ₂ : 0.855 PCO ₂ : -1.37

* See discussion on UE-25 p#1 in "MIXING VOLCANIC AND CARBONATE WATERS" and Table 3.

When plotted on piper diagrams, these zones compare closely to the Yucca Mountain volcanic wells (Table 2). The largest discrepancy comes from the lack of Cl⁻ and SO₄²⁻ minerals in the model, causing a Cl⁻ and SO₄²⁻ deficiency, which is evident when compared to the Yucca Mountain wells.

Mixing Volcanic and Carbonate Waters

Previous research indicated that the water sampled from the volcanic interval of well UE-25 p#1 is a mixture of both carbonate and volcanic waters (Craig and Robinson, 1984; Waddell et al., 1984). As stated previously, other Yucca Mountain wells might also be influenced by upward flow from the lower carbonate aquifer, so the next part of the modeling consisted of mixing volcanic and carbonate waters to verify these hypotheses.

Through a mass balance of the water analyses of the modeled Zone IV and the volcanic and carbonate samples from UE-25 p#1, BALANCE suggested that the volcanic sample from UE-25 p#1 was a mixture of 81 percent Part IV water and 19 percent UE-25 p#1 carbonate water. Using PHREEQE, these waters were then titrated together with the sample analyses of UE-25 p#1 (Table 3). Similar mixing computations were done with modeled Zone IV and carbonate water analyses from Devils Hole, Test Well C, Army 1 and Test Well F. These attempts suggested that the sample from UE-25 p#1 was a mixture of 70 percent Part IV and 30 percent carbonate waters. These mixing attempts compare favorably with the 28.6 percent carbonate water influence in well UE-25 p#1 that was suggested by Craig and Robison (1984, p. 49) from a borehole flow study. The only large discrepancy between the UE-25 p#1 models using the carbonate water from UE-25 p#1 and other carbonate sources is the pH. The carbonate water from UE-25 p#1 has a low pH of 6.6; thus, the pH of the sampled volcanic UE-25 p#1 at 6.8 is also lower than other wells. The other carbonate water sources have pHs ranging from 7.2 to 7.8; thus, their mixtures with Zone IV (pH 7.51) are correspondingly higher than the UE-25 p#1 mixture.

TABLE 3. COMPARISON OF SAMPLES AND MODELS OF WELL UE-25 p#1, YUCCA MOUNTAIN, NEVADA.

	Sample	Model 1	Model 2	Model 3	Model 4	Model 5
	(mmoles/l)					
pH	6.80	6.95	7.46	7.61	7.30	7.59
Ca	0.924	0.623	0.458	0.518	0.683	0.473
Mg	0.412	0.308	0.200	0.237	0.336	0.274
Na	4.004	2.822	2.202	2.241	3.221	1.836
K	0.143	0.062	0.074	0.065	0.118	0.044
Cl	0.367	0.162	0.179	0.196	0.297	0.138
SO ₄	0.396	0.334	0.249	0.259	0.237	0.168
HCO ₃	4.624	5.148	3.666	3.830	5.462	3.577
SiO ₂	0.816	0.855	0.817	0.732	0.777	0.722
Temperature	44.3	47.1	50.7	39.6		
Log PCO ₂	-1.22	-1.37	-1.93	-2.16	-1.72	-2.14
Log SI Calcite	-0.382	-0.377	-0.025	0.037		

Model 1: 81 percent Zone IV: 19 percent UE-25 p#1 carbonate

Model 2: 70 percent Zone IV: 30 percent Test Well F

Model 3: 70 percent Zone IV: 30 percent Devils Hole

Model 4: 70 percent Zone IV: 30 percent Test Well C

Model 5: 70 percent Zone IV: 30 percent Army 1

When the carbonate and mixed waters are compared to the Yucca Mountain volcanic wells, it was seen that these three groups have different signatures. The volcanic waters are high in Na + K, and low in Ca and Mg. As more carbonate water is added, the waters become more enriched in Ca, Mg, Cl and SO₄, as would be expected and the volcanic wells are generally undersaturated with calcite, while the carbonate wells are saturated. In addition, the amount of CO₂ in the volcanic waters decreases as the saturation of calcite increases, suggesting that the CO₂ is being removed as the calcite is forming. This correlates with the computer model, where the deeper zones have more calcite precipitating than the shallower zones.

RESULTS AND IMPLICATIONS

The purpose of this study was to further define the possibility of upward flow from the regional carbonate aquifer into the overlying Tertiary volcanic tuff aquifers, using a variety of geochemical modeling techniques and isotope analyses.

A hypothetical flow path through a tuffaceous system was modeled using PHREEQE, and divided into six parts based upon diagenetic mineral zones. Water/rock interactions within each zone were controlled by reactions with diagenetic smectites, zeolites and feldspars.

The modeled tuffaceous waters from each zone appeared similar to well analyses from that zone. Adding carbonate waters to these volcanic zones changed the resultant chemistry enough to show that the Yucca Mountain wells do not appear to be a mixture of volcanic and carbonate waters. The model suggests that the volcanic wells analyses may be caused solely through infiltration of water through the stratigraphic column, and that there is little, if any, contribution from the lower carbonate aquifer. The modeling of well UE-25 p#1 predicted a mixture of 70 to 81 percent volcanic water (from Part IV) with 30 to 19 percent carbonate aquifer water. These ratios also correlate well with mixing values of 28.6 percent carbonate water reported by Craig and Robison (1984).

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INFLUENCE OF THERMAL PHENOMENA AND VERTICAL FLOW ON REGIONAL FLUX ESTIMATES

Tom Brikowski and Sandra J. Haws

INTRODUCTION

The original intent of this project was to investigate the interaction between groundwater and heat flow in the saturated zone around Yucca Mountain using numerical models. These two fluxes can be strongly linked, and neither should be considered independently of the other. A number of studies suggests that this linkage may be important in the Yucca Mountain regions. These include studies indicating that vertical groundwater flow affects observed heat-flow values in the southern Great Basin (Sass et al., 1988; Sass and Lachenbruch, 1982) and that topography and basin structure can strongly influence heat and groundwater flow (Forster and Smith, 1988; Bachu, 1985; Bachu, 1988; Smith and Chapman, 1983; Woodbury and Smith, 1985).

All of these studies make the fundamental assumption that heat input is constant at the base of the system being studied, i.e., that temperature is constant at some arbitrary depth (usually 10 to 30 km). Recent geophysical evidence may indicate that this assumption is invalid in the southern Great Basin (Blakely, 1988). This would eliminate an important constraint on heat/fluid flow models in this region, and makes it difficult to isolate the effects of groundwater flow on heat flow, and vice versa. In light of Blakey's results (Blakely, 1988), the interaction of heat and groundwater flow will be difficult to quantify in the Yucca Mountain region. The principal effect of heat flow on groundwater flow will be to reduce fluid viscosity (Forster and Smith, 1988). If this thermal effect was included in flow models, groundwater velocities would be increased, and head values would be decreased by a factor of 10 to 20 percent throughout the model. At this time, this effect should be regarded as a source of additional uncertainty that has been ignored. A fully three-dimensional, coupled fluid-heat flow model would be required to adequately treat this problem. Computer codes that can do this exist (Woodbury and Smith, 1985).

Because of the above discussed limitation, the thermal modeling portion of this project was postponed, and other problems in saturated zone modeling at Yucca Mountain were pursued.

VERTICAL FLOW

Activities

Heat flow and thermal buoyancy effects act in the vertical direction. Before thermal effects can be considered, a model of isothermal (hydrologic) flow in the

vertical direction is required. Existing models of the saturated zone at Yucca Mountain treat flow as strictly horizontal (i.e., areal flow models) (Czarnecki and Waddell, 1984; Waddell, 1982), and implicitly average conditions in the vertical direction. The task of constructing a vertical flow model was given to a graduate student (Sandy Haws) as part of her Master's thesis. Constructing a vertical flow model is often difficult, because inputs that give consistent results in a horizontal flow model are often inconsistent in the vertical direction. Considerable time is required to adjust the model to give consistent results. This task has been largely completed, and the results will be presented as a thesis at the University of Nevada, Las Vegas, an abstract and presentation at the Fall American Geophysical Union Meeting, and hopefully as a peer-reviewed publication.

METHODS

A numerical model of Yucca Mountain was constructed in cross section in order to investigate the stratigraphic and structural controls on groundwater flow in the saturated zone. Previous numerical models of Yucca Mountain and surrounding areas have been done by Waddell (1982), Czarnecki and Waddell (1984), and Rice (1984). These models are areal models of the region which represent all water bearing units as a single aquifer and treat all flow as horizontal. Sinton (1986) did a pseudo three-dimensional model assuming an upper and a lower aquifer. A cross-sectional model can represent many layers of hydrogeology units and simulate leakage between these layers. In cross section, hydraulic properties can be estimated in the vertical as well as the horizontal given head distributions from field observations.

A finite element code, VAM2DH, from HYDRO Geologic, was chosen because of availability of code and documentation and its ability to model unsaturated and saturated flow in cross section. This study did not intend to investigate unsaturated zone properties, but the presence of an unsaturated zone allows free movement of the water table under varying conditions. This makes it possible to model up to the water table instead of at some predetermined level below the water table and does not make the assumption of horizontal flow.

A cross section was defined to follow a streamline determined from a previous study (Czarnecki and Waddell, 1984). The cross section is 84.4 km long and extends from Beatty Wash, just south of Timber Mountain, to Franklin Lake Playa, the generally accepted discharge area for the hydrologic subbasin containing Yucca Mountain.

Theoretically, a section following a streamline has no in or outflow of water except along the model boundaries. Top and bottom boundaries were made impermeable but recharge was allowed where the section crosses Fortymile Wash. Heads were held constant at either end of the section. The north end heads were fixed

equal to estimated values reported from Waddell et al. (1984) and the south end was fixed to the playa surface elevation (Czarnecki and Waddell, 1984).

The cross section was constructed using well logs and available geological and geophysical interpretations of the area to define hydrogeologic units. The assumption made in the model area is that geologic units and hydrogeologic units coincide. Initially, hydraulic conductivities were assigned to each hydrogeologic unit as estimated in previous works (Winograd and Thordarson, 1975; Czarnecki and Waddell, 1984; Sinton, 1986). Hydraulic conductivities were refined to make a best fit between model and observed heads along the section. The hydraulic conductivity of each unit was varied widely to test its influence on water levels at Yucca Mountain.

RESULTS AND IMPLICATIONS

Preliminary conclusions find three hydrogeologic units dominant in replicating observed heads at Yucca Mountain: the underlying carbonate aquifer, the aquitard, and a low permeability zone corresponding to the high gradient zone north of the proposed repository. Upward flow from the carbonates to the volcanics seems to be required to maintain heads at observed levels. The aquitard is necessary between the two aquifers to maintain the upward gradient from the carbonates to volcanics. Without an aquitard between the two aquifers under most of Yucca Mountain it does not appear possible for the model to reproduce observed head gradients along the cross section.

Just upgradient of the proposed repository there is a zone of steep head gradient. The cause of this zone is not well understood. The high gradient could be structurally controlled, either by variations in the density of fracturing, or by faulting. The high gradient could also be caused by a nose of the Eleana Formation, an aquitard outcropping to the east at the Nevada Test Site, or the gradient could be a model artifact caused by a low permeability zone to the east of the modeled cross section. This zone could divert water flow to the west causing high gradients in the cross section without a corresponding permeability variation in the section.

The cross-sectional model emphasizes the fact that present understanding of the saturated zone at Yucca Mountain is limited. The area of steep hydraulic gradient north of Yucca Mountain is a primary influence on the features of the "Furnace Creek-Franklin Lake Playa Hydrologic Subsystem" that includes Yucca Mountain. Models of the saturated zone at Yucca Mountain will be quite sensitive to the parameters chosen for this area, and to its assumed geometry. Only one well at Yucca Mountain penetrates the carbonate aquifer and no wells are located in the area of steep gradient. Further field data are needed to confirm model results and help in understanding the carbonate aquifer, the aquitard, and the high gradient zone.

Studies should be concentrated on: 1) defining the nature and extent of the aquitard including the amount and spatial variability of leakage between the carbonate and volcanic aquifer; 2) the distribution and properties of the low hydraulic conductivity zone responsible for the high gradient near the proposed repository; and 3) the nature and extent of the carbonate aquifer with emphasis north and under Yucca Mountain.

STEADY-STATE CONSIDERATIONS

Activities

While conducting preliminary work on thermal influences, it became clear that another feature of the saturated zone models was inadequate: existing models assume the hydrologic system is in steady-state. Such an assumption is usually reasonable because aquifers can adjust to new conditions faster than natural processes change those conditions (e.g., climate change or tectonic activity). Basin and Range hydrologic systems are so large and complex, however, that the assumption of steady-state may be incorrect.

The approach taken was to investigate the errors that would arise from an inappropriate application of the steady-state assumption. If these proved to be significant, then the steady-state assumption should be carefully examined and justified in Yucca Mountain models.

Numerical models were run on a highly simplified approximation of the Yucca Mountain region to approximate the recovery of the system from a pluvial recharge pulse (e.g., Czarnecki, 1985). Current models of the saturated zone assume that the head distribution observed in the field is the final, or steady-state distribution. Inverse models are then applied to derive an approximate transmissivity distribution from this head distribution. If an erroneous head distribution is used, an erroneous transmissivity distribution will be computed.

In this study, transient flow models were used to compute the difference between the transient and final (steady-state) head distributions vs. time. The difference between transient and steady-state values of discharge were computed as well. These two types of error can propagate through the modeling process, especially when observed head distributions are used to estimate transmissivities of the saturated zone (e.g., Waddell, 1982). Without having the actual inverse model in hand, it is difficult to quantify the errors in transmissivity that result from head-distribution errors (i.e., inappropriate assumption of steady-state). Indications from this study are that the transmissivity errors can be significant up to 80 percent of the time to steady-state. Basin and Range settings are more apt to exhibit long response times to hydrologic changes (e.g., changes in recharge) because aquifer connectivity is often

limited. The combination of these results indicates that the steady-state assumption is somewhat risky at Yucca Mountain.

The preliminary findings of this study were presented at AGU in Spring 1989. A manuscript describing the final results has been prepared, and awaits some additional theoretical work on the response time of idealized aquifer systems. This manuscript should be finished and submitted for publication by December 1989.

RESULTS AND IMPLICATIONS

These results indicate that the assumption of steady-state is another source of uncertainty in saturated zone models at Yucca Mountain. This is an example of how seemingly innocuous assumptions can increase the uncertainty of models at this location, and the unlikelihood of producing a truly accurate performance model for Yucca Mountain. Too many assumptions have to be made, and often there is no way, or not enough time to carefully justify each one.

In the manuscript described above, the probability that the Yucca Mountain saturated zone (or at least the DOE model view of it) is not in steady-state will be quantified. There is a significant chance that the system is still responding to a recharge pulse that may have occurred 10,000 to 12,000 years ago (Spaulding, 1985).

This study highlights one of many sources of model uncertainty that have been overlooked in current studies of Yucca Mountain. If these models claim to be accurate, each such source of uncertainty must be carefully examined and justified. This has not been done in the case of the steady-state assumption. The results of this study indicate that errors in transmissivity (and therefore travel-times) resulting from inappropriate assumption of steady-state in existing saturated-zone studies (Czarnecki and Waddell, 1986; Waddell, 1982) may be larger than the estimation errors reported in these studies. DOE must show that the saturated zone is indeed at steady-state before this source of uncertainty can be dismissed.

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ESTABLISHING PAST PRECIPITATION AND VEGETATION AT YUCCA MOUNTAIN: PACKRAT MIDDEN STUDIES

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INTRODUCTION

The prospect of Yucca Mountain becoming a repository for high-level nuclear waste means that the intended waste containment area must be well beyond the reach of the hydrologic system, not only under present climatic conditions, but under the range that may reasonably be expected during the next 10,000 years. Although studies of orbital mechanics, and global climate models, provide speculative notions of future climatic trends, they cannot predict how these trends might be manifested in the immediate area around Yucca Mountain. The generally accepted approach to this question is to consider the climatic variations that have occurred during the last 10,000 years, and use these as a guide to the likely range of future variation in climate. However, because climatic studies around the world suggest we are potentially on the verge of another ice age, we should also consider the conditions that predominated around Yucca Mountain during the Pleistocene, as well as the Holocene.

The specific objective of this project is to determine the vegetational history of Yucca Mountain during the last 20,000 years. By integrating the data from our own studies of pollen records, woodrat middens and tree-ring sequences with the data already obtained by others from southern Nevada, a regional climatic record will be generated that will be correlated to corresponding data from Yucca Mountain itself to formulate a local climatic sequence. This record can then be used to determine the magnitudes of climatic variation that have occurred during the past 20,000 years or so, and provide estimates of rainfall that can be used by geohydrologists in modeling the infiltration rates and travel times of groundwater to be expected during the next 10,000 years at Yucca Mountain.

Possible increased recharge due to pluvial climatic conditions could affect the site's ability to meet the EPA standard (40 CFR Part 191) for release of radionuclides from the waste package to the accessible environment. This investigation will directly address the question of "how much wetter" has the climate been at Yucca Mountain and should result in information on temperature and duration of wetter and drier episodes. The study is directly related to previous studies conducted by DOE contractors evaluating past regional climates, but will be more accurate because it will include data from several sources that are more continuous and more amenable to calibration.

METHODS

Pollen from stratified deposits in lakes, marshes and alluvium, and from plant remains preserved in ancient woodrat nests (middens), is used for reconstructing past vegetation and climate. Pollen analysis provides information on both regional terrestrial and local aquatic vegetation. In addition, sediments often hold seeds of aquatic plants that reflect fluctuating water table. Although pollen records are not as specific as woodrat middens about the plant species growing in an area, they can provide a continuous record of plant community change that woodrat middens do not. To reconstruct past vegetation communities, fossil pollen spectra are compared to pollen samples collected in modern plant communities. Modern communities that are selected as analogues are used to infer information on precipitation and temperature.

Woodrats forage plant remains (twigs, flowers, seeds, etc.) from within a 50 m radius. As a result, their nests (preserved due to aridity or protection in caves and overhangs) are excellent repositories of ancient vegetation that provide site-specific information about the plants that grew within a very restricted locality at a specific point in time. The record of vegetation derived from woodrat middens provides uniquely detailed information about past climate and soil conditions at a particular site. Distribution of many plants is determined by specific moisture and temperature conditions, thus their occurrence in the past at elevations above or below today's provides clues to changing temperature and precipitation.

Tree-ring analyses have recently been integrated with pollen and woodrat midden studies, to provide a means of calibrating these data and to derive more specific data on rainfall and temperature. By comparing recent tree-ring data to historic climatic records, a transfer function can be generated that allows interpolation of temperature and precipitation to the beginning of the tree-ring record. This can, in turn, be used along with the data derived from analogous modern plant communities to generate a second transfer function to infer past climate.

Furthermore, vegetation has a direct influence on groundwater infiltration and chemistry, and changes in vegetation need to be considered in analyzing variations in future groundwater chemistry as it may react with stored or mobile radioactive wastes. However, no such site-specific studies have been completed. Spaulding, with USGS support, has studied middens from the Sheep Range, Eleana Range, and Point of Rocks, among others, but has concentrated primarily on the general outlines of vegetation history and the underlying climatic change. This study proposes to broaden the regional and elevational coverage of woodrat midden studies in southern Nevada and to integrate the methods of palynology and tree-ring analysis to detail the reconstruction of vegetation history and climate change in southern Nevada, and at Yucca Mountain in particular, for the last 20,000 years.

Pollen Data: Pollen localities were identified and cored to provide a continuous, overlapping record of Holocene sediments. The cores were closely sampled at the top to provide a nearly continuous record of vegetation response to changing regional climate during the period of historic weather data. The remainder of the core was sampled to provide as much detail as possible for recording short-term, as well as long-term, vegetation responses to climatic change. To fulfill the intent of this sampling procedure, a minimum of 200 samples will be counted at each locality. To arrive at statistically significant results, counts of terrestrial pollen from each pollen sample will have to be on the order of 400 to 600 grains. Tight chronometric controls will be necessary to acquire the accurate, as well as detailed, climatic record necessary to serve as the basis for predicting future climatic trends. This will require radio-carbon and, when possible, cesium and lead isotope dating and the use of tephrochronology.

Pollen and Pollen Ratio Indices: Using principal component and factor analysis of the complete pollen record, climatically sensitive pollen variables are identified (Birks and Gordon, 1985). Transfer functions can then be generated using closely sampled upper 30 to 40 years of pollen cores that have been dated using cesium (Ritchie et al., 1973; Battarbee, 1978) and lead (Brugam, 1978) isotopes. These transfer functions link either individual pollen types or ratios of pollen types with specific climatic parameters much as do tree-ring width indices. Once calibrated, these indices can be tested against the earlier portion of the historical weather record for the region. After the transfer functions have been refined, they can be used to reconstruct the rainfall and temperature record for the remainder of the pollen record.

Analyses of Pollen Spectra: Past climate can also be reconstructed by comparing fossil pollen spectra with modern surface pollen spectra that characterize specific modern plant communities. Using the squared-cord distance-dissimilarity coefficient, the closest modern analogue for past vegetation communities can be determined (Overpeck et al., 1985). From the climatic parameters of analogous modern plant communities, past climatic parameters for particular fossil plant communities are derived. These can then be used to construct indices of regional temperature and precipitation (e.g., Heusser et al., 1980; Mathewes and Heusser, 1981; Bartlein and Webb, 1985). Realistically, these indices can be extended to about 8,000 or 9,000 years ago when modern analogues for past plant communities can no longer be found.

Woodrat Midden Data: The numerous woodrat middens that have been identified at the sample sites cross-cut several vegetation formations as well as variations in rock substrate and other terrain factors. The woodrat nests will be intensively sampled to ensure as continuous a coverage through time as possible. Because the

occurrence of woodrat middens seems to cluster in time, we would want to sample sufficiently to discover most of these Holocene clusters. This is partly because data thus far seem to indicate that this clustering may be climatically linked (Mehring and Wigand, in press).

Initially, past local vegetation for a particular area and point in time will be reconstructed using only half of the midden data available for that area. Then, using the modern remote sensing vegetation map of the area as a baseline, we will shift in steps all the mapped vegetation assemblages either toward more (or less) relatively mesic conditions until the modeled communities fit the reconstructed vegetation distribution based upon the woodrat midden studies. The fit of this model will then be tested with the remaining woodrat midden data from the area.

Once the past vegetation has been reconstructed in this way, the modern climatic parameters for each of the plants identified in the woodrat middens given a particular slope, aspect, rock substrate, and elevation will be determined. The paleoclimatic parameters of particular localities at particular points in time will be reconstructed given the intersection of the climatic parameters of the species identified in the midden. The climatic parameters of these paleomicroenvironments will then be used to reconstruct regional paleoclimate by taking into account the peculiarities of slope, aspect, elevation and rock substrate.

Tree-ring Data: Tree-ring data will be acquired at each of the sample sites from several stands in order to characterize the climatic record. Tree-ring cores will be collected, prepared, ring widths measured, and the results statistically analyzed to generate standardized indices for each stand.

Reconstruction of past climate using tree-ring widths requires the use of a transfer function that links the tree-ring width of any particular year with the climatic conditions that occurred during that year (Lofgren and Hunt, 1982). Some of the variables that must be considered include temperature, precipitation, previous year's weather, rock substrate, stand density and insect infestation. Each of these can be factored out and taken into account so that past climate can be reconstructed.

Initially, a transfer function is created that links the historical record of temperature, precipitation or stream discharge for the past 30 or 40 years with a statistically standardized tree-ring index derived from the tree-rings of a particular grove. This calibration is then tested and refined by comparing it with the weather records that precede those used to create the calibration. Once the transfer function has been tested, it can be used to reconstruct the climatic record for the remaining period for which there are tree-rings.

Paleoclimatic Data Integration: Reconstruction of the final paleoclimatic sequence for an area will require the integration of tree-ring, pollen and woodrat mid-

den data sets (Figure 1). Initially, the regional paleoclimatic indices stemming from analysis of tree-rings will be compared with those derived from pollen. Differences, if they occur, will be resolved by comparison, when possible, with the climatic data derived from woodrat midden studies. Especially important at this point will be the carbon isotope data on temperature derived from the study of plant materials recovered from the woodrat middens.

Future Climate Prediction: Although the prediction of future climate is not the intent of this project, a potential outgrowth of the formulation of detailed records of past climatic change is the possibility of examining this possibility. To predict future climate we must determine whether there have been recurrent patterns of climate change in the past. If such patterns are evident, we will compare the climate reconstructed for the past 1,000 years or so with these past periods of Holocene climatic change. Using the paleoclimatic record as a template we can attempt to assess the possibility that we are on the verge of, within, or just after, a period of climatic change. Using previous periods of climatic change we can attempt to identify a pattern that might indicate the potential direction of climatic change.

LOCALITIES

Sediments containing well preserved pollen are rare at the NTS. Springs that could have provided such records have been severely disturbed in historic times. However, three areas (spring deposits in Oasis Valley and Ash Meadows west and south of Yucca Mountain and Lower Pahranaagat Lake east of the NTS) have already been sampled and analysis of the Oasis Valley and Lower Pahranaagat Lake cores is well under way (Figure 2). Each of these records contains continuous information about changes in regional and local marsh vegetation covering the last 3,000 to 5,500 years.

However, past research has indicated that several areas immediately adjacent to the NTS contain relatively undisturbed sediments with well-preserved pollen. Among these are spring mounds and marsh deposits associated with springs in Oasis Valley and Ash Meadows and Lower Pahranaagat Lake.

Ancient woodrat middens abound in the area around Yucca Mountain and the NTS. Little Skull Mountain (west of Mercury), the Pahranaagat Range (northeast of the NTS) and the Devil's Hole Hills (southwest of Mercury) have been sampled (Figure 2). Thus far, analyses of the middens from Little Skull Mountain and from the Hancock Summit area of the Pahranaagat Range have been completed. Study of middens from two areas collected in the Pahranaagat Range is well under way, though sorting and identification remain to be completed. Analysis of middens from Owl Canyon in the Devil's Hole Hills is in progress (Table 1).

FIGURE 1. Time and Space Relationships of Pollen, Woodrat Midden and Tree-Ring Data.

STUDY LOCATIONS

FIGURE 2. Pollen, Woodrat Midden and Tree-Ring Localities Included in this Study.

TABLE 1. STATUS OF WORK ON WOODRAT MIDDENS FOR YUCCA MOUNTAIN PALEOENVIRONMENTS.

Midden #	Sampled	Soaked	Screened	Pollen	Picked	Dried	Weighed	Dated	14C Age Material
Little Skull Mountain									
LSM151182LP1 2(1) (LSM111582LP1 B(III))	X	X	X	X	X			X	13,740 $\pm$ 130 (juniper)
LSM151182LP1 2(2) (LSM111582LP1 B(II)bot)	X	X	X	X	X	X	X	X	14,280 $\pm$ 180 (dung) 14,970 $\pm$ 340 (juniper)
LSM151182LP1 2(3) (LSM111582LP1 B(II)top)	X	X	X	X	X			X	11,970 $\pm$ 110 (juniper)
LSM151182LP1 2(4) (LSM111582LP1 B(I))	X	X	X	X	X	X	X	X	10,460 $\pm$ 140 (dung)
LSM151182LP1 3(1) (LSM111582LP1 C(I))	X	X	X	X	X			X	10,030 $\pm$ 120 (dung)
LSM151182LP1 3(2) (LSM111582LP1 C(II))	X	X	X	X	X			X	9,480 $\pm$ 370 (dung)
LSM151182LP1 4 (LSM111582LP1 D)	X	X	X	X	X	X	X	X	8,480 $\pm$ 130 (dung)
LSM151182LP1 1 (LSM111582LP1 A)	X	X	X	X	X			X	6,680 $\pm$ 240 (dung)
LSM141282RR1 (1) (LSM121482RR1)	X	X	X	X	X	X	X	X	1,940 $\pm$ 80 (dung)
LSM091282LP1 (1) (LSM120982LP1)	X	X	X	X	X	X	X	X	1,090 $\pm$ 70 (dung)
Timpahute Range									
TR160987PEW1 (1)	X	X	X	X	X			X	10,040 $\pm$ 130 (juniper)
Pahrnagat Range-Petroglyph Rocks									
PR271087PEW1 (1)	X	X	X	X	X	X	X		
PR271087PEW1 (2,1) (PR271087PEW2 (1)bot)	X	X	X	X	X	X	X	X	1,060 $\pm$ 150 (juniper) 1,400 $\pm$ 100 (dung)
PR271087PEW1 (2,2) (PR271087PEW2 (2)mid)	X	X	X	X	X	X	X		
PR271087PEW1 (2,3) (PR271087PEW2 (3)top)	X	X	X	X	X	X	X		
Pahrnagat Range-Hancock Summit									
PR100588PEW1 (5,3)	X	X	X	X	X	X	X	X	22,730 $\pm$ 1,080 (dung)
PR100588PEW1 (1)	X X	X X	X X	X X				X X	12,120 $\pm$ 90 (dung) 11,530 $\pm$ 150 (juniper)
PR100588PEW1 (5,1)	X	X	X	X	X	X	X	X	11,710 $\pm$ 150 (dung)
PR100588PEW1 (4,1) (PR100588PEW1 (4) bot)	X	X	X	X				X	9,120 $\pm$ 110 (dung) 9,540 $\pm$ 120 (juniper)
PR100588PEW1 (5,2)	X	X	X	X	X			X	7,030 $\pm$ 130 (dung)
PR100588PEW1 (4,2) (PR100588PEW1 (4) top)	X	X	X	X				X	5,820 $\pm$ 90 (dung)
PR100588PEW1 (2,3) md	X	X	X	X				X	860 $\pm$ 70 (dung)
PR100588PEW1 (2,4) frt	X	X	X	X				X	170 $\pm$ 60 (dung)
PR100588PEW1 (3)	X	X	X	X				X	170 $\pm$ 70 (dung)

TABLE 1. STATUS OF WORK ON WOODRAT MIDDENS FOR YUCCA MOUNTAIN PALEOENVIRONMENTS (cont.).

Midden #	Sampled	Soaked	Screened	Pollen	Picked	Dried	Weighed	Dated	14C Age Material
PR100588PEW1 (2,2) mdb	X	X	X	X				X	80±60 (dung)
PR100588PEW1 (2,1) bk	X	X	X	X				X	MODERN (dung)
PR100588PEW1 (5, top-1)	X	X	X	X					
Pahranagat Range-East Badger Mountain Road									
PR110588PEW3 (1,1)									
PR110588PEW3 (1,1) bt									
PR110588PEW3 (1,2)									
PR110588PEW3 (1,2) md									
PR110588PEW3 (1,3)									
PR110588PEW3 (1,3) tp									
Pahranagat Range-Petroglyph Cave									
PR120588PEW4 (1)	X	X	X	X	X				
East Pahranagat Range									
PR120588PEW5 (1)									
PR120588PEW4 (1)	X	X	X	X					
Last Chance Range									
LCR130588PEW1 (1)	X	X	X	X					7,790±120 (dung)
Pahranagat Wash									
PRW090688PEW1 (1)									
PRW090688PEW1 (2)	X	X	X					X	720±90 (dung)
Pahranagat Range-South Fork									
PR100688PEW1 (1,1)									
PR100688PEW1 (1,2)									
PR100688PEW1 (1,3)									
PR100688PEW1 (1,4)									
PR100688PEW1 (1,5)									
PR100688PEW1 (1,6)									
PR100688PEW1 (1,7)									
PR100688PEW1 (2)									
PR100688PEW1 (3,1)									
PR100688PEW1 (3,2)									
PR100688PEW1 (3,3)									
PR100688PEW1 (3,4)									
PR100688PEW1 (4)									
PR100688PEW1 (5)									
PR100688PEW1 (6)									
PR100688PEW1 (7)									

TABLE 1. STATUS OF WORK ON WOODRAT MIDDENS FOR YUCCA MOUNTAIN PALEOENVIRONMENTS (cont.).

Midden #	Sampled	Soaked	Screened	Pollen	Picked	Dried	Weighed	Dated	¹⁴ C Age Material
Pahrnagat Range-North Fork									
PR110688PEW1 (1,1)									
PR110688PEW1 (1,2)									
PR110688PEW1 (2,1) bit									
PR110688PEW1 (2,2) tp									
PR110688PEW1 (2,3) tpf									
PR110688PEW1 (3,1) bot									
PR110688PEW1 (3,2) top									
PR110688PEW1 (4)	X	X	X	X					
PR110688PEW1 (5)									
PR110688PEW1 (6,1) bot	X	X	X	X	X			X	2,370 $\pm$ 90 (dung)
PR110688PEW1 (6,2) top									
Pahrnagat Range-South Valley									
PR110688PEW2 (1)									1,210 $\pm$ 120 (yucca)
PR110688PEW2 (1,1) bit	X	X	X	X					
PR110688PEW2 bit									
Pahrnagat Range-"Mick Jager Formation"									
PR110688PEW3 (1)									
PR110688PEW3 (2)	X	X	X	X					20,280 $\pm$ 190 (dung)
Ribbon Cliffs									
RC250588LCP1 (1)	X	X	X	X	X				9,330 $\pm$ 140 (juniper)
	X	X	X	X	X				10,610 $\pm$ 120 (dung)
Crankshaft Junction									
CJ190389CLN1 (1)									
Devil's Hole Hills-Owl Canyon									
OC150589PEW1 (1)									2,970 $\pm$ 50 (dung)
OC150589PEW1 (2)									
OC150589PEW2 (1)									12,260 $\pm$ 110 (dung)
									12,570 $\pm$ 230 (juniper)

These middens, combined with others previously examined from southern Nevada, provide the opportunity to determine past climates and vegetation at Yucca Mountain from both data acquired in the immediate proximity and through regional extrapolation from more remote sites. Middens are found in areas of both volcanic and sedimentary substrates, and occur at elevations from valley floors to tops of mountain ranges. Analysis of large numbers of middens from each of these areas provides detailed information on the differing effects of substrate and elevation.

These middens are found in relatively close proximity to the pollen localities (Figure 2), therefore, the data obtained can be integrated with pollen records to derive more detailed information on the magnitude of climatic change and the areal extent of its impact. Although the pollen record thus far spans only the past 4,000 years, and the midden record over 23,000 years, overlap permits correlation of these data sets.

A variety of trees and shrubs may provide tree-ring data, but some species yield more reliable data than others. Juniper may be used, but its growth characteristics make reliable records difficult to obtain. Far better records can be recovered from pinyon pine, such as those occurring on Pinnacles Ridge, just north of Yucca Mountain, and from Pahute Mesa and other ranges to the north. Juniper on Yucca Mountain may be used to correlate longer pinyon tree-ring records to the north with climatic conditions prevailing on Yucca Mountain during the past 100 years or so. These data could then be interpolated beyond the limit of the juniper record for Yucca Mountain.

Thus far, access restrictions to the NTS have inhibited progress of tree-ring studies beyond examination and analysis of already extant tree-ring data sets from the Sheep and Spring Ranges, and their correlation to the modern climatic data from the area. Construction of a tree-ring record progresses rapidly once begun, and analysis of pinyon pine on Pinnacles Ridge and Pahute Mesa is anticipated.

WORK PLAN

Analysis of woodrat middens collected from Badger Mountain in the Pahrana-gat area will be completed and the results added to data collected from the Little Skull Mountain and Hancock Summit areas. These data will be combined with all previously published data on woodrat middens collected from southern Nevada to reconstruct changing vegetation distributions during the Pleistocene and Holocene. Only three middens (at Hancock Summit in the Pahrana-gat Range, southeast of Badger Mountain in the Pahrana-gat Range, and Owl Canyon in the Devil's Hole Hills) need further collection due to their importance to this work.

Analysis of pollen collected from Oasis Valley and Lower Pahrana-gat Lake cores will be completed and integrated with results of pollen analyses conducted in the Tule Springs and Ash Meadows areas in the 1960s by Peter J. Mehringer, Jr. The combined length of these records is approximately 14,000 years. Collection and analysis of tree-ring records from Pinnacles Ridge and Pahute Mesa will be completed and, along with records from the Sheep and Spring Ranges, used to calibrate pollen records with modern climatic data.

A final report will be generated integrating these data into a well-dated vegetational history of southern Nevada and derived climate estimates. This integration will

include a history of effective precipitation and, perhaps, seasonality for the proposed repository site. These data, when integrated into models of infiltration and groundwater movement, may be used to assess the adequacy of measures taken to ensure isolation of radioactive wastes from the hydrologic system.

RESULTS AND DISCUSSION

The initial objective of this study was to develop a well-dated vegetation history and integrate it with climate and groundwater models as a means of determining the suitability of Yucca Mountain as a waste repository. However, as our data base accumulated, it became increasingly obvious that not only have there been dramatic shifts in precipitation in southern Nevada during the Holocene and Pleistocene, but these changes may have occurred very rapidly. The scope of this study, as originally envisioned, could not address the question of rapidity of climatic change. Rapid shift to effectively moister climatic conditions could severely affect the suitability of Yucca Mountain for either long- or short-term storage of nuclear wastes.

In a neopluvial episode, with a rapid shift to increased effective precipitation, not only would the overlying soil become quickly saturated, but fracture zones would fill and serve as pathways for rapid infiltration through the bedrock. As a result, groundwater recharge rates would be dramatically amplified. In this case, increased recharge of the hydrologic system under Yucca Mountain could occur within decades, rather than hundreds or thousands of years.

With this scenario in mind, it was decided that the emphasis of this investigation should directly address the question of how quickly climate could change at Yucca Mountain and how such changes would be manifested in the past vegetation record--an issue not yet addressed by previous studies conducted by DOE contractors evaluating past regional climates.

Fossil Woodrat Midden Data

The initial vegetation record reconstructed for this project was obtained from middens on Little Skull Mountain, southeast of Yucca Mountain on the NTS (Table 2). These middens occur on volcanic rocks on a southeast-facing slope at 3,850 ft (1,173 m). Vegetation at this locality is presently dominated by desert scrub consisting of creosote bush (*Larrea divaricata*), white bursage (*Ambrosia dumosa*), desert thorn (*Lycium andersonii*), and occasional gray mormon tea (*Ephedra nevadensis*) and barrel cactus (*Echinocactus polycephalis*). Today, shadscale (*Atriplex confertifolia*) occurs about 200 m downslope.

Fossil woodrat midden data from Little Skull Mountain indicate a landscape dominated by Utah juniper (*Juniperus osteosperma*) from about 15,000 to about

TABLE 2. PRELIMINARY LIST OF THE CONTENTS OF WOODRAT MIDDENS FROM LITTLE SKULL MOUNTAIN, NEVADA.

Midden #	LSM 120982LP1	LSM 121482RR1	LSM 111582LP1 A	LSM 111582LP1 D	LSM 111582LP1 C(2)	LSM 111582LP1 C(1)	LSM 111582LP1 B(1)	LSM 111582LP1 B(2) top	LSM 111582LP1 B(3)	LSM 111582LP1 B(2) bottom
Radiocarbon Age	1,090 ± 70	1,940 ± 80	6,680 ± 240	8,450 ± 130	9,480 ± 370	10,030 ± 120	10,460 ± 140	11,970 ± 110	13,740 ± 130	14,280 ± 180/14,970 ± 340
Trees:										
<i>Juniperus osteosperma</i>				X				X	X	X
<i>Yucca brevifolia</i>									X	
Shrubs:										
<i>Artemisia dumosa</i>	X	X	X	X						X
<i>Artemisia</i> (sec <i>Tridentata</i>)	X	X	X						X	
<i>Atriplex confertifolia</i>	X	X								
<i>Atriplex lentiformes</i>	X									
<i>Atriplex polycarpa</i>	X									
<i>Celtis reticulata</i>				X	X					
<i>Ephedra</i> sp.	X		X	X						
<i>Larrea tridentata</i>			X	X						X
<i>Lycium andersonii</i>			X							
<i>Prunus</i> sp.				X						
<i>Salvia columbariae</i>	X				X				X	X
<i>Sabia domi</i>									X	
<i>Symphoricarpos</i> sp.										
Forbs:										
<i>Antennaria tessellata</i>				X	X			X	X	X
<i>Aster</i> sp.										
<i>Astragalus</i> sp.	X		X							
<i>Brockelia oblongifolia</i>				X						
<i>Brockelia watsonii</i>										
<i>Brockelia</i> sp.	X			X	X			X	X	X
Cactaceae										
<i>Cylindropuntia</i> sp.				X	X					
<i>Chamaecyparis micromera</i>				X						
<i>Chamaecyparis</i> sp.										
<i>Cryptantha angustifolia</i>	X			X						
<i>Cryptantha gracilis</i>				X						
<i>Cryptantha uranensis</i>				X						
<i>Cryptantha pterocarpa</i>				X						
<i>Cryptantha</i> sp.				X						
<i>Encelia virginensis</i>	X			X						
<i>Encelia</i> sp.										
<i>Eschscholzia minutiflora</i>										X
Lamiaceae										
<i>Guiera</i> sp.				X						
<i>Guiera</i> sp.										
<i>Halimolobos</i> sp.										
<i>Lepidium fremontii</i>										
<i>Lepidium lasiocarpum</i>	X			X	X					
<i>Menziesia albicaulis</i>										
<i>Muhlenbergia breviflora</i>				X	X					
<i>Muhlenbergia affinis</i>				X	X					
<i>Phacelia crenulata</i>	X			X	X					
<i>Phacelia</i> sp.										
<i>Plagiobothrys jonesii</i>	X			X						
<i>Silene verna</i>										
Solanaceae										
<i>Sphaeralcea ambigua</i>	X									
<i>Sphaeralcea grossularifolia</i>	X									
<i>Sphaeralcea</i> sp.	X									
Grasses:										
<i>Agropyron</i> sp.	X			X						
<i>Oxytropis hymenoides</i>	X									
<i>Stipa</i> sp.	X									

10,500 B.P. The end of more mesic conditions is reflected by the disappearance of Utah juniper macrofossils from a midden stratum dated at about 9,500 B.P. This evidence indicates a slight rise in lower tree-line between 10,500 and 8,500 years B.P. Reappearance of Utah juniper macrofossils in a midden stratum dated at 8,500 B.P. records a drop in lower tree-line prior to the final retreat of juniper to higher elevations after 8,500 B.P. Utah juniper macrofossils in middens at Little Skull Mountain are among the lowest and latest (about 8,500 B.P.) early Holocene occurrences in southern Nevada.

The midden stratum dated at 8,500 B.P. also records the final occurrence of several plants characteristic of Pleistocene vegetation, as well as the first appearance of several species that characterize the Holocene plant community on the southwest face of Little Skull Mountain. The appearance of desert scrub species in this midden suggest that warmer, drier conditions typical of the Holocene had existed long enough to encourage the migration of these species to higher elevations than during the Pleistocene.

The absence of mid-Holocene woodrat middens at Little Skull Mountain follows a general pattern found throughout the Great Basin. This may reflect environmental conditions unfavorable for either woodrat habitat or the preservation of woodrat dens in this locality.

New dates on juniper have been obtained from the Owl Canyon woodrat midden, 30 km south-southeast of Little Skull Mountain in the Devil's Hole Hills east of Ash Meadows, originally reported on by Mehringer and Warren (1976) and Spaulding (1981). These dates suggest that juniper woodland remained in the Owl Canyon area at about 790 m at least as late as 12,300 years B.P. Desert scrub vegetation is not recorded at this locality until about 10,260 B.P. (Spaulding, 1981). This seems to follow the pattern observed at Little Skull Mountain, with the exception that a return of Utah juniper between 9,500 and 8,500 B.P. is not seen. About 60 km northwest of Little Skull Mountain, however, an association of Utah juniper and limber pine from a fossil woodrat midden at the head of Thirsty Canyon, dating to as late as 9,330 $\pm$ 140 (Beta-32409), may reflect the potential drop in lower tree-line observed at Little Skull Mountain at 8,500 B.P. Today, the midden is located at the lowest occurrence of Utah juniper on southwest-facing volcanic slopes.

Fossil woodrat middens from limestone in the Hancock Summit area of the Pahranaagat Range east of the NTS reveal a similar sequence. Here, a set of north-northwest-facing middens ranging in elevation from about 1,550 m to 1,600 m and spanning the past 22,700 years indicates that Utah juniper occurred intermittently from 22,700 B.P. until about 9,500 years ago. Middens dating to 7,000 and 5,800 years ago evidence renewed depression of lower tree-line. The remaining middens from this locality, all dating from approximately the last 1,000 years, do not contain

Utah juniper. Utah juniper today occurs about 50 to 100 m higher in elevation in the Pahrnatagat Range.

A series of fossil woodrat middens associated with outcrops of welded air-fall tuff are located southeast of Badger Mountain in the Pahrnatagat Range. A fossil woodrat midden dated at 20,280 $\pm$ 190 B.P. (Beta-32407) and lying at 1,675 m--the present lower elevation of juniper in the area--on a gradual southeast-facing slope contains not only Utah juniper, but also limber pine (*Pinus flexilis*) and white fir (*Abies concolor*). The depression of limber pine and white fir of up to 900 m below their present distribution is indicated by both this locality and another at 1,990 m dated at 21,700 $\pm$ 500 B.P. from the Sheep Range just to the south (Spaulding, 1981). The onset of glacial maximum conditions is marked by a transition from a xerophytic juniper woodland to subalpine-conifer woodland dominated by bristlecone pine (*Pinus longaeva*) and limber pine (*Pinus flexilis*).

Fossil Pollen Data

Pollen records from the Oasis Valley (Figure 3) northeast of Beatty, Nevada and Lower Pahrnatagat Lake (Figure 4) south of Alamo, Nevada (Figure 2) form the basis for preliminary vegetation reconstructions east and west of the NTS (Figures 3 and 4 in map pocket). In these localities, regional terrestrial pollen and local littoral and aquatic plant pollen record both regional vegetation change and local water table fluctuations.

Perhaps the most dramatic change noted is the fluctuation of juniper pollen in the well-preserved record from Lower Pahrnatagat Lake. Juniper pollen values vary between 5 and 22 percent. These values reflect major changes in distribution, density and productivity of juniper on the landscape and, in fact, suggest that juniper may have grown near Lower Pahrnatagat Lake prior to 3,000 B.P. This suggests a drop in lower tree-line of several hundred meters. Woodrat midden data from the Sheep Range suggest that lower tree-line may have been depressed as much as 200 m about 3,300 years B.P. (Spaulding, 1985). The pollen record from Lower Pahrnatagat Lake suggests that the transition to higher juniper pollen values may have taken less than a few decades to complete. The local increase in effective precipitation necessary to effect this change must have been on the order of several centimeters per year. Two additional periods of increased juniper values indicate at least two episodes of increased precipitation during the last 3,000 years. Although each of these spanned only a few score years, the impact on regional vegetation suggests that the magnitude of increase was significant. Because these increases in effective precipitation are registered in both the Lower Pahrnatagat Lake and Oasis Valley records, it is clear that the events were regional.

Additional evidence for increased regional precipitation is recorded in the sequence of peat layers from Ash Meadows (Mehring and Warren, 1976). Though

complicated by dune movement and the possibility of neotectonic activity, formation of peats seems to reflect increased discharge of the major springs in Ash Meadows. These strata may indicate at least three increases in discharge during the last 3,600 years.

SIGNIFICANCE FOR YUCCA MOUNTAIN

If these periods of increased effective precipitation can be correlated, two important points can be made. First, it will be clear that these events were regional in scope, and affected the groundwater recharge of most of southern Nevada. Therefore, groundwater recharge would have been significant. Second, although these events were short in duration, increased effective precipitation was of sufficient duration and magnitude to result in major changes in regional vegetation. These included depression of lower tree-line and increased density of vegetation.

Changes of this magnitude may cause significant variation in water table elevations that would affect the storage of high-level nuclear wastes. The remainder of this project will be devoted to estimation of the potential magnitude of precipitation increases and their areal extent for input into geohydrological models of southern Nevada.

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NUMERICAL SIMULATION OF GAS FLOW THROUGH UNSATURATED FRACTURED ROCK AT YUCCA MOUNTAIN, NEVADA

Clay A. Cooper

INTRODUCTION

Gas flow (both air and water vapor) through the unsaturated zone at Yucca Mountain has been realized since the early 1980s. It has been noted in various DRI reports in 1987 and 1988 that several boreholes along the east flank of the mountain have "inhaled" and "exhaled" air with the atmosphere. This flow is significant because gas flow is a potential mechanism for moving gaseous radionuclides such as ^{129}I , ^{85}Kr , ^{14}C from the repository. These radionuclides could then be transported upward to the accessible environment.

Gas flow through the unsaturated zone was studied in relation to an open borehole subjected to barometric pressure variations. Numerical simulations were used to: 1) determine the extent of the pressure field; 2) identify the physical phenomena associated with the corresponding multiphase flow field; and 3) determine the amount of water vapor leaving the system.

ACTIVITIES

A model was formulated around the multiphase, multicomponent, nonisothermal flow code TOUGH (Pruess, 1987). One-dimensional radial flow was simulated through the Tiva Canyon hydrogeologic unit with fracture and matrix flow incorporated into a deterministic equivalent porous medium (EPM) model. A diurnal sinusoidal pressure wave was prescribed at the borehole as the inner boundary condition, and a constant pressure was prescribed at the outer boundary. Three general types of simulations were run to understand the magnitude of various pressure waves and to understand the effects created by them. The first was to apply a step-function pressure at the borehole which was higher than the initial formation pressure. The second type of simulation was to apply a pressure lower at the borehole than the initial formation pressure. The third simulation was to apply a diurnal barometric pressure fluctuation at the well.

Conceptual Model

Movement of gas in a deep unsaturated zone around an open borehole is the result of a differential pressure gradient created at the interface of the hole and the adjacent formation. The driving mechanism in this model only considers daily barometric pressure fluctuations.

The conceptual flow model is developed primarily from Weeks's (1979) model which explains water table fluctuations in deep unsaturated zones. Gas flow will

occur only if a well penetrating a deep unsaturated zone is uncased, or has a slotted screen, through some part of the zone. Initially, air pressure in the well is the same as that in the formation. An atmospheric pressure disturbance is transmitted instantaneously to the air in the well, however, the pressure wave is attenuated as it passes down through the unsaturated zone. This is caused by compression of the gas and friction with the porous medium as the pressure wave passes through the zone. The result of these two paths taken by the wave is a pressure imbalance created at the borehole/formation interface. If the atmospheric pressure disturbance is less than the original formation pressure, the pressure gradient will be directed from the formation into the well, causing vadose zone gas to be blown out of the well. If the pressure disturbance is greater than the original formation pressure, the situation is opposite and air will be drawn into the formation. Either situation alters the pressure and velocity field around the well. The degree of differential pressure at the borehole determines the pressure field in the surrounding well. The relative humidity difference between air in the borehole and air in the formation creates changes in the water balance in the formation.

Numerical Model

The simulator TOUGH (Pruess, 1987) was used in the modeling. This code differs from other partial saturation codes, primarily because gas is treated as a mobile phase. TOUGH solves a nonlinear mass balance equation for each active phase (liquid, gas) and an energy balance equation for the system. The governing mass and energy balance equations are

$$\frac{d}{dt} \int_{V_n} M^{(\kappa)} dV = \int_{\Gamma} \mathbf{F}^{(\kappa)} \cdot \mathbf{n} d\Gamma + \int_{V_n} q^{(\kappa)} dV \quad (1)$$

where M denotes accumulation of mass or heat, $\mathbf{F}$ is flux, q is a sink/source, and κ is a component ($\kappa = 1$: water; $\kappa = 2$: air; $\kappa = 3$: heat).

Mass accumulation is

$$M^{(\kappa)} = n \sum_{\beta=l,g} S_{\beta} \rho_{\beta} X_{\beta}^{(\kappa)} \quad (2)$$

where n is porosity, S_{β} is phase saturation, ρ_{β} is phase density, $X_{\beta}^{(\kappa)}$ is mass fraction of component κ within phase β , and β denotes a phase.

Heat accumulation is

$$M^{(3)} = (1-n)\rho_r C_r T + n \sum_{\beta=l,g} S_\beta \rho_\beta u_\beta \quad (3)$$

where ρ_r is mass density of the solid, C_r is specific heat of the solid, T is temperature, and u is internal energy of phase β . The first term on the right-hand side represents heat accumulation in the solid, while the second term represents heat accumulation in the fluids.

Mass flux terms are summed over the two mobile phases:

$$\mathbf{F}^{(\kappa)} = \sum_{\beta=l,g} \mathbf{F}_\beta^{(\kappa)} \quad (4)$$

where the flux of each phase is

$$F_\beta^{(\kappa)} = -k \frac{k_{r\beta}}{\mu_\beta} \rho_\beta X_\beta^{(\kappa)} (\nabla P_\beta - \rho_\beta \mathbf{g}) - \delta_{\beta g} D_{va} \rho_\beta \nabla X_\beta^{(\kappa)} \quad (5)$$

Here k is intrinsic permeability, $k_{r\beta}$ is relative permeability of phase β , μ_β is dynamic viscosity of phase β , ∇P_β is the pressure gradient across phase β , $\mathbf{g}$ is acceleration due to gravity, and D_{va} is the binary diffusion coefficient for water vapor in air. The kronecker delta, $\delta_{\beta g}$, indicates that binary diffusion is only modeled in the gas phase.

Heat flux is (conduction and convection)

$$\mathbf{F}^{(3)} = -\Lambda \nabla T + \sum_{\substack{\beta=l,g \\ \kappa=1,2}} h_\beta^{(\kappa)} \mathbf{F}_\beta^{(\kappa)} \quad (6)$$

where Λ is thermal conductivity of the rock-fluid mixture, and $h_\beta^{(\kappa)}$ is the specific enthalpy of component κ in phase β .

Constitutive Relationships

Liquid water retention as a function of pressure head is (van Genuchten, 1980)

$$\theta_l = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (a\psi)^\beta]^\lambda} \quad (7)$$

where θ_i is volumetric moisture content, θ_r is residual moisture content, θ_s is moisture content at saturation, ψ is pressure head, and α , β , and λ are curve fit parameters ($\lambda = 1 - 1/\beta$; $0 < \lambda < 1$).

Liquid relative permeability is determined using the water retention function above and the hydraulic conductivity expression of Mualem (1976)

$$k(\theta)_{lr} = \Theta^{1/2} [1 - (1 - \theta^{1/\lambda})^\lambda]^2 \quad (8)$$

where $k(\theta)_{lr}$ is relative permeability as a function of moisture content, and Θ is the dimensionless moisture content, $\frac{\theta_i - \theta_r}{\theta_s - \theta_r}$.

Equivalent Porous Medium

Because the Tiva Canyon unit is fractured, a deterministic equivalent porous medium (EPM) model was developed. This allows fracture and matrix flow to be modeled as a continuum, as opposed to modeling each flow discretely. Unless fractures in a large system have been characterized with respect to size, length, aperture, asperities, and degree of interconnectedness, it is impossible to model fracture flow discretely. This is the case for the Tiva Canyon unit. The EPM model centers around an averaging procedure that incorporates hydraulic properties of both matrix and fractures.

Major assumptions required in developing the EPM follow: 1) Darcy's law is valid for both phases (gas and liquid) in the fractures and matrix; 2) thermodynamic equilibrium exists between the fractures and matrix; and 3) the sum of the relative permeabilities to gas and water, at any given moisture content, is one ($k_{rg} + k_{rl} = 1$). The EPM effective permeability ($\bar{k}_r$) is

$$\bar{k}_r = \frac{k_m k_m + k_f k_f}{k_m + k_f} \quad (9)$$

which describes the EPM relative permeability for a phase (gas, liquid) as a function of corresponding matrix and fracture relative permeabilities and intrinsic permeability of matrix and fractures.

The relative permeability subroutine in TOUGH was modified to include equation (9) as an option. Relative permeabilities in matrix and fractures are first computed separately using equations (7) and (8). EPM relative permeability is then computed using equation (9).

RESULTS AND IMPLICATIONS

The TOUGH code was used to simulate one-dimensional, multiphase, multi-component, radial flow through the Tiva Canyon hydrogeologic unit. Determined from the EPM model, $\bar{k}$ is $1.18 \times 10^{-12} \text{ m}^2$, equivalent to a medium sand. The grid is formulated with 129 elements. Element spacing nearest the borehole is 1 mm; the mesh extended out to 10,000 m. The fine mesh around the well is needed to determine the effects of capillarity, liquid saturation, and temperature around the borehole.

During the phase of the boundary pressure wave that is greater than the formation pressure, dry air from the borehole blows into the humid formation. In response to the drop in humidity, liquid water evaporates and S_l drops several percent. Since heat is given off during evaporation, the temperature around the borehole drops, though an insignificant amount (0.03°C). The air pressure gradient forces gas into the formation, while the lowered S_l around the borehole causes ψ to drop (become more negative) so that liquid water flows toward the borehole. This effect is called multiphase countercurrent flow. However, the entire phenomenon occurs only within 5 cm of the borehole. Beyond 5 cm, liquid water flows away from the borehole, in the same direction as the gas phase.

When the borehole pressure is less than the formation pressure, causing gas to blow from the formation, water vapor is lost to the borehole. The physical properties of the formation remain the same because water vapor from farther areas of the system replaces vapor lost to the borehole. This is partly due to the nature of the outer boundary; it is prescribed pressure boundary that acts as a source for water vapor. This vapor is the same humidity as that escaping to the borehole, hence S_l , ψ , and T remain constant in the formation.

The above simulations helped to understand flow modeled around an uncased borehole with a diurnal pressure wave prescribed at the borehole. Results show that during a typical June day, the pressure wave propagates about 140 m into the surrounding formation. A steady-state wave is established after about 3.2 days. Because of the rather high $\bar{k}$, the wave is transmitted fairly instantaneously over much of the domain. After one hour, the pressure wave has traveled 40 m, about one-third the distance it travels at steady-state. This is significant because in the near-field (<40 m), the pressure distribution is strongly a function of the present borehole boundary condition. The phase lag is only two hours at 40 m. Between 40 and 80 m, a wave exists in the formation, though its amplitude is only about 10 Pascal. Past 80 m, the pressure response is so small that a wave, if present, is not discernible.

Liquid saturation varies between 0.68 and 0.71 during this simulation. Because the formation around the borehole is always drier than the initial S_l , liquid water

always flows toward the borehole, irrespective of which phase of the pressure wave is presently prescribed at the borehole. As with the outward-directed pressure simulations, this condition only occurs within about 5 cm of the borehole.

The amount of water leaving the system as vapor is $9 \times 10^{-4} \text{ m}^3/\text{day}$ (900 cc d^{-1}). This is significant to repository performance because without net recharge, the unsaturated zone should be drying. For the small affected area (the vicinity of a borehole), a loss of 900 cc d^{-1} could be a major component of the water budget. Yet it is not clear if or how much recharge is occurring. It could be that fluid movement in the unsaturated zone is transient. Field experiments coupled with further multidimensional modeling would help to better understand the physics of unsaturated zone liquid and gas movement.

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QUANTITATIVE ANALYSIS OF GROUNDWATER FLOW SYSTEMS USING ENVIRONMENTAL ISOTOPE-CALIBRATED FLOW MODELS

Robert Byer

INTRODUCTION

Yucca Mountain was chosen as a potential repository for the storage of high level nuclear wastes now being temporarily stored at various nuclear power generating stations across the United States. The proposed repository is located within the Basin and Range physiographic province, approximately 105 kilometers northwest of Las Vegas, Nevada. A major concern regarding this site is the potential for radionuclides to leach from the storage facility and contaminate the groundwater. Knowledge of the regional groundwater flow system in and around Yucca Mountain would greatly enhance our understanding of the fate of contaminants should the integrity of the site be compromised.

The approximate boundaries of the regional groundwater flow system lie within 36 and 38 degrees north latitude and 115 and 117 degrees west longitude. These boundaries may be refined as this research progresses and more information becomes available. The study area generally contains three lithologies which control groundwater movement: 1) alluvium (valley fill); 2) volcanic rocks; and 3) carbonate rocks (Feeney et al., 1987). Deep regional groundwater flow occurs in carbonate rocks of Paleozoic age. Groundwater flow within the study area may be classified as follows (Winograd and Thordarson, 1975): 1) movement of perched water; 2) intra-basin movement of water; and 3) interbasin movement of water. Deep regional groundwater flow associated with the Paleozoic carbonate rocks occurs as interbasin movement and is generally south to southwest (Winograd and Thordarson, 1975; Waddell, 1982).

The groundwater flow system of Yucca Mountain and vicinity has been studied extensively by several researchers. Waddell (1982) developed a two-dimensional finite element model of the study area, which included parts of three groundwater basins. The model provided reasonable agreement between observed and model-derived hydraulic heads. In areas of recharge or discharge, where vertical flow components exist, the model did not accurately predict head values. The author, however, recognized this flow.

A second finite element model was developed by Czarnecki and Waddell (1984). The modeled area was smaller in scope than Waddell's (1982) finite element representation, including part of the Alkali Flat - Furnace Creek Ranch groundwater basin. Again, the model produced acceptable results except in those areas with vertical flow components.

A two-dimensional finite difference model of the NTS and vicinity was applied by Rice (1984). Adjusted transmissivities were used to provide agreement between model generated hydraulic head distributions and head distributions from kriged and head-contoured maps. Rice (1984) found that her model generated estimates of recharge and discharge that were in good agreement with published data. She concluded that although recharge is important, a significant amount of water enters the study area as underflow from the carbonate aquifer.

A different approach was chosen by Feeney et al. (1987) to model the flow system of the western NTS, in which a modified mixing cell model was used. A discrete-state compartment (DSC) model was calibrated with the stable isotope deuterium to delineate groundwater flow. It is not a hydraulic model, so hydraulic parameters were not needed to calibrate the model. In addition to recharge and discharge estimates and groundwater flow paths, estimates of aquifer storage properties and groundwater residence times were determined.

Applying the DSC model to the western NTS, Spencer (1988) used carbon-14 decay ages to calibrate the model. The decay ages were corrected for soil carbon-13 using the method of Ingerson and Pearson (1964). Although the basic model of Feeney et al. (1987) was proved valid, Spencer (1988) had to adjust porosities and recharge values to obtain calibration.

ACTIVITIES

A DSC model will be applied to the flow system in and around Yucca Mountain to obtain estimates of recharge rates, residence times, aquifer storage volumes, and general flow paths. The model described herein uses theory developed by Simpson and Duckstein (1976) and a version of the computer code developed by Campana (1975). DSC models have been applied to several flow systems of the southwestern United States (Campana and Mahin, 1985; Kirk and Campana, 1988; Feeney et al., 1987; Roth, 1988).

DSC models are sophisticated mixing cell models capable of relating carbon-14 decay ages to residence times and aquifer recharge rates. Transport of water and dissolved matter is governed by a set of recursive equations derived from conservation of mass principles.

The hydraulic system is represented by an interconnected array of mixing cells. These cells may be arranged in a one-, two-, or three-dimensional configuration. Cell structure is determined from tracer distribution data, prior hydrogeologic knowledge, or other information that may be available to the modeler.

In this study, corrected carbon-14 decay ages, expressed as percent modern carbon (pmc), of spring and groundwaters are being used as the tracer to calibrate

the model. Model calibration will be achieved when sufficient agreement is reached between observed carbon-14 decay ages and model-generated carbon-14 decay ages.

Numerical models such as the DSC model do not produce unique solutions. They are dependent upon the modeler's knowledge of the hydrogeologic system and intuition. Some prior knowledge of the hydrogeologic system is required to specify recharge and discharge parameters and flow directions. Recharge and discharge estimates will be based upon published Reconnaissance Series Reports. Initial flow directions will be similarly based upon published information such as Rice (1984) and Waddell et al. (1984). Calibration will involve adjustment of these initial estimates to achieve the best agreement between observed carbon-14 decay ages and calculated carbon-14 decay ages.

The flow system will be represented by a two- or three-dimensional cell configuration. Corrected carbon-14 decay ages (Spencer, 1988 or other applicable method) will be used to calibrate the model. Model calibration will yield estimates of groundwater residence times, aquifer mixing properties, general groundwater flow paths, and aquifer storage properties.

A data gathering phase was initiated in August-September 1988. The environmental isotope which was to be used to achieve calibration of the DSC flow model was oxygen-18. The oxygen-18 data base was completed in December 1988. In January 1989, it was decided to change the calibration isotope to carbon-14. The carbon-14 data base was completed by the end of June 1989.

Various methods of correcting carbon-14 data were researched. It was decided that data previously corrected by Boughton (1986), Lyles and Hess (1988), and Spencer (1988) would be used as corrected. Remaining data was corrected following the format of Spencer (1988). To date, all corrected data have been plotted on the site base map. Preliminary site boundaries have been sketched. At the present time, mixing cells are being constructed. Cell design should be completed by October 1989.

RESULTS

Presently, there are no numerical results to discuss regarding the modeling exercise. As with virtually all numerical models, results cannot be documented until the model is in the calibration process. Therefore, it is premature to speculate how well the DSC model will describe the regional flow system, however, it is expected that the model will provide additional information regarding regional recharge rates, residence times, and general flow paths.

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THE USE OF FRACTAL GEOMETRY FOR CHARACTERIZATION OF RADIONUCLIDE TRANSPORT IN FRACTURED TUFF

Stephen W. Wheatcraft and Scott W. Tyler

INTRODUCTION

The basic purpose of this project is to develop new theories for the flow of fluid and the transport of solutes in heterogeneous porous media and fractured media using concepts of fractal geometry. Fractal geometry is a class of geometry that has been developed in the last ten years that allows one to describe natural phenomena such as clouds, trees, landforms, and rivers in very realistic ways. We propose that if fractal geometry can be used to describe such natural phenomena so realistically, then it may be possible to use it to describe naturally heterogeneous porous media and fractures in potential host rocks. These fractal descriptions could then be used to develop new theories of transport in such materials.

In order to meet the requirements of 10 CFR 960, it must be shown that groundwater travel time from the repository to the accessible environment is greater than 1,000 years. The proposed repository at Yucca Mountain would be located in the unsaturated zone, in tuffaceous porous rock material that is highly fractured. Our theoretical understanding of unsaturated flow and transport is in its infancy; as a result, we do not have a clear understanding of how to characterize such a flow regime. The regulatory requirements and our limited theoretical understanding of unsaturated fracture flow place the most stringent demands on our theories of transport in porous and fractured media, in terms of their predictive capability. This has happened at a time when careful field studies have shown that traditional theories of transport in porous media are not capable of predicting solute migration at the field scale in even mildly heterogeneous porous media. Theories of flow in saturated fractured media have had very limited field validation. Unsaturated fracture flow theories have had virtually no field validation. Although we have a reasonably good understanding of the physics of porous and saturated fracture flow, there is much to learn about the physics of unsaturated fracture flow. These problems are compounded by the fact that real geologic materials have spatially variable hydraulic and transport properties.

Several researchers have developed stochastic transport theories in order to deal with the problem of field-scale spatial variability. These theories obtain parameters such as macrodispersivity to describe the dispersion that results from field scale heterogeneity in terms of the statistical properties of the hydraulic conductivity spatial distribution. Most stochastic theories have been developed for porous media that display mildly heterogeneous properties with a finite correlation scale and will therefore be inadequate to describe transport over long time (and large space) scales.

Because fractal geometry has been so successful at modeling landforms over a very large range of spatial scales, it seems quite reasonable to assume that a transport theory based on fractal models of the hydraulic conductivity distribution should be capable of predicting the migration of solutes over long time and large space scales.

If the theory is truly successful, then it will be capable of extrapolation, as well as prediction. Here, we find it useful to distinguish between prediction and extrapolation. We define an extrapolative theory to be one in which parameters are measured in a relatively small space, and the theory is capable of being successfully used to predict the transport of the dependent variable(s) into a much larger space. An example of this would be a valid physical, conceptual and mathematical model of a deep burial nuclear waste repository, which must be able to extrapolate the behavior of the radionuclide transport away from the repository (i.e., into a much larger volume). We define a predictive model to be one in which measurements of parameters in a given space are used to predict the dependent variable distribution within that same space. An example of a predictive model is the physical, conceptual and mathematical model of a hazardous waste site in which the objective is to provide a remedial action strategy to remove contaminants from an aquifer. Here the parameters are measured (sampled at some density) over the contaminated space, and the remedial action consists of a pumping scheme that removes contaminants from the aquifer. Hence, the capability of a predictive model is limited to the space in which parameters have been measured. From these definitions, one can see that an extrapolative model is always predictive, but the reverse is not necessarily true. Also, an extrapolative model is more powerful than one which is just predictive.

ACTIVITIES

Numerical Experiments on the Flow and Transport Properties of Fractal Porous Media

The first set of experiments was reported on in detail in the paper by Wheatcraft and Tyler (1988). Lagrangian models were developed for dispersion in fractal streamtubes and the results compared to classical one-dimensional advection-dispersion theory, existing fractal and stochastic theories, and to a summary of field-measured dispersivity data. It was found that the dispersion process in fractal media will grow faster than it would in homogeneous porous media, or in heterogeneous porous media described by stochastic theories. The fractal model is capable of explaining the rate of growth of the dispersion process that is observed in the field data better than any of the current stochastic theories. However, caution must be observed in making this comparison because the field data comparison is based on information collected at many different field sites. For the comparison to be completely valid, dispersivity values from one site taken over many scales of observation are needed;

this kind of data has not yet been collected, except for some sites that are very homogeneous.

The simple, one-dimensional random walk model developed in Wheatcraft and Tyler (1988) was only a first step in the sense that it represented the traces (in a two-dimensional plane) of fractal pathways taken by particles. The next step was to develop models of fractal porous media and run numerical flow and solute transport experiments in these fractal media. The basic assumption made was that the fractal porous medium was composed of elementary building blocks in which an REV could be defined. This assumption is similar to the way most current stochastic theories start in their development. It is also consistent with the fact that a fractal cut-off needs to be established; otherwise if the fractal algorithm is carried on to smaller and smaller scales, the paths taken by particles get unrealistically long. The first fractal algorithm used to create a fractal porous medium was the Sierpinski carpet. This algorithm is similar in principle to the fractal facies model that was discussed and shown in Figure 1 of Wheatcraft and Tyler (1988). Programs were written to generate this fractal. The "holes" were assumed to be areas of relatively low permeability, and the areas in between were made to be 100 times more permeable than the "holes". The programs generated an output data set that could be read as the coordinates for the hydraulic conductivity pattern by the numerical codes that solved the flow and transport problems. Codes developed at Battelle Pacific Northwest Laboratories were used and modified to suit project needs. The flow code is called MULTIGRID, and uses a very efficient numerical scheme to solve the steady-state flow problem. This code produces a velocity field for the given hydraulic conductivity distribution that is read by a standard particle tracking code. Statistics were collected on the particle arrival time distributions at the exit point and at several intermediate points. The results were compared to the simple Lagrangian model results discussed above. As long as the fractal hydraulic conductivity field is generated in a way that is analogous to our fractal particle traces, the results from the Sierpinski carpet aquifer compare favorably with the results from the fractal particle trace experiments. This work was presented at an American Geophysical Union (AGU) Special Symposium on Hierarchical Porous Media, Fall, 1988. The paper is entitled *Fluid Flow and Solute Transport in Fractal Porous Media*. It will become Chapter 11 in The Dynamics of Fluids in Hierarchical Porous Media, ed. by John H. Cushman, to be published by Academic Press in February, 1990.

The next step after the transport in deterministic Sierpinski carpet porous media was to examine transport in stochastic fractal media using fractional Gaussian noise as the model for hydraulic conductivity distribution. This study required Monte Carlo simulations, in which 200 realizations were created of the stochastic fractal hydraulic conductivity distribution, and ran transport experiments through each one to obtain ensemble statistics of the solute breakthrough curves. Three sets of 200 realizations

were run, each at a different length scale (32, 64 and 128 length units). The objective of the study was to see if the same type of fractal scaling behavior occurred as seen in the Sierpinski carpet and the simple one-dimensional simulations. The Monte Carlo simulations showed similar fractal scaling behavior, with dispersion growing (with increased scale) at a rate faster than could be predicted by non-fractal theories. The results of these experiments were reported at the NATO Advanced Study Institute on Transport in Porous Media, held in July 1989 at Washington State University, Pullman, Washington. The paper is entitled *Transport in Fractal Porous Media*, and will become a chapter in Proceedings of the NATO Advanced Study Institute on Transport in Porous Media, edited by Jacob Bear and Yavuz Corapcioglu.

Non-Linear Dynamics and Fractals

The basic concepts of fractals and how they relate to the problem of interest are discussed in the introductory section, and in the paper by Wheatercraft and Tyler, published in *Water Resources Research*. In this section, how non-linear dynamics are related to fractals and how this subject area is of primary importance in determining the suitability of the Yucca Mountain site for the waste repository is discussed. The science of non-linear dynamics (often referred to as chaos) consists of studying dynamic (time-varying) systems that display chaotic behavior. The major breakthrough in this area came in the late 1970's and early 1980's. It is now recognized that many physical systems that have been treated as stochastic (random) are actually deterministic (non-random) systems that display chaotic behavior. One of the important characteristics of chaotic behavior is *sensitive dependence on initial conditions*, which means that a small change in initial conditions will result in a very large change in the behavior of the system at some later time. In non-chaotic systems, a small change in the input (initial conditions) results in a suitably small change in the system behavior. From the point of view of developing a predictive model of a system, if it displays (or is capable of displaying) chaotic behavior, then an error (no matter how small!) in measuring the initial conditions will result in the actual system behaving **very** differently from the system model. In other words, our ability to predict the future behavior of chaotic systems is limited, **no matter how much is known about the initial conditions of the system**. Systems which display chaotic behavior are governed by sets of coupled, non-linear differential equations. It is the non-linear feedback between equations which causes the sensitive dependence on initial conditions, and causes the system to lose information about its initial state.

From this, it will be very important to know if it is possible for a saturated or unsaturated groundwater flow system to display chaotic behavior. The degree of chaos displayed by a system is measured by a parameter called the Lyapunov exponent, the time rate at which information about the state of the system is lost. Systems with positive Lyapunov exponents display chaotic behavior, while systems with nega-

tive Lyapunov systems are non-chaotic. It turns out that the Lyapunov exponent is closely related to the fractal dimension, and many chaotic systems are also fractal in nature. What types of groundwater systems might be capable of displaying chaotic behavior? The most likely systems are unsaturated flow systems, and in particular unsaturated fracture flow systems. Unsaturated flow systems are governed by non-linear coupled sets of differential equations and are, in principle, capable of chaotic behavior. In other words, if it can be shown that the flow system is capable of chaotic behavior, then no matter how much site characterization is done (or how well it is done), it will not be possible to predict the system behavior very far into the future.

The area of chaos and non-linear dynamics is seen as an extremely important avenue to pursue because of the important implications of the limits of predictability and the fact that many chaotic systems are fractal in nature. We are currently learning more about non-linear dynamics by studying chaotic systems and trying to determine the chaotic nature of certain systems. In particular, the hydrothermal system of the Old Faithful Geyser in Yellowstone National Park was chosen as a likely candidate to display chaotic behavior. Time-series data were obtained at the time between eruptions of Old Faithful and treated in the same way as one of the classic chaotic systems, the dripping faucet. It was found that this hydrothermal system displays chaotic behavior. The traditional view of this system is that if enough was known about the underground geometry of the hydrothermal system, predictions with certainty of future eruption sequence of the geyser could be made. Until now, the uncertainty of the time between eruptions has been attributed to a lack of complete knowledge about the underground geometry and mechanics of the system. However, the chaotic behavior found in this system indicates that it is impossible to predict the eruption sequence very far into the future, even if nearly perfect knowledge of the present conditions and geometry of the underground hydrothermal system is available. A paper has been completed to be submitted to *Science* on the findings entitled "Is Old Faithful a Strange Attractor?" A great deal was learned about chaotic systems from this exercise with Old Faithful and these results have encouraged us to delve more deeply into the questions of how to measure the potentially fractal and chaotic nature of a hydraulic conductivity distribution.

Based upon our current knowledge of chaotic systems, it seems that the most likely system for chaotic behavior is unsaturated fracture flow. A laboratory model has been developed to simulate unsaturated fracture flow using two glass plates spaced very closely together, whose internal surfaces have been sandblasted to give a roughed surface. Preliminary experiments have been conducted using injected dyed water that show flow behavior that is strongly suggestive of chaotic flow. The laboratory apparatus is being modified to give the capability to repeat the exact conditions of an experiment so that sensitivity to initial conditions can be tested. A paper was written entitled "Quantifying the Nature and Degree of Heterogeneity Using Con-

cepts of Non-Linear Dynamics and Fractals," and is in the proceedings of a conference titled: New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers, published by the National Water Well Association.

Fractal Moisture Release Curves for the Unsaturated Zone

The proposed repository at Yucca Mountain is in the unsaturated zone, thus it is important to consider the flow properties of the unsaturated zone in terms of how well they can be characterized. A model for the interaction between moisture content and soil suction based on fractal particle-size distributions was developed which shows that the empirical fitting parameter in the Arya and Paris (1981) soil water retention model is equivalent to the fractal dimension of the particle-size distribution. Because the model now has physical significance, it enables one to obtain soil water retention data, estimated strictly from particle-size distributions. These estimated retention curves are shown to match measured data quite well. The physically-based fractal model should prove useful for efficient estimation of water retention data where field or laboratory measurements are not available. A paper on this work, entitled "Application of Fractal Mathematics to Soil Water Retention Estimation," was published in the *Soil Science Society of America Journal*, v. 53, no. 4, July-August, 1989.

This work has been carried further by proposing a physical conceptual model for soil texture and morphology that is based on an analogy to Sierpinski carpets. The soil textural properties are related to the fractal dimension by viewing the soil pore-size distribution as a Sierpinski carpet, which contains self-similar holes (or pores) over a wide range of scales. Clay-type soils with very slow dewatering characteristics are shown to have low fractal dimensions, while a sandy soil with relatively rapid dewatering characteristics is shown to have a relatively high fractal dimension. The models are extended to cover some standard relative permeability functions. This work is discussed in a paper entitled "Fractal Processes in Soil Water Retention," which has recently been accepted for publication by *Water Resources Research*.

Theoretical Development of Basic Transport Equations for Fractal Porous Media

During the summer of 1988, work started with Dr. John Cushman of Purdue University on developing transport equations for fractal porous media. This is a very difficult problem, but the understanding gained on the behavior of particles moving in fractal porous media from our numerical experiments is helping to lead us in the right direction. To date, the most important results are in determining which kind of approaches will not work, and which approaches may be promising. Volume averaging approaches rely on the porous medium possessing a characteristic scale, which fractal media do not. There is no way to average over an REV, because an REV can not be defined for fractal media. Stochastic theories which rely on perturbation the-

ory also require a characteristic length scale over which the properties of the porous media are statistically correlated. Fractal porous media display infinite correlation (or correlation over all scales for which the media display fractal properties). A statistical mechanical approach to developing mass balance equations for fractal porous media has been taken. This approach has the advantage of describing the position and momentum of individual particles (molecules) and taking an ensemble average over the number of particles in the system to determine behavior at larger scales. Volume averages have no meaning in fractal porous media, but the number of particles in a system are not affected by the fractal nature of the porous medium. This work uses the fractal scaling relationships for velocity and position that were developed in Wheatcraft and Tyler (1988) and Cushman's stochastic distributions formulation in conjunction with the statistical mechanical approach. Some preliminary equations of mass balance for a fractal porous medium have been developed. These equations have similar characteristics to the fractal scaling relationships, including the build-up of a "virtual mass" in the system. There is an apparent change in storage in the fractal porous medium that is due to the fact that the particles take a fractal path, but we always measure their transport distance using normal "Euclidean" type tools, i.e., cartesian coordinate systems. These equations were developed during the latter half of 1988, but are awaiting the results of numerical experiments, which would either verify, or refute such counter-intuitive transport behavior. The numerical experiments actually show such behavior, therefore, more work on this theory is planned for the near future.

RESULTS AND IMPLICATIONS

The original work on fractal random walks resulted in the paper by Wheatcraft and Tyler (1988). This paper provides the first explanation for the type and amount of dispersion seen in the field in heterogeneous porous media. It shows that dispersion grows with scale in a fractal porous medium at a faster rate than predicted by traditional dispersion theory, and faster than predicted by more modern stochastic theories. Some field evidence suggests that this behavior is consistent with field data, although caution must be used in such interpretation because comparisons with many different field sites were made, where a proper comparison would be with only one site. The promising results of this work prompted numerical experiments using the usual governing equations for groundwater flow and transport on fractal hydraulic conductivity distributions to be conducted. The results of these experiments are consistent with the random walk experiments and equations.

The most important conclusion from this portion of the project is that field-scale dispersion grows more rapidly in porous media displaying fractal characteristics than it does in homogeneous porous media, or porous media with limited correlation scales (the stochastic approach). That dispersion grows more rapidly in fractal

porous media than would be predicted by traditional theory, or even relatively new stochastic theories, has potential impact on travel time estimates of radionuclides from the proposed repository.

The project work on the fractal properties of soils and moisture retention curves has shown that a fractal model of soil texture is powerful and robust for predicting the moisture retention properties of many different soil types. One of the primary arguments in favor of Yucca Mountain as a repository is that there is a thick, unsaturated zone in which to emplace the nuclear waste. An understanding of the moisture retention properties of the host material is essential to obtaining travel time estimates. Traditional methods of measuring the unsaturated properties of soil and rock material may produce very inaccurate results if the fractal nature of the soil and rock material is not accounted for.

Investigation into the chaotic nature of unsaturated fracture flow has potentially very serious implications on Yucca Mountain as a suitable site for the repository. Our goal is to find the range of conditions under which chaotic behavior in unsaturated fracture flow systems can be expected. If it can be shown that the Yucca Mountain system is capable of, or displays chaotic behavior, then it can be rigorously proven that it is impossible to predict the system behavior very far into the future, no matter how well current conditions are understood.

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SECTION III
Professional Papers/Publications – Abstracts

ABSTRACT

THE STEADY-STATE ASSUMPTION IN REGIONS OF LARGE HYDRAULIC GRADIENT: THE POTENTIAL FOR CONCEPTUAL MODEL ERROR

By
T.H. Brikowski

Presented at
AGU, Baltimore, May 1989

Regional flow models of the saturated zone often assume steady-state behavior in spite of evidence that recharge into the system may have varied considerably in the past. The assumption of steady-state can introduce errors when modeling systems with long equilibration times, a common phenomenon where zones of large hydraulic gradient are present. Regional hydrologic systems in the southern Great Basin are examples of such systems. To evaluate the errors generated by the steady-state assumption in models of this area, the results of transient and steady-state models of a southern Great Basin flow system were compared. Differences were considered to be errors in the underlying conceptual model.

The models were run using a generalized version of Czarnecki's (1984) model geometry for the vicinity of the proposed Yucca Mountain Nuclear Waste Repository in southern Nevada. A zone of large hydraulic gradient is present immediately up-gradient from the repository, and the entire hydrologic system is believed to be responding to a Late Wisconsin-age recharge pulse (Claassen, 1985). Existing models of the saturated zone for this area assume steady-state behavior (Waddell, 1982; Czarnecki and Waddell, 1984; Czarnecki, 1984). Transient models of the system's recovery from Late Wisconsin conditions indicate that steady-state models can underestimate permeability in the large-gradient zone by up to 100 percent (factor of 2). In addition, the extent of the zone of low permeability responsible for the large gradient can be overestimated by up to 25 percent in the direction perpendicular to groundwater flow. Differences between the models are greatest in the area up-gradient from the large-gradient zone.

These errors become important when the numerical models are used to make quantitative predictions of future hydrologic behavior, or to quantify the nature of large-gradient zones. A steady-state model that attempts to make quantitative predictions in a large-gradient setting should consider potential conceptual model errors, and quantify these errors if the predictions are to be useful.

ABSTRACT

CROSS-SECTIONAL FINITE ELEMENT MODEL OF GROUNDWATER FLOW AT YUCCA MOUNTAIN

By

T.H. Brikowski and S.J. Haws

To be presented at

AGU, San Francisco, Fall 1989

A cross-sectional flow model was constructed to aid the understanding of stratigraphic/structural controls on vertical groundwater movement in the saturated zone at Yucca Mountain, southern Nevada. The cross section was constructed along a streamline estimated from areal flow model results of Czarnecki and Waddell (1984) and extends 84.4 kilometers mainly north-south through Yucca Mountain and the proposed repository site.

The section consists of four hydrogeologic units: an underlying carbonate aquifer, overlain at Yucca Mountain by an aquitard and a volcanic aquifer (subdivided laterally into three zones of differing hydraulic conductivity), and an overlying alluvial aquifer down-gradient from Yucca Mountain in the Amargosa Desert.

This cross-sectional view of Yucca Mountain indicates three major influences on head distributions: 1) the hydraulic conductivity or average transmissivity of the lower carbonate aquifer; 2) the distribution of the aquitard; and 3) the presence of an apparent decreased permeability zone in the volcanic aquifer immediately up-gradient from the proposed repository.

Upward leakage from the carbonate into the volcanics appears necessary to maintain heads at the levels observed at Yucca Mountain. The aquitard controls the distribution and rate of upward leakage. Enhanced leakage down-gradient from the proposed repository seems to give the best fit between modeled and observed heads. The low permeability zone up-gradient from the repository site is required in cross section to reproduce the corresponding high head gradients. This zone may represent an extension of the low permeability zone postulated by Czarnecki and Waddell (1984, zone 11), or it may be an artifact caused by three dimensional flow effects at the west end of the impermeable zone 11.

ABSTRACT

NUMERICAL SIMULATION OF GAS FLOW THROUGH UNSATURATED FRACTURED ROCK AT YUCCA MOUNTAIN, NEVADA

By

Clay A. Cooper, Scott W. Tyler and Stephen W. Wheatcraft

To be presented at

AGU, San Francisco, December 1989

Gas flow (both air and water vapor) through an unsaturated zone was studied in relation to an open borehole, subjected to barometric pressure variations. Numerical simulations were used to: 1) determine the extent of the pressure field; 2) identify the physical phenomena associated with the corresponding multiphase flow field; and 3) determine the amount of water vapor leaving the system.

The model was formulated around a multiphase, multicomponent, nonisothermal flow code. One-dimensional radial flow was simulated through the Tiva Canyon hydrogeologic unit with fracture and matrix flow included into a deterministic equivalent porous medium (EPM) model. A time varying sinusoidal pressure wave was prescribed at the borehole as the inner boundary condition, and a constant pressure was prescribed at the outer boundary. The borehole pressure wave fluctuated symmetrically about the formation pressure. Results indicate that for a series of days with 400 Pa maximum pressure amplitudes, a steady-state wave is established at about 2.5 days. The pressure wave propagates about 200 m into the surrounding formation with a maximum phase lag of 4 hours.

When the borehole pressure is greater than the initial formation pressure, dry air is injected into the humid formation. In response to the formation's lowered relative humidity, liquid water evaporates, temperature decreases, and the capillary pressure becomes more negative. Multiphase countercurrent flow develops in the vicinity of the hole. Liquid water flow is towards the borehole in response to the capillary pressure gradient, and gas flow is away from the borehole in response to the advective air pressure gradient. When the borehole pressure is less than the formation pressure, gas travels from the formation into the borehole, with no change in formation properties. The cumulative effect of both wave components creates an overall drying phenomenon around the borehole, though liquid saturation varies only a few percent. The corresponding countercurrent flow field is established within only a few centimeters of the borehole. Gas diffusion is negligible. The amount of water vapor leaving the system at steady-state is $9 \times 10^{-4} \text{ m}^3 \text{ d}^{-1}$.

ABSTRACT

QUANTIFYING THE NATURE AND DEGREE OF HETEROGENEITY USING CONCEPTS OF NON-LINEAR DYNAMICS AND FRACTALS

By

Stephen W. Wheatcraft and Scott W. Tyler

Presented at

New Field Techniques for Quantifying the Physical
and Chemical Properties of Heterogeneous Aquifers
Summit Hotel, Dallas, Texas, 1989

Field techniques for measuring the nature and degree of heterogeneity rely on determination of the semi-variogram or covariance of the hydraulic conductivity distribution. The covariance can produce good results in cases where there is a characteristic scale of heterogeneity, thus producing a finite correlation scale. If the heterogeneity of the porous medium displays fractal scaling properties, standard geostatistical methods fail because the range on a semi-variogram will appear to be scale-dependent. For fractal heterogeneity, it will be important to determine the fractal dimension of transport process (i.e., fractal dimension of the traces that particles make through the fractal porous medium). However, for the theory to be truly useful from a predictive standpoint, we should be able to measure the fractal dimension of the particle traces. We show the results of several numerical experiments using different fractal models for the hydraulic conductivity distribution, and discuss the relationship between the fractal dimension of the hydraulic conductivity distribution and the fractal dimension of the particle traces. These results lead us to propose some possible techniques for measuring fractal dimensions in the field. One of these techniques relies on an analogy to fractional Gaussian noise. Another parameter which may be important to determine is the Lyapunov exponent. Some fractal distributions display non-linear dynamic characteristics. The Lyapunov exponent measures the rate of information loss in state-space for a non-linear dynamic system. Another way of looking at this is that the Lyapunov exponent measures the rate at which points (particles) in state-space move away from each other. Positive Lyapunov exponents imply chaotic dynamics, i.e., points that are nearby in state-space diverge from one another at an exponential rate. Chaotic systems lead to sensitive dependence on initial conditions and place absolute limits on how far into the future a prediction can be made (no matter how much detail one may have with respect to porous medium heterogeneity). Many chaotic systems possess fractal characteristics that are related to the non-linear dynamic nature of the system. We show the relationships between the fractal dimension and the Lyapunov exponent. The use of these parameters to measure heterogeneity may provide us with new and important information regard-

ing the behavior of solute transport in natural geologic materials that serve as aquifers. Field techniques to measure these parameters need to be tried and compared to more traditional geostatistical techniques.

ABSTRACT

UTILIZING THE HISTORICAL CLIMATIC RECORD TO CONSTRUCT AN ANALOGUE OF PAST (WETTER) CLIMATIC REGIMES IN THE SOUTHERN GREAT BASIN

By
Peter M. Leffler

Presented at
American Nuclear Society
Las Vegas, Nevada, September 1989

Data from the historical climatic record in the southern Great Basin were grouped on the basis of wet, average, and dry years to compare characteristics under various climatic conditions. Precipitation during wet years increased 57 percent for winter and 36 percent for summer compared to average years. Annual average temperatures were approximately the same (less than 0.5°F difference) for wet and average years. Daily precipitation data for wet and average years were modeled with Markov chains for daily sequences and the Weibull distribution for daily storm depths. Statistical modeling of daily data provides a basis for computer generation of climate data for input to a water balance model to determine effects of climatic variability upon recharge.

ABSTRACT

IS OLD FAITHFUL A STRANGE ATTRACTOR?

By

Michael J. Nicholl, Stephen W. Wheatcraft and Scott W. Tyler

Submitted to

Nature, June 1989

Geysers are systems that exhibit hydrothermal eruptive behavior at relatively regular intervals. Because these systems behave according to strongly non-linear governing differential equations, it is reasonable to expect that they are capable of displaying chaotic behavior. State-space reconstruction of eruption time data shows that Old Faithful Geyser erupts at chaotic intervals. Establishing that chaos occurs in the system indicates that one can predict eruption intervals in the short term, but it is impossible to determine Old Faithful's long-term eruptive behavior.

ABSTRACT

FRACTAL PROCESSES IN SOIL WATER RETENTION

By

Scott W. Tyler and Stephen W. Wheatcraft

Submitted to

Water Resources Research

May 1989

In this paper, we evaluate the retention properties of both synthetic and real soils to show the application of fractal concepts to pore sizes and distributions. Results are presented for a regular and random Sierpinski carpet. The empirical soil water relation developed by Brooks and Corey (1964) and Campbell (1974) is then shown to represent an approximate fractal scaling of pore sizes and pore numbers in real soils. Such representation suggests the nature of soil pore structure may be deduced from basic recursive algorithms. In addition, the empiricism of the power-law water retention model commonly used in modeling transport in soils is significantly reduced. Suggestions are also presented for the application of fractal scaling concepts to the hydraulic conductivity function.

ABSTRACT

FLUID FLOW AND SOLUTE TRANSPORT IN FRACTAL HETEROGENEOUS POROUS MEDIA

By

Stephen W. Wheatcraft, Gregory A. Sharp and Scott W. Tyler

Chapter 11 to be published in
The Dynamics of Fluids in Hierarchical Porous Media
February 1990

Prediction of transport in heterogeneous porous media is one of the most important problems currently being addressed by groundwater hydrologists, chemical engineers and mechanical engineers, just to name a few. The specific goals differ somewhat, depending on the discipline, but the basic questions and problems are universal. Traditional porous media continuum theory averages microscopic balance equations to a Representative Elementary Volume (REV). This theory is based on the assumption that there is a natural scale of the porous medium, below which the microscopic equations apply, and above which, the geometry of the solids and voids can be averaged in a meaningful way to be replaced by a fictitious continuum at the macroscopic (REV) scale (Bachmat and Bear, 1986). The price for obtaining this fictitious continuum is that the unknown details of geometry at the microscopic scale are replaced with average parameters at the macroscopic scale that can be measured and used in the macroscopic equations to provide a predictive model.

Just as it is not possible to know the geometry of the pore space on the microscopic scale, the aquifer can be heterogeneous enough on a macroscopic scale that it is not possible (or at least not practical) to know all the geometry of the heterogeneity on a macroscopic, or field, scale. A common approach is to use stochastic theories, characterized by ensemble averages of the macroscopic variables (Gelhar, 1986). These theories result in scale-dependent parameters (such as macrodispersivity) which are functions of the statistical nature of the hydraulic conductivity distribution. Most of these theories also rely on the assumption that there is a natural scale to the heterogeneity, e.g., the correlation scale.

In many field situations, the existence of a natural scale may be a reasonable assumption, especially if some limit is placed as to how far into the future we require the model to be able to extrapolate. However, these assumptions of the existence of a natural scale are artificial separations that may not exist in many real situations. There may be multiple scales of heterogeneity, or there may be a continuous variation over space and time with no characteristic scale. The latter situation may be described as possessing fractal characteristics.

ABSTRACT

APPLICATION OF FRACTAL MATHEMATICS TO SOIL WATER RETENTION ESTIMATION

By

Scott W. Tyler and Stephen W. Wheatcraft

Published in

Soil Science Society of America Journal

August 1989

In this paper, we present an analysis correlating the fitting parameter α in the Arya and Paris (1981) soil water retention model to physical properties of the soil. Fractal mathematics are used to show that α is equal to the fractal dimension of the pore trace and expresses a measure of the tortuosity of the pore trace. The fractal dimension of the particle-size distribution can be easily measured and related to the α parameter of the Arya and Paris model. By suggesting a physical significance of the coefficient, the universality of the model is greatly improved. Soil water retention data, estimated strictly from particle-size distributions, are proven to match measured data quite well. The fractal dimension of pore traces range from 1.011 to 1.485 for all but one soil tested.

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