U.S. GEOLOGICAL SURVEY RESEARCH IN RADIOACTIVE WASTE DISPOSAL--FISCAL YEAR 1981

By Robert Schneider and N. J. Trask

U.S. GEOLOGICAL SURVEY

Water Resources Investigations Report 83-4105

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UNITED STATES DEPARTMENT OF THE INTERIOR

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SI UNITS AND INCH-POUND SYSTEM EQUIVALENTS

[SI, International System of Units, a modernized metric system of measurement. All values have been rounded to four significant digits except 0.01 bar, which is the exact equivalent of 1 kPa. Use of hectare (ha) as an alternative name for square hectometer (hm^2) is restricted to measurement of land or water areas. Use of liter (L) as a special name for cubic decimeter (dm^3) is restricted to the measurement of liquids and gases; no prefix other than milli should be used with liter. Metric ton (t) as a name for megagram (Mg) should be restricted to commercial usage, and no prefixes should be used with it. Note that the style of meter^2 rather than square meter has been used for convenience in finding units in this table. Where the units are spelled out in text, Survey style is to use square meter]

SI unit		Inch-Pound equivalent	
Length			
millimeter (mm)	=	0.039 37	inch (in)
meter (m)	=	3.281	feet (ft)
	=	1.094	yards (yd)
kilometer (km)	=	0.621 4	mile (mi)
	=	0.540 0	mile, nautical (nmi)
Area			
centimeter^2 (cm^2)	=	0.155 0	inch^2 (in^2)
meter^2 (m^2)	=	10.76	feet^2 (ft^2)
	=	1.196	yards^2 (yd^2)
	=	0.000 247 1	acre
hectometer^2 (hm^2)	=	2.471	acres
	=	0.003 861	section (640 acres or 1 mi^2)
kilometer^2 (km^2)	=	0.386 1	mile^2 (mi^2)
Volume			
centimeter^3 (cm^3)	=	0.061 02	inch^3 (in^3)
decimeter^3 (dm^3)	=	61.02	inches^3 (in^3)
	=	2.113	pints (pt)
	=	1.057	quarts (qt)
	=	0.264 2	gallon (gal)
	=	0.035 31	foot^3 (ft^3)
meter^3 (m^3)	=	35.31	feet^3 (ft^3)
	=	1.308	yards^3 (yd^3)
	=	264.2	gallons (gal)
	=	6.290	barrels (bbl) (petroleum, 1 bbl = 42 gal)
	=	0.000 810 7	acre-foot (acre-ft)
hectometer^3 (hm^3)	=	810.7	acre-feet (acre-ft)
kilometer^3 (km^3)	=	0.239 9	mile^3 (mi^3)
Volume per unit time (includes flow			
decimeter^3 per second (dm^3/s)	=	0.035 31	foot^3 per second (ft^3/s)
	=	2.119	feet^3 per minute (ft^3/min)

SI unit		Inch-Pound equivalent	
Volume per unit time (includes flow)—Continued			
decimeter^3 per second (dm^3/s)	=	15.85	gallons per minute (gal/min)
	=	543.4	barrels per day (bbl/d) (petroleum, 1 bbl = 42 gal)
meter^3 per second (m^3/s)	=	35.31	feet^3 per second (ft^3/s)
	=	15 850	gallons per minute (gal/min)
Mass			
gram (g)	=	0.035 27	ounce avoirdupois (oz avdp)
kilogram (kg)	=	2.205	pounds avoirdupois (lb avdp)
megagram (Mg)	=	1.102	tons, short (2 000 lb)
	=	0.984 2	ton, long (2 240 lb)
Mass per unit volume (includes density)			
kilogram per meter^3 (kg/m^3)	=	0.062 43	pound per foot^3 (lb/ft^3)
Pressure			
kilopascal (kPa)	=	0.145 0	pound-force per inch^2 (lbf/in^2)
	=	0.009 869	atmosphere, standard (atm)
	=	0.01	bar
	=	0.296 1	inch of mercury at 60°F (in Hg)
Temperature			
temp kelvin (K)	= [temp deg Fahrenheit (°F) + 459.67]/1.8		
temp deg Celsius (°C)	= [temp deg Fahrenheit (°F) − 32]/1.8		

U.S. Geological Survey Research in Radioactive Waste Disposal--Fiscal Year 1981

By

Robert Schneider and N. J. Trask

ABSTRACT

The report summarizes progress on geologic and hydrologic research related to the disposal of radioactive wastes. The research is described according to whether it is related most directly to (1) high-level and transuranic wastes; (2) low-level wastes, or (3) uranium mill tailings. Included is research applicable to the identification and geohydrologic characterization of waste-disposal sites, to investigations of specific sites where wastes have been stored, and to studies of regions or environments where waste-disposal sites might be located. A significant part of the activity is concerned with techniques and methods for characterizing disposal sites and studies of geologic and hydrologic processes related to the transport and (or) retention of waste radionuclides.

INTRODUCTION

It is generally recognized that the transport of radionuclides to the human environment from radioactive wastes at or below the land surface will involve water. The transport of water and its solutes is related to the hydrologic features of the environment which, in turn, are controlled by climatic, topographic, geologic, and geochemical conditions. Owing to the long half lives of some waste radionuclides, certain wastes need to be isolated from the human environment for such long periods of time that it becomes necessary, in selecting disposal sites, to take into account the effects of dynamic geologic processes which could change the hydrologic regime and alter rates and directions of subsurface radionuclide transport. For these reasons and because the U.S. Geological Survey (USGS) is the principal earth-science agency in the Federal Government, the various agencies concerned with nuclear facilities and testing nuclear weapons have requested the advice of the USGS for many years on the relation of geology and hydrology to the isolation of radioactivity from the biosphere.

The research of the USGS as a whole, includes almost every area of earth science. The specific research activities described in this report are part of the USGS program that is directly related to radioactive waste disposal. They include geologic and hydrologic research of general applicability to the identification and characterization of waste disposal sites, investigations of specific sites where wastes have been stored,

and studies of regions or environments where waste disposal sites might be located. The activities discussed in this report are divided arbitrarily into three categories according to whether they relate most directly to: (1) high-level and transuranic wastes[1], (2) low-level wastes,[2] and (3) uranium mill tailings.

Some of the generic research described in the section on high-level and transuranic wastes, particularly the work on techniques and methods for characterizing disposal sites and studies of geologic and hydrologic processes, could also be applicable to low-level waste disposal. Conversely, the section on low-level wastes includes research on geologic and hydrologic processes that could be useful in problems related to the disposal of high-level and transuranic wastes.

This is the third report of progress of USGS research in radioactive waste, the previous one being by Schneider and Trask (1982)[3].

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1. High-level wastes include fission products that initially have a high level of beta and gamma radiation and a high rate of heat generation; they also include transuranic elements with a long toxic life. Transuranic waste contains long-lived alpha emitters at concentrations greater than 10 nCi/g and generates little or no heat.

2. The term low-level wastes has carried a changing and imprecise definition over the years. Currently, it generally means waste which does not fit the definition of high-level waste and in which the concentration of transuranic elements is less than 10 nCi/g. It consists in part of miscellaneous solid materials that have been irradiated and contaminated through use as well as products of reactors and fuel reprocessing plants.

3. Schneider, Robert, and Trask, N. J., 1982, U.S. Geological Survey Research in Radioactive Waste Disposal - Fiscal Year 1980: U.S. Geological Survey Open-File Report 82-509, 110 p.

RELATION TO PROGRAMS OF OTHER AGENCIES

For about 30 years, the USGS, Department of the Interior (DOI), has provided technical consultation to the Department of Energy (DOE) and its predecessors, the Energy Research and Development Administration and the Atomic Energy Commission. The USGS has also assisted the Department of Defense; the Nuclear Regulatory Commission (NRC); and the Environmental Protection Agency (EPA). The work has included assistance to the DOE staff at Germantown, Maryland; starting in fiscal year 1981, this assistance was provided also to the DOE staff in Columbus, Ohio. A variety of regional and detailed geologic and hydrologic studies and generic research related to waste disposal has been conducted at the Savannah River Plant, South Carolina; Oak Ridge National Laboratory, Tennessee; Idaho Nuclear Engineering Laboratory; the Hanford Reservation, Washington; and to weapons testing and(or) waste disposal at the Nevada Test Site and other localities. These activities are referred to collectively as cooperative programs in contrast to those activities supported by direct Congressional appropriations to the USGS.

With regard to high-level and transuranic wastes, the specific responsibility for selection of sites for waste repositories, as well as their design, lies with the DOE. The NRC and EPA are responsible for licensing the facilities and establishing criteria for judging their environmental effects. The DOE program, known as the National Waste Terminal Storage (NWTS) program, includes support for cooperative investigations by the USGS. The part of the USGS research on high-level wastes that is funded by its own appropriations is designed to complement and augment the DOE program and to provide needed information from an agency that has neither operational nor regulatory responsibilities in waste disposal.

Some sites being studied in foreign countries have provided the opportunity for the USGS to conduct research of mutual benefit to both countries. Some research on borehole geophysical logging is being conducted in cooperation with Atomic Energy of Canada, Limited, at the Underground Research Laboratory in southeastern Manitoba. The geochemistry of ground waters at the Stripa mine site in Sweden is under study in cooperation with the Swedish Nuclear Fuel Supply Company/Nuclear Fuel Safety Project which is operated for the Swedish Nuclear Power Utility Industry (see section on Geochemistry of trace elements in natural waters).

For several years, the USGS has been conducting specific geohydrologic studies at low-level disposal sites on behalf of the DOE at the Idaho National Engineering Laboratory and at the Oak Ridge National Laboratory, Tennessee.

BUDGET SUMMARY -- FISCAL YEAR 1981
(in millions of dollars)

High-level and transuranic wastes and related generic research		
USGS appropriation	4.26	
DOE transfer of funds	5.53	
		9.79
Low-level wastes and related research on geologic and hydrologic processes		
USGS appropriation	2.11	
DOE transfer of funds	0.41	
		2.52
Uranium mill tailings		
USGS appropriation	0.11	
		0.11
Total		12.42

HIGH-LEVEL AND TRANSURANIC WASTES

GEOLOGICAL SURVEY PROGRAM FOR IDENTIFYING ENVIRONMENTS SUITABLE FOR DISPOSAL OF HIGH-LEVEL WASTE

By M. S. Bedinger and K. A. Sargent, Lakewood, Colo.

Screening activities to locate sites for radioactive waste repositories have been underway for many years, principally outside the USGS. Typically, they involve the study of successively smaller geographic regions with a progressive increase in the level of detail of study. Only recently, however, has there been an appreciation of the need to consider, at the earliest stage of this process, environmental factors that can provide multiple barriers to radionuclide migration (Interagency Review Group on Nuclear Waste Management, 1979, p. 37-43). The term multiple barriers includes man-made barriers and natural barriers in the form of specified hydrodynamic, geochemical, and geologic characteristics that would impede radionuclide transport. The factors of most significance include a geologically stable environment, a host rock of low permeability in a flow system with slow ground-water velocity, rocks with high sorptive capacity in the flow system, and long flow paths to discharge areas downgradient from the repository. Previously, attention was focused almost exclusively on the potential repository host rock, particularly its stability. While the host rock remains important, its characteristics must be considered in conjunction with the types of hydrologic and geologic barriers mentioned above.

This study is part of the USGS high-level waste program which was started in fiscal year 1979 with direct Congressional appropriations. Owing to the fact that the DOE has the responsibility for selecting sites, the overall program is closely coordinated with that of the DOE.

Objective To identify or contribute to the identification of geohydrologic environments with hydrodynamic, geochemical, and geologic characteristics which provide independent, multiple natural barriers to the migration of radionuclides and which may warrant intensive study.

Approach Eleven broad physiographic provinces, encompassing the 48 conterminous states, have been identified as the basic land units in the national screening process. During the screening, the provinces will be subdivided successively into regions, areas, and potential sites. The approach will generally follow the plan proposed by a subgroup of the DOE-DOI Working Group that developed the Earth Science Technical Plan (ESTP), (U.S. Department of Energy and U.S. Geological Survey, Subgroup I of the ESTP Working Group, 1980). Using the Basin and Range Province as a test area, the study will be conducted by a group of State and Federal earth scientists. The approach stresses the concept of identifying environments with relatively independent multiple barriers to nuclide transport.

Progress The announcement of the selection of the Basin and Range Province as the prototype study area was made in May 1981 to the Governors of the States in the Basin and Range -- Arizona, California, Idaho, Nevada, New Mexico, Oregon,

Texas, and Utah. The states were invited to cooperate in the study by participating in a Province Working Group (PWG). The PWG composed of one member from each participating state and two members of the U.S. Geological Survey, was organized, and plans and guidelines were formulated for the work of the PWG. The USGS program staff continued to assemble a data base for the screening effort. Published data and data in the files of the USGS were compiled for selected subjects of use in evaluating geohydrologic environments. National and regional overviews, useful for preliminary screening, exist for the occurrence of various rock types, mineral resources, seismic activity, and volcano-tectonic features. Data were gathered, assimilated, and compiled on mining districts and their commodities, and on the surface occurrences of potential host rocks including granite, tuff, argillaceous rocks, basalt, and salt. Preliminary reports on seismicity and regional tectonics have been completed. Data on magnetic surveys are now being assembled. The available hydrologic data and information useful for characterizing the hydrology and delineating ground-water flow systems of the province have been assembled.

Efforts were directed toward automatic recording and processing the large amounts of map data needed for the screening process. Bibliographic files have been assembled for automatic data storage and retrieval by author, subject, and geographic area. Work continued on assessing the capabilities of and adapting ground-water models for use in interpreting regional flow systems and evaluating the potential for transport of radionuclides in geohydrologic environments.

Province screening will concentrate initially on the distribution of host rocks, ground-water flow systems, and tectonic stability. Drafting of base maps and maps of these features was begun for the use of the PWG.

Reports

Bedinger, M. S., Sargent, K. A., and Schneider, Robert, 1981, Evaluation of geologic and hydrologic characteristics in the Basin and Range province relative to high-level nuclear waste disposal, in Proceedings of the 1981 National Waste Terminal Storage Program information meeting: U.S. Department of Energy Publication DOE/NWTS-15.

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Interagency Review Group on Nuclear Waste Management, 1979, Report to the President by the Interagency Review Group on Nuclear Waste Management: Springfield, Virginia, National Technical Information Service, TID 29442.

U.S. Department of Energy and U.S. Geological Survey, Department of the Interior Subgroup I of Earth Science Technical Plan Working Group, 1980, Plan for identification and geological characterization of sites for mined radioactive waste repositories: U.S. Geological Survey Open-File Report 80-686, 73 p.

Department of Energy Program for Locating and Characterizing Disposal Sites

The Geological Survey is conducting various scientific investigations for the DOE which has the responsibility for developing repositories for the permanent isolation of nuclear wastes. The DOE's National Waste Terminal Storage program, established in 1976, is composed of three separate coordinated elements which include many investigations related to locating and characterizing disposal sites: the technical program of the Office of Nuclear Waste Isolation (ONWI) of Battelle Memorial Institute located in Columbus, Ohio; the Basalt Waste Isolation Project (BWIP) in Hanford, Washington; and the Nevada Nuclear Waste Storage Investigations (NNWSI) at the Nevada Test Site (NTS). This section of the report is confined to those DOE investigations for which the USGS is conducting research. The ONWI investigations, in which the USGS is involved, include the Paradox Basin, Utah, and the Gulf Coast salt-dome region. The Geological Survey is also carrying out geologic and hydrologic investigations related to the Waste Isolation Pilot Plant near Carlsbad, New Mexico, which is intended for the storage of defense generated nuclear waste. This latter work is being done for the DOE's Albuquerque Operations Office.

Nevada Test Site and Vicinity

The USGS has been assisting the DOE in evaluating the suitability of various geohydrologic environments and rock masses for locating repositories on or near the Nevada Test Site (NTS) for the disposal of commercially generated high-level radioactive wastes and wastes from DOE facilities. An essential part of this work is defining the geology and hydrology of the area in order to assess the potential for the transport of radionuclides from a repository to the human environment. In addition, the potential for disruption of a repository as a result of volcanic or tectonic activity or accelerated erosion is being evaluated.

Search for Potential Sites

By Gary L. Dixon and V. M. Glanzman, Lakewood, Colo.

Objective To locate and characterize rock masses at the NTS and in southern Nevada suitable as host media for high-level commercial radioactive wastes; to describe the areal and depth distribution and structural integrity of these rock masses; and to assess the potential for contaminant release by hydrologic transport or as a result of tectonic and (or) volcanic activity.

Approach From previous geologic work at NTS, the general geology is well known. Areas likely to have suitable host rocks and hydrologic conditions at depths appropriate for a repository are evaluated by detailed surface mapping, surface geophysical methods, exploratory drilling, and borehole geophysical techniques.

Progress Much of the field work was concentrated on characterizing the Yucca Mountain area (fig. 1). Detailed subsurface studies are being used

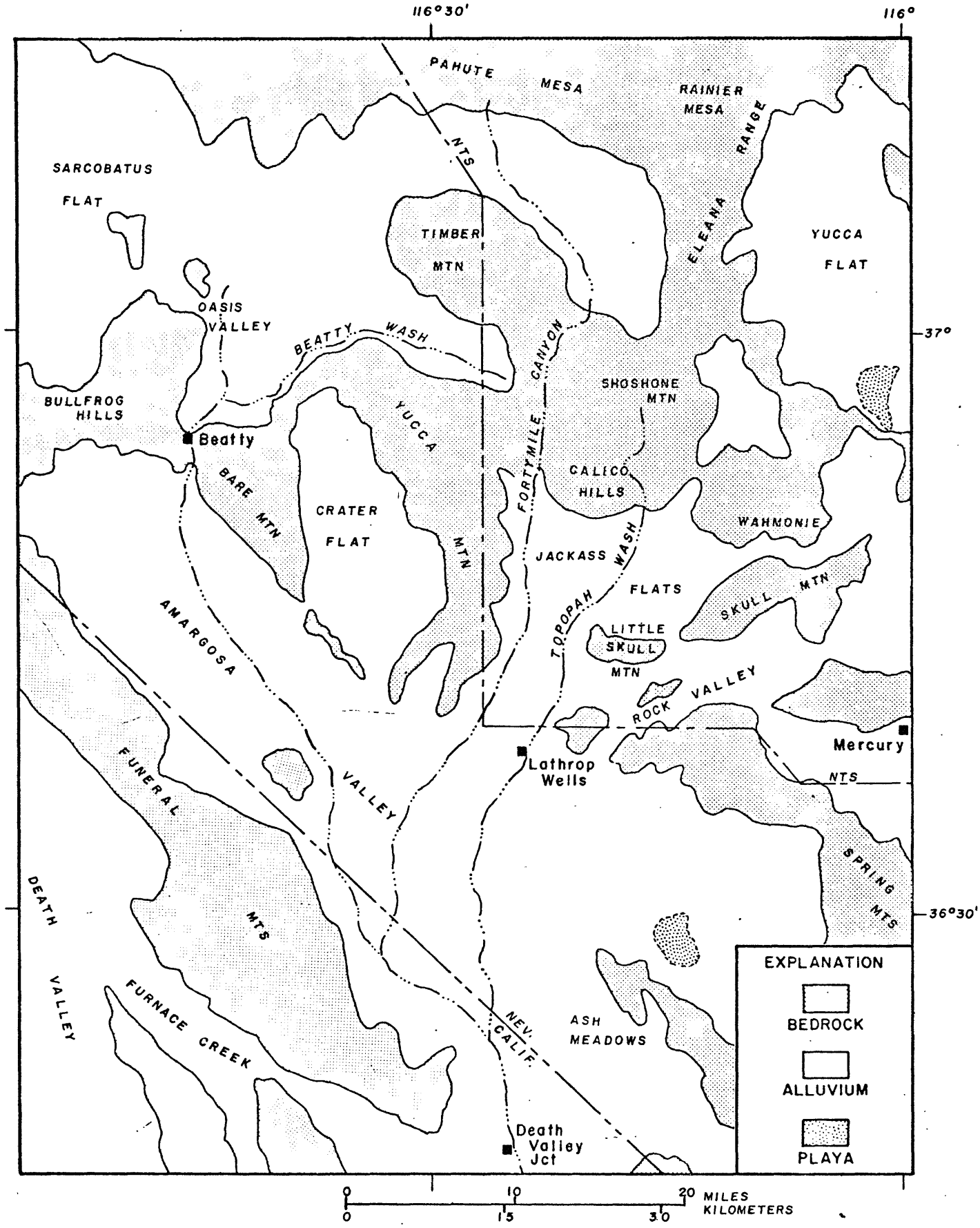

Figure 1.--Location of Yucca Mountain, Nevada.

to investigate the stratigraphic continuity and structural complexity of volcanic rocks underlying Yucca Mountain. Drill holes USW-G1, -H1, -G2, and UE25b-1H (fig. 2) have penetrated the volcanic section to depths varying between 1,219.2 and 1,828.8 m. Most stratigraphic units dip southeastward 3°-6°. A report on the 1,829-m drill hole, USW-G1, was completed (Spengler and others, 1981). Continued petrographic studies of the Crater Flat Tuff and older tuffs in drill hole USW-G1 have demonstrated that the lithic-rich tuff between depths of 1,202.7 and 1,500 m correlates with the pre-Crater

Table 1. Major geologic units identified in drill holes, Yucca Mountain, Nevada Test Site and Vicinity

Rock unit	Range of thickness[1] Feet	Meters
Alluvium and colluvium----------	0-150	(0-45.7)
Paintbrush Tuff (Miocene)		
Tiva Canyon Member----------	0-243	(0-74.1)
Yucca Mountain Member----------	0-100	(0-30.5)
Bedded tuff----------	0-155	(0-47.3)
Paintbrush Tuff (cont'd.)		
Pah Canyon Member----------	35-261	(10.7-79.6)
Topopah Spring Member----------	995-1,225	(303.4-373.5)
Tuffaceous beds of Calico Hills---------	353-947	(107.6-288.7)
Crater Flat Tuff (Miocene)		
Prow Pass Member----------	373-597	(113.7-182.0)
Bullfrog Member----------	300-521	(91.5-158.9)
Tram unit----------	499-1,078	(152.2-328.7)
Dacite lava and flow breccia----------	0-392	(0-119.5)
Tuff of Lithic Ridge----------	632-994	(192.7-303.1)
Older ash-flow and bedded tuffs---------	47-1,060	(14-323)
Flow breccia and lava (USW-G2)----------	0-1,132	(0-345)

[1]Thickness includes thin bedded tuffs underlying each ash-flow tuff.

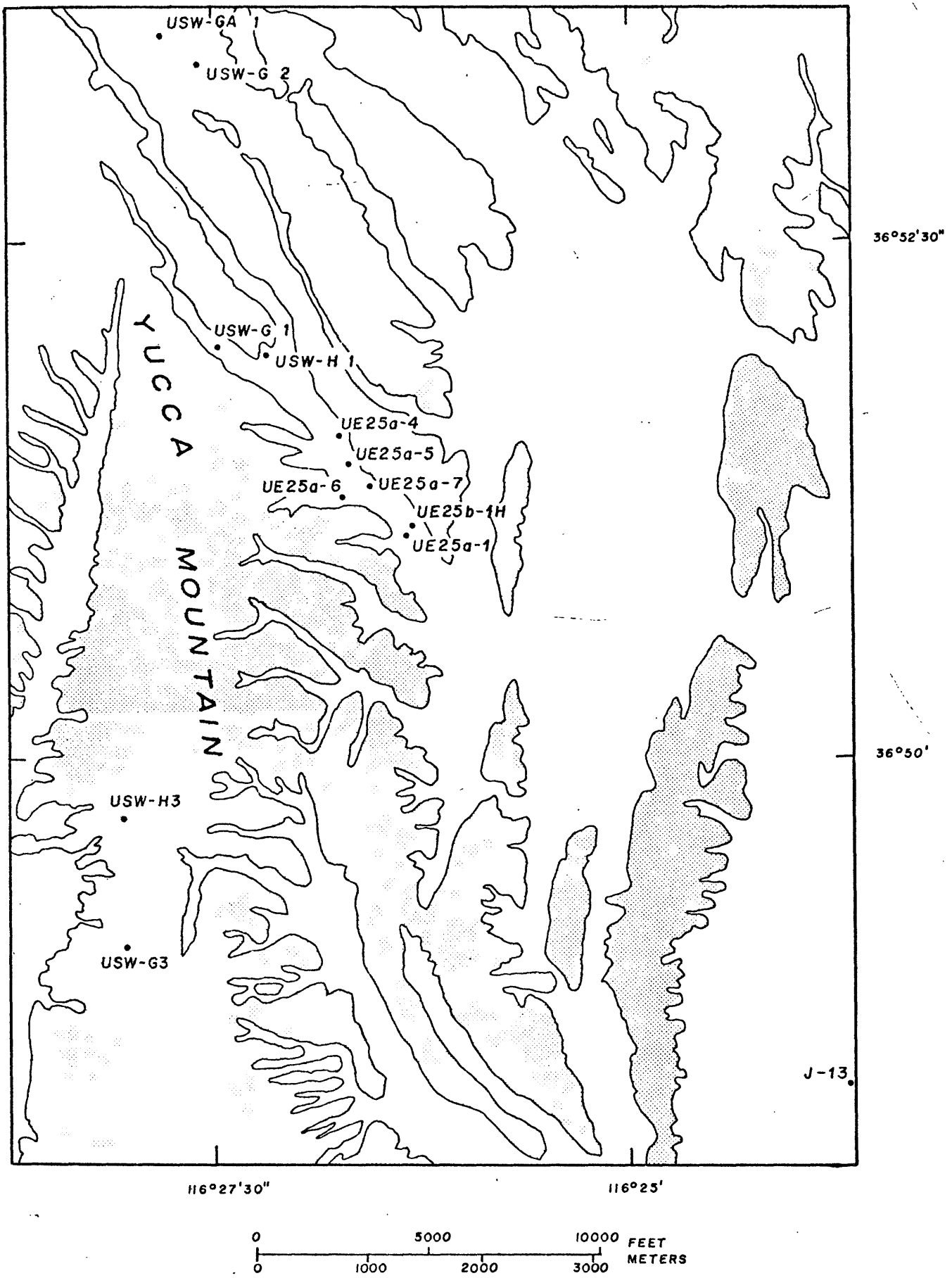

Figure 2.--Location of drill holes at Yucca Mountain, Nevada.

Flat Tuff unit below 981.5 m in well J-13. Petrographic comparisons also have established a similar correlation with a pre-Crater Flat Tuff unit at three different surface localities.

Field work for mapping the geology of the Yucca Mountain area at a scale of 1:12,000 continues. A geologic map of the southwest quadrant of NTS was completed. Reports on geophysical investigations of the Calico Hills and Wahmonie sites were released (Kauahikaua, 1981; Ponce, 1981; Snyder and Oliver, 1981).

Paleomagnetic studies of core samples from drill holes USW-G1, -G2, and -H1, as well as samples from six surface localities, should provide a check on the accuracy of the orientation technique used in the deep drill holes. Of interest is a rather unusual remanent direction (nearly horizontal to the southwest) of the lithic-rich tuff in USW-G1. This unusual direction may allow paleomagnetics to be extremely useful in identifying this unit elsewhere.

Study of borehole geophysical data from drill holes UE25a-1, -4, -5, -6, and -7 together with detailed geologic information shows: (1) the rocks near drill hole UE25a-5 are primarily laterally homogeneous and layered, (2) the rocks near drill holes UE25a-6 and -7 contain high-resistivity anomalies that may indicate resistive bodies in the layered section, and (3) a complex pattern of resistivity lows, located southwest of drill hole UE25a-4, is probably caused by variations in alluvium thickness (Daniels and others, 1981).

A new experimental tensor audio-magnetotelluric system developed at the University of California, Berkeley, was used to better define lateral electrical boundaries in the Yucca Mountain area. Time domain electromagnetic soundings employing the Sirotem instrument were conducted in the area to evaluate this relatively new electromagnetic sounding method (See section on High Resolution Electromagnetic Sounding Methods). Preliminary evaluation shows that known faults cause only minor perturbations on the data and suggests that the tuffs may have large coefficients of anisotropy.

An interpretation of gravity profiles, using 3-dimensional and 2 1/2-dimensional models, shows that part of southeastern Yucca Mountain is underlain by relatively high-density rocks (2.60-2.70 g/cm^3) at depths near 1.2 km. Southwestern Yucca Mountain and southern Crater Flat are underlain by about 3 km of relatively low-density rock, probably mostly tuff. Thus, the models suggest that the subsurface Paleozoic rocks of Bare Mountain extend eastward beneath Crater Flat as a downdropped slab involving a complex combination of ancient calderas and sector graben now filled with 1-3 km of tuff and alluvium.

Magnetic-anomaly modeling and interpretations of seismic P-wave delays are also being performed in connection with Yucca Mountain studies. Preliminary interpretations have provided evidence supporting the interpretations of gravity data.

Measurements in drill holes USW-G1, -H1, the conductor holes, and in Crater Flat show the holes are essentially in thermal equilibrium, and all indicate at least a potential for vertical water movement. The temperature profiles in the unsaturated zone also show considerable variation, and they are being studied for their possible significance regarding water flow.

Reports

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Kane, M. F., Webring, M. W., and Bhattacharyya, B. K., 1981, A preliminary analysis of gravity and aeromagnetic surveys of the Timber Mountain area, southern Nevada: U.S. Geological Survey Open-File Report 81-189, 40 p.

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Spengler, R. W., Byers, F. M., Jr., and Warner, J. B., 1981, Stratigraphy and structure of volcanic rocks in drill hole USW-G1, Yucca Mountain, Nye County, Nevada: U.S. Geological Survey Open-File Report 81-1349, 50 p.

Tectonics, Seismicity, and Volcanism of the Southern Great Basin

By W. J. Carr and A. M. Rogers, Lakewood, Colo.; and
B. M. Crowe, Los Alamos National Laboratory, Los Alamos, New Mexico

Objective To assess the potential for faulting, damaging earthquakes, recurrence of volcanism, and local acceleration of erosion in parts of the southern Great Basin.

Approach Work is focusing on the region surrounding the southern part of the Nevada Test Site by (1) investigating the rate, intensity, and distribution of faulting, particularly during the last 10 m.y.; (2) monitoring and interpreting seismicity; (3) studying the history of volcanism and deriving estimates of the risk of recurrence of volcanism in certain areas; and (4) developing a better understanding of regional and local tectonics in relation to rates of erosion and deposition. W. J. Carr is interpreting the tectonics; he is assisted by D. L. Hoover and W. C. Swadley, who are analyzing the geomorphology and mapping and interpreting the surficial deposits. The work is done in close collaboration with A. M. Rogers on seismology and J. N. Rosholt, B. J. Szabo, C. W. Naeser, and R. F. Marvin on geochronology. B. M. Crowe of Los Alamos National Laboratory is principal investigator of basaltic volcanism.

Progress Tectonics--Mapping of surficial deposits and Tertiary rocks in the Bare Mountain and Big Dune 15-minute quadrangles (fig. 3) was completed in 1981. Data were collected on the Pliocene and Pleistocene stratigraphy and history of the Tecopa basin, an important link in the Amargosa drainage system of southwestern Nevada. As a result of studies in the Amargosa Valley and Tecopa basin, several important conclusions have been reached: (1) the Amargosa Valley was probably a closed basin containing lakes and ponds during the period from about 4 to 2 m.y. ago; (2) the Amargosa Lake may have spilled into the Tecopa basin through a basalt dam near Eagle Mountain approximately 2.5 m.y. ago; (3) time of lake sediment deposition apparently did not overlap significantly between the Tecopa and Amargosa basins; (4) only minor faulting and tectonic adjustment have occurred in the Amargosa Valley since about 2.5 m.y. ago; (5) no faulting of consequence has occurred in the Tecopa basin since about 500,000 years ago; (6) some regional tilting (about 3 m/km) to the south or southeast appears to have occurred in Quaternary time; (7) a lake in the Tecopa basin spilled into Death Valley, and the Amargosa River system became through-going and integrated about 500,000 years ago, probably as the indirect result of continuing tectonic activity in Death Valley.

Geochronology studies, aided by uranium-trend dating by John Rosholt, have continued to refine the ages of faulting and surficial deposits in the region (Szabo and others, 1981). The current chronology of these units is summarized in fig. 4. Hoover and others (1981) describe the stratigraphy in detail.

Five trenches were dug and mapped in the southeastern part of Crater Flat to study the near-surface deposits. Two of the trenches exposed fluvial or beach gravels, lake or pond deposits, and alluvium; the other three were dug across old fault scarps in alluvium. These scarps are the closest

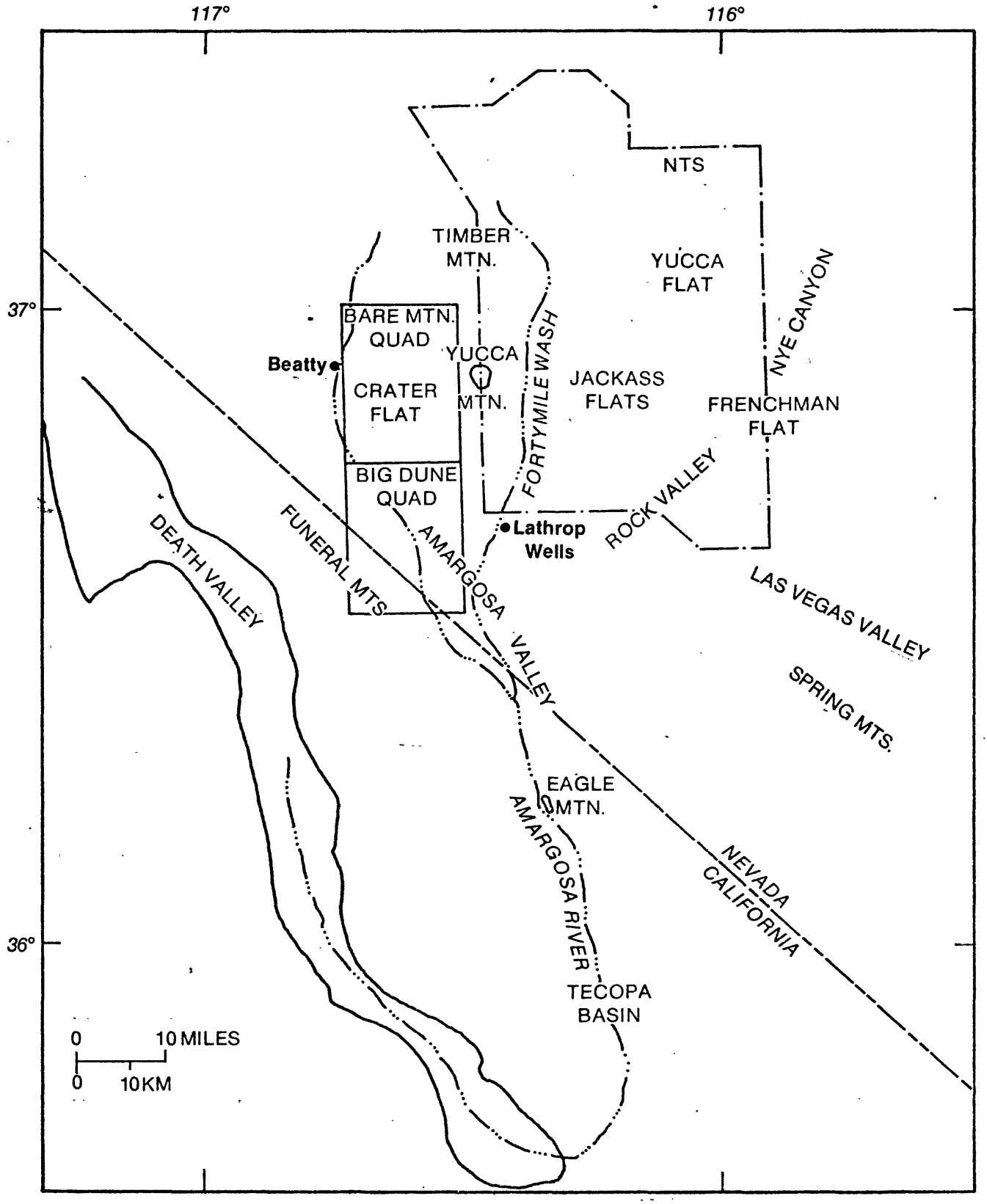
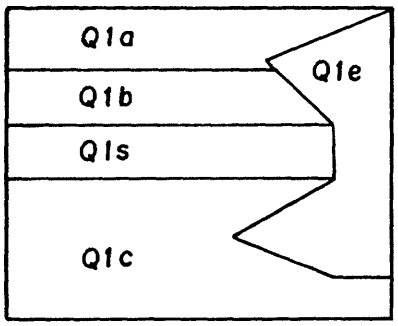
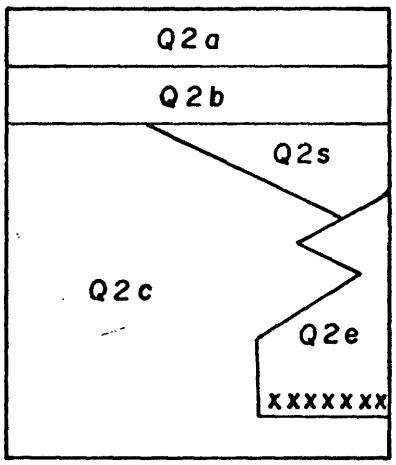


Figure 3.--Index map of southern Nevada Test Site region.



Q1a <150 yr
Q1b <4000yr
Q1s 4000-7000yr
Q1e } >7000 yr?
Q1c } <8500yr?

REGIONAL UNCONFORMITY



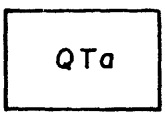
Q2a >30,000 yr
<80,000 yr

Q2b >30,000 yr
<160,000 yr

xxxxx BISHOP ASH (730,000 yr)

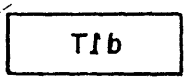
Q2c >235,000 yr
<750,000 yr?
SOILS AT 270 ± 35 k.y.
310 ± 30 k.y.
430 ± 40 k.y.

REGIONAL UNCONFORMITY



QTa >1.1 m.y.
<2.43 m.y.

UNCONFORMITY



T1b SEDIMENTS OF LAKE AMARGOSA
>2.43 m.y.
<3 m.y.

Figure 4.--Chronology of deposits of late Tertiary and Quaternary age in the Nevada Test Site region. Details given in Hoover and others (1981).

known Quaternary faults to the area at Yucca Mountain being explored for a repository. Relationships exposed in the trenches confirm the maturity of the faults; displaced alluvium is middle to early Quaternary in age and has a well developed carbonate layer that is not displaced. In one of the trenches, a basalt ash was found in the fault itself, overlapped by undisplaced calcrete. The source of the basalt ash has been identified as the southernmost of the four 1.1-m.y.-old basalt cones in Crater Flat. This discovery indicates that (1) the faulting and volcanism were synchronous, and (2) the fault last moved 1.1 m.y. ago.

Work by D. L. Hoover has shown that Yucca Mountain has had relatively low rates of erosion in the last 10 m.y. or so, as shown in table 2. Except for stratigraphic unit Tpc, the units correspond to those in figure 4.

Table 2.--Maximum depth of erosion and erosion rates of late Tertiary and Quaternary surfaces in the Yucca Mountain area

Unit surface	Age (yr)	Maximum depth of erosion (m)	Rate of erosion ($m/10^3$ yr)
Q1b	[1]/100	2.14	21.4
Q1c	[2]/$7X10^3$	6.1	0.87
Q2a	[3]/$5X10^4$	9.1	0.18
Q2b	[4]/$1.6X10^5$	8.5	0.053
Q2c	[5]/$3X10^5$	25.9	0.082
Tpc	[6]/$10X10^6$	218.2	0.22

1 Approximate age of tree-root exposure in gullies.

2 Minimum age, based on correlation of Altithermal period with unit Q1c. Age estimated by interpolation between 30,000-year-old and 80,000-year-old units.

3 Age estimated by interpolation between 30,000-year-old and 80,000-year-old units.

4 Maximum of two uranium-series ages on unit Q2b.

5 Average of two uranium-series ages on unit Q2c having soils typical of that unit.

6 Approximate beginning age of development of surface across Tiva Canyon Member of the Paintbrush Tuff and 10-m.y.-old basalt dike.

Hoover has also determined, on the basis of Quaternary alluvium and terraces along Fortymile Wash, that this major drainage just east of Yucca Mountain probably captured the moat drainage of the Timber Mountain caldera between about 160,000 and 300,000 years ago, resulting in local incision of the drainage.

Seismicity--A report (Rogers and others, 1981) was released on results of seismological investigations in the southern Great Basin in 1980. Preliminary interpretation of data thus far confirms that small, relatively shallow earthquakes are occurring fairly continuously on the northeast-trending Rock Valley fault system in the area between Frenchman Flat in the southeastern part of NTS southwestward across the Amargosa Valley to the Funeral Mountains. This contrasts with much of the activity elsewhere in the southern Great Basin, which tends to be quite sporadic with respect to both time and location. The fact that this activity correlates well with a zone of surface Quaternary faults indicates large earthquakes have occurred on the system, but the continuous nature of the seismicity and its distribution with respect to the faults and the thick Paleozoic carbonate-rock aquifer in the region, suggest strongly that ground water may be facilitating fault movement, releasing the stress in numerous, but small, events. To obtain a better understanding of the Rock Valley system seismicity, a multi-station digital seismometer network was operated for about 2 months. Data obtained are currently being interpreted and form the initial phase of a source parameter experiment.

Six new high-gain telemetered stations were added to the regional network. These are located on and around Yucca Mountain at a 5-8 km spacing. One or two very small earthquakes were detected on Yucca Mountain in 1981. Construction explosions on Yucca Mountain and the monitoring of nuclear explosions are being used to help refine velocity models for the area. Seismic station delays were also obtained from the network by monitoring nuclear explosions. Relatively early P-wave arrivals within a zone through NTS, including Crater Flat and southwest to the Funeral Mountains, indicate velocities in this region are generally higher than the derived regional model that best fits all the data. Preliminary results obtained by H.M. Iyer and M. Monfort using teleseismic earthquake data from the southern Great Basin seismic network suggest that trends of velocity anomalies in the NTS area are similar to those derived from nuclear explosions. These trends may parallel or roughly coincide with the zone of slightly greater tectonic flux and basaltic activity at the east edge of the Lahontan subsection of the Great Basin as described in the 1980 annual report (Carr and Rogers, 1982, p. 11-15).

Faults with northwesterly trend, including the important Death Valley-Furnace Creek system west of the NTS, have remained virtually inactive seismically, despite obvious evidence of very youthful faulting on the Death Valley system. A few small events ocurred in Las Vegas Valley, southeast of the NTS, but they appear to line up in a northeast direction, instead of being related to the northwest-trending Las Vegas Valley shear zone.

An automatic event-detector system has been added to the data-processing system in Golden, Colo., greatly facilitating the analysis and recording of the data.

Volcanism--A tentative volcano-tectonic history for Crater Flat has been interpreted from a variety of data, including petrography, geophysics, mapping, paleomagnetics, geochronology, and drill-hole information. A hole, USW-VH-1 (shown as VH-1 on Fig. 5), was cored in the south-central part of Crater Flat to investigate the source of a circular aeromagnetic anomaly and to explore for basalts older than those exposed. No additional basalts were found in this hole, but the sequence of welded tuffs and an interpretation of the low-level aeromagnetic map suggest that a resurgent dome of a caldera may be buried beneath southern Crater Flat. Other evidence points to the possibility that this part of Crater Flat may be the source area for the Bullfrog Member of the Crater Flat Tuff, and that northern Crater Flat may be the caldera source area for the Tram unit of the Crater Flat Tuff.

In addition to developing a volcano-tectonic history for Yucca Mountain and Crater Flat, work with F.M. Byers, Jr. has contributed to a much better understanding of the stratigraphy of the Crater Flat Tuff and older tuff units in the southern NTS region. This is important in evaluating the area at Yucca Mountain being explored for a repository.

Several new dates were obtained on volcanic rocks, which confirm the 1.1-m.y. age for all four Quaternary basalt centers in western Crater Flat and the 250,000-300,000-year age for the center northwest of Lathrop Wells. Basalts from eastern NTS, including one penetrated by a drill hole in Yucca Flat, gave ages of 6.3, 8.1, and 8.5 m.y. These dates, together with others previously obtained, suggest additional, nearly synchronous pulses of basaltic-eruptive activity at several places in the eastern NTS area. An age of 13.9 m.y. was obtained for dikes on Bare Mountain that are possibly outer ring dikes associated with silicic lava activity precursory to eruption of the Tram unit of the Crater Flat Tuff.

Mapping and sampling of the Lunar Crater and Reveille basalt fields in northern Nye County, central Nevada, at the north end of the basalt belt that trends through NTS were completed. The Black Rock flow in the Lunar Crater area gave an age of 570,000 years, somewhat older than expected. Basalt flows in the walls of Ubehebe Crater (northern Death Valley) and Lunar Crater (central Nevada) gave ages of 1.1 and 4.2 m.y., respectively. Both are close to or identical to the age of pulses of basaltic activity at Crater Flat. A plot (fig. 6) of basalt ages obtained thus far emphasizes the temporal clustering of activity in the NTS region.

Field work in Jackass Flats, east of Yucca Mountain, showed that as many as five separate basaltic-eruptive sequences are present rather than the two previously mapped. The additional basalts are not Quaternary but are probably between 9 and 4 m.y. old.

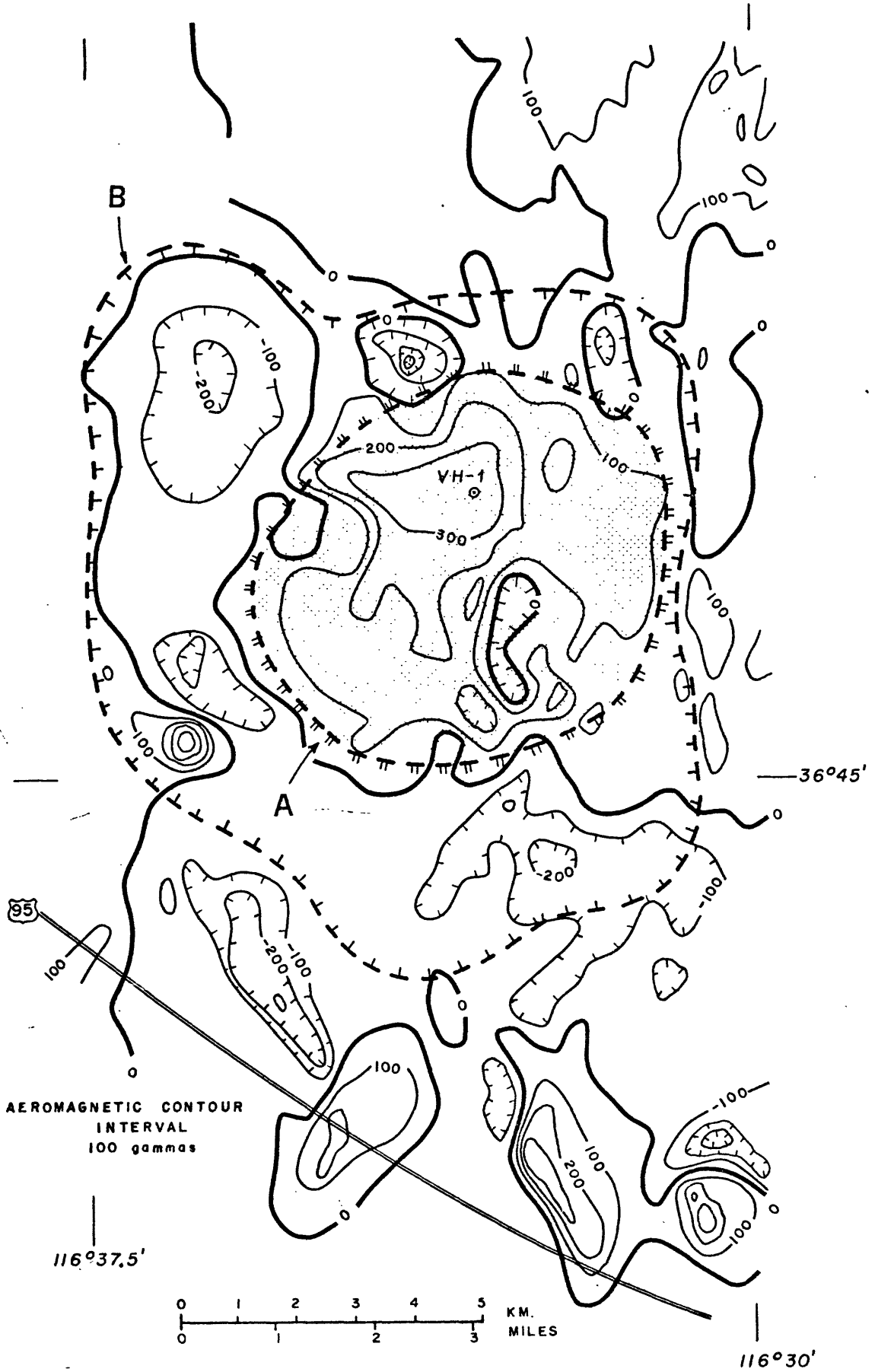


Figure 5.--Aeromagnetic map of southern Crater Flat area showing possible caldera boundaries and resurgent dome. (A) Resurgent dome associated with Bullfrog Member of Crater Flat Tuff. (B) Caldera boundary associated with Bullfrog Member of Crater Flat Tuff. Aeromagnetic surveys flown in 1978 and 1979.

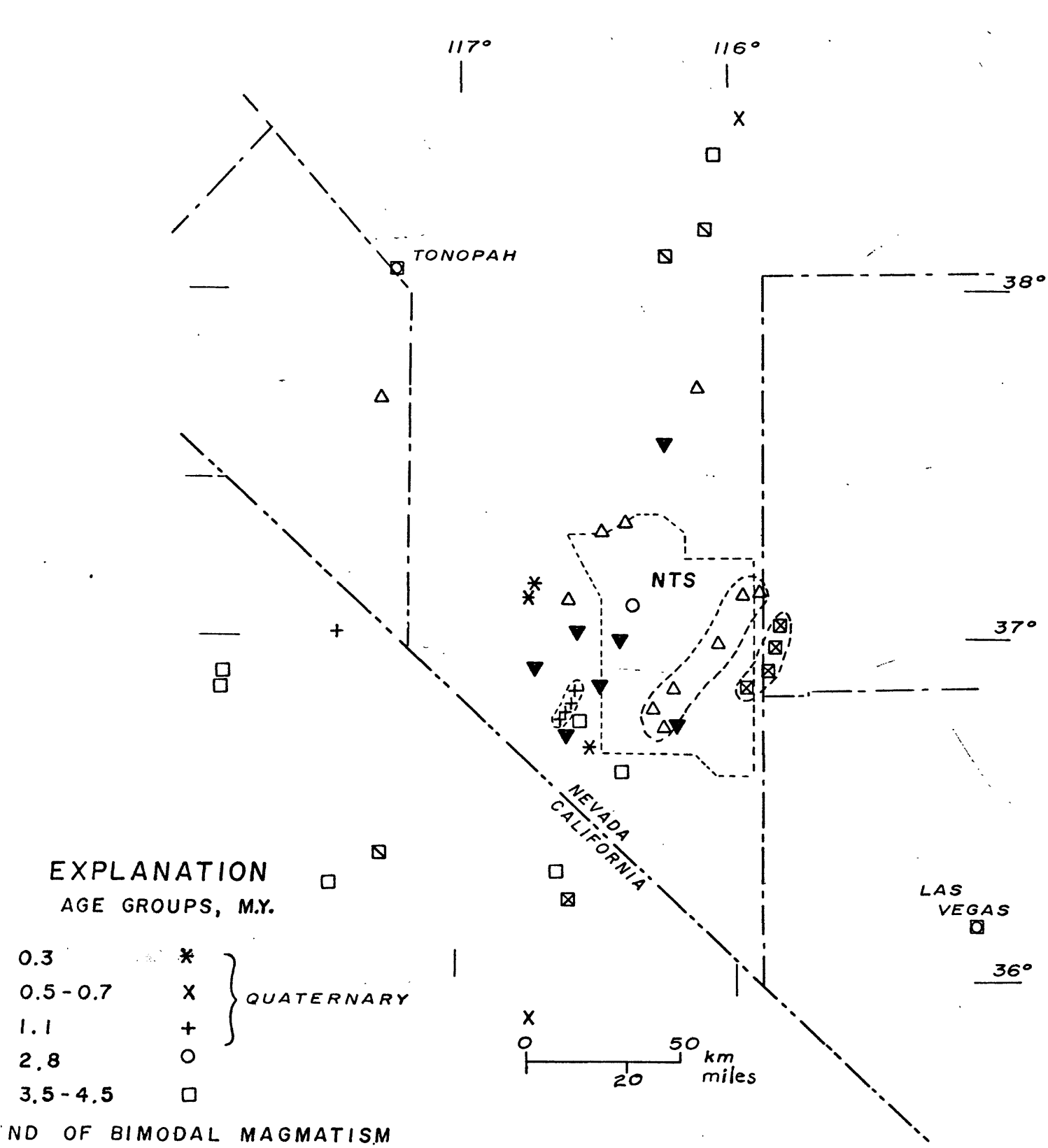


Figure 6.--Late Tertiary and Quaternary basalts of the Nevada Test Site region dated by K-Ar or other methods.

Results of fission-track analysis were received from C. Naeser on four samples of tuff from Nye Canyon (fig. 3). Three of the samples showed thermal effects of a basalt plug intruding the tuff. At distances of 1 to more than 7 m from the plug, zircon from the tuff yielded ages of 6-8 m.y., the approximate age of the basalt. At 25 m from the basalt plug, zircon gave the correct age of the tuff, indicating that heating did not exceed about 650°C at that distance. These figures thus yield evidence of the distance that the thermal disturbance might affect tuff in a repository as a result of a basalt intrusion.

Work on the field relations, chemistry, and petrologic evolution of southern Great Basin basalts continued in cooperation with D.T. Vaniman and others at Los Alamos National Laboratory. Studies have yielded the following significant results in 1981: (1) petrologic data suggest the rate of basaltic magma rise in the NTS region has been relatively slow--on the order of 0.1-0.5 m/s (Crowe and others, 1981); (2) fairly Quantitative estimates of the amount of magma erupted in quaternary fields have been derived from several parameters, including study of the ratios between cone, scoria sheet, and lavas; (3) the calculated magma volumes for individual centers ranged from about $7.8X10^5$ to $1.0X10^8$ m^3; (4) study of the abundance of lithic fragments in scoria shows that the amount of erupted wall rock can range from about 0.009 to 0.060 percent by volume of erupted material, and that the fragments are almost all derived from depths of less than about 200 m.

Among other results obtained in 1981 are that the rate of Pliocene and Quaternary basaltic eruptions in the NTS basalt belt appears to be increasing, but the volume of erupted material is decreasing. The three groups of basalts of Crater Flat, southwest of Yucca Mountain, have similar composition, suggesting similar magmatism, but trace elements indicate possible variations of source region with time (Vaniman and Crowe, 1981).

Reports

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Szabo, B. J., Carr, W. J., and Gottschall, W. C., 1981, Uranium-thorium dating of Quaternary carbonate accumulations in the Nevada Test Site region: U.S. Geological Survey Open-File Report 81-119, 35 p.

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Carr, W. J., and Rogers, A. M., 1982, Tectonics, seismicity, volcanism and erosion rates in the southern Great Basin, in Schneider, Robert, and Trask, N.J., U.S. Geological Survey Research in Radioactive Waste Disposal--Fiscal Year 1980: U.S. Geological Survey Open-File Report 82-509.

Hydrology

By W. E. Wilson, Lakewood, Colo.

Objective To determine present and past hydrologic regimes of the NTS area in order to predict the potential for ground-water transport of radioactive waste to the accessible environment.

Approach Test drilling and hydraulic testing are being conducted to characterize in detail the hydrologic regime of the Yucca Mountain area as part of an evaluation of its suitability for a waste repository. Results will provide information on potential ground-water flow pathways, bulk hydrogeologic properties of potential host rocks and surrounding rock units, and ground-water chemistry and age.

Digital models simulating ground-water flow and solute transport are required to predict rates and directions of movement of radioactive species and their concentrations in ground water if they should be released from a repository on or near the NTS. Data will be assembled to define the regional hydrology of southern Nevada and to characterize in detail ground-water flow from prospective repository sites to points of present and possible future discharge.

Worldwide changes in climate during the Pleistocene Epoch (glacial and interglacial stages) resulted in repeated changes in the ground-water regime. Future climatic changes are probable in the time period of significance to a repository for high-level and transuranic wastes. Paleohydrologic studies are being used to estimate water-table depths, hydraulic gradients, and flow paths to points of ground-water discharge during Pleistocene pluvial cycles in order to assess the differences between present hydrologic regimes and those that will prevail under wetter climates in the future.

Progress on tuffs Under the direction of F.E. Rush, hydraulic testing was conducted penetrated by three test holes on or near Yucca Mountain: wells USW-H1, UE25b-1H, and USW-VH-1. Hydraulic data were obtained during drilling and by means of tracejector surveys, pumping tests, and injection tests using both single and straddle packers. Preliminary results for each well follow:

(1) The unsaturated zone penetrated by well USW-H1 is 573 m thick and includes, in descending order, the Tiva Canyon, Yucca Mountain, Pah Canyon, and Topopah Spring Members of the Paintbrush Tuff; tuffaceous beds of Calico Hills; and the upper 7 m of the Prow Pass Member of the Crater Flat Tuff (see table 1). The upper three stratigraphic units and the tuffaceous beds of Calico Hills generally have high matrix porosity, commonly on the order of 40 percent. Pore saturation is variable and ranges from about 30 to nearly 100 percent, the latter value being in the lowest unit. The densely welded Topopah Spring Member of the Paintbrush Tuff has much lower matrix porosities, ranging from about 20 percent in its upper part to about 10 percent near its base. However, much of the Topopah Spring Member is highly fractured.

The saturated zone at well USW-H1 was penetrated from a depth of 573 m to 1,829 m and includes most of the Prow Pass Member, all of the Bullfrog Member and Tram unit of the Crater Flat Tuff and tuff of Lithic Ridge, and the older ash-flow and bedded tuff. Most of the units have relatively porous rock at or near their contacts. Nearly all of the relatively permeable rock is in the upper half of the Prow Pass Member of the Crater Flat Tuff in the depth interval 573-653 m. The transmissivity for this zone is 150 m^2/d, representing mostly the depth interval 573-597 m. Low-permeability rock occurs between depths of 653 and 792 m in the lower part of the Prow Pass and the upper part of the Bullfrog Members of the Crater Flat Tuff. The transmissivity for this zone is about 1 m^2/d, representing mostly the depth interval 736-741 m in the Bullfrog Member. Below a depth of 792 m to the total depth of the well, the rocks are relatively impermeable; transmissivity is less than 3×10^{-2} m^2/d.

(2) The tracejector survey in test hole UE25b-1H indicated that the water yielding zones occur from the water surface at a depth of 471 m in the Calico Hills to the top of the zone of no flow at 2,877 m, near the bottom of the Bullfrog Member. The most productive geologic unit, in the lower part of the Bullfrog Member, consists of bedded tuffs which have been reworked by streams. This unit contributed approximately 50 percent of the water produced from this hole. The second most productive geologic unit is the tuffaceous rocks in the lower part of the Calico Hills; these contributed approximately 30 percent of the water from this hole. The remaining 20 percent of the water was contributed by two fracture zones in ash flow beds in the upper part of the Prow Pass Member.

An observation well, UE25a-1, was used for monitoring water-level fluctuations during both the drawdown and recovery parts of pumping tests of test hole UE25b-1H. A pumping test of the total saturated thickness (749 m) for test hole UE25b-1H gave a transmissivity value of 1,000 m^2/d and an average hydraulic conductivity

of 1.4 m/d. During three pumping tests, water was discharged respectively at rates of 13.8, 35.7, and 37 L/s.

Average hydraulic conductivity for stratigraphic units, determined from pumping and injection tests, ranged from 0.001 m/d for the Tram unit of the Crater Flat Tuff to 36 m/d for the Bullfrog Member. The relatively low hydraulic conductivity for the Tram unit probably is representative primarily of the matrix of unfractured rock, and the relatively high hydraulic conductivity for the Bullfrog Member probably is representative primarily of bedded and reworked tuffaceous beds.

(3) Well USW-VH-1 was drilled to a depth of 762 m to obtain information about the geologic structure, volcanic stratigraphy, and hydrology of the upper volcanic deposits at Crater Flat. Aquifer tests showed that a zone in the Bullfrog Member of the Crater Flat Tuff extending from a depth of 626 m to the bottom of the well, is an artesian aquifer with a transmissivity of about 2,400 m^2/d and an estimated storage coefficient of 1×10^{-5}.

R. K. Waddell and J. V. Tracy have modified a two-dimensional finite-element transport code to describe transport of radionuclides including their decay-chain daughters, through porous media. The code contains terms for linear sorption, decay of sorbed and nonsorbed radionuclides, a first-order dissolution and precipitation reaction controlling the source term for radionuclides, and an analytic solution for the inventory of radionuclides in the source (repository). The code was written to describe the transport of radionuclides from a repository on a regional scale but will probably be modified to a three-dimensional code for repository-scale modeling. Methods for performing sensitivity analyses are being developed.

Geophysical and drillers' log data from the Amargosa Desert and Jackass Flats, Nevada, are being compiled by R. K. Waddell and W. J. Oatfield for use in developing a transport model to predict movement of radionuclides from a potential repository beneath Yucca Mountain. These areas are underlain by alluvium, playa deposits, volcanic tuffs, and perhaps carbonate rocks. To aid in these efforts, H. C. Claassen has analyzed geochemical data from samples collected from the alluvial and tuffaceous aquifers.

Tests by R. K. Waddell of test hole UE29a-2 in upper Fortymile Canyon, about 9 1/2 km (6 mi) northeast of test hole USW-G2 (figs. 1 and 2), indicated that the depth to water was much less than expected, providing evidence for the presence of low-permeability rocks north (upgradient) of Yucca Mountain. Pumping tests of three different horizons were performed, and samples were collected for determination of the general water chemistry; the ^{18}O, ^{16}O, ^{13}C, ^{3}H, and ^{14}C contents, and the D/H ratios. Dissolved-oxygen content varied with depth, decreasing from approximately 5 mg/L at a depth of 250 m to approximately 2 mg/L at 305 m.

Climatic changes over the last 65,000 yr in southern Nevada were interpreted by W. G. Spaulding (University of Washington), on contract to the USGS. Spaulding analyzed the species distribution and radiocarbon ages of fossilized vegetative remains in rat middens at the Nevada Test Site and vicinity. He concluded that during the late Wisconsin glacial maximum (about 18,000 yr

B.P.), vegetation at high elevations in southern Nevada was dominated by limber pine and bristlecone pine. At lower elevations, in the Amargosa Desert area, Utah juniper and single-needle pinyon and juniper prevailed. Sagebrush, horsebrush, and rabbitbrush were widespread.

From these vegetative conditions, Spaulding concluded that the climate during the glacial maximum was cooler and wetter than today's climate. Temperatures averaged as much as 7°C lower, and mean annual precipitation was 30-40 percent higher. Precipitation patterns were characterized by a significant absence of summer rainfall (less than 10 percent of the total). Based on these results at Yucca Mountain where today's average annual precipitation is about 130 mm, average rainfall during the late Wisconsin glacial maximum was probably 150-180 mm per year. Thus, although climatic conditions were slightly cooler and wetter, the effective amount of moisture available was not significantly higher than today.

A mineralogic study of borehole samples of alluvium is being made by B. F. Jones in an effort to identify features that would be diagnostic of formerly saturated conditions. Such a tool could be used to recognize the positions of higher water tables during Pleistocene time. Mineralogic and associated chemical investigation of matrix fines in alluvium from north of Frenchman Flat has been completed. Core from borehole U11g about 6 km north and about 90 m above the playa provided the only suitable samples for studying the paleohydrology over the full interval of about 90 m above the modern water table (depth 302 m). Properties of smectite clays and zeolite abundance have suggested evidence of increased hydration up to 55 m above, but clay accumulation just below the present water table argues for the water level being static over a long period. It is not certain how much of the differences in the degree of hydration may be related to conditions of deposition. A report is undergoing revision following review.

Reports

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Wilson, W. E., 1980, Status of geohydrologic investigations that are part of the Nevada Nuclear Waste Storage Investigations program (abs.), in Proceedings of the 1980 National Waste Terminal Storage Program Information Meeting: Office of Nuclear Waste Isolation Report ONWI-212 (addendum), p. 8-9.

Waste Isolation Pilot Plant, New Mexico

The DOE has been investigating an area about 45 km east of Carlsbad, New Mexico, to determine its suitability as a site for the Waste Isolation Pilot Plant (WIPP) (figs. 7 and 8), a geologic repository for nuclear wastes generated by defense activities. The geology and hydrology of the area are being studied in cooperation with Sandia Laboratories to provide the DOE with information on which to base an assessment of the site, particularly with respect to geologic stability, long-term isolation of waste radionuclides, and the potential for the hydrologic system to provide a barrier to radionuclide transport. The WIPP site is located in the Delaware Basin, a tectonically stable region. The potential host rock is bedded salt of the Salado Formation of late Permian age.

Salt Dissolution and Deformation Studies

By R. P. Snyder, Lakewood, Colo.

Geologic studies in and near the WIPP site are concerned with the identification and evaluation of salt dissolution and salt deformation processes and phenomena to determine their possible effect on the geologic integrity of the area. Included in the features under study are breccia pipes, dissolution fronts, and salt deformation structures.

Objective To characterize the salt dissolution and salt deformation features, and to determine whether they will have a negative effect on the integrity of the WIPP site.

Approach The geologic investigations involve the acquisition, analysis, and interpretation of subsurface data from (1) shallow core tests (<350 m) drilled to investigate dissolution phenomena in the Salado and Rustler Formations and (2) deep wells (>500 m) drilled to determine the nature of geophysical anomalies, to investigate deep dissolution, or to explore for oil and gas. The work involves the examination and analysis of cores, cuttings, and geophysical logs from the drill holes, and it includes regional geologic reconnaissance, detailed mapping, and the analysis of geophysical data. Samples are selected for age determination to estimate the rate at which the "dissolution front" is advancing and to date the formation of breccia pipes.

Progress Analysis of the data indicates that there are four known breccia pipes in the Delaware Basin (fig. 7). These pipes are all above the Capitan Limestone, an arcuate, mostly buried bounding reef of the Delaware Basin. The data included gravity and magnetic surveys and drill-core analysis from two vertical holes purposely drilled into suspected pipes. The sequential development of these pipes (generally about 250 m in diameter at the surface) includes periods of both gentle and catastrophic subsidence. At least one

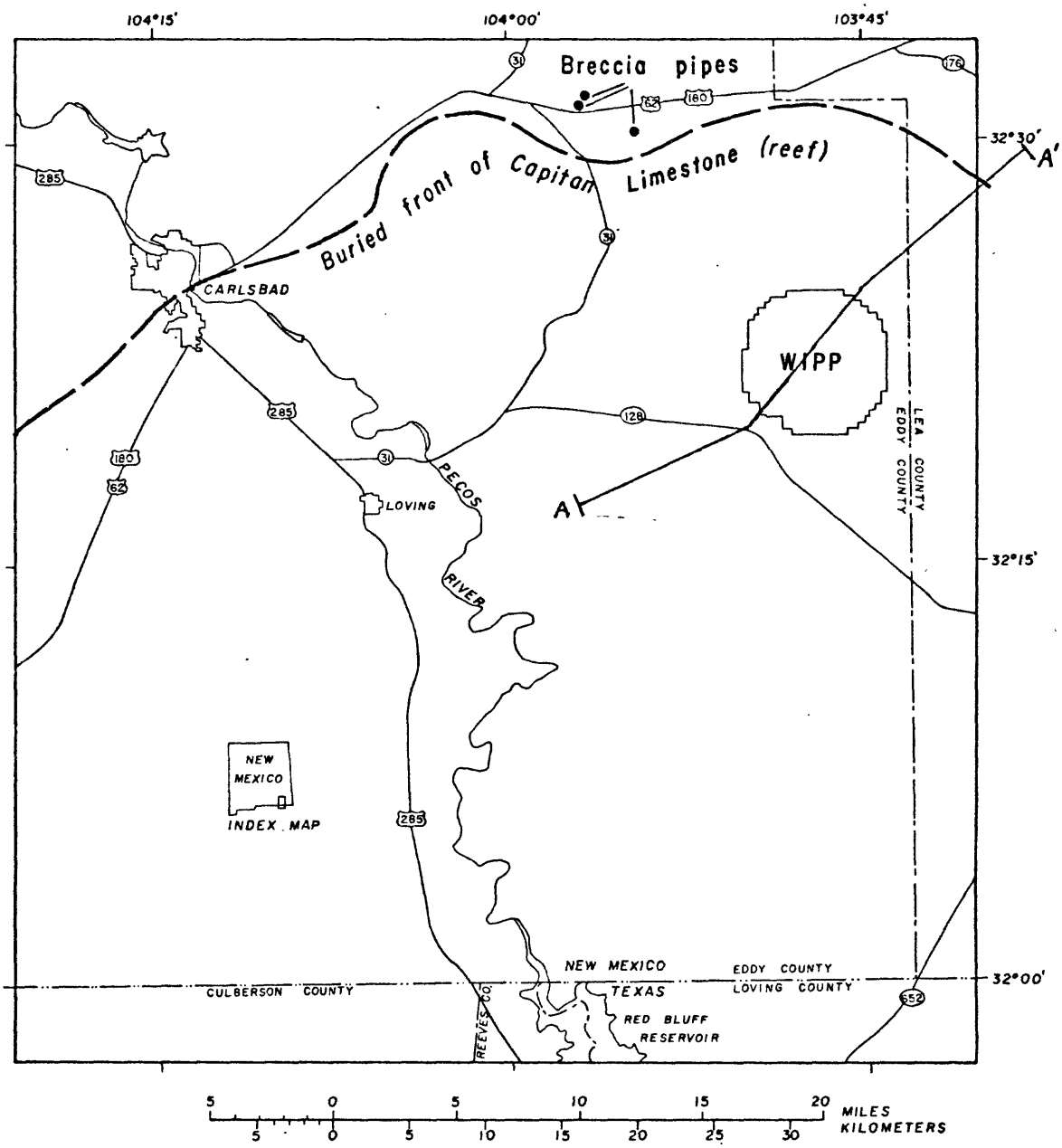

Figure 7.--Map of southeastern New Mexico showing location of the Waste Isolation Pilot Plant (WIPP) site, three of four known breccia pipes, and location of cross section A-A' shown in figure 8.

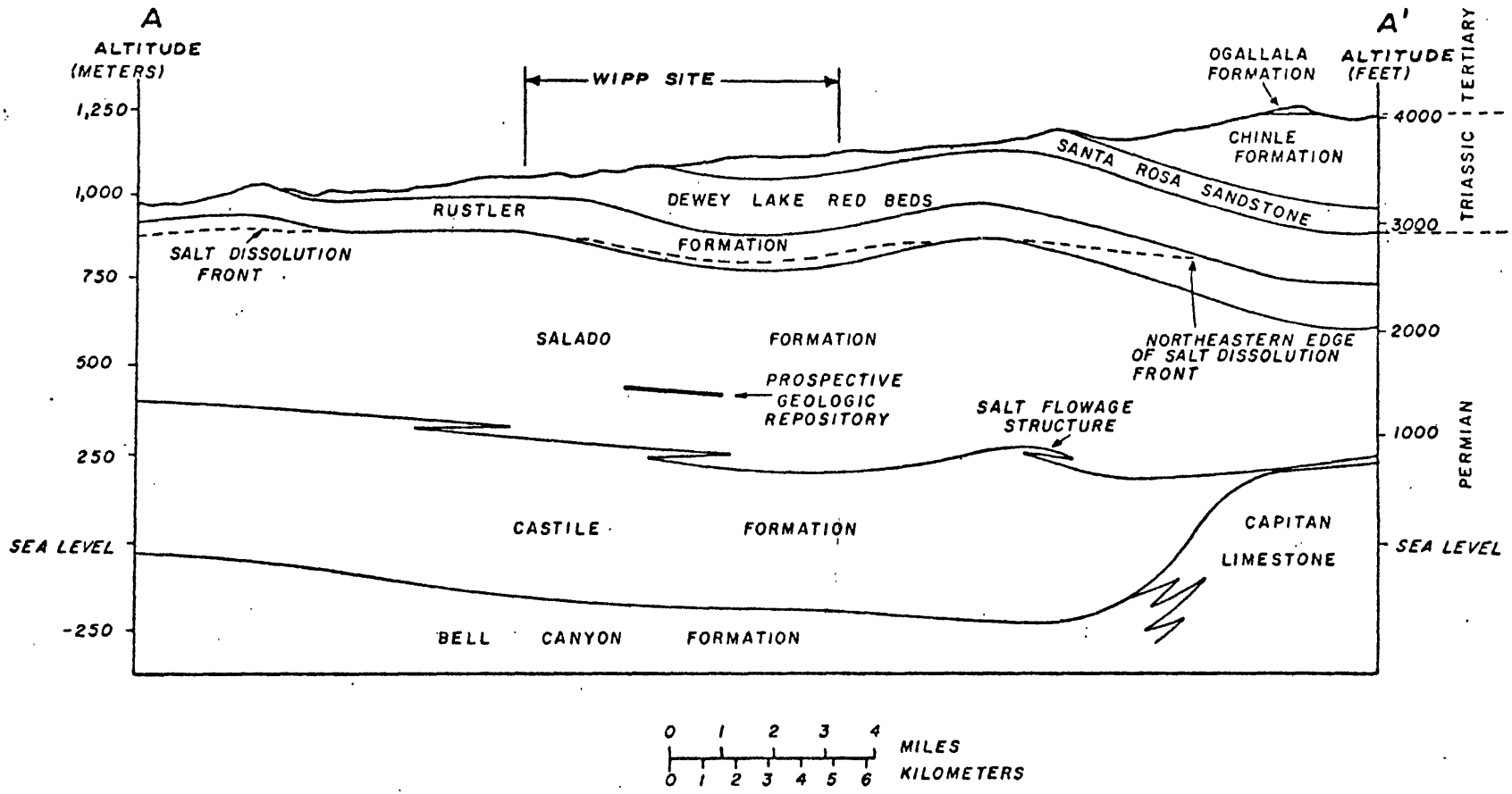

Figure 8.--Geologic section through Waste Isolation Pilot Plant site.

pipe is known to be rooted in the Capitan Limestone.[1] The pipes seem to have formed prior to 500,000 yr B.P. Later erosion leveled the area and probably helped fill in the depressions of the collapse areas. After leveling of the area, the Mescalero Caliche (500,000 yr B.P.) was deposited across the area and, sometime after that, halite was removed from the Rustler and Salado Formations around the pipes. This removal of halite lowered the surface surrounding the pipes, leaving the Mescalero Caliche to dip outward quaquaversally from the existing hills and providing a means for identifying the pipes at the surface.

Subsurface studies at and in the immediate vicinity of the WIPP site are designed to investigate deformational features in the evaporite section. These studies involve seismic reflection surveys and stratigraphic, mineralogic, and lithologic work on cores from several holes drilled to investigate the subsurface.

At the present time, an area in the northern part of the WIPP site called the "Disturbed Zone" (fig. 9) is being analyzed. The name "Disturbed Zone" comes from the fact that seismic signals in this area were not returned to the surface in an understandable manner but rather in a disturbed fashion. Apparently, the reflector horizons of anhydrite in the Castile Formation underlying the Salado Formation (repository horizon) are dipping at more than their regional 1° dip. Drill-hole correlations indicate that halite units in the Castile thicken and thin drastically in the disturbed zone. This may be due to salt flowage. Studies to date indicate that some of this flowage occurred in Permian time shortly after the Castile was deposited, and some of the flowage occurred sporadically as late as post-Triassic time.

This movement of halite has tilted and probably broken the middle and upper anhydrites of the Castile causing scrambled returns of the surface-generated seismic signals. In drill hole ERDA 6, the uppermost anhydrite was breached by the underlying halite unit, and no upper anhydrite was found in the drill hole (Jones, 1981a). A report on these subsurface studies is being written by personnel of the USGS and Sandia National Laboratories.

Reports

Jones, C. L., 1981a, Geologic data for borehole ERDA-6, Eddy County, New Mexico, U.S. Geological Survey Open-File Report 81-468, 59 p.

_____ 1981b, Geologic data for borehole ERDA-9, Eddy County, New Mexico: U.S. Geological Survey Open-File Report 81-469, 50 p.

Snyder, R. P., and McIntyre, A. F., 1980, Geological data for borehole WIPP 33, in Basic data report for borehole WIPP 33 (Waste Isolation Pilot Plant (WIPP): Sandia National Laboratories Report SAND2011, p. 4-22.

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[1] In the report for fiscal year 1980 (Schneider and Trask, 1982, p. 19) it was stated erroneously that a fragment of the Culebra Dolomite Member of the Rustler Formation was found at 30 m below its normal depth. The depth should be 252 m.

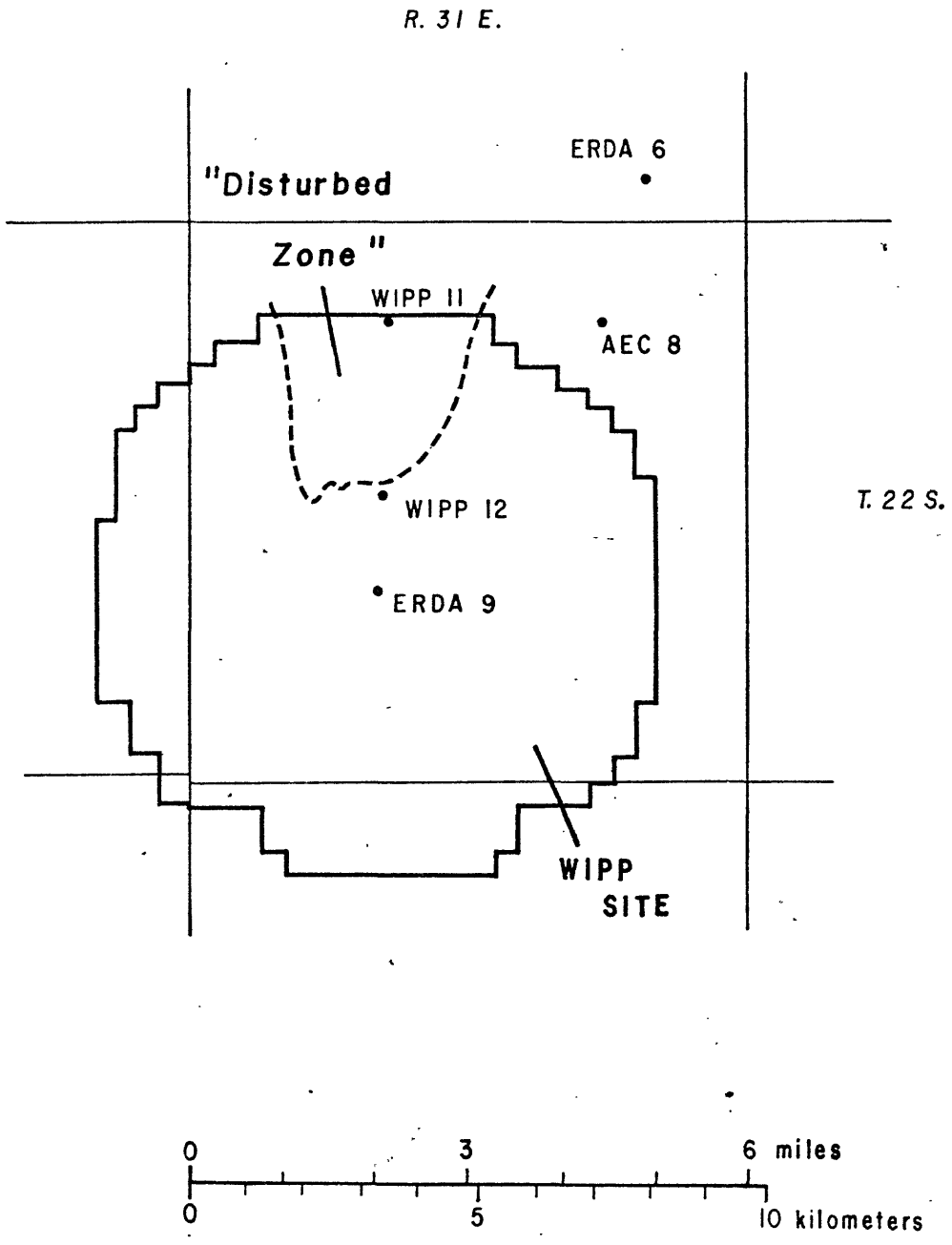

Figure 9.--Waste Isolation Pilot Plant site, southeastern New Mexico, showing selected drill holes and "disturbed zone." See location in figure 7.

Geochronology and Isotopic Studies

By John Rosholt, W. C. Gottschall, Barney Szabo, John Obradovich, and M. Tatsumoto, Lakewood, Colo.; and James R. O'Neil, Menlo Park, Calif.

Objective To date the time of formation of various geologic materials, and by use of natural isotopes, determine and describe geologic processes pertinent to the geologic stability and integrity of a waste repository at the WIPP site.

Approach Samples of solids, liquids, and gases are collected and isotopic ratios determined by various techniques involving mass spectrometry. The results are interpreted in terms of ages or descriptions of geologic processes.

Progress Geochronology and isotopic studies fall into three categories: hydration and solution of potash and anhydrite, dating the formation of breccia pipes, and stable isotope studies.

Hydration and Solution of Potash, Anhydrite, and other Minerals (John Rosholt, W.C. Gottschall, and Barney Szabo, Lakewood, Colo.)--This part of the project is aimed at determining the time at which subsurface solution of potash and alteration of anhydrite and polyhalite to gypsum (which develops where shallow ground waters first interact with the anhydrite formation) have occurred near the WIPP site. Investigation of cores from the WIPP site, using the uranium-trend method, was continued to determine times of subsurface dissolution processes.

Uranium and thorium analyses of samples from the upper part of the Salado Formation at test hole WIPP-25 (8 km west northwest of the center of the WIPP site) gave a value of >800,000 years B.P. for any dissolution process. These results confirm previously indicated long-term stability at this location.

Results from the upper part of the Rustler Formation at test hole WIPP-27 (15 km northwest of the center of the WIPP site) also gave a value of >800,000 years before present. Samples from the lower part of the Dewey Lake Red Beds (or the very top of the Rustler Formation) at WIPP-27, however, gave a value of about 470,000 years since dissolution activity. Several complications during analysis of the WIPP-27 samples prevent a firm conclusion that dissolution occurred less than 800,000 years ago.

No further work is planned for this project.

Dating the Formation of Breccia Pipes (John Obradovich and M. Tatsumoto, Lakewood, Colo.)--These studies are attempting to date the time of formation of breccia pipes and help to determine their origin, as well as date the times of diagenesis and deformation metamorphism of the evaporite deposits. This is being done through K-Ar and K-Ca dating of samples of sylvite, polyhalite, langbeinite, diagenetic silicates, or other appropriate minerals from breccia pipes.

Clays, which could possibly be authigenic, were collected along the face of a breccia pipe in one of the drifts of the Mississippi Chemical Co. mine (MCC). K-Ar dating of three samples gave ages ranging from 304 to 344 m.y. As the age of the evaporite deposits is Late Permian (approximately 240 m.y.) it is clear that no subsequent diagenesis of the clays or thermal overprint was involved during the formation of this breccia pipe.

The following table gives the K-Ar and K-Ca age determinations. Efforts to do simultaneous K-Ar, K-Ca, and Rb-Sr on the same fragment of sylvite have not been successful.

Sample Number	K-Ca age (m.y.)	K-Ar age (m.y.)
	Mississippi Chemical Co. mine	
MT-2 Clays at Breccia Pipe		333 ± 5
		304 ± 6
		344 ± 9
MT-4 Sylvite	3.7	6.5
	4.2	14.8
	2.3	5.0
	1.7	9.9
	3.3	
	1.7	
	Duval mine	
MT-5 Sylvite		7.5
MT-6 Sylvite	32.9	17.8
	36.8	13.9
	37.0	14.6
		13.1
		19.2
MT-6 Langbeinite		164 ± 2
MT-7 Polyhalite		241 ± 5

The results suggest two different periods of recrystallization for the two separate sets of samples from the Mississippi Chemical Co. and the Duval mines. All of the analyses deal with separate fragments from single, large hand samples. Samples MT-5 and MT-6 (Duval mine) have K-Ar ages ranging from 7.5 m.y. (MT-5) and 13.1 m.y. to 19.2 m.y. (MT-6). K-Ca ages on MT-6 range from 33 to 37 m.y. Langbeinite from the same hand sample gives a K-Ar age of 164 m.y. Because the degree of solubility decreases from sylvite through langbeinite to polyhalite, we believe that the sylvite was dissolved and recrystallized in middle Tertiary time by a process that did not affect the langbeinite. Loss of argon by diffusion can be called upon to explain the discordant K-Ar and K-Ca results, but this is not a totally satisfactory

explanation, because the reverse discordancy is seen in sample MT-4. Excess radiogenic calcium-40 contained in the fluid inclusions may also be called upon to explain some of the discordancy.

For sample MT-4, the K-Ar ages are older than the K-Ca ages. Although the levels of radiogenic calcium measured are low (from 1.7 to 12 percent), the degree of precision of the calcium-isotopic measurements are such as to indicate that the K-Ca ages are meaningful. That is, we believe that the youngest ages to be a realistic assessment of the time of dissolution and recrystallization. Any variation in age is thought to reflect incorporation of both radiogenic calcium-40 and argon-40 in the fluid inclusions. The concentration level of calcium averages about 2 ppm, ranging from 1.2 to 3.5 ppm.

Stable Isotope Studies (James R. O'Neil, Menlo Park, Calif.)--Most of the brines in the Delaware Basin appear to be genetically related and composed of mixtures of Permian seawater and ground water under varying conditions. The brine from test hole ERDA No. 6 and halite inclusions found at the ERDA No. 9 site most probably formed from waters released from the complete dehydration of gypsum and were subsequently diluted by additions of ground water attendant on recrystallization of halite. Under unusual chemical and hydrologic conditions, anhydrite could have been a primary precipitate (Cody and Hull, 1980), but we accept the more common notion of gypsum precipitation followed by slow release of water after burial. There is no doubt that complex processes of ion and isotopic exchange (Lambert, 1978) occurred in restricted areas of the basin. For example, whereas the D and ^{18}O contents of brines from the Duval mine (5 km southwest of the WIPP site) and from the Todd wells (5-6 km south of the site) are similar, there is a marked enrichment of potassium in the Duval mine waters, these waters being active seeps through potash deposits. However, the simple model of repeated inundations and evaporations of seawater, culminating in a mixing with local ground waters, accounts for essentially all of the geochemical characteristics of the Delaware Basin samples that we analyzed.

It is clear that ground waters have entered the evaporite system in the Delaware Basin but there is no evidence for circulation of fluids in this system. In fact, the isotopic ratios of the brine at the ERDA No. 6 site are so unusual that small amounts of this water could be easily detected should it move to another part of the basin.

Report

Szabo, B. J., Gottschall, W. C., Rosholt, J. N., and McKinney, C. R., 1980, Uranium-series disequilibrium investigations related to the WIPP site, New Mexico: U.S. Geological Survey Open-File Report 80-870, 22 p.

References

Cody, R. D., and Hull, A. B., 1980, Experimental growth of primary anhydrite at low temperatures and water salinities: Geology, v. 8, p. 505-509.

Lambert, S. J., 1978, Geochemistry of Delaware Basin groundwaters: New Mexico Bureau of Mines and Mineral Resources, Circular 159, p. 33-38.

Schneider, Robert, and Trask, N. J., 1982, U.S. Geological Survey research in radioactive waste disposal-Fiscal Year 1980: U.S. Geological Survey Open-File Report 82-509, 110 p.

Hydrology

By Jerry W. Mercer, Albuquerque, N. Mex.

Objective To evaluate the hydrologic systems on a regional and site-specific basis with regard to their potential for radionuclide transport.

Approach Data are being acquired and assembled to define in detail the hydrology of the WIPP site including its relationship to regional ground-water systems. These data will be used to improve digital models simulating ground-water flow and solute transport. The models will be needed to predict rates and directions of movement of radioactive species and their concentrations in ground water if they should be released from a repository.

Progress The drilling and hydrologic testing of 30 test holes have resulted in the identification of three water-bearing zones above the salt and one below which could serve as pathways for waste transport. Testing and analysis of data were completed in 1981.

Potentiometric-surface maps show flow to the west toward Nash Draw at the Rustler-Salado contact and in the Magenta Dolomite Member of the Rustler Formation and flow to the south in the Culebra Dolomite Member of the Rustler Formation (see table below). Flow in the Bell Canyon Formation below the evaporite section generally is toward the northeast.

Permian stratigraphic formations associated with the Salado Formation in the WIPP area

Series	Formation	Lithology	Thickness (m)
Ochoan	Dewey Lake Red Beds	Siltstone and sandstone	30-170
	Rustler	Anhydrite, dolomite, and sandstone	85-130
	Salado	Rock salt; minor amounts of anhydrite, polyhalite, and potash ores	530-610
	Castile	Anhydrite with some limestone and salt	400-405
Guadalupian	Bell Canyon	Sandstone	305

Calculations from pump, slug, and pressure-pulse tests indicate that transmissivities vary laterally within as well as between water-bearing beds. The Culebra Dolomite Member of the Rustler Formation, the most permeable zone, also has the greatest variability in transmissivity with values ranging from 13 to 10^{-5} m^2/d. Transmissivity of the Magenta Dolomite Member ranges from 10^{-2} to 10^{-4} m^2/d while that for the Rustler-Salado contact (the least productive zone) ranges from 10^{-2} to 10^{-6} m^2/d. The data indicate that the variability of transmissivity within the Rustler Formation, particularly in the Culebra Dolomite Member, is caused by subsidence and fracturing of overlying dolomite beds due to local dissolution of the evaporites.

Hydrologic testing of drill holes in Nash Draw, a prominent topographic depression with closed drainage about 3-8 km west of the WIPP site, was completed. The feature was probably developed by a combination of dissolution resulting in subsidence and accelerated erosion. The result was the development of an area under which the rock formations have a much higher transmissivity than those at the WIPP site. It is believed that this feature is along the flow path of waters passing through the WIPP site.

Report

Mercer, Jerry W., and Gonzales, D. P., 1981, Geohydrology of the proposed Waste Isolation Pilot Plant in southeastern New Mexico: New Mexico Geological Society, Special Publication No. 10, p, 123-131.

Hanford Reservation Region, Washington

The DOE, through its contractor, Rockwell Hanford Operations, is investigating the feasibility of and the technology for designing and constructing a repository for commercial high-level radioactive waste at the Hanford Reservation in basalt flows of the Columbia Plateau (fig. 9). In support of this effort, the USGS has been requested by the DOE to make reconnaissance geologic maps of the Columbia River Basalt Group. This work is being conducted in parallel with additional geologic studies by Rockwell within the Hanford Reservation and vicinity. The model studies of ground-water flow in basalt aquifers, which were conducted in fiscal years 1979-80, were discontinued.

Geologic Mapping of the Columbia Plateau

By Donald A. Swanson, Vancouver, Wash.

Basalt flows of the Columbia River Basalt Group of Miocene age underlie most of the Columbia Plateau (fig. 10). Recent advances in knowledge of the basalt permit it to be subdivided into many mappable units (Swanson and others, 1979). This has made possible the mapping of these units and evaluation of the amount and style of basalt deformation on a regional scale. Such information heretofore has been unobtainable except for local areas; for the first time a geologic overview of the entire Columbia Plateau is being achieved.

Objective To prepare a geologic map of the Columbia River Basalt Group in Washington, Oregon, and Idaho at a scale of 1:250,000. The map will be used in the DOE's evaluation of the regional tectonic and stratigraphic features as they pertain to the underground storage of radioactive waste.

Approach The geology of the region is mapped on quadrangle maps or aerial photographs by standard field methods. Individual lava flows or several similar flows are traced in the field. The stratigraphy of the lava flows was defined using physical characteristics supplemented by a large number of chemical analyses which demonstrated clear distinctions between otherwise similar flows. Use is also made of the fluxgate magnetometer to identify normal or reversed magnetic polarity of the flows (which indicates whether the earth's magnetic field was normal or reversed when the lava flow solidified).

Progress Nearly all of the Columbia River Basalt Group in and east of the Cascades has now been mapped. The principal map units, in descending stratigraphic order, are: the Wanapum Basalt, the Grande Ronde Basalt, and the Picture Gorge Basalt. The major unmapped portion is in the John Day Basin, underlain wholly by Picture Gorge Basalt. In addition, a large area of basalt in and bordering the Willamette Valley has been mapped. The following personnel conducted field work in fiscal year 1981: M. H. Beeson, P. R. Hooper, D. A. Swanson, and W. H. Taubeneck.

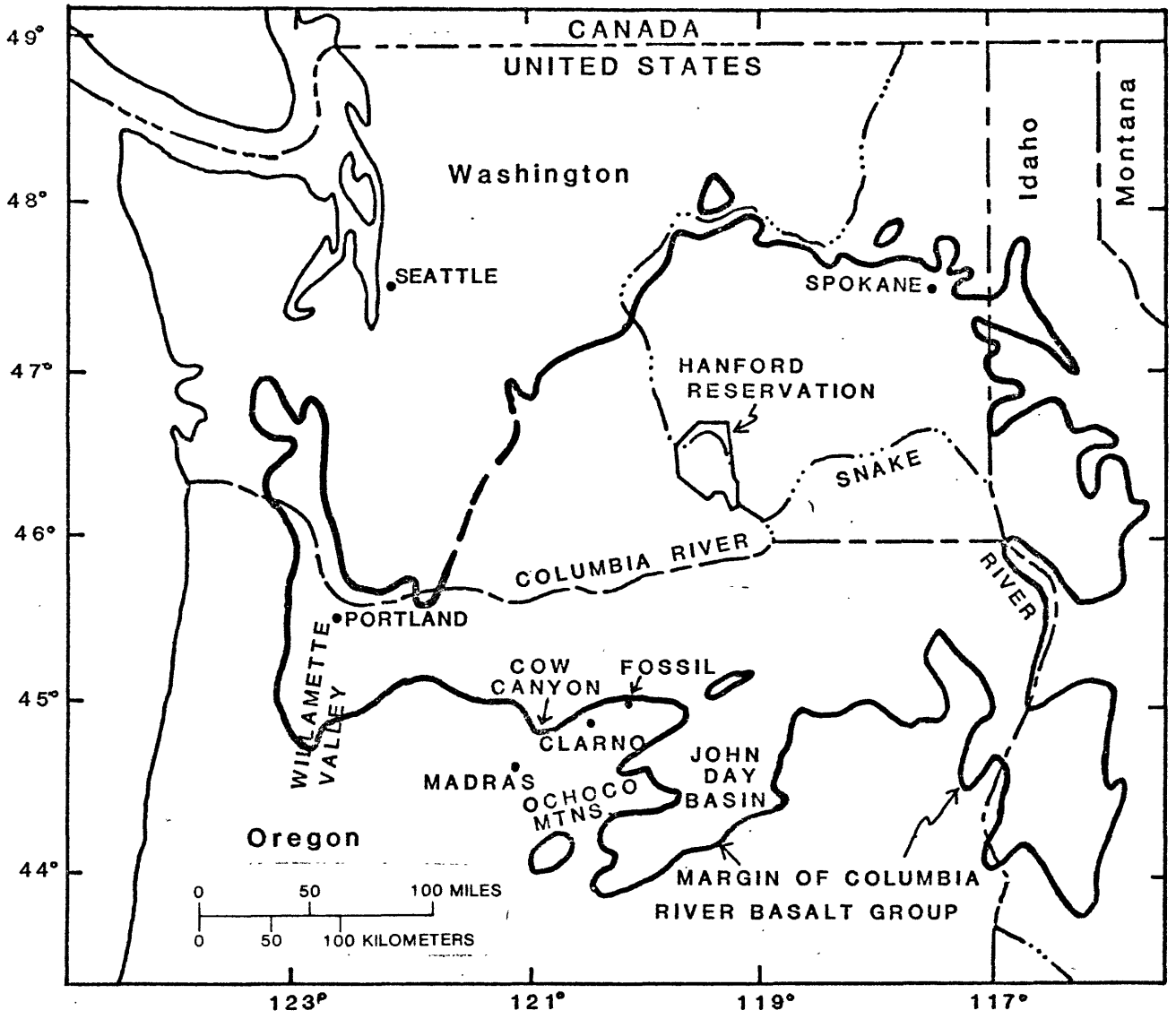

Figure 10.--Index map of Columbia Plateau.

The Frenchman Springs Member of the Wanapum Basalt has been found just south of the 45th parallel in the region of the Bend 1:250,000 sheet, west-central Oregon. This is the southernmost known occurrence of any member of the Wanapum Basalt. The outcrops occur as high as 1,005 m on the Shaniko surface and indicate that this surface, a dip slope extending north from the core of the Ochoco Mountains (fig. 10), acquired its slope after eruption of the Frenchman Springs.

Several normally magnetized flows of Prineville chemical type are present in the N_2 part of the Grande Ronde Basalt in the Madras basin-Clarno area of north-central Oregon. These flows, in places separated from one another by thin sedimentary interbeds, underlie low MgO-type Grande Ronde in most places. Nowhere were they found to overlie Grande Ronde. Near Clarno, a Prineville-type flow rests on Picture Gorge Basalt. At Cow Canyon, two Prineville-type flows comprise the lower 180 m of section. The extent and thickness of these flows indicate that the Prineville is a major chemical type in the southwestern Columbia Plateau.

Normally magnetized flows of Picture Gorge Basalt occur extensively in the Clarno-Fossil, Oregon, area. They underlie the R_2 magnetostratigraphic unit of the Grande Ronde Basalt in places and the N_2 unit elsewhere. The westernmost occurrence is about 11 km west of Clarno, nearly 20 m farther west than previously known.

Numerous small northwest-trending strike-slip faults (probably right lateral) were mapped in the north-central part of the Bend 1:250,000 sheet. Several northeast-trending strike-slip faults (probably left lateral) were also found. These sets of faults continue patterns previously found farther north and illustrate the pervasive nature of lateral shear in post-Wanapum time in the western Columbia Plateau.

Reports

Swanson, D. A., and Wright, T. L., 1980, The regional approach to studying the Columbia River Basalt Group, p. 58-80, in Deccan volcanism and related basalt provinces in other parts of the world: Geological Society of India Memoir 3.

Swanson, D. A., Anderson, J. L., Camp, V. E., Hooper, P. R., Taubeneck, W. H., and Wright, T. L., 1981, Reconnaissance geologic map of the Columbia River Basalt Group, northern Oregon and western Idaho: U.S. Geological Survey Open-File Report 81-797, scale 1:250,000.

Reference

Swanson, D. A., Wright, T. L., Hooper, P. R., and Bentley, R. D., 1979, Revisions in stratigraphic nomenclature of the Columbia River Basalt Group: U.S. Geological Survey Bulletin 1457-G, 59 p.

Paradox Basin, Utah

The portion of the Paradox Basin in eastern Utah is being explored by the DOE through its contractor, the Office of Nuclear Waste Isolation of Battelle Memorial Institute, to locate a potential repository site. Geologic investigations are being conducted by Woodward-Clyde Consultants and the U.S. Geological Survey; the Utah Geological and Mineral Survey is reviewing the mineral resource potential of the area.

Geology

By Robert J. Hite, Lakewood, Colo.

The initial investigations focused on Salt Valley, one of a series of northwest-trending diapiric salt anticlines along the northeast edge of the Paradox Basin in southeast Utah. In fiscal year 1980, the investigations were expanded to include study areas at Gibson Dome, Lisbon Valley and Elk Ridge (fig. 11). Efforts in fiscal year 1981 were focused on the Gibson Dome study area.

Objective To assist DOE and its contractors in the acquisition and interpretation of basic geologic data from drill cores in the Paradox Basin area.

Approach The core is described and logged using visual and nondestructive optical aids. Bromine content, insoluble residues, water content, gas inclusions, hydrocarbon and kerogen contents, mineralogy and petrology of the marker beds, and various physical properties are determined on samples of the cores.

Progress Characterization of the cores from the Gibson dome test hole (G.D. No. 1) was 50 percent complete at the end of fiscal year 81. This work included; (1) sampling all halite beds from Salt 4 to 15 [1/], (2) X-ray analyses of whole rock samples and insoluble residues for Salt 4, 5, 6, 7, 8, 9, 10, and 13, (3) determination of bromine values on 0.6-m sample intervals through Salt 6, mineralogy of the marker bed above and below Salt 6, and pyrolysis fluorescence on samples from the marker beds above and below Salt 6. In addition, cores from the potash-bearing intervals in Salt 13 and 18 were quartered and submitted to USGS laboratories for chemical analyses.

Some of the preliminary work on Salt 6 (the potential repository layer) can be summarized as follows:

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1 Stratigraphic nomenclature for the salt section in the Paradox Basin is described in Hite and Lohman (1973).

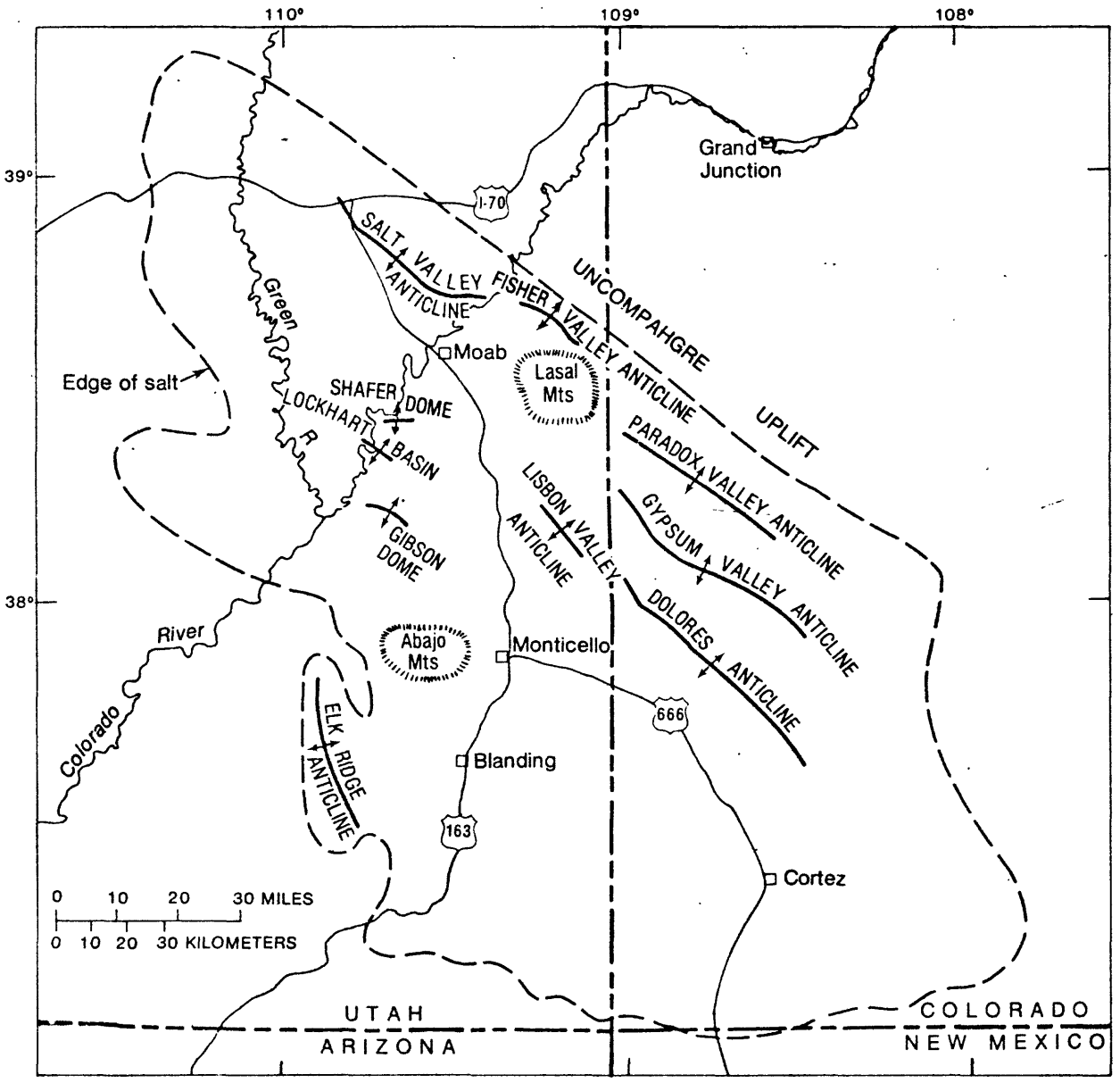

Figure 11.--Paradox Basin, Utah and Colorado.

The carnallite marker, which is regional in extent, is well developed in the core of test hole G.D. No. 1. It is about 43 m thick and occupies the upper half of the salt bed. It consists primarily of halite rock that contains carnallite ($KCl.MgCl_2.6H_2O$) and kieserite ($MgSO_4.H_2O$). The amount of carnallite present in any of the sample intervals does not exceed 8.0 percent and thus it does not constitute a potash resource.

Regional correlations show that the carnallite marker cuts across stratigraphic boundaries.

Water insoluble residues for Salt 6 average about 4 weight percent. This material consists primarily of anhydrite, with minor amounts of quartz, talc, corrensite, dolomite, calcite, and kieserite. Plots of the vertical distribution of weight percent insolubles, in Salt 6 in test hole G.D. no. 1 and in a corehole located about 30 km north at Shafer dome, show good correlation. From these correlations it can be shown that regional thinning (Salt 6 is 100 m thick at Shafer dome) is accomplished principally by internal thinning. There appears to be no loss of halite at the top of Salt 6 in test hole G.D. no. 1 due to dissolution.

The plot of vertical distribution of bromine in Salt 6 halite in test hole G.D. no. 1 shows a normal profile. At the base of the bed, Br values are about 80 ppm, but rapidly increase to about 220 ppm at the base of the carnallite marker and remain in this range to the top of the bed. No diagenesis (solution and recrystallization) is indicated by this profile.

In fitting the lithologies of the marker bed above Salt 6 with the various geophysical logs run in test hole G.D. no. 1, it was discovered that almost 10 m of core was lost in this critical interval. We are now attempting to determine the actual intervals of loss by fitting lithologic units in the remaining core to appropriate intervals of the geophysical log.

We were requested by ONWI to analyze halite samples from the Asse Mine in West Germany for water content using our methanol extraction technique.

The samples have been received and prepared for this determination. Because of the highly fractured nature of some of these samples we developed a technique of dye impregnation which makes micro-fracturing, induced by the coring process, highly visible. This technique is very useful for selecting core samples for water-content determination. Samples which are highly fractured will have lost much of their inclusion water.

It has been suggested by investigators in West Germany that in the system methanol + H_2O + NaCl, chemical bonding may tie up part of the H_2O, and that a Karl Fischer titration of the methanol may not account for all of the H_2O in the system. Thus, methanol extraction of halite rock may give H_2O determinations which are too low. Our experiments concerning this matter showed that bonding of H_2O is not a problem in the determination of H_2O in halite samples. We were able to recover all of the H_2O experimentally added to static systems of methanol + NaCl + measured amounts of natural H_2O.

All bromine determinations for halite rock at Salt Valley were finished and plotted. These data along with insoluble residue data, megascopic core descriptions, and geophysical logs are now being used for the final structural interpretation of test hole DOE No. 3 at Salt Valley.

Geologic cross sections through Elk Ridge and Lisbon Valley are now complete and ready for drafting. The Elk Ridge cross section shows reverse faulting in the Paradox Member of the Hermosa Formation in the Kidd well and normal faulting in the Kubat well. Also, an anomalous zone of complex salt flowage is present in the Mountain Fuel and Supply Milk Ranch well in the Elk Ridge area.

Reference

Hite, R. J., and Lohman, S. W., 1973, Geologic appraisal of Paradox Basin salt deposits for waste emplacement: U.S. Geological Survey Open-File Report, 75 p.

Quaternary Geology of the Fisher Valley Area, Utah

By Steven M. Colman and Fred F. Hawkins, Lakewood, Colo.

The geology of the Fisher Valley area, Utah, (figs. 11, 12) relates to a variety of factors that are significant in evaluating the potential of the Paradox Basin for locating a waste repository. The salt diapir and the contiguous Quaternary sediments in the Fisher Valley area provide the best record of Quaternary salt deformation in the Paradox Basin; in addition, the physical stratigraphy, buried soils, and fossil content of the Quaternary sediments provide the most complete record of Quaternary environments and climates in this region. Thus, the history of the Fisher Valley area has important implications for radioactive waste disposal anywhere in the Paradox Basin.

Objective To determine the extent and timing of deformation of Quaternary sediments and attendant drainage modifications in the Fisher Valley area and the relation of this deformation to the adjacent salt diapir; to determine the paleoclimatic and geomorphic significance of the physical stratigraphy, buried soils, and fossil content of the Quaternary sediments; and to estimate possible future climatic and geomorphic changes.

Approach The Quaternary geology of the area was mapped in detail, including the measurement of stratigraphic sections, to determine the pattern of deformation of the Quaternary sediments and the relation of this deformation to the salt diapir. The sediments and soils in the section were sampled for soils analysis, paleomagnetism, thermoluminescence, and uranium-series analysis. These samples will provide chronologic, paleoenvironmental, and paleoclimatic information.

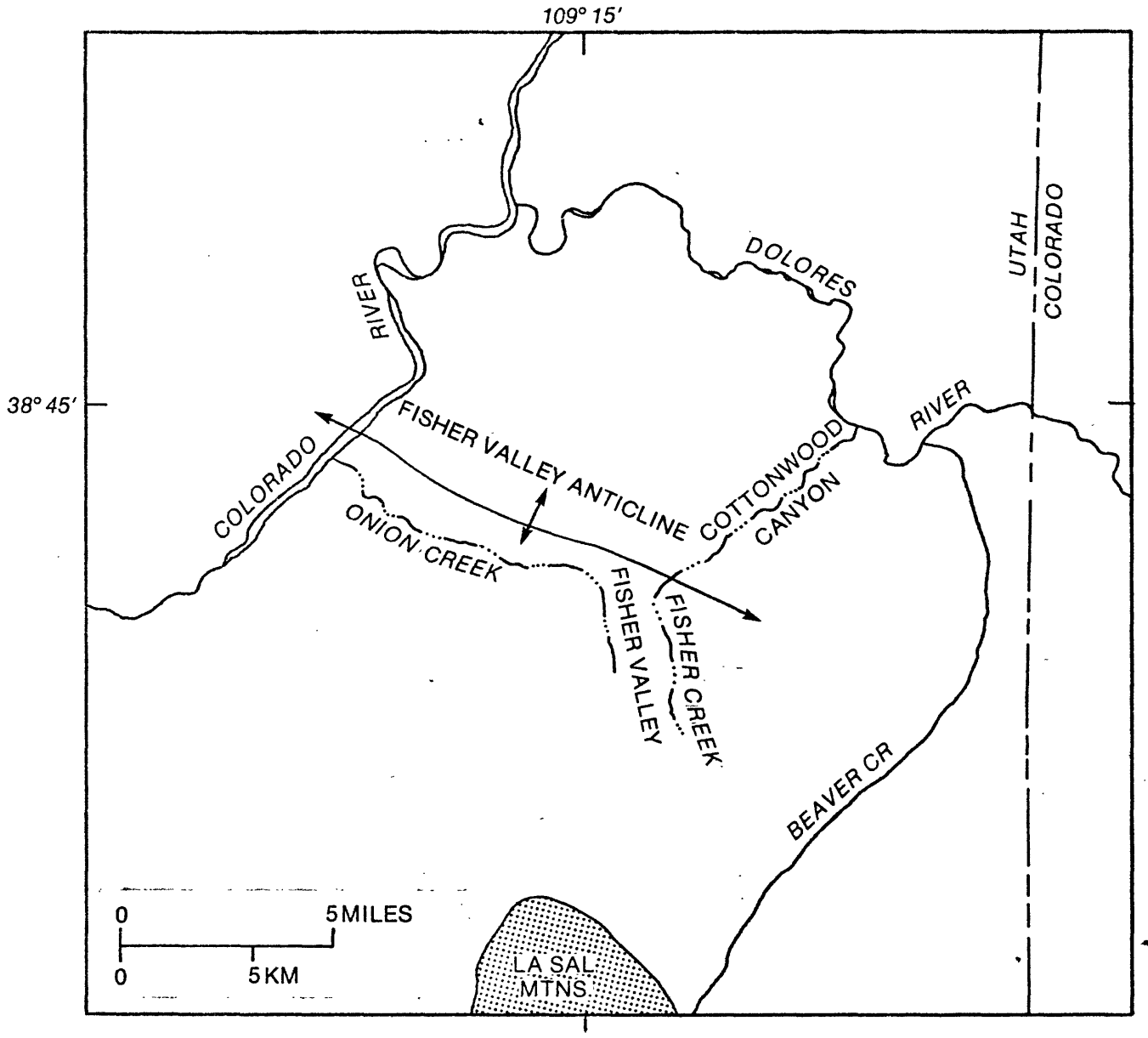

Figure 12.--Sketch map showing location of Fisher Valley anticline and geographic features in the vicinity of Fisher Valley, Utah.

Progress Mapping of the surficial geology of the Fisher Valley area, including plane-table mapping of the ash-bed stratigraphic markers, suggests a complex pattern of deformation of the Quaternary sediments. The sediments define a depositional basin that corresponds approximately to the present erosional amphitheatre at the head of Onion Creek (fig. 12). Most of Fisher Valley is underlain by relatively thin Quaternary sediments and shallow bedrock. The sediments can be divided into three units: (1) a lower unit composed of massive eolian sand interbedded with fluvial sand and gravel that contains the 700,000-year-old Bishop ash near its top, (2) a middle unit composed of well-sorted, thin-bedded sand that contains the 600,000-year-old Lava Creek ash at its base, and (3) an upper unit composed of poorly sorted fluvial sand and gravel interbedded with massive eolian sand. A strongly developed soil is present in the top of the upper unit, and the unit is overlain by Holocene eolian sand. Holocene alluvium is present along Onion Creek in the erosional amphitheatre.

Preliminary results of grain-size, carbonate, and bulk density analyses suggest that both the upper and the lower unit contain several well-developed buried soils. These soils, in addition to the ashes, suggest that the section represents at least the last 850,000 years and probably records much of the Quaternary history of the area. Of all the Quaternary deposits in the Paradox Basin (Biggar and others, 1981), the Fisher Valley section contains by far the most complete record.

The surficial mapping builds on earlier mapping of the Fisher Valley salt diapir (Shoemaker, 1954). Small remnants of highly deformed gravels containing many rock fragments derived from the La Sal Mountains are infolded into the caprock of the salt diapir and are unconformably overlain by the lower Quaternary unit. These gravels are very similar to the conglomerate in Castle Valley, which has been estimated as Pliocene or early Pleistocene in age (Hunt, 1958). Fisher Creek, the only possible source of the gravels, does not presently drain the La Sal Mountains; the presence of the gravels thus indicates profound geomorphic changes since their deposition. Fisher Creek appears to have once headed in the La Sals and drained to the Colorado River (fig. 12); its headwaters were probably captured by Beaver Creek, and it appears that movement of the salt diapir blocked Fisher Creek and diverted it into Cottonwood Canyon and the Dolores River.

The lower Quaternary unit dips radially away from the nose of the salt diapir, and deformed remnants of the unit occur on top of the caprock of the diapir. The diapir has thus clearly moved in Quaternary time, probably since the end of the deposition of the lower unit 600,000 to 700,000 years ago. The middle and upper units are not in contact with the caprock of the diapir, so younger movement of the diapir is difficult to identify. However, the Quaternary section dips inward around the edges of the depositional basin and contains several angular unconformities, especially between the major units. These units become nearly flat lying and conformable in the center of the basin. This pattern of deformation suggests periodic subsidence of the depositional basin, perhaps due to solution and removal of salt below the basin.

References

Biggar, Norma, Hardin, Debra, and Gillam, M. L., 1981, Quaternary deposits of the Paradox Basin, in Wiegand, D. L., ed., Geology of the Paradox Basin: Rocky Mountain Association of Geologists--1981 Field Conference, p. 129-148.

Hunt, C. B., 1958, Structural and igneous geology of the La Sal Mountains, Utah: U.S. Geological Survey Professional Paper 294-I, p. 305-364.

Shoemaker, E. M., 1954, Structural features of southeastern Utah and adjacent parts of Colorado, New Mexico, and Arizona: Utah Geological Society Guidebook 9, Stokes, W. L., ed., p. 48-69.

Hydrology

By Merrick S. Whitfield, Lakewood, Colo.

Objective To determine the geologic and hydrologic relationships between the bedded-salt deposits and the regional ground- and surface-water flow systems in the Paradox Basin of Utah and Colorado (fig. 11). The results are intended to provide a regional hydrogeologic framework upon which to base more detailed investigations of potential repository sites for high-level radioactive wastes.

Approach Regional hydrogeologic reconnaissance studies were conducted primarily using available data and reports supplemented by data on existing wells and measurements of the specific conductance of streams. Test drilling and hydraulic testing were undertaken in Salt Valley near Moab, Utah.

Progress The second of two site-specific reports (Wollitz, and others, 1982) was released evaluating the geology and hydrology of caprock overlying bedded-salt deposits. The number of site-specific reports was erroneously reported as three in the progress report for fiscal year 1980 (Schneider and Trask, 1982).

Indicated below is the status of five reconnaissance reports describing the regional characteristics of ground-water recharge and discharge and water quality for the two major aquifer systems in the basin.

The upper system overlies the salt and discharges to major streams within the study area. It includes from top to bottom, water-bearing units in the following stratigraphic units: Dakota Sandstone (Cretaceous), Entrada Sandstone (Jurassic), Navajo Sandstone (Jurassic and Triassic (?)), Wingate Sandstone (Triassic), and Cutler Formation (Permian). The lower system is in the Mississippian Leadville Formation which does not crop out in the Paradox Basin.

The reports on the Green River-Moab area in the northwestern part of the Paradox Basin and on the results of hydraulic tests in wells in Salt Valley, Grand County, Utah, have been approved for release.

The following four reports are being reviewed:

Ackerman, D. J., Reconnaissance of geohydrology of the San Miguel River Basin, southwestern Colorado

Whitfield, M. S., Jr., Zimmerman, E. A., Rueger, B. F., Oatfield, W. J., and Thordarson, W., Regional hydrology of the Blanding-Durango Area, Utah and Colorado.

Wier, J. E., and Maxfield, E. B., and Hart, I. M., Reconnaissance hydrology of the Moab-Monticello Area, Grand and San Juan Counties, Utah, and San Miguel County, Colorado.

Wier, J. E., Jr., Maxfield, E. B., and Zimmerman, E. A., Reconnaissance geohydrology of the Dolores River Basin, Colorado and Utah.

Geophysics

By Raymond D. Watts, Lakewood, Colo.

Objective To use geophysical data to characterize and differentiate subsurface lithologies, structural configurations and inhomogeneities in areas of interest.

Approach Surface, airborne, and drill-hole electromagnetic and seismic refraction methods are employed to obtain information on the geologic structure and the presence or absence of significant amounts of ground water.

Progress Forty-three vertical electrical soundings were obtained in the Gibson Dome-Lockhart Basin study area (fig. 11). They revealed anomalous conductors to the north of Lockhart Basin, adjacent to the Lockhart fault system. The anomalies may be due to local thickening of the shaley Moenkopi Formation of Triassic age or to the presence of brine that is the result of dissolution of salt. The occurrence of brine is the favored explanation, but local thickening of the Moenkopi Formation is known to occur near Trough Springs Canyon, 15 km northeast of the Lockhart Basin, and also in an oil exploration well drilled in 1980 near one of the observed anomalies.

A deep anomalous conductor was discovered on the south side of Lockhart Basin. Such a feature could be caused by the dissolution that resulted in Lockhart Basin indicating southward migration of that solutioning, but detailed hydrologic surveys would be needed to confirm such a hypothesis. Alternative explanations are that the conductor is caused by local thickening of a conductive formation, similar to the thickening of the Moenkopi Formation near Trough Springs Canyon, or that the conductor is related to the presence of relatively old brines.

Gulf Coast Salt-Dome Region

North Louisiana

By G. N. Ryals, Alexandria, Louisiana

The DOE is investigating the suitability of salt domes in the north Louisiana salt-dome basin as potential sites for the disposal of radioactive wastes. The Geological Survey, in cooperation with DOE, is studying the regional hydrogeology of the area. The north Louisiana salt-dome basin includes all or parts of 11 parishes, an area of about 7,800 km^2 (figs. 13 and 14). The basin is a structural depression bounded on the west by the Sabine uplift and on the northeast by the Monroe uplift. The strata of principal concern to this study are of Late Cretaceous and Tertiary age, dip generally southeast, and are less than 900 m below land surface. Hosman (1978) described the general geohydrology of the area based on available data and discussed the need for additional data and studies.

Objective To describe the regional geohydrology and define the ground-water flow system of the north Louisiana salt-dome basin with particular attention to the potential for transport of radionuclides from a repository in a salt dome.

Approach Construct a regional, three-dimensional digital model that will simulate flow in the multilayered ground-water system to depths of 900 m or more. The deepest water-bearing unit to be modeled is the Nacatoch Sand of Late Cretaceous age. Other principal units in the model will be the Wilcox Group, undivided, of Paleocene and Eocene age, and the Carrizo Sand, Sparta Sand, and Cockfield Formation of Eocene age.

A series of 17 regional geohydrologic maps depicting specific geologic and hydrologic properties of the aquifers and confining beds, needed for input to the model, has been completed. Other maps necessary for model input cannot be made without data from a regional test-drilling program.

Progress Work continued on the analysis of geohydrologic data from the fiscal-year 1980 test-drilling program. Data from that program, as well as a discussion of data needs in north Louisiana, were incorporated in a report that is currently being reviewed.

Most of fiscal-year 1981 was devoted to developing location and site-characterization plans for Vacherie salt dome (fig. 14). The plans which have not been approved, were developed by representatives of the State of Louisiana, the U.S. Geological Survey, Louisiana State University's Institute for Environmental Studies, and the Office of Nuclear Waste Isolation of Battelle Memorial Institute.

Progress toward the goal of developing a regional ground-water flow model has been delayed because data needed from a regional test-drilling program have not been obtained. The test-drilling program in fiscal-year 1980 provided only a small part of the data needed to develop the model.

Figure 13.--Location of northern Louisiana salt-dome basin showing area to be modeled.

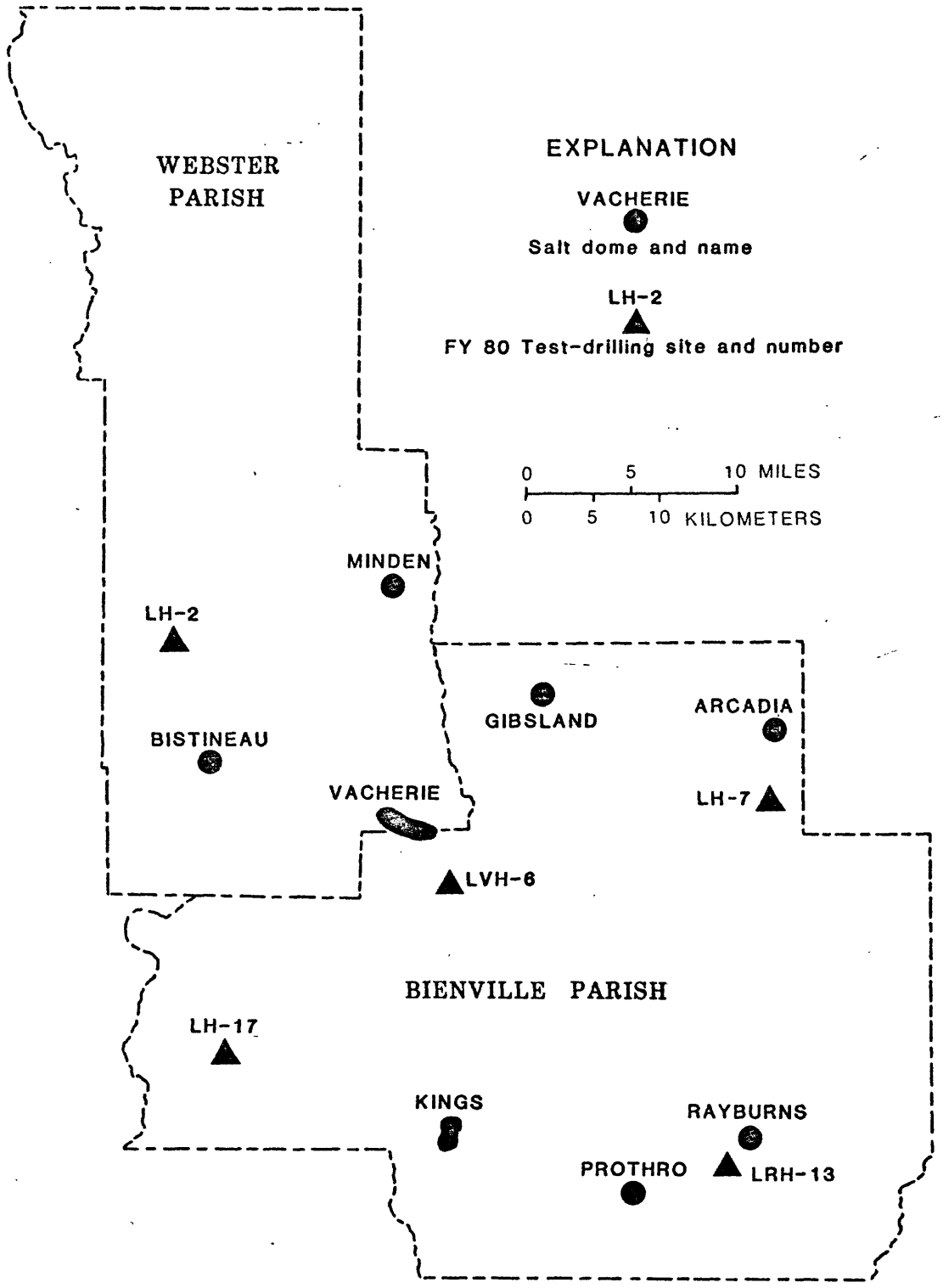

Figure 14.--Location of salt domes and fiscal year 1980 test-drilling sites, Bienville and Webster Parishes, Louisiana.

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Reference

Hosman, R. L., 1978, Geohydrology of the northern Louisiana salt-dome basin basin pertinent to the storage of radioactive wastes--a progress report: U.S. Geological Survey Water-Resources Investigations 78-104, 27 p.

Mississippi

By P. A. Dooley and C. B. Bentley, Jackson, Miss.

The DOE is conducting investigations in the Mississippi interior salt-dome basin to determine the suitability of salt domes as potential sites for the disposal of radioactive wastes. Knowledge of the geohydrology of the basin, especially of the ground-water-flow regimes peculiar to the 50 piercement-type salt domes within the basin, is very limited. Three domes in Mississippi are among those that were selected by the DOE for consideration in identifying a potential waste repository site. Cypress Creek, Lampton, and Richton domes (fig. 15) are among eight in the Gulf Interior Region of Louisiana, Mississippi, and Texas that the DOE evaluated on the basis of minimum geologic, hydrologic, environmental, and socioeconomic criteria for a waste repository. The domes intrude most of the Tertiary section, and the caprock of each occurs at a Miocene horizon. The Tertiary section is composed predominantly of sands and clays with minor units of marl and limestone. Regional dip is approximately 6m/km to the south-southwest. The Geological Survey, in cooperation with the DOE, is studying the regional ground-water hydrology of the basin.

Objective To describe the ground-water hydrology of the salt-dome basin, with emphasis on determining rates and directions of water movement.

Approach Following the preparation of a preliminary summary of the geohydrology of the salt-dome basin (Spiers and Gandl, 1980), a drilling, testing, and sampling program was conducted in order to gather data necessary to more accurately describe the geologic and hydrologic conditions of a region within the basin that includes Cypress Creek, Lampton, and Richton domes. Future investigations may be focused on a yet smaller area close to one or more of these domes.

Progress Recommendations were made to the DOE concerning future investigations in the Mississippi salt-dome basin. Aspects of the geohydrology near Cypress Creek, Lampton, and Richton domes that have not yet been adequately evaluated include ground-water movement on the flanks of the domes, dome dissolution, ground-water movement in the caprock, and the vertical permeability of the confining layers. Additional drilling and testing are required to investigate these aspects of the geohydrology and to meet project objectives.

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Spiers, C. A., and Gandl, L. A., 1980, A preliminary report of the geohydrology of the Mississippi salt-dome basin: U.S. Geological Survey Water-Resources Investigations Open-File Report 80-595, 45 p.

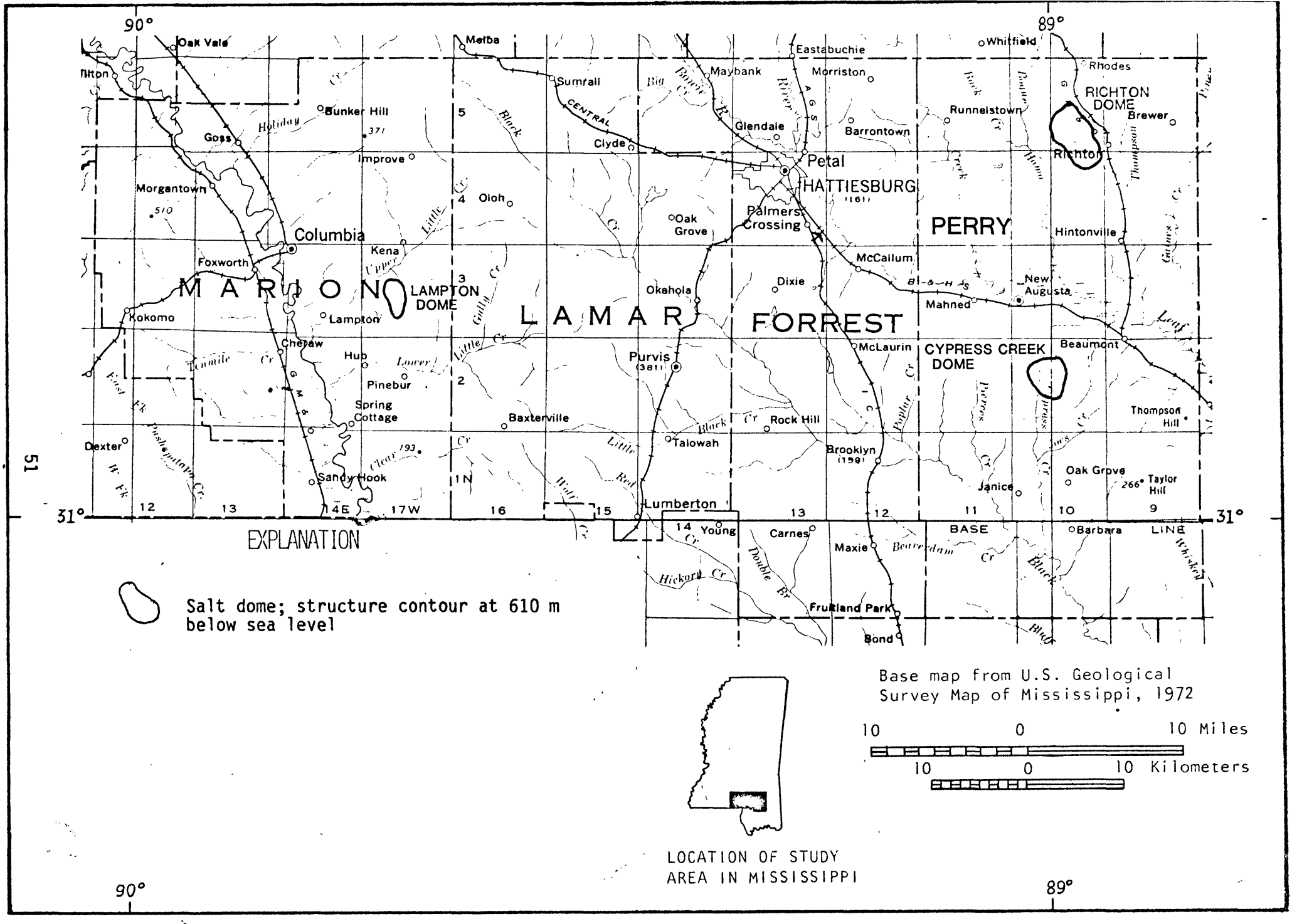

Figure 15.--Location of salt-dome study area, southern Mississippi.

GENERIC RESEARCH

The research described below is concerned with the properties of selected geohydrologic environments and rock types that may be suitable for the emplacement of high-level and transuranic wastes, how they may be explored and characterized, and how various geologic and hydrologic processes may affect the integrity of a repository. Some of the work is being done at localities described in the preceding section because they provide convenient and suitable locations and needed supporting studies and data, but the results obtained should be applicable to other localities.

As additional areas are identified where waste-disposal sites might be located, some of this research will become more site specific because generic studies must inevitably give way to detailed characterization of sites. However, much of the research will continue to have general applications to many geographic localities as well as to national needs other than disposal of radioactive wastes.

With two exceptions, the projects described below were supported by the Geological Survey's direct appropriation; the work described in the sections entitled, "Salt-brine-waste-canister interactions", and "Fluid inclusions in salt", were funded by the DOE.

Studies of Rock Types and Environments for Emplacing Wastes

Western Cretaceous Shales

By C. E. Neuzil, Reston, Va., and T. C. Nichols, Lakewood, Colo.

Previous studies of the Dakota regional aquifer system (Dakota Sandstone and equivalent rocks) suggest that the overlying Cretaceous shales, which act as a confining layer for the aquifer, are low in permeability. These investigations indicate that the shales could isolate wastes for long periods of time.

A number of questions remain to be answered before a repository could be considered seriously. Principal among these questions are:

1. Does the low-permeability suggested by the hydrologic-model analysis indicate flow through the rock matrix; flow through small, closed joints and fractures; or flow through widely-spaced, large fractures?

2. What are the problems, particularly rock mechanics problems, associated with putting hot wastes in highly montmorillonitic shales? High-temperature wastes would cause a phase change in minerals with an associated release of water. Would the physical properties of the shale change during this process?

Objective The general objective is to evaluate the geohydrologic conditions and physical properties of the thick Cretaceous shales of the western United States in relation to their potential use as a host rock in high-level radioactive-waste repositories. Concerning the physical properties, a specific objective is to evaluate, in situ, the state of stress and mechanical properties of the Pierre Shale.

Approach The approach will involve completing a hydrologic model analysis of a large region as a prototype for studying the Cretaceous shales. Concurrently, core drilling and in-situ testing will be done to obtain laboratory and field data on the permeability of the Pierre Shale. In addition, field measurements will be made to determine in-situ stress and other physical and engineering properties of the rock. Constant-strain rate and creep tests will be conducted on the cores under pressure and temperature conditions to be expected in repositories. Four shallow test holes will be strategically located to sample the entire stratigraphic sequence of Cretaceous shales above the Dakota aquifer.

The mechanical effects on the shale of emplacing hot wastes will be analyzed by model studies. This will include developing a viscoelastic model for deformation. Laboratory testing will be required to provide the physical-property data needed to support the model analysis. Based upon rock displacements calculated from this analysis, calculations will be made of the probability of producing joints and fractures which would change the virgin permeability values.

The sorption properties of the shales will be determined in the laboratory. The results will be incorporated into a transport model to obtain insight into nuclide-transport processes in these shales. Initial transport predictions will be made at ambient ground-water temperatures without the influence of heat.

Progress Test drilling, coring, and in situ testing--Boreholes were drilled in South Dakota in September and October 1981 on a linear trend identified on aerial photographs in an attempt to locate fractures which permit ground-water flow through the shales.

Several modified slug tests were conducted in one borehole. The results from these tests differ substantially from those of earlier tests and appear to reflect a higher permeability. The pressure-decline curve does not have the form expected in a test in homogeneous rock. Further analysis is necessary to determine whether this behavior results from flow in fractures. However, results of these and earlier tests and an analysis of stress changes induced by the borehole indicate that the shale is significantly underpressured.

Analysis of the tests suggests that changes are necessary in the modified "slug" test procedure introduced by Bredehoeft and Papadopulos (1980). These changes have been presented by Neuzil in a paper submitted to Water Resources Research entitled, A note on conducting the modified "slug" test in tight formations.

Approximately 200 feet of core was preserved for later hydraulic and mechanical testing. Further permeability tests on both intact and fractured core samples are planned on the special apparatus built by Terra Tek in Salt Lake City.

Earlier consolidation-test data have been analyzed for hydraulic conductivity and specific storage. The results indicate a range of values. They also suggest that the matrix anisotropy in conductivity is small; $K_h/K_v \cong 2$. The planned permeability testing will provide an independent check of these data.

Laboratory and in situ testing of physical properties--A borehole gravimeter survey was conducted in one drill hole to a depth of 137.2 m over intervals of 10.7-19.8 m. The results show a trend of increasing specific gravity with depth, i.e., 2.14 at 42.7 m to 2.22 at 137.2 m. Above the 42.7-m level the specific gravity increased slightly to 2.16 at 15.2 m. Field specific-gravity measurements made on core samples taken from equivalent depths to 71 m were consistently about 2 percent lower than the borehole gravimeter results, indicating a nearly instantaneous rebound of the samples.

In addition to the specific gravity measurements, cores taken to a depth of 71 m were immediately tested in the field laboratory van for moisture content, degree of saturation, and time-dependent rebound deformation. The initial results indicate that the shale is saturated over the 71-m interval but that the total moisture content decreases with depth. At 20.4-m depth, the samples tested had a moisture content of 26 percent by volume, decreasing to 23 percent at 62.8 m. Rebound deformation continued on cores from depths shallower than 30.5 m but not on those taken deeper than 30.5 m. On the shallower cores, about 0.2 percent axial strain occurred in the first 24 hr and has continued at a much reduced rate for 4 months.

Other tests run in the boreholes included determination of compressional- and shear-wave velocities and measurement of the temperature profile.

The primary-wave velocities were measured to a depth of 90 m and the shear-wave velocities to a depth of 45 m. Initial velocity calculations indicate that the compressional-wave velocity is nearly a constant 1900 m/s below 5-m depth.

The shear-wave velocities have not yet been calculated.

The temperature profile was measured to a depth of 183 m. The gradient between 25 and 183 m is 68°C/km, with the temperature at 183 m being 22.3°C.

Selected cores were maintained as closely as possible at natural field moisture contents for laboratory testing. The following thermal, mechanical, and physical-properties tests are planned:

1. Thermal conductivity

2. Thermal coefficient of expansion

3. Specific heat

4. Primary- and shear-wave velocities

5. Constant-strain-rate tests at 10^{-5} to 10^{-8} per second; temperature to 200°C; and pressures to 50 MPa.

6. X-ray mineralogy and size analyses

7. O^{18}/O^{16} and deuterium fractionation of pore water

8. Whole rock chemical analyses.

Laboratory testing accomplished during the year included the completion and initial calibration of a consolidation and constant-strain-rate system at the University of Colorado for the study of deformation properties of the Pierre Shale. This work has been described by Dessenberger (1981).

Other laboratory testing at the University of Colorado was performed on a 4-in cube of Pierre Shale taken from a sample near Ainsworth, Nebraska. The cube was tested in a multiaxial cell used to determine anisotropic mechanical properties (Atkinson and Ko, 1973). The tests demonstrated that under a confining pressure of 6.90 MPa, the shale has significant anisotropy between the vertical (normal to bedding plane) and horizontal directions (parallel to bedding plane). Young's modulus normal to bedding was 0.19 GPa and in two arbitrary directions 90° apart in the bedding plane Young's moduli were 0.45 and 0.63 GPa.

P. L. Swanson, working under a grant from the U.S. Geological Survey at the University of Colorado and the Imperial College of London, determined the threshold of subcritical fracture growth in a shale and other rock types (two basalts, one intrusive, and a granite). This is a continuation of work done by Swanson (1981) on subcritical fracture growth in rocks. Based on the research for the grant, Swanson concluded that the shale and the granite were most susceptible to subcritical fracture growth. His report entitled, "Subcritical fracture measurements in rock using a relaxation technique," is intended for publication in the International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts. He is continuing experimental work to provide information on the increased accuracy and precision necessary for failure-prediction analyses in rocks, with special attention to the effects of increasing temperature.

In addition to the work described above, an array of holes was drilled at the site of earlier (1978) drilling. Using these holes, F. S. Riley, U.S. Geological Survey, Lakewood, Colo., installed an extensometer which will permit measurement of very small changes in thickness of a 130-meter section of the shale. Small changes in the thickness of the shale may provide information on its in-situ mechanical properties and stress history.

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Water Flux in the Unsaturated Zones of Deserts

By Jacob Rubin, Menlo Park, Calif.

The unsaturated zone in deserts is one of the barriers to the movement of radioactive solutes which could be utilized in connection with designing repositories for high-level radioactive wastes. In order to predict the effectiveness of such a barrier, one should be able to estimate the prevailing long-term water fluxes at considerable depths for a specific location. Field data on fluxes of this type are extremely scarce.

Soil-water conditions in the uppermost (root zone) layers of arid, unsaturated zones are known to fluctuate widely with time. Theoretical considerations show that the effects of these fluctuations are transmitted downward but are rapidly attenuated with depth. As a result, at sufficient depths, near steady-state water fluxes may exist in unsaturated zones. Such fluxes reflect long-term trends. By studying profiles of selected water properties at appropriate depths in the unsaturated zone, it should be possible to find indications of whether an approximate steady state exists, and to measure the extant water fluxes.

Objective To determine, long-term averages of the downward water fluxes in the unsaturated zone for several types of desert conditions.

Approach The approach involves studying water conditions in the unsaturated zone, with particular attention to determining sampling depths at which water fluxes are apt to reflect long-term trends. Using pressure-head and hydraulic-conductivity data, existing water fluxes will be computed from which estimates of long-term flux trends will be extracted. These estimates will be compared with analyses based on isotopic data and with simulation based predictions.

Progress In order to evaluate long-term average, downward water fluxes and obtain representative values of areally extensive unsaturated zones, a rapid, steady-flow method for determining hydraulic conductivities of unsaturated, sediment cores has been developed and is being tested. Substantial changes have been introduced into the original design of the instrumentation constructed to make the measurements, including strengthening the coreholder and making it possible to accommodate sediments with a larger range of water-suction values. In addition, a special "touch-minitensiometer," required by the method, was designed, built, tested, and proven to perform satisfactorily.

Tests of the method were carried out with repacked, precompacted, unsaturated cores of Oakley sand. The tests have shown that it is possible to measure, in half a day or less, unsaturated hydraulic conductivities as low as 10^{-6} cm/s. The reproducibility of measurements obtained with different cores of the same material was very good, the variations in hydraulic conductivities observed being less than two percent of the measured values.

The method offered an opportunity to test the validity of extending Darcy's equation to relatively dry, unsaturated porous media. Such tests have shown for sediment columns with water at tension of -89±3 cm (reached at 35±2 percent of full water saturation) that in spite of a 24-fold increase in flux (from 8.5×10^{-5} cm/s to 2.0×10^{-3} cm/s), unsaturated hydraulic conductivity remained almost constant; the observed variation was from 1.26×10^{-6} to 1.12×10^{-6} cm/s, which was probably caused by a slight, inadvertent decrease in water tension and content. This observation confirms the validity of the generalized Darcy equation. Definitive, that is steady-state, tests of this equation have not been carried out previously for porous materials at such low values of tension and hydraulic conductivity.

Salt-Brine-Waste-Canister Interactions

By I. M. Chou, Reston, Va.

Brines in rock salt tend to be mobilized by an increase in temperature, by fracturing due to thermal expansion, by the migration of fluid inclusions, and by dehydration of hydrous minerals. The presence of brines can be expected to increase the possibility of corrosion of canisters and leaching of waste, decrease the rock strength, and decrease sorptive properties of the host rock. One or more of these factors could affect the retrievability of wastes and, at the worst, might threaten the integrity of waste containment.

A thermal pulse peaking many tens of years after waste emplacement and lasting hundreds of years is currently being anticipated in the design of repositories that can accommodate spent fuel. The maximum temperature to be attained over tens of meters of salt in which wastes have been buried can be kept below 100°C by the choice of canister spacing or thermal output. However, surface temperatures of the canisters may be higher.

Objective To determine the likely interactions among salt, brine, canisters, and waste at a range of temperatures and pressures that may be anticipated in disposal of high-level radioactive waste or spent fuel. To determine the properties of the resultant reaction products at temperatures up to 300°C.

The focus of this project is on the characterization of the physicochemical properties of the fluids and solids in the system Na, K, Ca, Mg/Cl, SO_4, Br, and reaction products formed by interaction of these components with those of the integrated waste-disposal system. These data will help in the design of the waste-disposal system, hydrophilic materials, and radionuclide adsorbers.

Approach The system Na, K, Ca, Mg/Cl, SO_4 is being investigated at temperatures up to 300°C. These are the major components in natural salt-brine systems, including the brine fluid inclusions in bedded salt, which tend to migrate to a heat source. A multi-component system simulates to some extent the effects of adding waste components to the brines. The resulting brines will be characterized as to (1) solubility and phase equilibria, (2) vapor pressure, boiling points, and freezing points, (3) volumetric properties of the brines, and (4) hydrolysis reactions in bitterns.

Interactions among brines, salt, canister materials, and "waste" are also being investigated up to 300°C. Canister reactions to be studied include (1) Ti ± NaCl ± $CaSo_4$ ± bittern brines, (2) Cu ± $CaSO_2$ ± bittern brines, (3) Zr alloy ± NaCl ± $CaSO_4$ + bittern brines, (4) Steel (ss) ± NaCl ± $CaSO_4$ + bittern brines. Studies simulating the effects of high-level wastes include (1) effect of Cs, Sr, and U on solubilities and phase equilibria, (2) effect of Cs, Sr, and U on vapor pressure, (3) partitioning of Cs, Sr, and U between the brine and potential solid phases.

Processes involving salt, brine, and waste reactants will be modeled at temperatures up to 300°C. Processes examined will include solution and mass transport, fluid inclusion migration and decrepitation, and hydrogen evolution.

Progress (1) A large percentage of the heat generated by decay of fission products in spent fuel aged more than 5 years can be attributed to ^{137}Cs and ^{90}Sr. In the presence of alkali and(or) alkaline earth chloride-bearing brines, these radionuclides are leachable from spent fuel and other waste forms as ionized chlorides. Brines containing ^{90}Sr and ^{137}Cs possess their own heat source. Their migration could disturb the designed thermal evolution of a repository. In order to better assess the problem, a knowledge of the solubility of Sr and Cs in complex brines is necessary.

Solubility of $SrCl_2$ in complex brines has been reported by Clynne, Chou, and Haas (1981). Solubility relations in the ternary system NaCl-CsCl-H_2O at 25, 50, and 75°C have been reported by Plyushchev and others (1957). However, the data presented by Plyushchev and others are not internally consistent. The solubility of halite in this ternary system has been redetermined between 20° and 100°C (Chou, 1982).

The solubility relations in the CsCl-rich region of the ternary system NaCl-CsCl-H_2O are complicated by the presence of a new compound $Na_2CsCl_3 \cdot 2H_2O$ and the presence of "solid solutions." These solubility relations, including the locations of two tie triangles (NaCl-$Na_2CsCl_3 \cdot 2H_2O$-solution; solid solution-$Na_2CsCl_3 \cdot 2H_2O$-solution) and the tie lines for coexisting solution and solid solution, have been determined at 25°C. For $Na_2CsCl_3 \cdot 2H_2O$, 1,206 independent data points (corrected for absorption) were used to find and refine the crystal structure, which consists essentially of the CsCl type (simple cubic Cl with Cs at the body center), but Cs atoms in alternate layers have been replaced by H_2O molecules. Between H_2O molecules in adjacent cubes, Na atoms are inserted in the center of the Cl_4 square shared by the cubes. Cs is in contact with 8 Cl atoms at distances ranging from 3.440 to 3.834 Å (±0.001Å); Na (two kinds) is surrounded in an octahedron by 4 Cl atoms at 2.807 to 3.015Å and $2H_2O$ at 2.367 and 2.399Å. The crystal is monoclinic, space group I2/C, with a = 13.620(2), b = 5.831(1), c = 10.709(2) Å, β = 91.27(1)°. Its refractive indices are n_α =1.520, n_β =1.540, and n_δ = 1.552.

(2) Brine inclusions present in natural salt can migrate toward the waste if the temperature and the temperature gradients in the vicinity of the radioactive waste are large enough. This migration is due to the dissolution of salt at the hot side of the salt-brine interface, ion diffusion through the brine droplet, and the precipitation of salt at the cold side of the salt-brine interface. In order to quantify the problem, the migration rate of these brine inclusions must be estimated under various repository conditions. Several different models of the migration process were reviewed recently (Anthony and Cline, 1971; Jenks, 1979; Cheung and others, 1980; Kovar and Steinborn, 1980). Among them, the model presented by Anthony and Cline (1971) is considered as being most complete because it accounts for most of the phenomena known to occur in the migration process. However, application of their model is difficult because of an insufficient data base.

The migration rates of brine inclusions in NaCl single crystals have been calculated between 50° and 200°C using Anthony and Cline's model and the available NaCl solubility and density data for four brine compositions (WIPP-A [1], NBT-6 [2], 2.41 m $MgCl_2$, and NaCl-H_2O). Since no data were available for the Soret coefficients of NaCl in these halite saturated brines, the maximum migration rates were calculated as a function of the Soret coefficient, and a simple linear function was derived from Anthony and Cline's model. In these calculations, the uncertainties arising from the diffusion coefficient estimations for NaCl were estimated, and the effect of the temperature gradient magnification factor was investigated. These calculated migration rates were compared with those measured experimentally. The data of Bradshaw and Sanchez (1968) are too scattered to be used to verify the model. In a reasonable range of Soret coefficient values, all of the calculated maximum migration rates are much higher than the rates measured by Roedder and Belkin (1980) and A.J. Shor and C.F. Baes[3]. These discrepancies are probably due to the interface kinetics which are neglected in the calculations and which might be an important retarding factor for the migration rates of inclusions. At present, meaningful estimates of the interface kinetics are not possible because of the large uncertainties associated with the estimated values of the diffusion coefficient of NaCl and the other parameters involved in the migration rate calculations.

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1 A synthetic brine used to simulate those at the WIPP site, New Mexico.

2 A synthetic brine containing 5 weight percent NaCl, 5 weight percent KCl, 10 weight percent $MgCl_2$, 10 weight percent $CaCl_2$, and 70 weight percent H_2O.

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Fluid Inclusions in Salt

By Edwin Roedder, Reston, Va.

The storage of radioactive waste in natural salt was originally suggested, in part, because salt mines are dry. However, microscopic fluid inclusions are known to be present in most salt deposits. Most of these inclusions will migrate toward a source of heat such as a waste canister and bring in proximity to it an amount and composition of brine whose consequences must be assessed. In addition, the inclusions are fluids that either were present when the salt was deposited or moved in later and became trapped (due to recrystallization of salt); in the latter case, they provide information on the previous movement of fluids through the rocks.

Objective To determine: (1) what information can be obtained from fluid inclusions that may help in determining if, when, and how fluids moved through the salt in the past and whether this may occur in the future; (2) how much fluid is present in any given site, and what are its distribution, properties, and composition; and (3) what predictions can be made as to the behavior of these fluid inclusions following storage of waste.

Approach Specially prepared samples are examined by microscope for fluid inclusions and appropriately sized portions are removed for study on a microscope with freezing, heating, and crushing stages. The temperature of first melting of a completely frozen inclusion provides a measure of the eutectic temperature of the chemical system within the inclusion. The temperature of disappearance of the last solid phase and the composition of that phase, when compared with appropriate phase diagrams, place some limits on the fluid composition.

In the heating stage, the temperature at which the inclusion formed can be inferred from the temperature at which the shrinkage vapor bubble disappears. In salt samples, this determination is somewhat ambiguous because of the possibility of post-entrapment flowage of the host salt crystal. Gas pressure within an inclusion is estimated from the volume of the bubble in an inclusion under the microscope before and after cracking the inclusion or dissolving the host crystal in water. Rate of migration of inclusions in a thermal gradient (by solution at the hotter and reprecipitation at the cooler end) is determined by measurements under the microscope before and after subjecting the sample to a controlled static thermal gradient at a constant ambient temperature for weeks.

Progress Salt cores from several localities were studied during this fiscal year. Considerable time was spent in preparing samples from the WIPP site for isotopic analysis (H/D and $^{18}O/^{16}O$) of the inclusion fluids by J. O'Neil. A series of samples containing relatively large inclusions in recrystallized salt were isolated by careful cleaving and analyzed. The resulting data, plotted on a standard δD vs $\delta^{18}O$ diagram, show a clear trend, the explanation of which is somewhat ambiguous. For this reason, a special pair of samples, containing only primary inclusions of

presumably unchanged brines from the Permian salt basin, has been prepared by laborious handpicking of small grains to yield enough brine for determinations of both H/D and $^{18}O/^{16}O$. These samples have yet to be run.

Cooperative studies with the University of Texas of the water content and inclusions in samples of bedded salt from the Palo Duro Basin in the Texas Panhandle have continued this year. A stainless steel vacuum decrepitation chamber has been designed and fabricated to permit accurate testing of weight loss from decrepitation of sections of whole 1.5-cm core at temperatures of as much as 350°C. A series of 15 samples from cores in Randall County, Texas, have been run, and yielded weight loss of 0.20 to 1.44 wt. percent (Bassett and Roedder, 1981). These losses are in addition to the 0.0156 to 0.853 wt. percent losses during careful drying at 35°C mentioned in the fiscal year 1980 report.

The analysis of the water content of salt samples has been considered a routine matter in the past, and frequently the resulting data are reported without even a statement of the method used. Another result of this cooperative study with the University of Texas has shown that most such determinations are not truly comparable, that many contain serious and, in part, systematic errors, and that the results are generally on the low side. These problems arise from a combination of the multiple modes of occurrence of water in the samples, and the sampling, sample preparation, and analytical techniques used (Roedder and Bassett, 1981).

The core samples from the Palo Duro Basin also show some interesting, very regular banding in individual salt crystals. Some crystals of ~ 1-cm size contain vast numbers of tiny primary fluid inclusions (i.e., Permian age fluids). These occur densely but randomly distributed within bands parallel to (100) and separated by very thin septa of inclusion-free salt. The individual band pair width ranges from 0.40 to 0.85 mm in different crystals but is very regular within a given grain. I believe these bands represent diurnal variation in the surface evaporation rate in Permian times. The inclusion-rich salt represents fast crystallization during the day, and the clear bands represent slow crystallization during the night. As many as 10 regular band pairs can be found in a given crystal. If this diurnal concept is correct, the sharpness of the bands places severe restraints on the maximum possible depth of brine in the evaporating pond.

A series of 12 core samples from the Asse salt mine in the Federal Republic of Germany were examined in connection with a planned international cooperative brine migration test with the United States. The aim was to determine the amount and nature of the fluid present in the salt. The samples were badly fractured due to the coring procedure used, and hence were completely unsuited for quantitative analysis of the water present, but some qualitative petrographic studies could be made (Roedder and Belkin, 1981).

As a member of the Brine Migration Task Group organized by ONWI, the author made detailed reviews of several versions of a report on brine migration by Jenks and Claiborne (1981).

Reports

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Methods for Characterizing Environments for Emplacing Wastes

Identification of suitable repository sites requires that a body of rock and its local and regional geologic and hydrologic environment be well understood and characterized as to its physical and chemical properties and the potential for disrupting the containment properties of the environment by future geologic events or processes. At the same time, the characterization must be done with a minimum number of penetrations by drill holes and shafts. For some of this characterization, existing techniques are adequate or can be modified to provide the needed information. For other aspects, some new geophysical and geochemical techniques are being developed which can make the task easier, give more accurate results, or provide desirable information that is unobtainable at present.

In many respects geophysical studies of possible repository sites involve an unconventional use of geophysics. Usually geophysicists look for faults, hydrothermal alteration, secondary minerals, and other anomalies, rather than for the absence of such features. The research described below is aimed at better defining the capabilities and limitations of existing methods and improving these methods for the specific needs of the waste-isolation program. All geophysical techniques need to be assessed further and improved from the point of view of distinguishing from normal background variations, fine-scale inhomogeneities that may be of concern in evaluating the waste-isolation properties of the site.

The research in geochemistry involves the improvement of existing methods and development of new methods of isotopic dating of rocks, soils and minerals.

Surface Seismic Methods

By Hans Ackermann, Lakewood, Colo.

Controlled-source seismic methods, both reflection and refraction, are useful tools in exploring for suitable sites for nuclear-waste repositories in areas of layered sedimentary rocks with relatively simple structures; these methods generally offer better resolution of subsurface variations in structure and lithology than other geophysical techniques. While surface seismic techniques have been used for many years in petroleum exploration and a variety of equipment and techniques are readily available, the emphasis has been on deep penetration whereas exploration for waste-repository sites will require higher resolution at much shallower depth--from a few hundred to one or two thousand meters.

Although data-processing techniques may be readily scaled to shallower targets, data-acquisition techniques may not because of the difficulty in scaling the frequency of the seismic pulse and the surface wave which is a major source of noise. Some improvement has been made during the past few years by using the higher frequency portion of the seismic pulse.

The value of shear-wave velocity for determining the physical properties of subsurface materials is well known. However, shear waves are seldom used in seismic refraction surveys because (1) high-energy shear waves are difficult to generate, (2) they attenuate more rapidly than compressional waves, and (3) interfering noise trains are generated due to conversion from shear to compressional energy. The use of shear waves, particularly in shallow cross-hole engineering studies and reflection surveys, is becoming more common, and these methods may also be applied to refraction surveys.

Objective To devise modifications to standard seismic-data acquisition methods for obtaining information applicable to the depth and levels of resolution of interest in identifying and characterizing potential sites for nuclear-waste repositories.

Approach Slight variations of well known techniques of obtaining seismic reflection data for petroleum exploration permit high-resolution recording of such data from depths of less than a few hundred meters. However, the low-frequency surface effects remain an important source of noise for high-resolution surveys. Various techniques will be tested which are aimed at removing this noise for surveys using the close seismometer spacings necessary to obtain high resolution.

Progress A 1,200-m-long vibroseis seismic-reflection survey was conducted at Yucca Mountain on the Nevada Test Site near drill holes USW-G1 and H1 (fig. 2). The purpose was to determine the feasibility of the seismic-reflection method for mapping geology in such an area. The stratigraphic section, based on well logs to a depth of 1,800 m, consists mainly of a thick sequence of ash-flow tuff and volcanic breccia (Spengler and others, 1981). Recording of parameters was geared toward obtaining reflections

within the upper 2,000 m, a formidable task in view of the results of previous reconnaissance seismic surveys (Barry, 1980). Twenty-four-fold data were recorded with stations spaced at 15-m intervals. Three vibrators were used in a 30 m linear end-on configuration. Sweep frequency was 48 to 6 hz with a total of 30 sweeps per station. Receiver arrays consisted of 72 geophones in a 30- x 60-m rectangular grid resulting in 100 percent ground overlap.

The data were swamped by horizontally propagating noise trains. Brute stacks using various filters and stacking velocities showed little evidence of reflections. Additional processing using selected portions of the data and automatic statics resulted in sections showing possible intermittent reflections which correlated with the geology in only a limited way. The task of differentiating the apparent reflections from stacked noise continues. Results of this work suggest that standard reflection methods are inadequate for use at Yucca Mountain and that, if reflections are to be obtained, a more sophisticated technique for noise cancellation is needed.

In addition to this reflection work, activities have continued in converting our seismic-refraction ray-tracing computer programs into forms which can be used by mini-computers. The Society of Exploration Geophysicists has asked that these conversions be made before our paper on this subject is published in its monograph series.

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High Frequency Electromagnetic Methods

By David L. Wright, Lakewood, Colo.

Inhomogeneities and structural flaws in a rock mass are potential problems for its use as a host medium for radioactive wastes. Radio waves seem to offer a good means of finding such features. Unfortunately, radio probing of rock at present is comparable in its stage of development to seismic prospecting in the 1940's and 50's: some basic capabilities exist, but considerable improvement is needed in 1) instrumentation, 2) understanding of the wave-propagation phenomena, and 3) interpretive tools and techniques.

Electrical properties of rocks are very strongly affected by the water in the rocks. Low-porosity, unfractured rocks contain very little water and are quite resistive; porous rocks that contain more water are less resistive.

Thus, a rock's electrical resistivity may be, in a gross way, proportional to its suitability as a host medium for wastes. Rock salt and granite are known to be excellent media for radio probing, largely due to their dryness. There is, at present, a lack of understanding of the fundamentals of radio-wave propagation in geologic media. A suitable radar operating frequency cannot be selected without first characterizing radio-wave propagation, absorption, and scattering in the various rock types. Because these measurements involve bulk variations in the rocks, the measurements cannot be made in the laboratory.

To be useful in the early stages of repository exploration, radar must be functional from boreholes; mined openings will not be initially available for radio-probing activities. Use of boreholes introduces many practical problems for radar work such as the effects of the borehole fluids on antenna performance and interactions between the logging cable and the antennas.

Objective To determine the capabilities and limitations of high-frequency electromagnetic techniques for evaluating the homogeneity and continuity of salt and other low-conductivity media, to develop and field-test prototype equipment, and to develop or enhance interpretive techniques.

Approach Both theoretical analysis and experimental scale-model studies are being applied to answer some questions regarding propagation and antenna behavior in fluid-filled boreholes, particularly if the fluid is a highly conductive one like saturated brine. Secondly, a full-scale prototype borhole radar system development program was launched in order that an actual borehole radar might be tested and made available, along with other geophysical methods, for site-characterization activities. Finally, data-acquisition and data-processing techniques are being developed appropriate to borehole radars of the monopulse variety.

Progress An intense effort was continued to define and design a prototype borehole radar system. Both frequency modulated continuous wave (FMCW) and repetitive monopulse experiments were conducted. Although the FMCW approach has some attractive features, it was decided that the monopulse approach could more rapidly lead to a working system and was adopted as the primary design path.

A prototype borehole radar system was completed and initial field tests were carried out in granite at a site near Gold Hill, Colorado. Preliminary examinations of the data are encouraging and clearly show that the radar is generating and receiving reflected signals.

Borehole Geophysical Logging

By W. Scott Keys, Frederick L. Paillet, and Ulrich Schimschal,
Lakewood, Colo.

Test drilling is essential for the investigation of potential rock types and sites for the disposal of radioactive waste, and wells must be drilled at operating sites to monitor the movement of artificial radioisotopes. Borehole geophysical logging not only provides a synergistic suite of measurements to aid in the evaluation of sites, but these measurements permit the lateral and vertical extrapolation of data from hydrologic tests and core analyses. Borehole geophysical logging may also provide data on the location, orientation, and width of fractures which can be useful in determining their capability to transmit fluids. Gamma spectrometry in monitoring wells permits the identification and semiquantitative analysis of migrating radioisotopes behind well casings where sampling may be difficult or impossible.

Objective The objective is to develop specialized well-logging equipment and log-interpretation techniques for application to the unique problems and conditions encountered in geohydrologic investigations of existing and potential sites for the disposal of radioactive waste.

Approach The research is divided into borehole geophysical techniques for characterizing potential disposal sites and those techniques useful for monitoring waste migrating with ground water at existing sites. Site characterization methods include acoustic, nuclear, and resistivity logging that can provide data on the properties of rocks related to ground-water movement and solute transport. Temperature, fluid conductivity, and flowmeter logging can be used to analyze the spatial distribution of permeability when the system is hydraulically stressed. Special attention is focused on methods that provide information on fractures because they constitute a significant problem in evaluating fluid transfer conditions at proposed sites. The geophysical data are digitized in the field and computer methods are used for collation and interpretation in order to maximize the cost-benefit ratio.

Site monitoring techniques available for use in boreholes include gamma spectrometry, neutron activation, and temperature and fluid logging. All of these can provide real-time data on the vertical and horizontal distribution of certain types of waste without sampling.

Progress A comprehensive study on the use of borehole methods to characterize crystalline rocks for nuclear-waste storage has been completed, and a report by C. C. Davison, W. S. Keys, and F. L. Paillet is undergoing review. In this study, a large number of borehole geophysical methods and hydrologic test methods were used at the Whiteshell Nuclear Research Establishment, Manitoba, and the Chalk River Nuclear Laboratory, Ontario, Canada. The data were interpreted with regard to their synergistic relationships and evaluated for use in site investigations.

An evaluation of impression packers as a technique for obtaining information on fractures was completed at a University of Arizona field test site at

Oracle, Ariz., (See section on Fluid Flow in Fractured Rocks) and in calibration pits at the Denver Federal Center which were installed cooperatively by the DOE and USGS. The conclusion is that acoustic televiewer logs are cheaper and provide more useful, continuous data.

Research on the acoustic characterization of fractured rocks was continued with the development of computer methods for processing the data to produce acoustic amplitude logs that closely correlate with measured permeability in igneous and metamorphic rocks (Paillet, 1981a and b). The method has proven very effective for crystalline rocks containing isolated fractures at depth, so recent efforts have been expanded to include the study of relatively shallow rocks with multiple intersecting fractures and variable lithology where there is a complex interaction between acoustic amplitude and the basic rock matrix. A comprehensive study of the theoretical background for acoustic fracture characterization has resulted in two papers, one by F. L. Paillet (1981c), and another by F. L. Paillet and J. E. White, which has been accepted for publication in "Geophysics," on the acoustic modes of propagation in the borehole and their relationship to rock properties.

Additional borehole data were recently obtained at the Underground Research Laboratory being developed by Atomic Energy of Canada Limited in southeastern Manitoba, Canada. The data include acoustic waveforms and acoustic televiewer logs in depth intervals that have been hydraulically fractured. The televiewer detected hydraulically induced fractures that were reported to be less than 1 mm wide. Preliminary analysis of acoustic waveform data shows that hydraulically induced fractures with small apertures can be differentiated from natural fractures with relatively large apertures.

Theoretical model studies related to waveform analysis have also lead to an improved understanding of shear-wave arrivals in the borehole. Recent analysis shows that internal fluid resonances are strongly coupled to shear body waves in the borehole wall, so that recognizable shear waves are only excited under certain geometric conditions related to tool frequency and borehole diameter. Typical experimental results are illustrated in figure 16 where observed compressional-wave and shear-wave arrivals are characterized by distinctly different periods corresponding to frequencies (F_0) of 31 and 38 kHz respectively, which agrees with theoretical predictions (Paillet, 1981c). A computer-controlled compensated neutron porosity sonde was successfully tested in the American Petroleum Institute (API) calibration pits, the calibration pits at the Denver Federal Center, and a test well in Texas. The agreement with core analyses at the API pits is excellent and resolution at low porosity or moisture content is probably on the order of several tenths of one percent. Tests also indicate that the borehole geometry detectors in this probe will detect very narrow open fractures in low-porosity rock.

Research was continued on the quantitative analysis of gamma spectra recorded in boreholes. The use of sodium iodide crystals should be restricted to the movement of radioisotopes with peaks at energies greater than about 0.5 MeV. Gain stabilization is also essential in order to reduce errors in measurement; a ^{133}Ba source is used in the probe for stabilization at the present time.

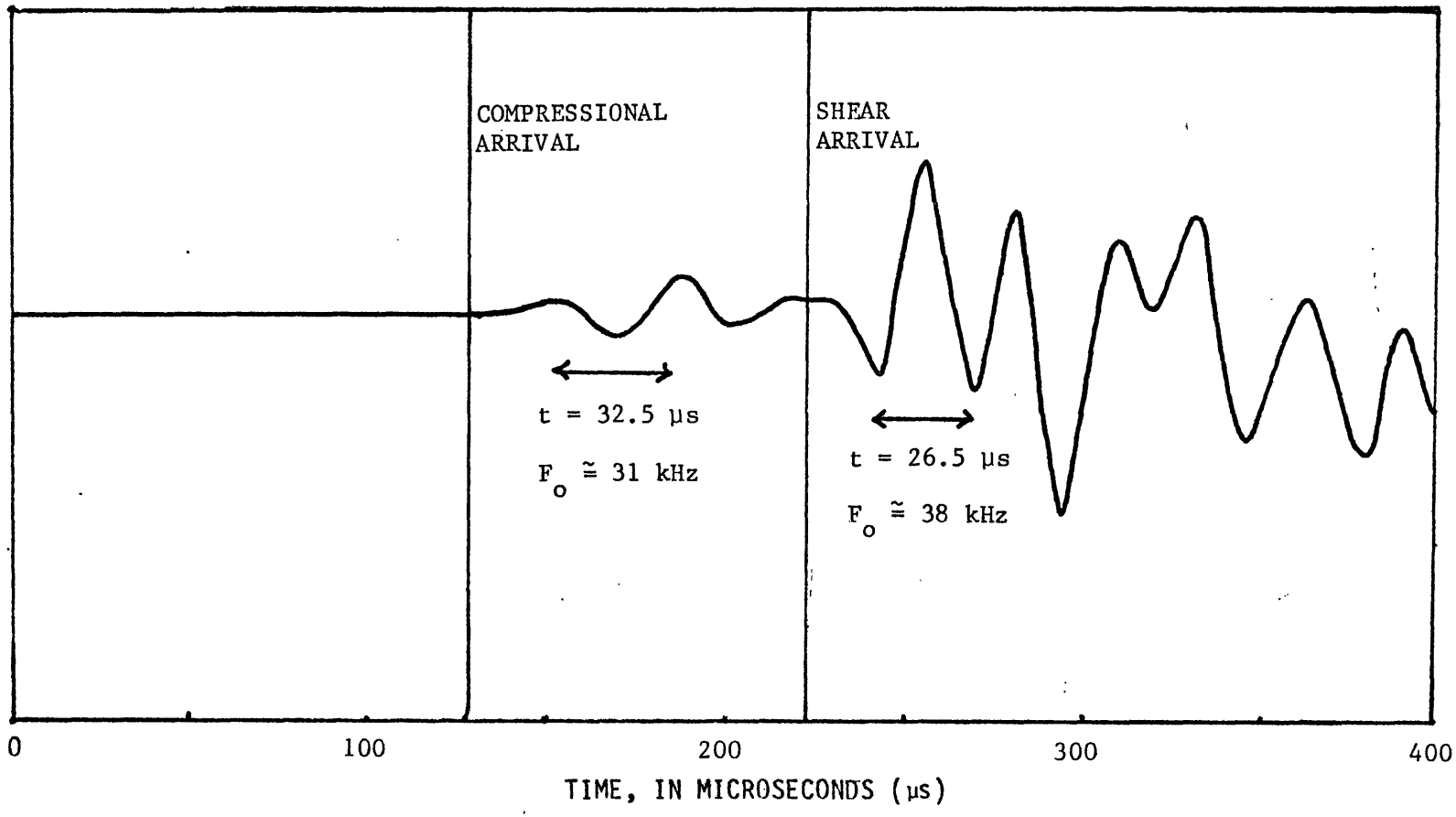

Figure 16.--Experimental waveform for borehole in granite test block showing distinctly different frequencies for compressional-wave and shear-wave arrivals.

A computer program has been written to aid in the stripping of ^{137}Cs and ^{60}Co from the background of naturally occurring radioisotopes.

Reports

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Acoustic and Electric Techniques

By J. J. Daniels, Lakewood, Colo.

Hole-to-hole and hole-to-surface geophysical measurements have the capability of detecting vertical, horizontal, structural, and lithologic features (i.e., faults, fractures, lenses, cavities, and alteration zones).

Objective To develop and test new borehole geophysical techniques for locating geologic inhomogeneities that are beyond the range of detection of conventional well-logging probes.

Approach Hole-to-surface, direct-current resistivity systems are being developed together with field systems capable of operating to depths of 200 m. Hole-to-hole geophysical measurements are made by placing multiple sources and receivers at various depths in vertical drill holes spaced a few tens of meters to several kilometers apart. The signals measured at the receiver drill hole are interpreted for inhomogeneities that may be present between the source and receiver drill hole. The results are interpreted by means of specialized computer modeling procedures.

Progress Hole-to-surface resistivity measurements appear to be a useful technique for determining the presence of fracture zones away from a drill hole. Computer modeling capabilities have been developed to compute the effect of topographic variations on hole-to-surface resistivity measurements. These modeling techniques are being applied to data from the Nevada Test Site and the Paradox Basin, Utah.

Reports

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High Resolution Electromagnetic Sounding Methods

By Frank Frischknecht, Lakewood, Colo.

Electrical methods are useful in the exploration and characterization of potential sites for nuclear-waste repositories. Many features such as zones of abnormal fracturing or alteration, which are important in site selection, are good targets for electrical methods. Electrical methods are effective for locating both horizontal and steeply dipping boundaries, and some rock types in the subsurface can be predicted from established relationships between rock type and resistivity.

Existing resistivity and electromagnetic methods work well and are used on a routine basis for depth sounding when the earth can be represented approximately as a horizontally layered medium. However, to make a conventional resistivity or frequency domain loop-loop EM sounding, the electrode configuration or loop spacing must be two or three times the desired depth of investigation. The presence of major lateral boundaries or other inhomogeneities near an electrode or loop causes distortion of the sounding curve and interpretation of the results is difficult and very time consuming if the distortion is severe. An electromagnetic technique which employs concentric loops or a single loop should be less susceptible to the effects of lateral boundaries than conventional methods. However, to achieve the necessary sensitivity for deep probing with such a configuration, frequency domain measurements must be made with extreme accuracy or time domain wave forms must be employed.

Objective The primary objective is to develop time domain electromagnetic (TDEM) sounding methods using the concentric or single-loop configurations. A secondary objective is to evaluate and demonstrate the method in areas where potential repository sites have been or are being investigated with other geophysical methods.

Approach Initial tests of the concentric and single-loop time domain techniques were carried out using a commercially available TDEM system designed for mineral prospecting. A larger system for sounding to depths as great as 1,300-2,000 m is being developed and will be used in subsequent field tests. Methods for rapid display and computer inversion of the data are being developed. Three-dimensional model studies are being made to determine correction factors for such structures, if feasible, and to establish limitations and capabilities of the method.

Progress Scale-model studies show that single loop TDEM data are much more easily interpreted than separated-loop, frequency-domain data when

lateral boundaries are present. In addition to developing an inversion program, which requires use of a high-speed computer, other programs for processing and displaying data in the field were written for a desk-top computer. A high-power transmitter was designed and partly constructed. The initial design for the receiver for the new system was completed, and components were procured.

Field measurements were made using the Sirotem instrument at a number of localities at the Nevada Test Site including a profile (fig. 17) extending west from Yucca Mountain (see section on Nevada Test Site and vicinity). The signal-to-noise ratio was much better for the loop configuration than for the central- or concentric-loop configuration allowing single-loop measurements to be made to times corresponding to greater depths (fig. 17). Results obtained with the two configurations generally agree in areas removed from lateral boundaries. Results obtained with the central-loop configuration are affected most near areas of sharp lateral variations in resistivity. Most of the data obtained have been inverted using a computer program which was developed. The results of this inversion indicate that layering is more regular than is indicated by the dipole-dipole resistivity results (Frischknecht and others, 1981). Nevertheless, the TDEM results do show discontinuities at the major mapped and inferred faults.

Report

Frischknecht, F. C., Anderson, W. L., and Raab, P., 1981, Experiments with the control loop and coincident loop time domain electromagnetic sounding methods (abs.): Geophysics, v. 47, no. 4, p. 433.

Isotope Geochronology

By Meyer Rubin, Joseph G. Arth, and John F. Sutter, Reston, Va.

Improvements in the dating of past geologic events will allow better estimates of the rates at which changes have occurred and the likely consequences of such changes over the life of a repository; they also will allow us to place higher confidence limits on such estimates. Events that have occurred between about 30,000 to 1,000,000 years ago fall in a time range that is not now covered by standard dating techniques. In addition, reducing the size of sample needed for age determinations will allow us to date materials that cannot be dated at present and thus expand the applicability of the techniques involved.

The research described below is supplemented by the Geological Survey's extensive activities in Quaternary research under its Earthquake Hazards, Climate, and Reactor Hazards programs. All of these programs include research on improving techniques for dating relatively recent geologic events and materials.

Objective To develop new methods of determining the ages of rocks and geologic events and to improve the time range and sensitivity of several existing techniques.

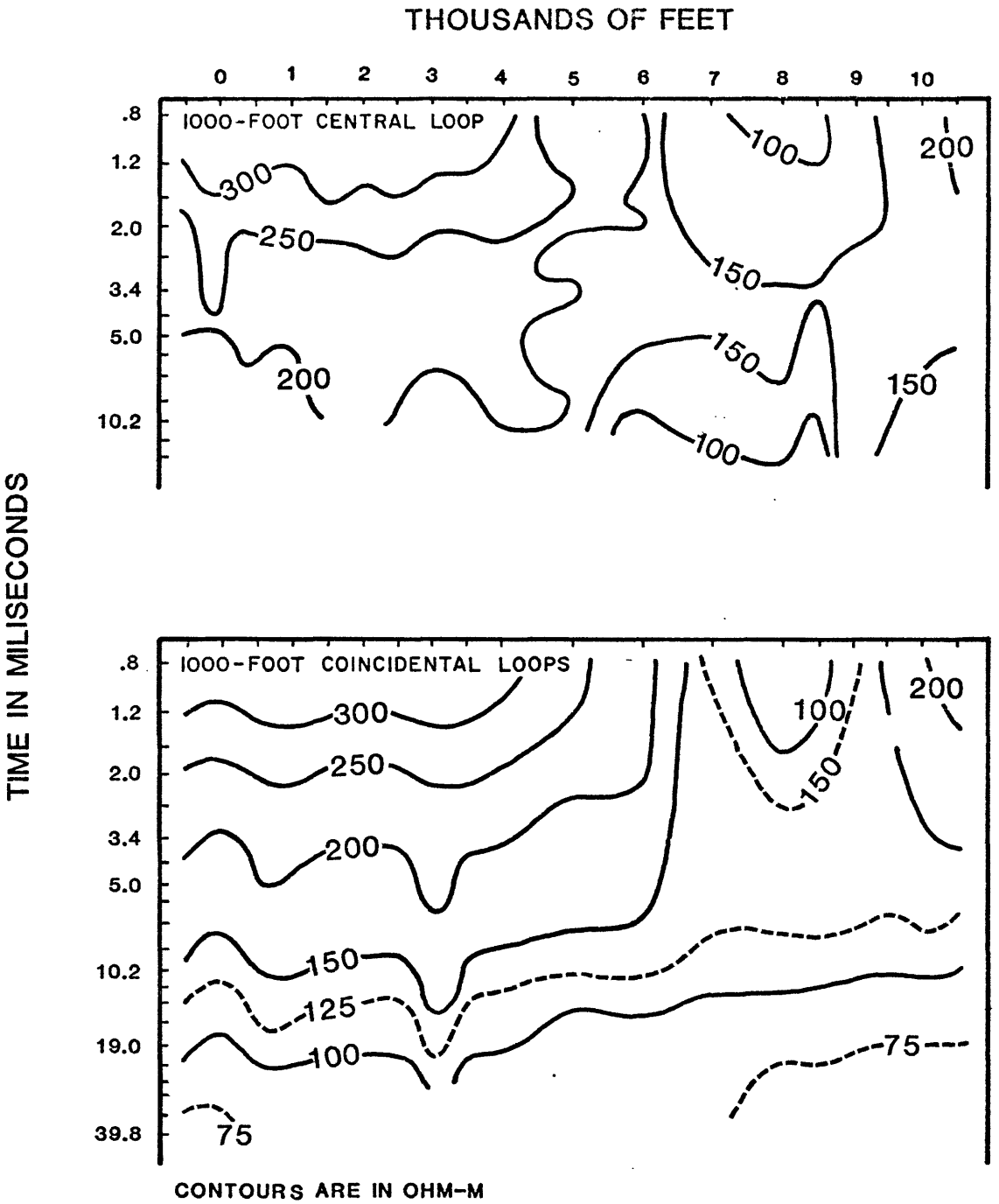

Figure 17.--Time domain electromagnetic pseudosections for central and coincidental loop configurations, Yucca Mountain, Nevada Test Site.

Approach The present limit of the carbon-14 technique of dating ground water and carbonaceous materials is about 30,000 years. Measuring carbon isotopes with the tandem Van de Graaff mass spectrometer has the potential to extend this limit to 70,000 years and reduce the sample size needed by a factor of 100 to 1,000. A group at the University of Rochester has been pioneering this technique, and Meyer Rubin is collaborating with them; equipment dedicated to this technique will be obtained if the results warrant it.

Work at a number of institutions has suggested that ground waters may be datable up to 200,000 years by chlorine-36 and krypton-81, and sediments and sedimentation rates up to 1 million years by beryllium-10, aluminum-26, and silicon-32. Like carbon-14, these isotopes are generated by cosmic rays in the upper atmosphere; they become incorporated in sediments or ground water and slowly decay with half lives somewhat longer than carbon-14. In order to make use of these isotopes, very small amounts of them must be measured and current research efforts are focused on use of cyclotrons or Van de Graaff accelerators.

Joseph G. Arth and his colleagues are in the process of assembling a laser probe mass spectrometer for dating the time of formation of rocks, minerals, and fluid inclusions by potassium/argon methods. This recently-developed technique reduces the sample size by several orders of magnitude and allows ages to be determined on microscopic samples. Its development should enable us to date periods of shearing and faulting, rock alteration, metamorphism, and volcanism by looking at smaller domains within the rock mass than is currently possible.

Progress Part of the problem in the Van de Graaff accelerator method is how to present the carbon to the cesium beam sputter source to produce a large beam current strength. Rubin's work on this has resulted in a report entitled "Sample preparation for electrostatic accelerator dating of radiocarbon" which has been accepted by the American Chemical Society for publication (Symposium Series, no. 176, Nuclear and Chemical Dating Techniques, p. 89-93). The carbonate precipitated from ground water is reduced with magnesium to produce a carbon black which is then heated with Al to yield the carbide. This proves to be an effective target for the cesium beam. The Rochester accelerator has also been used this past year in beryllium-10 studies. A new sample holder with 18 positions for target samples is in use, and a much improved sputter source has been installed and tested.

Development work on the laser probe mass spectrometer continued with the successful interfacing of the microscope and the laser. Preliminary experimental results show that laser heating and(or) ablation of portions of individual mineral grains can be accomplished in situ in a rock with a "spot size" resolution of about 10 microns in diameter.

Investigations and Modeling of Geologic and Hydrologic Processes

A major objective of the USGS research related to the disposal of high-level wastes is the identification and understanding of the critical geologic and hydrologic properties and processes involved in radionuclide migration from a repository to the biosphere. One group of properties and processes is related specifically to the thermal and mechanical stresses imposed by the emplacement of high-level wastes. The effects of these stresses on the underground flow of fluids (including vapor) and heat cannot be modeled at present for fractured rocks and unsaturated alluvium. To accurately describe the flow of fluids in these media requires an understanding of rock mechanics, heat transport, saturated ground-water flow in fractured rock, nonisothermal water fluxes in the unsaturated zone, and combined unsaturated-saturated zone flow in thick alluvium.

The research described below is supported from USGS appropriations.

Fluid Flow in Fractured Rocks

By P. A. Hsieh, Tucson, Ariz.

The success of an attempt to predict the movement of fluids in a low-permeability, fractured rock mass will depend on the ability to (1) mathematically describe the physical laws that govern the movement of fluids in such an environment, and (2) quantitatively characterize the porosity and permeability of the rock mass and the flow system by meaningful and measurable quantities.

Objective The objective is to examine the validity of characterizing a fractured rock mass as an anisotropic porous medium. Two questions are to be addressed: (1) Under what circumstances are the mathematical equations for fluid flow in anisotropic porous media applicable to an actual field site? (2) On what scale must the flow system be examined and measurements taken?

Approach At present, two general approaches have been proposed to predict the movement of fluids in fractured rocks--the discrete approach which attempts to characterize fluid flow in individual fractures, and the continuum approach which characterizes the fractured rock mass as an anisotropic, and possibly "double," porous medium. The current research follows the continuum approach.

The approach to examining the validity of a mathematical model is to predict, by theory, the response of a flow system that is subjected to a known stress and then to compare the predicted behavior with the actual behavior observed in a field test conducted at a site where conditions are similar to those assumed in making the theoretical predictions. The effect of scale will be examined theoretically by computer simulations and experimentally by making measurements for different volumes of rock during field testing. Specifically, the approach involves (1) reviewing the literature on fluid flow in fractured rock, (2) deriving analytical solutions

of equations for flow in an anisotropic porous medium for various field testing schemes, and developing methods of computing the hydraulic conductivity tensor from field data, (3) conducting field tests at a site located on fractured crystalline rock of moderate permeability (i.e., about 10^{-6} cm/s), (4) comparing theoretical predictions and observed results, examining differences between the two, and possibly modifying the theory to account for discrepancies, (5) examining the effect of scale by analyzing field data taken for different volumes of rock and by computer simulations, and (6) obtaining additional data from other sites (e.g., Stripa, Sweden) for similar analysis, with emphasis on data from field tests on rocks of low permeability (i.e., 10^{-9} cm/s or less).

Progress Field equipment designed for conducting borehole packer tests was constructed in cooperation with the Department of Hydrology and Water Resources of the University of Arizona. The equipment can be described in terms of four components: (1) the downhole instruments, (2) tubing and cable system, (3) water-injection tanks, and (4) data acquisition system.

The downhole instruments consist of three pressure transducers and two packers which are separated by a perforated pipe. When the packers are inflated, the portion of the borehole between the packers is isolated for testing. In a water-injection test, an air-operated valve is opened, and water is injected into the test zone. Alternatively, a pressure-pulse test can be performed by activating a displacement piston which can instantaneously discharge approximately 14 ml of water into the test zone. The discharge creates an instantaneous pressure increase, which is followed by a period of pressure decay as water flows from the test zone into the rock formation. Downhole fluid pressure is monitored in the test zone as well as in the zones above and below the straddle-packer equipment. Pressure measurements are made with transducers which are housed in a waterproof container attached to the upper packer.

The tubing and cable system consists of a steel cable, which is used to raise and lower the packers with a boom-and-winch assembly, several plastic tubes which serve as conduits for water and compressed air, and a 12-conductor electric cable which supplies power to the transducers and carries output signals from the transducers to the land surface.

The injection tanks consist of four cylindrical tanks which supply water for injection into the test zone. Injection pressure is provided by connecting the tanks to a controlled compressed-air source. Water level in each tank can be viewed in a clear plastic sight tube (manometer) connected to the tank. The four tanks are of different diameters and are designed to allow accurate measurement of flow rates over a wide range (from approximately 1 ml/min to approximately 5,000 ml/min.

The data acquisition system consists of a monitor unit with digital display, several strip-chart recorders, and a data logging unit.

A hydraulic testing program has begun at a field site provided by the Department of Hydrology and Water Resources, University of Arizona, near Oracle, Arizona. (See section on Borehole Geophysical Logging).

The program consists of a series of water injection tests being conducted in four boreholes, each approximately 98 m deep, drilled in the granitic rock at the site. Constant-pressure water-injection tests and instantaneous pressure-pulse tests are conducted on 4-meter test intervals successively along the entire saturated portion of each borehole. Data from these tests are being analyzed to (1) compare various methods (transient and steady-state) for computing hydraulic conductivity and specific storage, (2) characterize the variations of hydraulic properties of the rock mass, and (3) construct a permeability profile of the borehole which can be compared with various borehole geophysical logs (e.g. neutron, acoustic televiewer).

Field Tests of Flow in Unsaturated Alluvium

By E. P. Weeks, Lakewood, Colo.

If unsaturated alluvium in arid regions is considered for the host medium in high-level waste repositories, models must be developed to estimate the flow of water that might leach radionuclides and transport them toward the water table, considering ambient thermal conditions and the presence of a heat source. These models will be useful also to evaluate effects of extreme climatic events and of climatic changes on the integrity of the repository.

Objective To develop and field test operational models to simulate combined saturated-unsaturated flow under anisothermal conditions at a small scale and on a precise theoretical basis; also, to simulate saturated-unsaturated zone interactions at an areal scale on a more empirical basis.

Approach Field, laboratory, and modeling studies will be used to achieve the objective. Field studies will include the measurement of subsurface moisture tension, temperature, and humidity to determine the flow of heat and water.

Data from field tests of unsaturated flow will be used to develop and test an operational small-scale model for combined unsaturated-saturated zone flow under anisothermal conditions. The model will permit the simulation of various conditions of infiltration and soil-moisture depletion by evapotranspiration. Results of the small-scale model studies will be used to develop a more empirical large-scale model that will include the approximate effects of the unsaturated zone.

Progress Additional instrumentation has been emplaced at the Jackass Flats (fig. 1) caisson installation at the Nevada Test Site, including an automated weather station, three nests of thermocouple psychrometers installed from the surface to a depth of 1 m, and thermocouple psychrometers installed at 60-cm-depth intervals to a total depth of 12 m in the west wall of the caisson. Soil-moisture tension data were collected periodically starting in

February 1981, and weather records were started in July 1981. These background data will continue to be collected until the winter of 1982-83 when a heater experiment will be started.

A heater experiment, involving a 3-m-long cylindrical electric heater installed at a depth of 3-6 m, was started in September 1981 at the University of Nebraska Sandhills Agricultural Laboratory near Tryon, Nebraska. Temperatures, moisture contents and moisture tensions are being monitored at several radial distances from the heater and to a depth of 25 m.

Data collection on a laboratory bench-scale experiment, involving a cylindrical heat source in the center of a barrel filled with partially saturated Valentine sand, was completed. During the test, temperatures and moisture tensions were monitored periodically. Moisture redistribution was determined at the end of the test by sampling, and redistribution during the test was determined by computing moisture content from the tension data and the moisture characteristic curve. A draft of a report, "Experimental determination of two-dimensional coupled heat and moisture movement in unsaturated sand," by E.G. Lappala and D.I. Stannard, is being reviewed.

Efforts to model the anisothermal vapor transport are continuing.

Report

Lappala, E. G., 1981, Modeling of water and solute transport under variably saturated conditions--state of the art, in Little, C. A., and Stratton, L. E., compilers, Modeling and low-level waste management: An Inter-agency Workshop: Oak Ridge National Laboratory Publication ORO-821, p. 81-138.

Nonisothermal Water Fluxes in Unsaturated Alluvium

by W. N. Herkelrath, Menlo Park, Calif.

In view of the low water flux usually found in the unsaturated zone in arid regions, this environment has been suggested as being worthy of further consideration for locating high-level waste repositories.

Initially, the wastes will be at higher temperatures than their surroundings and will probably be placed in a medium that is relatively dry and is approximately at atmospheric pressure. Therefore, assessments of plans for containing waste in the unsaturated zone must be based on models which use nonisothermal water-flow theory applicable to porous media with low water contents and air pressures. In addition, vapor as well as liquid water flow must be taken into account.

Currently, there exist two competing theoretical approaches to the flow of vapor and liquid in response to thermal gradients: one is based on hypotheses about the mechanism involved while the other is largely empirical and based on the principle of irreversible thermodynamics. Few critical experimental checks of these approaches are available, and almost none of them are for transient conditions. In those carried out, soil temperatures and water suctions are considerably lower than those anticipated near the high-level radioactive waste, at least for some time after burial. These tests and certain theoretical considerations have demonstrated significant shortcomings of the available theories.

Objective To examine critically the adequacy of the available theories for nonisothermal liquid and water-vapor transport under various conditions of water content, temperature, and air pressure expected to be associated with the presence of high-level radioactive waste.

Approach The approach will include conducting laboratory tests to examine the theoretical concepts. Laboratory measurements of relevant properties will be made for samples taken from field test sites to estimate parameter values for computer modeling of field transport conditions.

Progress Laboratory investigations of the physics of nonisothermal flow of water and vapor in unsaturated soil at elevated temperatures continued. Standard methods of measurement were found to be unreliable at temperatures above 40°C, consequently, new techniques had to be developed. A significant achievement was made through our development of a submersible pressure outflow cell (SPOC), which enabled rapid and reliable measurement of soil-moisture content and soil-moisture potential at temperatures from 4°C to 100°C.

As reported previously, the SPOC showed that thermally induced flow of water in the unsaturated soil under study was as much as 10 times larger than predicted by theory. Also, it was found that the unsaturated-soil hydraulic conductivity changed much more rapidly as a function of temperature than predicted by theory. These results suggest that computer simulations of thermally induced flow of water in the unsaturated zone may be seriously in error if they are based on the standard transport model.

Laboratory studies of transient water-vapor flow in soil at temperatures up to 200°C also continued. Adsorption of water vapor on the surface of soil particles was found to have a dramatic effect on vapor transport. The adsorbed water serves as a large source of vapor, which buffers pressure changes in the porous medium. In order to incorporate adsorption into a vapor-flow theory, empirical water adsorption isotherms were measured at temperatures up to 200°C with an apparatus that we invented especially for this purpose. The data obtained were used to verify a vapor-flow model which had been developed earlier.

Reports

Constantz, J., 1982, Temperature dependence of unsaturated hydraulic conductivity of two soils: Soil Science Society of America Journal, v. 46, no. 3, p. 466-470.

Herkelrath, W. N., and Moench, A. F., 1982, Laboratory investigations of the physics of steam flow in a porous medium: U.S. Geological Survey Open-File Report 82-95, 38 p.

Modeling Fluid Flow and Energy Transport in Unsaturated Alluvium

By D. W. Pollock, Reston, Va.

The transport of water and energy in an unsaturated porous medium are strongly coupled. To adequately evaluate the thermal effects of high-level radioactive waste disposal in unsaturated alluvium, it is necessary to consider the simultaneous transport of water and energy.

When an unsaturated porous medium is exposed to a heat source (such as a container of high-level waste), water vapor pressure increases with increasing temperature which causes vapor to move away from the heat source by a combination of diffusion and gas flow. Liquid flow toward the heat source occurs in response to large gradients in liquid water potential which develop as the material surrounding the heat source dries. The net result is the gradual formation of a dry zone that expands at a rate controlled by the net water flux.

Heat-conduction analyses can provide first-order estimates of temperature changes in an unsaturated porous medium. However, heat transport in an unsaturated medium is strongly affected by the movement of water vapor and the liquid water content. Latent heat transfer by vapor has the effect of increasing the apparent thermal conductivity of the porous medium. On the other hand, the thermal conductivity of an unsaturated porous medium decreases with decreasing liquid water content. The temperature distribution in a repository will depend on the balance between these competing effects.

Objective The objective is to develop mathematical models which can be used to (1) simulate the transport of water and energy near hypothetical repositories in a variety of unsaturated media, and (2) simulate field and laboratory experiments designed to reproduce conditions that will exist in a waste repository.

Approach A numerical model of fluid flow and energy transport in unsaturated porous media will be developed and used to study the effects of relatively high temperatures on the movement of water and energy in the vicinity of a repository. A numerical model provides a means of studying the relative merits of a variety of repository designs and unsaturated hydrogeologic environments. Concurrent field and laboratory experiments will result in a much improved understanding of nonisothermal transport processes in unsaturated porous media. New infomation about the physics of the transport processes will be incorporated into the numerical model as it becomes available.

Progress A two-dimensional, axisymmetric finite-difference numerical model was developed to solve the equations which describe the simultaneous transport of water and energy in an unsaturated porous medium. The model has been used

to simulate the near-field effects of waste disposal on the temperature and liquid water content distributions within a repository consisting of an array of canisters. Results indicate that the rate of development of a dry zone and its ultimate extent are controlled primarily by the magnitude of the imposed thermal stress and the mobility of the liquid phase. Thermal loads which produce maximum temperatures of approximately 100°C cause dry zones to form which can persist for periods of a hundred to a few thousand years, depending on the mobility of the liquid phase.

A one-dimensional model which includes the additional effects of gas flow and dry air transport was also developed. Simulations using this model indicate that under most conditions and for many varieties of alluvium, the material is permeable enough that gas pressures would not build up, and vapor transport due to gas flow would be relatively unimportant compared with vapor diffusion.

Transuranium Elements in Ground Water

By J. M. Cleveland, Lakewood, Colo.

In view of the long half lives of many of the transuranium elements (plutonium, neptunium, and americium) and uncertainties regarding their chemical and physical speciation, it is difficult to predict their transport and distribution characteristics over the long term. In particular, it is fruitless to attempt to make distribution measurements of the transuranium elements without first determining their chemical forms in the ground waters of interest. This speciation is relatively straightforward for all elements except plutonium, which is most subject to hydrolysis, polymerization, and complexation.

Research in this area is included in the high-level waste program because of its significance in evaluating the far-field consequences of disruption of a high-level waste repository.

Objective To define the chemical and physical speciation and the chemical and hydrologic behavior of transuranium elements (particularly plutonium) in contaminated ground waters.

Approach The approach has been to sample leachates or ground waters from selected disposal sites where there is sufficient plutonium to permit the necessary separations and analyses. The water is passed through a sequence of submicron membrane filters of successively smaller pore sizes to determine the distribution of plutonium among the various particle sizes and to establish the fraction in true solution. Only the plutonium passing through the smallest pore-size filter can be in true solution; therefore, chemical studies were limited to this fraction. These studies included ion exchange to determine the charge of the plutonium species and various carrier precipitation and solvent-extraction procedures to establish the oxidation state of the plutonium.

Recently the approach has been changed to permit evaluation of the behavior of plutonium in a broad range of ground-water types. The new procedure involves obtaining ground-water samples from various rock types, characterizing them chemically, and adding a small amount of dissolved plutonium to measured volumes of each water. After standing for time intervals ranging from 1 to 30 days, the waters are sampled and subjected to the 0.05-μm filtration and oxidation-state analysis procedures described above.

To provide data necessary for solute transport modeling, a program has been initiated to determine stability constants of plutonium complexes with geochemically important anions such as sulfate.

Progress Analysis and interpretation of plutonium speciation in ground waters at the Idaho Chemical Processing Plant, Idaho National Engineering Laboratory, have been completed (see section on Idaho National Engineering Laboratory). A paper by J. M. Cleveland and T. F. Rees which has been accepted for publication in "Environmental Science and Technology," gives the speciation results and conclusions from this study. Of the four wells sampled, water from only one contained plutonium at concentrations above our detection limit of 10 femtocuries per liter (fCi/L). The majority of the plutonium was in true solution and in the tetravalent form. The 49 fCi/L of Pu-238 found in water from this well was lower than the concentration level in the waste liquid added to the nearby disposal well by a factor of approximately 16. Because the dilution to be expected (based on analyses of other constituents) between the disposal well and the well referred to is only a factor of two, it was concluded that more than 80 percent of the plutonium added at the disposal well was precipitated or sorbed by the rock along the flow path before it reached the sampling point. The insolubility of plutonium in these waters is attributed to the absence of strong organic complexing agents. The dissolved organic carbon contents of these waters were in the range of only 4 to 8 mg/L, and results of analyses indicated the absence of detectable (25 μg/L) concentrations of ethylenediaminetetraacetic acid (EDTA), the compound shown to be primarily responsible for plutonium solubilization in trench leachate waters from the low-level waste disposal site at Maxey Flats, Kentucky (see section on Maxey Flats, Kentucky).

Trench leachates were sampled at the Sheffield low-level waste disposal site in Illinois, but the plutonium concentrations were too low to permit speciation (see section on Sheffield, Illinois).

Report

Cleveland, Jess M., and Rees, Terry F., 1981, Characterization of plutonium in Maxey Flats radioactive trench leachates: Science, v. 212, no. 4502, p. 1506-1509.

Redox Potentials in Natural Waters

By D. C. Thorstenson, Reston, Va.

As originally conceived, this project was entitled, "Redox potentials and chemistry of actinides in water." The title was changed because of the very broad applicability of this work in the field of aqueous geochemistry. One of the more important practical applications, however, is to the geochemistry of nuclear-waste disposal.

To model the chemical behavior of the actinides, particularly as it relates to their transport in ground water, it is necessary to know (among many other properties) the redox potential and factors affecting it in the natural environment as well as the redox chemistry of the actinides. For many environments, electrode measurements of redox potentials by other techniques are only slightly better. The measurement errors can be large enough to result in incorrect predictions of mineral occurrences and order-of-magnitude errors in solubility or chemical speciation calculations.

Objective To improve our understanding of and ability to determine redox potentials and reactions in ground-water systems and to evaluate the response of the actinides to these potentials.

Approach Originally, the approach was designed to focus attention on measurement techniques, and it consisted of one or more of the following: (1) use of electrode materials other than the usual inert metals; (2) testing the applicability to natural waters of a wide variety of available chemical redox indicators; (3) equilibration with large-volume samples with a small volume of a solution containing a known electroactive, and thus measurable, redox couple; (4) analysis of electrode responses to electrical or chemical perturbations on the sample; or (5) further work on the estimation of the redox characteristics of natural waters based on analytical data for multiple redox couples in the same water.

Because of the findings of a study of the theory of redox reactions (see section on progress), the emphasis on electrode characteristics has been decreased.

Progress A paper entitled, "The concept of electron activity and the redox potential of aqueous solutions," which contains the results of the theoretical study of redox reactions, was prepared for presentation at a Symposium on Geochemistry of Nuclear Waste Disposal at the meeting of the American Chemical Society. Following is a summary of the important results.

The lack of hydrated electrons (in the absence of radiation) precludes the possibility of directly measuring an electron activity in aqueous solution. The implication of this for hazardous-waste disposal lies in the fact that any ground water containing redox-active constituents at disequilibrium (for example sulfate and dissolved organic carbon) does not have a uniquely defined redox potential. If a standard platinum-electrode Eh measurement is made on such a water, the measured value specifically will reflect the

kinetics of the relative reaction rates of the two solutes on the electrode surface. There is no ubiquitous chemical species, analogous to the hydrated proton, to which the platinum electrode can respond. Prediction of the valence states of contaminant species in a ground water based on Eh measurements will be valid only to the extent that the behavior of the contaminants mimics the behavior of platinum metal with respect to the solute species. It must be emphasized that this is not simply a measurement problem - it is an intrinsic characteristic of solution chemistry.

If hydrated electrons do not exist to act as reactants, the final valence state of contaminants introduced into a ground water will depend on the relative kinetics of its reactions with specific electron donor or acceptor species in the ground water. Chemical modeling must thus be based not on a measured (or postulated) Eh but rather on a knowledge of the chemical interaction between the particular redox-active contaminants and in situ chemical species in the ground water at any given disposal site.

Solute Transport in the Unsaturated Zone

By Jacob Rubin, Menlo Park, Calif.

If the unsaturated zone is to be considered a host medium for the emplacement of radioactive wastes, the medium must act as an effective barrier to radionuclide transport. The design of a suitable repository depends on our capability to predict the effectiveness of this medium as a barrier. Predictive models have been proposed, and others are being developed for solute transport in unsaturated porous media. The usefulness of these models is in question, however, and will remain so until they are based on laboratory and field data that relate solute-transport properties to water content. Also, these data must be compared against model predictions.

Objective To develop data-based, laboratory, and field-tested mathematical models useful for predicting transport of waste radionuclides in the unsaturated zone.

Approach The types of mathematical solute-transport models needed will require, in the early stages of the project, a combination of laboratory and theoretical work. The models to be developed and tested must be capable of simulating the most significant physical and chemical conditions characteristic of the unsaturated zone. These include wide variations in water content and in water-flow rates as well as a multiplicity of chemical reactions.

Progress A broad, theoretical analysis of the formulation of mathematical transport problems for reacting solutes has been completed. A draft of a report entitled, "Transport of reacting solutes in porous media: Relation between mathematical nature of problem formulation and chemical nature of transport-affecting reactions," is being reviewed prior to submitting it to a technical journal for publication. In particular, the relation referred to was studied for formulations which employ descriptions of chemical reactions ordinarily used in physical and surface chemistry, rather than relatively

coarse, less generally applicable approximations of such descriptions. Problem formulations considered involved six broad classes of chemical reactions: three classes of reactions for which the local-equilibrium assumption is acceptable (Class I -- homogeneous reactions; Class II -- heterogeneous, surface reactions; and Class III -- heterogeneous reactions of classical chemistry) and three kinetics-controlled classes of reactions for which the local equilibrium assumption is not feasible (Classes IV, V, and VI, which correspond, respectively to Classes I, II, and III above). Simple, representative examples of the six classes were considered. Known formulations were used whenever such were available. However, in the case of one broad and important class (Class III) no formulation existed, and one was especially devised. The operational transport equations needed for solving the various classes of chemical reactions exhibited considerable mathematical diversity which often involved rather fundamental differences (Table 3). In order to ascertain how firm and intrinsic was the observed association between the mathematical diversity and chemical characteristics, it was necessary to explore how and why this association is established. The results of such an exploration suggest that the associations observed usually are necessary consequences of certain basic chemical characteristics of the relevant reaction types and of the means used to describe them.

Experimental studies were continued utilizing the two previously developed approaches to studying the influences of water content and of water-flow rate on transport of reacting solutes in unsaturated sediments. The approach employing miscible displacement in short (5-cm long) columns lead to separate assessment of water content and water flux factors. For example, samples of a sandy soil with volumetric water content of 0.089 + 0.02 showed hydrodynamic dispersion coefficients of 5.0×10^{-7} and 4.4×10^{-6} cm^2/s, when average (macroscopic) water velocities were 1.33×10^{-4} and 1.32×10^{-3} cm/s respectively.

The experimental approach employing miscible displacement and relatively long (50-cm long) laboratory columns of unsaturated soil is still in the instrument redesign stage.

Table 3--Mathematical classification of selected operational solute transport equations

Systems of Equations		Classes of Reactions
1. A system of simultaneous, algebraic equations, some of them nonlinear, coupled with:	A. Independently-solvable, linear, single-unknown PDE's 1/ subject to fixed boundaries;	Class I
	B. A linear, single-unknown PDE, subject to a moving boundary.	Class III
2. A system of simultaneous, nonlinear PDE's with fixed boundaries and with nonlinear terms which:	A. Contain partial derivatives of the unknown functions;	Class II
	B. Do not contain partial derivatives	Class IV; also certain examples of Classes V and VI
3. A PDE or an integro-PDE with m independent, space variables, coupled with:	A. A nonlinear PDE with m+1 independent, space variables and subject to a fixed boundary;	Certain examples of Class V (some of which involve an integro-PDE and some do not)
	B. A linear PDE with m+1 independent, space variables and subject to moving boundaries.	Some examples of Class VI (do not involve an integro-PDE)

1. Partial differential equations

Predictive Models of Radionuclide Transport in Ground-Water Systems

By David B. Grove, Lakewood, Colo.

It is generally agreed that leaching and transport of radioactive wastes by ground water are the most likely mechanisms by which radionuclides might enter the biosphere. The partial differential equations that describe the movement of dissolved chemical species through the ground-water system are difficult to solve. Numerical solutions using high-speed computers presently seem to be the most attractive means to solve such equations. When the equations describe solute movement with little or no dispersion, a "shock front" phenomenon results which is even more difficult to analyze with existing techniques. The method of characteristics is one rather primitive method of solving such equations, and efforts are now underway to provide more attractive techniques from the standpoint of both accuracy and decreased computer costs.

Objective The objective is to develop and evaluate numerical modeling techniques to predict changes in water quality during the transport of radioactive solutes through the zone of saturation.

Approach The approach is to solve the mass-transport equation using finite-difference and finite-element methods to produce a model that will predict the effects of perturbations of the ground-water system caused by the introduction of radionuclides.

Progress Three mathematical models describing one-dimensional flow with single-species solute transport, together with diffusion into an adjacent zone of dead-end pore spaces, were compared with reference to the migration of radionuclides in specific types of tuff and granite. It was found that the mechanism of solute diffusion into a zone of dead-end pore spaces provides significant transport-rate retardation and attenuation of the peak concentrations, that the simplifying mathematical assumption of an infinite thickness for the zone of dead-end pore spaces is unrealistic because diffusive transport rates in the zone of dead-end pores are of comparable magnitude to the convective solute transport rates in the mobile water zone, and that the simpler models are adequate for high diffusional transport rates.

Laboratory flow devices have been constructed to test computer models for evaluating the movement of hazardous chemicals through porous media containing zones of dead-end pore spaces. Limited results to date have shown that the computer model is useful for predicting the movement of boron in a system of this type.

A 3-year study was begun to verify a nuclide- and chemical-transport model with data on an occurrence of shallow ground-water contamination from a uranium scrap recovery plant near Wood River Junction, Rhode Island. The areal extent of the plume of contaminated ground water is about 0.4 by 0.8 km, and it contains radionuclides and chemical solutes derived from liquid-waste-disposal ponds. Twenty water-table wells were drilled to define the water table and indicate flowpaths in the study area, and a well was drilled to bedrock to locate the bottom of the contamination plume near the disposal

ponds. Analyses are being made to determine the nuclides that are contributing most to the observable gross alpha and gross beta activity. The specific nuclides that are sorbing onto the sediments are being identified. The immediate objective is to develop a nuclide- and chemical-transport model of the shallow unconfined aquifer to simulate the movement of selected nuclides and solute chemicals.

Field sampling continued at Telluride, Colorado where ground waters have been contaminated with hexavalent chromium from mining operations. Laboratory tests of the collected chromate samples indicate that acidization in the field, prior to analysis, reduces the hexavalent chromate, converting it to trivalent. Since published manuals of sample-collection procedures have not addressed this problem, many published chromate analyses for chromium-contamination studies may be in error.

Reports

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Geomechanics

By H. S. Swolfs, Lakewood, Colo.

Within a mined repository for nuclear wastes, a thermal pulse will be generated by the radioactive decay of the shorter-lived fission products. The magnitude of the temperatures will be dependent primarily upon the isotopic composition of the waste, its age, concentration in the waste form, and spacing of the canisters; the maximum temperatures can be controlled by appropriate manipulation of these variables. The principal mechanical effect will be the development of thermal stresses superimposed on existing stresses (of geologic or mining origin) in the rock mass containing the repository. Heating is expected to increase the compressive stress in the mass adjacent to the repository but to reduce it at a somewhat greater distance. Such additional stress changes could produce slippage on pre-existing fractures in the rock mass and changes in the permeability.

Modeling the thermally induced stress requires knowledge of the initial stress conditions prior to mining. In the absence of such information, it has been necessary to assume zero or lithostatic stress (the increase in weight of the overlying rocks with depth); this assumption has resulted in considerable modeling errors. Some information on the initial stress can be obtained from measurements in boreholes in mined excavations. However, it would be desirable to have data from many locations as far removed from the effects of mining as possible. Existing borehole instruments could make such measurements in advance of mining and during the exploration stages, but the significance of the measurements obtained by such instruments must first be evaluated.

Objective To test existing borehole instruments that provide information on the state of stress in rocks under controlled conditions; to evaluate such equipment in the field in areas where stress is known or can be evaluated independently; and to develop the use of such techniques for application to mined repositories.

Approach A large variety of borehole instruments has been developed and marketed during the last several decades that reportedly convey direct information on the state of stress, strength, deformation, various moduli, and other essential properties of the rock mass. Many investigations of individual instruments have been published in the literature, but there have been very few attempts to compare the measurements from such instruments or examine them under laboratory conditions where the imposed stress is known and the significance and reliability of the measurements can be evaluated. To this end, a testing facility has been constructed in an experimental mine operated by the Colorado School of Mines near Idaho Springs, Colorado. This facility consists of a rectangular block (3 m long, 1 m wide, and 1.7 m deep) of gneiss partially excavated in the floor of the mine. Flatjacks inserted, cemented, and pressurized in narrow, vertical slots peripheral to the block will subject it to known stress levels up to 3×10^4 kPa. Holes of different diameters have been drilled vertically into the isolated block to accommodate the various instruments to be tested and calibrated (see also Swolfs and others, 1981).

To develop an efficient site-characterization methodology, a site near Golden, Colorado, has been chosen that allows the development of a theoretical model of the stress distribution in the rock mass. The borehole instruments already tested in the block will be used to determine the mechanical properties at this site, and such determination of stress, strength, deformation, and various moduli will be compared with similar information obtained from tests on core samples or derived from analytical methods. Thus, the geomechanics test site serves as an additional proving ground to test and evaluate existing instrumentation and to develop modifications, improvements, or new techniques as required.

Progress Calibration experiments on two additional borehole instruments and the evaluation of their response characteristics under controlled laboratory conditions have been completed. The Vibrating-wire Stressmeter, a "rigid-inclusion" stress-monitoring borehole device, is difficult to

calibrate precisely because its response is strongly dependent on initial wire tension, preload in the hole, contact angle (area) with the borehole wall, and the host-material elastic modulus. The performance of the Australian hollow-inclusion cell, an instrument designed to measure the complete stress state at a point in a single borehole, is seriously compromised in a changing temperature field because of the inadequate design of the strain-sensing bridge circuit and the very high thermal-expansion coefficient (150×10^{-6}/°C) of the cell material. Tests on an improved version of the cell that incorporates a temperature-compensating bridge circuit are in progress.

A second series of stress measurements at the geomechanics test site near Golden, Colorado, were completed in June 1981. These, together with similar measurements obtained in November 1980, reveal that the lava flow capping South Table Mountain is under a steady state of tensile stress of a few MPa that results from the gravitational spreading of the underlying much weaker sedimentary rocks.

Reference

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Synthesis of Neotectonic Conditions in the United States

By Carl M. Wentworth, Menlo Park, Calif., and
K. L. Pierce, S. M. Colman, and M. N. Machette, Lakewood, Colo.

The recent tectonic history of the country provides a basis for predicting and evaluating changes in the geologic setting of broad regions or potential repository sites over the next few hundred thousand years. The tectonic regime or setting determines: (1) the rates at which uplift and erosion may unroof a repository or change its hydrologic regime, or the rates at which downwarping and sedimentation may bury it deeper, (2) the potential for changes in geologic structural setting, including fracture density and permeability, new faults or extension of old ones that might cut the repository, and (3) the likely frequency and severity of earthquakes in the region. Tectonic factors conceivably can produce significant, undesirable changes in hydrologic conditions such as elevation of the water table, shortening of ground-water flow paths, and acceleration of rates of flow.

Objective To improve the ability to analyze and predict tectonic behavior and seismicity of parts of the conterminous United States during the next few hundred to one million years. To prepare a neotectonic map of parts of the conterminous United States that will show the patterns, styles, amounts, and rates of deformation (faulting, and broader horizontal and vertical movements) over the past few million years.

Approach Evidence of neotectonic deformation and the deformation history through Quaternary time will be gathered and compiled from existing literature and with the help of regional and topical specialists. This information will be synthesized into a coherent depiction of the neotectonic behavior of parts of the United States in terms of relative movements and their amounts and rates.

Evaluations at scales as large as 1:500,000 will be prepared for key areas of the country. Faults, folds, uplifts, downwarps, and tilts will be shown together with horizontal shortening, extension, and sheer, where resolvable, and kinds of geologic evidence. Evidence to be used includes local indication of fault offset, variations in local and regional datums such as unconformities and old shore lines, sedimentary evidence of upland erosion and basin subsidence and deformation, and geomorphic evidence of change or stability. Methods of approximation, particularly those based on geomorphic arguments, will be sought. Limits on deformation from negative evidence will be included. Effective means of portrayal and analysis will be designed.

Progress S. M. Colman completed compilation of 1:1,000,000 neotectonic map of Colorado, showing all available data pertaining to late Cenozoic tectonism. In addition, a more detailed (scale 1:125,000) neotectonic map was assembled for the Rio Grande rift of Colorado, the first map of the entire length of the structure that focuses on Quaternary faults and deposits. The map clearly shows the pattern of young faulting along the fronts of the Sawatch and Sangre de Cristo ranges and portrays the morphologic data for the fault scarps. Computer analysis of the scarp morphology data using a diffusion-equation model suggests that many of the faults have had similar histories.

M. N. Machette completed compilation of the first of seven 1:250,000-scale maps (in press) showing Quaternary and Pliocene faults in the Rio Grande rift of New Mexico and western Texas (Quaternary and Pliocene faults, Socorro 1x2 degree quadrangle, New Mexico, by M.N. Machette and G.R. Gimsey: U.S. Geological Survey Miscellaneous Field Investigations Map.) This map shows the recency of fault movement, age of faulted deposits, and amount of displacement on faults.

Data on fault scarp morphology for 32 of the more prominent Quaternary faults of the Rio Grande rift in New Mexico and western Texas have been collected. The final data set consists of about 250 scarp profiles. Estimates of ages of most recent movement for these faults is based on comparisons with the morphometric data collected for known ages of faulting along the La Jencia fault in central New Mexico.

The La Jencia fault has a history of four to seven discrete episodes of surface rupture during the past 33,000 yr as evidenced by the soil stratigraphy found in four trenches and by detailed study of fault-scarp morphology. Prior faulting in all of Pleistocene time is restricted to a single(?) episode along the northern half of the fault, about 150,000 yr B.P. Surface rupturing during the past 33,000 yr has produced a continuous, 35-km-long fault scarp of up to 7 m height. The most recent movement of the La Jencia fault was

along two discrete segments about 3,000 to 5,000 yr B.P.

Comparisons of fault-scarp ages with the model proposed by Nash (1980) reveal disparities that can be resolved only by considering variable rates of fault-scarp degradation related to climatic change in the late Pleistocene. Such constraints call for degradation rates of Holocene scarps that are three to four times greater than those during late Pleistocene time. The postulated increase in degradation rates during the Holocene is considered to be primarily the result of decreased vegetative cover and thus higher erosion potential.

Gravel deposits in the Basin and Range Province of southeastern Idaho are among the most extensive surficial deposits there and are a key datum for Quaternary faulting studies by K. L. Pierce and W. E. Scott. Soils, carbonate coats on stones, radiocarbon dating, and relations to local glacial deposits indicate that well-washed, clast-supported gravels are of Pleistocene age and were deposited under conditions with much greater runoff than present. In Holocene time, deposition has been limited to rubbly deposits at fan heads below steep mountain valleys and to fine-grained sediment along axial drainages.

Accumulation of information on neotectonic conditions of various parts of the conterminous United States is a slow process. Performance assessments for potential mined repositories for radioactive waste require estimates now of the likelihood of fault movement and earthquake occurrence at potential sites; and in the surrounding ground-water systems. N. J. Trask is reviewing the available information on the rates of neotectonic processes and their regional variations with a view to estimating upper bounds for the future rates of faulting and earthquakes near a site. These upper bounds can be lowered in future iterations of performance assessments as additional data on neotectonic processes become available.

Upper bounds for the rate of movement of faults can be derived from a continuum for the present rates which range from 10 mm/yr for obviously active faults along the western margin of the North American plate to as low as 10^{-4} mm/yr for recently documented faults in the Atlantic Coast province. Movement rates appear to be regionally consistent and to correlate broadly with the crustal stress provinces of Zoback and Zoback (1980). Faults that have moved under the current stress field, even at low rates, must be considered as potentially active during the time high-level radioactive wastes will remain toxic. Some previous performance assessments for radioactive-waste repositories have been based on assumptions which appear questionable in the light of current understanding.

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Computer Simulation of Geologic Stability of a Repository

By Herbert R. Shaw and Anne E. Gartner, Menlo Park, Calif.

Mathematical models are being developed to analyze the long-term risks of placing radioactive wastes in an underground repository. Starting from a particular geometric picture of a repository in its geologic and hydrologic setting and physical properties such as porosity, density, thermal expansion coefficient, effective viscosity of bedded salt (potential host medium for the wastes), and discharge rates of the aquifers, various parameters such as the area of the repository and thermal output of the waste can be varied and various possible causes of release of radionuclides examined in terms of their probability of occurrence with time.

Objective To establish the role of feedback behavior in the analysis of the geologic stability of any generic environment considered as a candidate for disposal of radioactive waste materials and to demonstrate the effectiveness of geological simulation methods in describing the ranges of possible release times and transport times of radionuclides from a repository.

Approach Feedback relationships between physical phenomena that may influence the geologic stability of a nuclear-waste repository are studied in relation to geometric studies of hydrologic transport paths through the repository environment. The approach uses the simulation language DYNAMO to explore potential mechanisms of radionuclide release. Conditions of instability, such as the creation of solution cavities in salt or regimes of high chemical-transport rates, are identified. Improved estimates of the probabilities

of initiating events are sought.

Progress Analysis of statistical data compiled for fault lengths by age and region within the United States (for movement during the past 15 m.y.) shows a resemblance to stream numbers and lengths. We have examined concepts of self-similarity for fault systems relative to the self-similar laws of order for stream systems and the correlation between earthquake magnitude and fault length. Two different logarithmic relations between fault orders and earthquake magnitudes relative to fault lengths have been identified. For the entire United States, the average length ratio for faults ordered like stream systems is $R_L \sim 3$. This relation indicates that earthquake magnitude is proportional to half the faulting order when defined on the same basis as stream order and when magnitude is defined according to the regressions on length; if fault length is derived from a correlation of fault length versus earthquake magnitude, however, then fault order and magnitude are directly proportional. Ordering faults in the same manner that streams have been ordered provides a new basis for investigations of the relation among rupture lengths, earthquake magnitudes, and regional source areas with respect to fault lengths and earthquake-energy flow in the Earth's crust. The laws of stream order are systematically interrelated; if analogous laws of order exist for faulting networks, our ability to forecast earthquakes is substantially increased. Our work suggests a need for a comparative study of river drainage and fault networks to be carried out in as great a detail as field data will permit.

Reports

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LOW-LEVEL WASTES

The principal method of disposal for low-level wastes in the United States has been, and continues to be, shallow-land burial in simple pits and trenches. Wastes from private and commercial sources are generally buried in commercially operated disposal sites, while government-generated wastes are disposed of in DOE operated sites.

In 1975, the Survey received direct appropriations to assume a new mission in the area of disposal of low-level wastes. The general purpose of this mission is to develop geohydrologic guidelines that can be used to establish technical criteria for selecting, evaluating, licensing, and operating new low-level waste-disposal sites. This program was designed initially to be a 5-year endeavor, including field studies at disposal sites at Sheffield, Illinois;

Maxey Flats, Kentucky; Beatty, Nevada; West Valley, New York; and Barnwell, South Carolina. To broaden the range of conditions under investigation, field studies were started in 1978 at the abandoned Argonne National Laboratory burial site in Illinois. A second phase of the program was designed to address specific aspects of the geohydrologic controls on radionuclide waste containment at some of these sites, and this activity will be continued for several more years.

Investigations of Disposal Sites

The general approach is to utilize the sites as field laboratories for long-term studies of the fate of buried wastes in relation to the unique geohydrologic, climatic, and waste-disposal conditions that prevail at each. The range and variety of conditions represented make this segment of the program particularly useful for deriving guidelines useful to the regulatory and operational agencies in establishing technical criteria for licensing new sites.

The studies involve the following specific tasks:

- defining the geologic and hydrologic conditions at disposal sites that are pertinent to the subsurface leaching and migration of waste radionuclides in ground water
- defining leach rates and source terms for modeling the transport characteristics of buried radionuclides
- defining the extent, rate of movement, and concentration of migratory radionuclides in ground water

In addition, a variety of conventional and innovative techniques are employed for sample collection and analysis, geophysical exploration, geochemical exploration, and numerical simulation.

Idaho National Engineering Laboratory

By J. T. Barraclough, Idaho Falls, Idaho

The Idaho National Engineering Laboratory (INEL), formerly the National Reactor Testing Station, was established in 1949 to test and develop peaceful uses of atomic energy in a remote location on the Snake River Plain in southeastern Idaho (fig. 18).

About 98 percent of the low-level aqueous radioactive waste and about 75 percent of the aqueous industrial (non-radioactive) waste is discharged to two on-site disposal facilities. Liquid wastes are discharged in the southern part of the reservation to ponds at the Test Reactor Area (TRA) and to a 183-m well at the Idaho Chemical Processing Plant (ICPP) which is open to the Snake River Plain aquifer. The aquifer, whose top is 137 m below these plants, is composed pre-

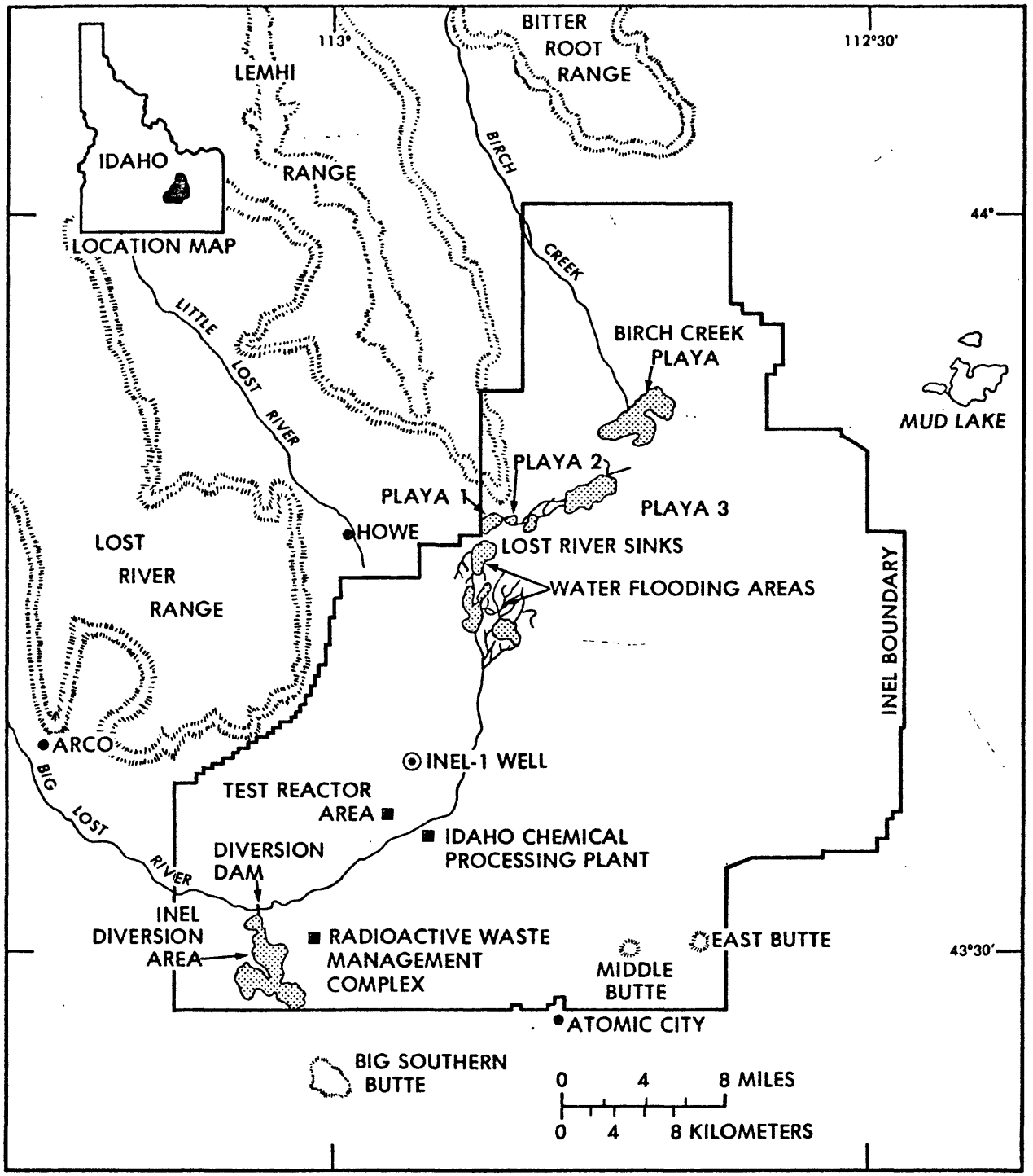

Figure 18.--Map showing selected facilities at the Idaho National Engineering Laboratory.

dominantly of basalt with some interbedded sedimentary layers. Solid radioactive wastes are buried at the Radioactive Waste Management Complex (RWMC) in the southwestern part of the reservation.

Six radioactive waste products can be identified in the aquifer; tritium, strontium-90, iodine-129, cobalt-60, cesium-137, and plutonium. Tritium has migrated the farthest. The other waste plumes have migrated much smaller distances because they are subject to sorption reactions. The speciation of plutonium in ground waters at the ICPP was studied by J. M. Cleveland (see section on Transuranium Elements in Ground Water). There are five indicators of chemical waste migration in the aquifer; chloride, sodium, specific conductance, nitrate, and chromium.

Objective To describe the effects of liquid and solid radioactive waste and liquid chemical wastes on the Snake River Plain aquifer; to verify principles of the movement of waste solutes in a fractured-rock aquifer; to determine the effects of dispersion, dilution, sorption, and radioactive decay on waste-solute migration; and to provide consultation to the DOE on a wide variety of geohydrologic problems.

Approach The geologic, hydraulic, and geochemical characteristics of the system and the migration of radionuclides in the aquifer are defined by periodic sampling of wells together with special analyses, various types of drilling, coring, sampling, and borehole geophysical logging.

Progress The waste plumes of various constituents in the aquifer were mapped periodically. The most mobile constituents have migrated downgradient (south) 13 km from the ICPP and TRA, covering an area of about 80 km^2 since disposal began in 1952.

The Ground-Water Data Acquisition System (GWDAS), which provides an independent means of continuously monitoring quantities of waste injected into the aquifer, was initially installed on a monitoring well near the ICPP disposal well; later the system was expanded to collect data from a second well. An automatic water sampler has been installed in parallel with the GWDAS. Groundwater tracer tests are presently being conducted utilizing this system.

The automatic tritium monitoring system, which is used in conjunction with the GWDAS, is undergoing further development to improve its sensitivity.

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Oak Ridge National Laboratory, Tennessee

By D. A. Webster, Knoxville, Tenn.

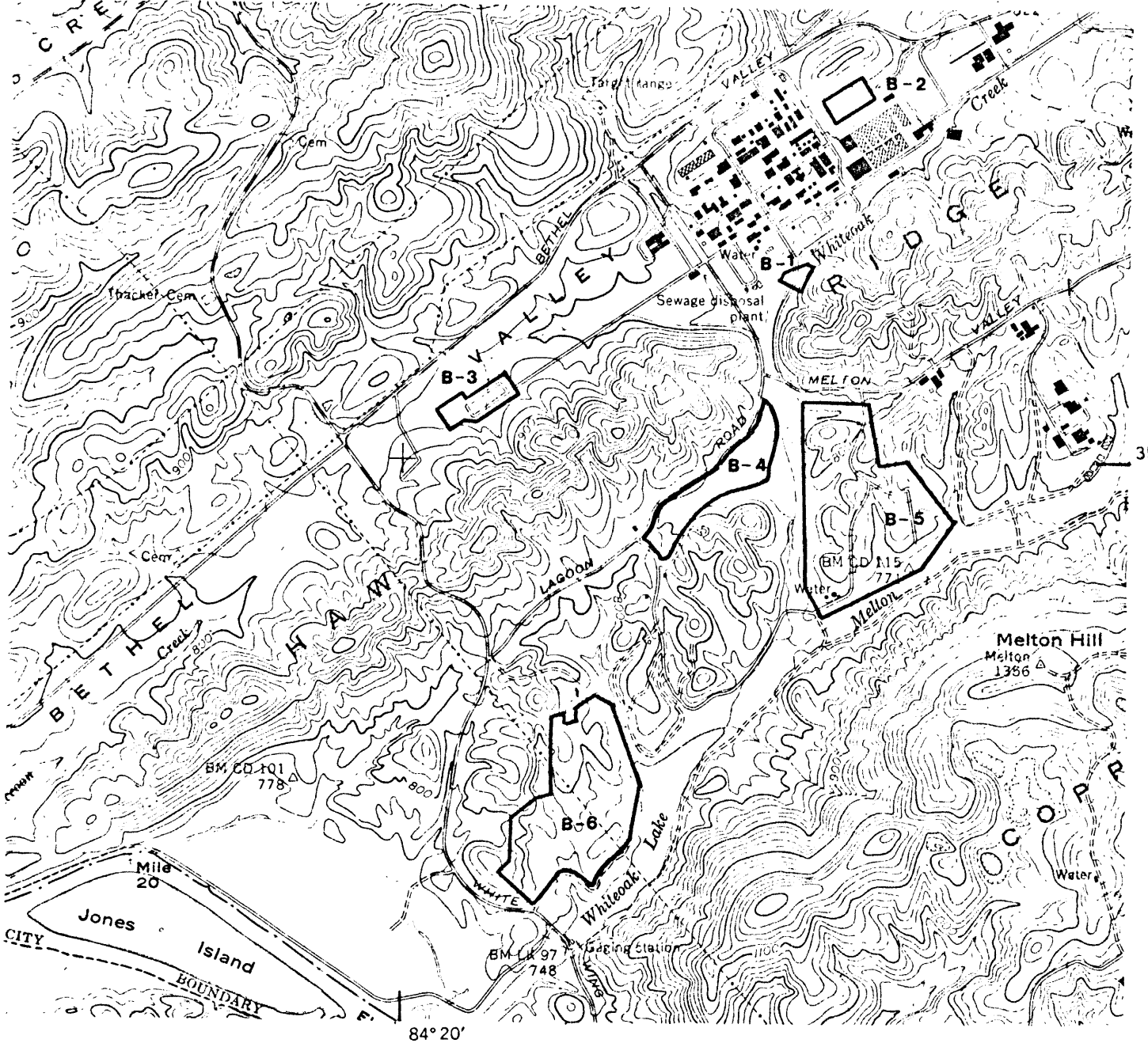
At the Oak Ridge National Laboratory (ORNL), solid low-level radioactive wastes have been routinely disposed of by burial in shallow trenches since the early 1940's. To date, six burial grounds (solid-waste disposal areas) have been used (fig. 19). Small but measurable concentrations of radionuclides have been detected in the streams in and near the four largest disposal areas, leading to the belief that radionuclides are being leached from the waste, transported in ground water, and discharged to those streams.

Objective To define the movement of water from the disposal areas so that an integrated ground-water--surface-water monitoring system can be developed, and to provide some of the hydrogeologic data necessary for the design of remedial measures to abate contaminant migration.

Approach The approach involves the collection and analysis of areal and transient water-table data from many shallow wells; the installation and testing of clusters of piezometers of varying depths to measure vertical head gradients and vertical distribution of hydraulic conductivity; the use of tracer tests to measure ground-water flow rates and directions; and the use of borehole geophysical logging, rock-core analysis, and hydraulic tests to determine some of the subsurface hydrologic characteristics of the rocks.

Progress Continuing the effort started in 1980, basic data obtained during the earlier years of the project were compiled into a series of data reports. The reports present information for approximately 200 wells in and near Burial Grounds 3, 4, 5, and 6, about 16,000 ground-water level measurements during 1975-1979, and precipitation data for Burial Grounds 5 and 6 during 1976-1980. The data base thus established provides information useful to the site managers and ORNL scientists performing various studies of the sites, a factual foundation for interpretive reports, and measured values of parameters in numerical models.

Field investigations, comprising a lesser part of activity during the year, focused on Burial Grounds 3, 5, and 6. An attempt was made to core sediment that has accumulated in the bottoms of two wells east of Burial Ground 3 (underlain by the Ordovician Chickamauga Limestone) and two wells in Burial Ground 5 (underlain by the Cambrian Conasauga Group). Geophysical logging earlier had identified the presence of cesium-137 at or near the bottoms of these wells, but left open to question whether the contaminant is sorbed to the bedrock or attached to the sediment. Cores were taken successfully from two of the wells, but mud samples only could be retrieved from the other two because of the low viscosity of the mud and the small thickness



EXPLANATION

Building

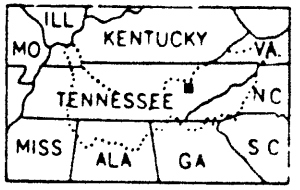
B-1 Burial Ground

SCALE 1:24 000

1000 0 1000 FEET

0 500 METERS

CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL



MAP LOCATION

Tennessee River drainage basin outlined by dotted lines

Figure 19.--Location of waste-burial grounds at Oak Ridge National Laboratory, Tennessee.

of the deposits. Analyses are not yet complete, but samples from each of the wells have been found to contain measurable amounts of cesium-137. The presence of this contaminant outside of Burial Ground 3 probably reflects transport of contaminated mud through solution channels in the limestone underlying that area. The origin of cesium in the Burial Ground 5 wells is more enigmatic. It may reflect the entry of contaminated mud below the bottom of the casings, settlement to the bottom of the well, and hence transport essentially through the upper weathered material; or, like Burial Ground 3, it could reflect transport through secondary openings deeper in the bedrock.

Slug tests, a type of hydraulic test, were made in 15 relatively shallow wells in Burial Ground 6 to derive estimates of the transmissivity of the weathered materials in the immediate vicinity of those wells. The results show that transmissivities at the majority of wells tested are low; some wells, however, penetrate zones of somewhat higher transmissivity that permit the movement of ground water at rates that could be considered significant with regard to the potential for waste transport away from the disposal site. The volume of material characterized hydraulically by slug testing is small. However, if such transmissive zones extend outward sufficiently far to communicate with other zones, they probably represent preferred pathways of flow along which contaminated water can move rapidly with minimal opportunity for sorption.

Much of the data obtained during 1975-79 on the potential for ground-water flow are from shallow wells in the upper, weathered geologic materials. In order to investigate flow through the underlying bedrock, a series of piezometers is planned with the initial installations to be in Burial Ground 5. The first cluster, somewhat experimental in design, was constructed intermittently between 1977 and 1979. Specifications for four additional clusters were drafted in 1980, and following numerous revisions in 1981 by the operators of ORNL and reviews by USGS personnel, construction of the clusters was started in August 1981.

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_____1981, Water-level data for wells in and near Burial Ground 4, Oak Ridge National Laboratory, Tennessee, 1975-1979: U.S. Geological Survey Open-File Report 81-339, 52 p.

Sheffield, Illinois

By James B. Foster, Richard W. Healy, and John R. Gray, Urbana, Ill.

The low-level disposal site located in northwestern Illinois near the town of Sheffield was operated commercially until April 1978 when all suitable space was used up. It covers about 8 ha of rolling terrain with well established drainage and is bordered on the northeast, north, and west by strip-mined land. The climate ranges from warm and humid in summer (average temperature 22.2°C) to very cold in winter (average temperature -7.5°C). Average annual precipitation is 890 mm.

Waste burial in the first trench began in August 1967. Twenty-one trenches were filled through April 1978 with a total volume of 83,147 m^3 of waste.

The U.S. Geological Survey initiated a study of the hydrogeology of the site in 1976 which was completed in May 1980. As a result of this study, a continuous pebbly-sand unit was mapped across the middle of the site, extending off site on the northeast and southwest corners. Because of its relatively high hydraulic conductivity, this unit is a control on the shallow ground-water movement to the east and would serve as a pathway for radionuclide migration. An additional study was started in October 1980 of the hydrogeology of the area extending east from the site to a discharge boundary in the hydrologic system consisting of a strip-mine lake and a creek.

To provide data useful in designing and constructing new low-level waste-disposal sites in hydrogeologic environments similar to those near Sheffield, a study was started in October 1980 of moisture movement in the unsaturated zone.

Also started at this time, because of its importance in establishing technical criteria for selecting new low-level waste-disposal sites, was a study of erosion and landform modification at the site.

Objective To define the stratigraphy and hydrology of the pebbly-sand unit extending eastward from the site to a discharge boundary in the shallow hydrologic system consisting of a strip-mine lake about 230 m northeast of the northeast corner of the site and a creek about 660 m from the east side of the site.

To define the mechanisms that control the movement of water and transport of radionuclides from disposal trenches through the unsaturated zone to the water table.

To study the processes of erosion and sediment transport by determining the relations among rainfall, runoff, and sediment yield and by defining the types and rates of geomorphic change.

Approach The investigation of the pebbly-sand unit will involve construction of test holes to define the stratigraphy of the glacial formations and the hydrology of both the confined and semiconfined strata. Hydraulic testing

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To study the processes of erosion and sediment transport by determining the relations among rainfall, runoff, and sediment yield and by defining the types and rates of geomorphic change.

Approach The investigation of the pebbly-sand unit will involve construction of test holes to define the stratigraphy of the glacial formations and the hydrology of both the confined and semiconfined strata. Hydraulic testing will be used to determine the hydraulic conductivity of the strata. Numerical modeling initiated as a part of the previous site study will be extended into the area east of the site. Water samples will be collected from test wells and analyzed for inorganic constituents and radionuclide content. An earth resistivity survey of a part of the area will be run to aid in delineating the extent of the pebbly sand.

Soil-moisture data on the unsaturated zone will be obtained by the use of a soil-moisture probe, suction lysimeters, and core samples. Soil suctions will be obtained from tensiometers and soil temperatures from thermocouples. Rates of soil-moisture flow will be calculated from calibrated tensiometers installed vertically and horizontally. Soil water collected with suction lysimeters will be analyzed chemically. Rainfall will be measured and used to interpolate between and evaluate soil-moisture measurements.

Radionuclide migration in the unsaturated zone will be monitored by radiometric analysis of soil-moisture samples collected at points throughout the system. The extent of migration will be determined from analysis of core samples. Moisture samples will be collected at the interface between the bottoms of waste trenches and the subsoil and analyzed for radionuclide and other chemical content. Natural-gamma and gamma-spectral logging will also be used to monitor radionuclide migration in monitoring wells. An evapotranspiration measurement station will be installed. The relation between infiltration and intensity and duration of rainfall will be determined from comparison of rainfall and soil-moisture data.

Numerical modeling of moisture flow in the unsaturated zone will be used to guide the data collection and to evaluate the mechanics of the system.

For the erosion and landform modification study, flumes will be installed to measure runoff and sediment discharge from three 0.8- to 2-ha drainage basins, two on the site to estimate long-term erosion rates and one adjacent

to the site to act as a control basin. Rainfall-runoff relations will be evaluated by numerical models and related to nearby long-term runoff records and precipitation records to estimate long-term trends.

Surface-water discharge and suspended-sediment concentrations will be used to calculate suspended-sediment discharge during all periods of runoff. Suspended-sediment-transport curves will be used with the estimated long-term runoff to estimate long-term erosion rates.

Three flumes will be installed within the site to collect runoff and suspended-sediment data from inter-trench areas or other areas where more localized data are required. Erosion pins will be implanted within the trench caps and adjacent areas to aid in defining relative rates of erosion and settling.

Samples of surficial materials will be collected and analyzed to evaluate their slope-stability and erosion potential. Data will include grain-size distribution, mineralogy, water content, compressive strength, plasticity, and permeability.

Progress The final report on the first phase of the investigation of the hydrogeology of the site was completed and is being reviewed.

Core samples from test wells showed that the pebbly-sand unit extends throughout most of the area east of the site, extending to the strip-mine lake to the northeast. Water samples were collected from these wells and analyzed for tritium. Tritium was found in water from two wells in concentrations well above background. The closest well to the site was about 80 m from the nearest waste trench, and the most distant well was about 125 m from the closest trench. The two wells containing tritium are situated in an area where the pebbly-sand unit is about 10 m thick.

In connection with the study of the unsaturated zone, cores were obtained of the sediments surrounding the 120-m-long tunnel that underlies four of the waste trenches. The cores were used to describe the stratigraphy of the formations in which the waste has been buried, to determine the hydraulic properties of these sediments, and to determine the extent of radionuclide migration from the trenches. Tritium is the only radionuclide that has been found in the soil moisture.

The unsaturated zone is composed of a layer of coarse sand overlain by a clayey silt and underlain by a sand-silt-clay till. Trench floors, which were thought to have been finished in the clayey silt, have been found to intercept the coarse sand.

The evapotranspiration station has been installed and has operated successfully through the winter.

A soil survey of the site was completed and analyses made of grain-size distribution for the study of erosion and landform modification. An automatic sediment sampler was installed on an existing Parshall flume. The drainage basins to be instrumented were surveyed, and two additional recording rain gages were installed.

J. M. Cleveland sampled trench leachates in his study of plutonium speciation (see section on Transuranium Elements in Ground Water).

Maxey Flats, Kentucky

By Harold H. Zehner, Louisville, Ky.

Low-level radioactive wastes were buried in a commercially operated facility in northeastern Kentucky, on a plateau called Maxey Flats, from 1963 to 1977. The burial site is about 104 m above surrounding valley bottoms. Wastes were buried in trenches 5 to 12 m deep, over an area of about 7.77 ha. Infiltrating water has accumulated in the trenches and is presently being removed and evaporated.

The ground-water system consists of at least eight rock units, each of which has different hydraulic properties, and all of which are fractured. Most ground water flows through the fractures. The lower boundary of the flow system is about 98 m below the top of the plateau. Most of the rocks are shale, including those in which waste is buried. The bottoms of most burial trenches are formed by a 0.5-m-thick sandstone interbed called the lower sandstone marker bed.

Objective To describe the subsurface hydrology of the site in terms of volumes, rates, and pathways of ground-water flow from burial trenches. Also, to relate the hydrology to the migration of leached radionuclides so that generalizations can be drawn regarding the fate of buried waste in this type of geohydrologic environment.

Approach The description of the ground-water system is based primarily on the collection of water-level and water-quality data from two recently constructed clusters of wells. Supplementary information from wells drilled in 1962 and 1973 is also used.

Progress The study was essentially completed early in the fiscal year, and a draft of the final report is being reviewed. All significant findings were reported by Zehner (1979) in a progress report.

Water-level data are being collected from about 20 wells and about 5 trenches by the Louisville District Office of the USGS.

A report on the speciation of plutonium sampled from trench leachates, prepared by Cleveland and Rees (1981), is listed in the section on Transuranium elements in ground water.

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Zehner, H. H. 1979, Preliminary hydrogeologic investigation of the Maxey Flats radioactive waste burial site, Fleming County, Kentucky: U.S. Geological Survey Open-File Report 79-1329.

Beatty, Nevada

By William D. Nichols, Carson City, Nev.

A commercial low-level radioactive-waste disposal site has been operating near Beatty, Nevada, about 150 km northwest of Las Vegas, since 1962. The 32-ha site is situated in a desolate region of the Amargosa River Valley, sometimes referred to as the Amargosa Desert. Average annual precipitation is only about 114 mm. The site is underlain by 175 m of unconsolidated, generally coarse-grained, alluvial-fan and flood-plain deposits. The water table is at a depth of 90 m.

Objective The objective was to investigate the geohydrology of the shallow, extremely dry, unsaturated zone at the site, with emphasis on determining the downward flux (recharge rate) of moisture through the alluvial deposits beneath the burial trenches.

Approach Determination of soil-moisture movement requires data on soil-moisture content, soil-water suction, and unsaturated hydraulic conductivity. Although the coarse texture of the alluvial deposits makes it difficult to obtain any reliable measurements of hydraulic conductivity, reasonable estimates can be made from data obtained in other research. Data on soil-moisture content and soil-water suction are being collected on a continuing basis and are being compiled for an analysis of infiltration based on field measurements. Volumetric soil-moisture content is measured to depths of 6 m using a neutron soil-moisture meter. Soil-water suction, between depths of 3 to 10 m, is being measured indirectly using psychrometric methods. Estimates of long-term infiltration are also being made using an evaporation/infiltration model.

Progress The investigation of the geohydrology of the site was completed, and a report is in preparation. Some of the results of this study are summarized below.

Detailed analysis of climatic conditions and precipitation patterns in the northern Amargosa Desert from 1949 to 1976 demonstrates that most of

the precipitation falls in the cool winter months when evaporative demands are at a minimum. Meteorological data collected at the site during the study were used to calibrate a long-term water-balance model based on National Weather Service data. The model was then used to determine when, and under what conditions, between 1962 and 1976, deep percolation might have occurred. The results suggest that deep percolation (below a depth of 2 m) could have occurred in 1968, 1973, and 1976. Definition of the antecedent conditions necessary to produce the percolation was accomplished by examining the precipitation record for the 12 to 16 months before each predicted occurrence.

A similar history of precipitation and soil-moisture conditions was recorded in 1978 and early 1979. Soil-moisture profiles from February 1978 to June 1980 provided documentation of deep percolation, resulting from this precipitation, during the late spring of 1979. These data provide conclusive evidence for deep percolation in areas of bare soil in the vicinity of the waste burial site. Considering the small amount of water involved (only 0.9 cm of the precipitation for the period 1978-79), deep percolation is not likely if vegetation is present.

Soil-water suction was monitored with thermocouple psychrometers to a depth of 10 m. The most reliable data were obtained at depths of 3, 6, and 10 m. Seasonal-type fluctuations were observed at all three depths but are most pronounced at 6 and 10 m. Measured soil-water potential ranged from -10 to -60 bars. These large changes in potential do not imply significant changes in moisture content; a reduction in potential from -50 to -15 bars can result from an increase in volumetric water content of less than 1 percent.

The unsaturated hydraulic conductivity of representative samples of the shallow subsurface sediments was determined using laboratory data and empirical relationships given by Hillel (1971) and Campbell (1974). The computed values of unsaturated hydraulic conductivity range from 10^{-13} to 10^{-4} cm/d. These values appear to be too small, but few other data are available for comparison for stoney soils at such low water contents and such large negative potentials.

A simplified analysis of transient unsaturated flow in the trench-backfill material is useful for the perspective it provides. The analysis assumes an unsaturated hydraulic conductivity for the backfill of 10^{5} cm/d and a gradient of 10^{4} cm/cm; the resulting transient flux rate would be 0.1 cm/d. Assuming (1) that this flux condition was imposed when the oldest trenches were closed in 1963 and 1964 and (2) that the flux rate was maintained at land surface, then the wetting front would have reached a depth of 6 m in the period 1963-80. This depth of penetration is comparable to the reported depth of the oldest trenches. However, the volume of water needed to sustain this flux rate, while not easily determined, is estimated to be several orders of magnitude greater than the volume of water expected to be available for deep percolation based on the long-term water-balance determinations. Steady flux rates in the unsaturated zone beneath the waste-burial trenches may be on the order of 10^{-5} cm/d, which implies a movement rate of about 4 cm/1,000 yr.

A new installation for monitoring soil-water potential to depths of 15 m is being designed with construction expected late in fiscal-year 1982. Additional studies and experiments related to evaporation and evapotranspiration are being developed.

References

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Hillel, D., 1971, Soil and water: physical principles and processes: New York, Academic Press, 288 p.

Barnwell, South Carolina

By James M. Cahill, Columbia, S. C.

The commercially operated radioactive-waste burial site near Barnwell, South Carolina, continues to be the only operating burial site in the eastern United States. As a result of an Executive Order by the Governor to gradually reduce the monthly volume of waste buried in South Carolina to 2,832 m^3 by October 1981, only about 50 percent of the country's waste is currently being shipped to South Carolina. The solid waste is buried in trenches, 6 to 7 m deep, excavated in unconsolidated clayey sand of Tertiary age and an overlying layer of eolian sand, ranging in thickness from a few millimeters to about 3 m.

The water table is generally at a depth of about 9 to 13 m. Ground-water recharge occurs locally from precipitation. Precipitation averages about 119 cm/yr, and it is estimated that about 40 percent recharges the ground-water system.

Objective: The objective was to describe quantitatively soil-moisture migration and ground-water flow at the disposal site and to assess the principal geohydrologic factors affecting radionuclide migration in unconsolidated coastal plain strata.

Approach Conventional field methods and numerical modeling techniques are being used to analyze the hydrologic system at the burial site. Special soil-moisture monitoring techniques are used to determine soil-moisture behavior in the unsaturated deposits at and near the burial trenches. Air samples above trench covers are passed through cold traps, and the condensed water is analyzed for radionuclide activity.

Progress A report on the hydrology of the site was prepared and is being reviewed.

Analyses of sediment cores, soil moisture, ground water, and atmospheric samples indicate that tritium has migrated downward, laterally, and upward from the buried waste. In 1977, the tritium activity was about 40,000 pCi/L in water from sediment cores obtained from a cluster of wells 3 m from the nearest trench. In 1980, a well in the cluster, 13-m deep, yielded water with a tritium activity ranging from about 70,000 to about 173,000 pCi/L. In 1981, the water table declined, causing the 13-m well to go dry. In the same year, tritium activity in water from a 21-m well, in more permeable sands beneath the clayey sediments, increased from the background level (1,000 pCi/L) to about 116,000 pCi/L. Tritium activity was near background level in water from wells located about 30 m from the nearest trenches.

Tritium activity ranged from 2,400 to 16,700 pCi/L in water condensed from air samples collected 20 mm above land surface over a trench completed in 1975. The tritium activity in a sample collected 600 mm above the land surface was 17,500 pCi/L.

Argonne National Laboratory Site, Illinois

By Julio C. Olimpio, Boston, Mass.

One of the world's first low-level radioactive-waste disposal site is located on former grounds of the Argonne National Laboratory, in the Palos Forest Preserve, about 22 km southwest of Chicago, Illinois.

Radiometric analyses of unconsolidated glacial deposits and ground water beneath the burial ground show that the concentration levels in a tritium plume, or contaminated zone, in the glacial drift range from $1x10^3$ to $1x10^7$ pCi/L. The plume extends 50 m northward from the burial site and 40 m vertically downward to dolomite bedrock. Tritium concentrations in water from bedrock wells 360 m downgradient from the burial site range from 200 to 1,400 pCi/L annually. Samples from these wells have not contained detectable concentrations of any other waste nuclides.

Objective Because of the apparent opportunity at this site to learn more about the long-term mobility of waste isotopes in geohydrologic environments similar to those in many other areas of the United States, a study was initiated to define the hydrologic and geologic properties of the drift which control ground-water flow and solute transport, and to determine the distribution and concentration levels of tritium beneath the site.

Approach The study, which began in 1978, is based on conventional drilling, sampling, well testing, and geochemical analyses. Analysis of the flow characteristics, using a simplified digital ground-water flow model, was used to guide the design of a network of monitoring piezometers. Water samples from the piezometers are collected and analyzed by personnel of the Argonne National Laboratory. A variable-saturation ground-water flow model is being used to predict water (tritium) movement in the drift beneath the site.

Progress The clay- and silt-rich drift is not a barrier to tritium movement. However, the drift is effective in controlling the direction of movement (predominantly vertically downward) and the rate of movement (6.3×10^{-6} cm/s). In effect, the drift is a 40-m-thick capillary fringe. The sediments have relatively high porosity, low permeability, and are variably, and almost completely, saturated.

Owing to the variability in the degree of saturation of the drift, it is necessary to use a saturated-unsaturated ground-water flow model to predict the movement of water. Specifically, the model is being used to test the effectiveness of the drift to limit, or retard, movement and to predict the change in moisture content and movement as a result of infiltration through a breached protective concrete cap over the site.

Pore-size distribution data were gathered from 20 core samples using mercury-injection techniques. Data from 38 tests were used to calculate the moisture content-pressure head and hydraulic conductivity-pressure head relations, effective porosity, air entry pressure, and saturated hydraulic conductivity of each sample. These data, together with hydraulic conductivity data from permeameter measurements, are providing values for the hydraulic parameters in the model.

Recent tests of a steady-state model show that the rate of downward moisture movement and the degree of saturation of the drift are most significantly affected by small variations in drift permeability and porosity.

Report

Olimpio, J. C., 1982, Low-level radioactive waste burial at the Palos Forest Preserve, Illinois, Part II. Geology and hydrology of the glacial drift as related to the migration of tritium: U.S. Geological Survey Open-File Report 82-78, 106 p.

Investigations and Modeling of Geologic and Hydrologic Processes

Geochemistry of Trace Elements in Natural Waters

By D. K. Nordstrom, Menlo Park, Calif.

The movement of radioisotopes, major elements, and trace elements through the hydrogeologic environment depends upon both biological and chemical as well as hydrodynamic processes. The chemical form of an element in an aqueous environment often determines which chemical or biological process is operating, e.g., adsorption on solids, precipitation, dissolution, uptake by biota, ion exchange, degassing, or oxidation-reduction. Chemical forms can be predicted from water analyses by simultaneous equilibrium calculations; however, there are several major uncertainties with this approach to chemical modeling.

Current limitations on chemical modeling include: (1) lack of adequate testing of speciation calculations against experimental and field data; (2) absence of a quantitative assessment of the redox status of natural waters; (3) absence of quantitative assessments of temperature, ionic strength, and compositional limits for use in specific models; (4) lack of adequate testing of adsorption model subroutines; (5) lack of an evaluation of available thermodynamic data; and (6) inadequate testing of equilibrium calculations against analytical determinations for specific forms of dissolved constituents.

Another aspect of hydrogeochemical processes of significance to the characterization of radioactive-waste repository environments is the evolution of ground-water chemistry in granitic terranes at great depth. Data on trace-element concentrations and trace-element geochemistry in deep granitic ground waters is almost non-existent. Such data would be valuable in assessing the hydrogeologic characteristics of granitic rock masses in relation to their suitability for repository purposes.

Objective The objective was to (1) define the limitations of current chemical models, (2) improve the reliability of current models to predict precipitation, dissolution, complexation, and bioavailability of elements in both contaminated and uncontaminated natural waters, and (3) to improve our knowledge of trace-element behavior in deeply buried granitic rock masses.

Approach A variety of laboratory, field, and theoretical techniques are being developed or adapted to overcome deficiencies in models and to test the reliability of models. These techniques include development of analytical methods for direct determination of free ion or bound species, compilation and evaluation of thermodynamic data used in speciation calculations, and investigations of field sites where water-mineral reactions can be observed directly and analytical and theoretical calculations can be tested. Water samples from the Stripa Mine in Sweden, an experimental site for studying the suitability of the crystalline igneous rock for developing a repository, will be used to develop concepts and methodology for studying trace-element behavior in granitic rock masses.

Progress Water samples have been collected from depths of 300-900 m in the Stripa granite and analyzed for 45 constituents, including 25 trace elements and 5 stable isotopes, in cooperation with the SKBF/KBS (Swedish Nuclear Fuel Supply Company, Nuclear Fuel Safety Project).

The preliminary analytical results indicate that salinity and pH increase with depth. In contrast, certain trace elements (Mo, B, and Cs) show almost no change in concentration with depth. Alkalinity is very low at great depth, and hydroxide is the main source of non-carbonate alkalinity, comprising 20-60 percent of the total alkalinity. These trends tend to suggest that the granite itself might be a source of the increased salinity. Other sources such as evolved marine pore waters or seawater intrusion

occurring during the last glaciation are also possible. Further isotopic and chemical analyses are being performed to resolve this issue.

Continued development of the WATEQ computer program has led to the incorporation of uranium species for chemical equilibrium calculations (Ball and others, 1981).

Highly reduced sulfur-rich springs from Colorado have been sampled and analyzed to examine the oxidation-reduction chemistry of dissolved sulfur species (sulfides, thiosulfate, polythioncites, sulfite and sulfate). These springs actively precipitate calcite, barite, and sulfur. The mineralogic and water chemistry data will provide a field test for the chemical model.

Report

Ball, J. W., Jenne, E. A., and Cantrell, M. W., 1981, WATEQ3 - A geochemical model with uranium added: U.S. Geological Survey Open-File Report 81-1183, 81 p.

Chemistry of Hydrosolic Metals and Related Substances in Water

by John D. Hem, Menlo Park, Calif.

Objective To understand the chemical processes that control solubility and movement in surface and ground water of metals such as iron, manganese, aluminum, and others which form hydroxides of low solubility and which may be adsorbed by or coprecipitated with such hydroxides.

Approach From published literature, chemical, thermodynamic, and other basic data are obtained and used to formulate quantitative models to predict metal solubilities in conditions like those of natural water systems. These models are tested by laboratory experiments and, where any additional solubility equilibria or kinetic data are required, they are experimentally determined. After laboratory work has indicated the hypotheses to be valid, the models are tested by field observations using published water and mineral composition data when available. Special site studies may be made if published data are lacking or are inadequate.

Progress Application of transmission electron microscopy (TEM) for identification of synthetic and naturally occurring manganese oxides has shown this to be an important tool. Electron diffraction patterns can be obtained from TEM for rather poorly crystallized natural manganese oxides and for very fine grained laboratory preparations. Ordinary X-ray diffraction techniques usually do not produce identifiable patterns for such material. A report by C. J. Lind, describing the procedures and demonstrating the results, has been approved for publication as Geological Survey Water Supply Paper 2204 entitled, "Characterization of mineral precipitates by electron microscope photographs and electron diffraction patterns."

As earlier work has shown, the species of oxide that are first to be deposited can evolve spontaneously to more thermodynamically stable structures at higher oxidation states. During this alteration process, which can occur in natural systems at almost the same time as the initial precipitation, the evolving oxide surface has highly active sites for promoting and catalyzing the oxidation of other ions. Laboratory studies which are aimed at evaluating this effect quantitatively are continuing.

The thermodynamic stability of a low-temperature initial precipitate, beta manganite (β-MnOOH), was determined to be about -129.8 kilocalories per mole, using a nonequilibrium steady-state model (Hem, and others, 1982).

Reports

Hem, J. D., 1981, Rates of manganese oxidation in aqueous systems: Geochimica et Cosmochimica Acta, v. 45, p. 1369-1374.

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Geochemical Kinetics

By Hans C. Claassen, Lakewood, Colo.

The interaction of the solid and liquid phases in natural ground- and surface-water systems results in a water quality which is a function of the chemical characteristics of rock and water, the temperature, the effective surface area of rock in contact with the water, and the interaction time. Differences in lithology and climatic conditions result in a range of water qualities which is surprisingly narrow when the broad range of variables is considered. This would suggest that chemical controls are operant, but it is not presently known whether they are thermodynamic (equilibrium) or kinetic (rate process).

Objective The primary objective is to study the rate and equilibrium processes controlling water quality in two model study areas in the San Juan mountains, southwest Colorado, where two types of silicate rock occur respectively: dacite-andesite tuff (Snowshoe Mountain Tuff of Oligocene age) and shale (Mancos Shale of Cretaceous age). Part of this study will include determining the influence of environmental factors such as precipitation quantity, quality, and time distribution; vegetative cover; and temperature, as well as the role of the soil zone, on water quality. A secondary objective is to develop a means for estimating the effective surface area of rock material through analysis of its influence on geochemical reactions.

Approach Temporal changes in water quality in the two model study areas are correlated with environmental factors to develop a mechanistic hypothesis of the chemical processes which control the dissolved species in ground water and surface water. This hypothesis is refined and verified by controlled kinetic laboratory experiments and tested against future changes in water quality brought about by changes in the environmental conditions in the model study areas.

Progress The aqueous geochemistry of the dacite-andesite tuff appears to be controlled primarily by weathering of augite and secondarily by weathering of calcium-rich portions of plagioclase (andesine) phenocrysts. The pattern of augite weathering is identical to that observed by Berner and others (1980). The weathering process is accompanied by precipitation of authigenic smectite and zeolite. Access to the phenocrysts where selective dissolution occurs is through microfractures about 4 μm in diameter. It is likely that the authigenic precipitates are magnesium-rich and that the rate of augite weathering, which generates soluble magnesium, limits the amount of precipitate formed. Thus, calcium and sodium accumulate in solution because they are generated at a faster rate than they are removed. The rates are being determined by a series of laboratory experiments just begun.

The aqueous geochemistry in the shale model study area appears to be controlled, in part, by microbiological processes. Biologically catalyzed sulfur oxidation and inorganic carbon fixation are indicated in short, shallow, easily recharged flow paths. Some of the hydrogen ions generated are consumed in exchange for calcium and magnesium ions on sodium-depleted clay minerals. Some dissolution of calcite and(or) magnesian calcite cement in the shale is also possible for these short shallow flow paths but may become the dominant process in the longer, less leached flow paths.

Report

Claassen, Hans C., 1981, Conceptual models governing leaching behavior and their long term predictive capabilities: Journal of Nuclear and Chemical Waste Management, v. 2, no. 4.

Reference

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Modeling Mineral-Water Reactions

By L. N. Plummer, Reston, Va.

Objective The migration of dissolved waste radionuclides or any other solutes in ground water is controlled in part by chemical reaction in the mineral-solution system. The principal objectives of this study are to understand the kinetics of chemical reaction systems.

Approach A weight-loss method has been adapted to study dissolution rate of single crystals suspended by platinum wires in known solutions. The solution pH is kept constant using automatic titrations. Numerical simulation techniques are being used to model thermodynamic chemical reactions in aqueous-mineral systems. Glass electrodes are used in thermodynamic studies of aqueous solutions. Carbonate reactions are investigated as a function of CO_2 partial pressures and temperature at 1 atm total pressure. Weight loss is measured to within 0.2 µg using an electronic balance. This method has proved far more reliable than batch experiments using a suspension of stirred particles.

Progress Experimental and theoretical work on the kinetics and thermodynamics of carbonate systems continued. A report (with D. L. Parkhurst and D. C. Thorstenson) describing the theory and methodology of testing reaction models in ground-water systems was written and submitted for publication. A new computer program (BALANCE - Parkhurst, Plummer and Thorstenson) was written to facilitate calculation of mass balance models in ground water. Preliminary results of this approach were presented in a symposium of the American Geophysical Union in Baltimore (Plummer, Thorstenson, and Parkhurst, 1981).

In the laboratory, new and improved solubility measurements of calcite, aragonite, and vaterite were made as a function of PCO_2 between 60° and 90°C. The new results show that all previous studies of calcite solubility conducted in hydrothermal bombs below 100°C failed to reach equilibrium and are in error by as much as 15 to 20 percent. The thermodynamic properties of the calcite, aragonite, and vaterite dissolution reaction were calculated between 0° and 90°C.

A new internally consistent method of calculating the total activity coefficient product of calcium and carbonate in seawater was developed with E. T. Sundquist. Results indicate that there is thermodynamic agreement between the apparent constants of calcite and aragonite measured in seawater and the thermodynamic equilibrium constants.

Experimental work was begun and continues in several areas:

1. Preparation of synthetic solids and determination of their solubility over the compositional series $CaCO_3$ - $SrCO_3$ (E. Busenberg).

2. Determination of ion association in the system SrO-CO_2-H_2O (E. Busenberg).

3. Revised determination of the rate constants for reaction of CO_2, H_2O and H+ with calcite and aragonite surfaces as a function of temperature (E. Busenberg and L. N. Plummer).

4. Determination of the adsorption effects of Ca^{2+} and HCO_3^- on kinetics of dissolution and crystal growth of calcite and aragonite surfaces (E. Busenberg and L. N. Plummer).

5. Measurement of ^{13}C fractionation factors in homogeneous and heterogeneous carbonate systems between 0° and 75°C using slow recrystallization reactions in sealed vessels (T. B. Coplen, L. N. Plummer, and J. A. Hopple).

Reports

Plummer, L. N., Thorstenson, D. C., and Parkhurst, D. L., 1981, Evaluation of chemical reactions in ground water: Example from the Floridan Aquifer (abs.): American Geophysical Union, EOS, v. 62, no. 17, p. 285.

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Reddy, M. M., Plummer, L. N. and Busenberg, E., 1981, Crystal growth of calcite from calcium bicarbonate solutions at constant PCO_2 and 25°C: A test of a calcite dissolution model: Geochimica et Cosmochimica Acta, v. 45, p. 1281-1289

Chemical Reactions at Mineral Surfaces

By James A. Davis, Menlo Park, Calif.

Physiochemical reactions at mineral surfaces are an important control on the rate at which some solutes are transported in water moving through soils, sediments, and rock formations. A detailed knowledge of the reaction mechanism is being sought to aid in the selection of appropriate disposal strategies for specific hazardous wastes such as radioactive wastes.

Objective To determine the effects of mineral surfaces (oxides, silicates, etc.) on the partitioning of solutes between dissolved and solid phases. To develop a thermodynamic data base that can describe the partitioning of specific elements or compounds between water and particular classes of solid phases.

Approach Current studies include the development of a theoretical model for quantifying adsorption reactions based on the concepts of surface complexations modified by corrections from electrical double layer theory. A model exists for well-characterized, clean hydrous oxides, but this model needs to be extended to consider more complex solid phases such as aluminosilicate minerals, minerals with secondary surface coatings, or

films of adsorbed organic material. Extension of the existing model will be based on experimental studies of these complex surfaces in the laboratory. Refinement of the model is accomplished by means of a chemical equilibrium computer program (MINEQL; Westall and others, 1976) which has been modified to include surface reactions in the computation of equilibrium.

The surface complexation model is based on the coordination chemistry of 100 surface -OH groups which are present at many mineral surfaces. The surface hydroxyl groups act as amphoteric Lewis acids or bases which can thus bond to either cations or anions. The current approach is to assess whether the surfaces of aluminosilicate minerals exhibit chemical behavior similar to hydrous oxides in their reactions with anions and cations, after making corrections for electrical effects with the theoretical model. Similarly, the chemical behavior of surfaces coated with natural organic matter of related model compounds is being studied. All soils and sediments contain natural organic material (fulvic and humic acids), and their influence on the surface chemistry of mineral phases needs to be determined.

Progress Work has begun on the characterization of surface hydroxyl groups on the mineral kaolinite. To date, this work has focused on the development of new techniques, such as tritium exchange, desorption of Al(III) in exchange positions, and reproducible preparation of the mineral for research purposes.

Another phase of the research on which work has started is modeling the adsorption behavior of natural organic matter with the surface complexation model. This phase is being carried out in two areas: (1) a study of the adsorption reactions of selected analogous compounds such as phthalate, salicylate, and catecholate on the alumina surface, and (2) mathematical fitting of the model to experimental adsorption data for the analog compounds and for natural organic matter. A report on related work was published (Davis and Gloor, 1981).

Work has continued on adsorption of lead by a natural streambed sediment using waters with variable Na^+ and H^+ concentrations.

Report

Davis, J. A., and Gloor, R., 1981, Adsorption of dissolved organics in lake water by aluminum oxide. Effect of molecular weight: Environmental Science and Technology, v. 15, p. 1223-1229.

Reference

Westall, J. C., Zachary, J. L., and Morel, F. M. M., 1976, MINEQL, a computer program for the calculation of chemical equilibrium composition of aqueous systems; Massachusetts Institute of Technology, Department of Civil Engineering, Water Quality Laboratory Technical Note No. 18, 91 p.

Microbial Reduction of Iron

By Garry G. Ehrlich, Menlo Park, Calif.

Leachates from shallow burial sites containing low-level radioactive wastes often have significant concentrations of dissolved ferrous (FeII) and manganous (MnII) ions. These ions are derived from materials contained in the wastes and from iron and manganese minerals in the soil. The metals in the precursor materials are usually in higher oxidation states such as Fe(III) and Mn(IV). Typically, compounds of iron and manganese in the higher oxidation state are only slightly soluble under the ambient conditions of a waste burial site; therefore, reduction is a necessary part of the solubilization process.

It is now commonly recognized that microbes are responsible for the reductive solubilization of these metals, but certain misconceptions about the mechanism of the process are widespread. The reduced state of the environment in a shallow burial site is a result of microbial activity. Solubilization is not caused by the reducing condition in itself but because some microbially produced reductant reduces the metal compounds. Fe(II) and Mn(II) ions do not appear under sterile conditions unless powerful chemical reducing agents are present. Under low Eh conditions and at neutral pH, Fe(II) and Mn(II) are stable, and the presence or absence of potential ligands is immaterial.

Alexander (1977) lists several mechanisms to account for microbial iron reduction. Increases in acidity accompanying fermentation promote iron dissolution. Another possible mechanism is the direct reaction of fermentation products with ferric hydroxides and oxides. Alternatively, iron reduction may involve a direct enzymatic reaction between the oxide and the bacterial electron donor. The iron functions as an electron acceptor in cell respiration in a manner analogous to the reduction of nitrate by denitrifying bacteria.

It is not known whether the organic acids are reductants and the cells merely catalyze the process in some way or whether iron reduction is a direct enzymatic process during which the intracellular production of the organic acids is inhibited.

Objective To determine quantitatively the role that microorganisms play in solubilization and mobilization of iron and managanese. This information will help to clarify the most significant chemical processes affecting the solubilization and mobility of many radionuclide and other substances of concern at waste-disposal sites.

Approach Microbial metabolism, biochemical reaction rates, and related quantitative studies are carried out in carefully controlled laboratory reaction vessels and flow columns. These laboratory studies are closely coordinated with field studies of actual disposal sites.

Progress Results of previous experiments in this study which suggested that reduction of Fe_2O_3 by bacteria occurred only if there was intimate contact between proliferating cells and the iron-containing mineral were confirmed by growing a large number of bacterial cultures, harvesting the cells, mixing washed cells with Fe_2O_3 and fresh growth medium, and incubating under anaerobic conditions. Cells grown in the absence of Fe_2O_3 but in the presence of the same growth medium, or held in the presence of Fe_2O_3 in a vegetative state, i.e. in the absence of nutrient medium, were used as controls. Only when cells were growing in the presence of Fe_2O_3 did Fe^{2+} appear in solution. The evolution of Fe^{2+} stopped if, during log phase of growth in the presence of Fe_2O_3, the nutrient medium was removed and replaced with nutrient-free mineral-salts medium. Biomass yields of cultures grown in the presence of Fe_2O_3 were not significantly different than if cells were grown in the absence of Fe_2O_3 under comparable culture conditions.

Liquid chromatographic analyses of spent-culture media by a newly developed method (Ehrlich and others, 1981) again showed significantly lowered formate (H_2CO_2) yields in the presence of Fe_2O_3 but comparable yields of acetate and butyrate in the presence or absence of Fe_2O_3. This finding is compatible with the previously reported interpretation that Fe_2O_3 reduction in saccharolytic clostridia is competitive with CO_2 reduction at the level of ferredoxin. The mechanism of electron transport from the cells to the Fe_2O_3 crystal is not known.

Report

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Influence of Benthic Geochemical Processes on Nutrient and Metal Cycling in Natural Waters

By E. Callender, Reston, Va.

Benthic sediment exchange processes may strongly influence the concentration of nutrients and metals in natural waters. Degradation of recently deposited organic matter and desorption-dissolution of precipitated iron and manganese oxyhydroxides result in pore-water concentrations that are significantly greater than those in overlying waters. Transport of pore-water nutrient and metal ions may be accomplished by molecular diffusion and several

advective processes including resuspension and bioturbation (sediment disturbance by benthic macroinvertebrates).

Objective To determine quantitatively the rates of nutrient and metal exchange from benthic sediment and the effect benthic exchange processes have on geochemical cycling in natural waters.

Approach Studies are divided into three basic approaches: the mass-balance approach where the effects of sedimentation and sediment regeneration are determined from input-output data; laboratory studies of adsorption/desorption of ions by suspended sediment and advection/diffusion of ions from incubated cores to overlying water; and field studies to measure ion concentration-depth profiles and estimate benthic fluxes directly.

Progress Application of Fickian diffusion models to an extensive set of interstitial water data has resulted in the calculation of diffusion rates of nutrient and major ions from estuarine benthic sediment to overlying water. These have been compared to measured in situ benthic flux rates which have been determined with experimental chambers emplaced on the bottom.

The ratio of measured in situ fluxes to calculated diffusion fluxes (flux enhancement) for ammonia, phosphate, and silica varied between 2 and 5 in the tidal river, between 2 and 20 in the transition zone, and from 1 to 5 in the lower estuary. The large flux enhancement from transition-zone sediments is attributed to macrofaunal irrigation. Nutrient flux enhancements are strongly correlated with inert radon-tracer flux enhancements, suggesting that fluxes may originate from a common region. The low fluxes of phosphate from tidal-river sediments reflect the control benthic sediment exerts on phosphorus through sorption by sedimentary iron oxyhydroxides.

The pore waters from 80 sediment cores taken throughout the Potomac Tidal River and Estuary have been analyzed for major chemical species and nutrients. The dominant diagenetic reaction appears to be the biochemical decomposition of organic matter via sulfate reduction and fermentation. Rates of reaction calculated using pore-water concentration gradients indicate that fermentation can degrade organic matter at rates nearly equal to those of sulfate reduction.

Reports

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URANIUM MILL TAILINGS

Radium Geochemistry

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In recent years, there has been increasing awareness among scientists and the general public of the radiological hazards resulting from natural radioactivity in the environment and from activities such as the mining and milling of uranium ores which increase the likelihood of exposure to the associated radiation. Another activity which has introduced radioactive materials into the environment is the management of residual products from radium-extraction industries. Although these industries were most active in the early 20th century, officials in several states are presently concerned about the health hazards of these materials whose nature is often poorly understood.

Objective To characterize some of the physical, chemical, biological, and mineralogical factors that may influence the mobility of radium and other uranium-series radionuclides in the surficial environment, with particular attention to uranium mill tailings.

Approach The distribution of radium-226 in the sediments of a coastal marsh receiving radium-bearing oil brines is being investigated in a cooperative study with the U.S. Navy and the University of New Orleans.

Samples of ore and the derived tailings were collected at an active, acid-leach uranium mill, to be studied by a sequential, selective extraction method to determine the effect of the milling process on the distribution and leachability of radium-226, thorium-230, and uranium.

Samples collected from a site in Denver, Colorado, which had previously been occupied by several radium-processing plants from 1915-25, are being studied to determine the distribution and leachability of the constituents mentioned above.

Progress A sequential, selective extraction procedure was used to assess the geochemical associations of uranium, thorium-230, and radium-226 in a uranium-ore blend and the tailings derived therefrom at an acid-leach uranium mill (Landa, 1982). Water-soluble fractions of U, Th-230, and Ra-226 were low (less than 1%) for the ore, but ranged from 3 percent

(Th-230) to 22 percent (U) for the tailings. Ion-exchange reactions appear to be of minimal importance in the release of U and Th-230 to aqueous solution for the ore and tailings solids. For Ra-226, extraction by leaching with an NaCl solution was about 4 percent from the ore and 13 percent from the tailings.

The total extraction sequence removes about 60 to 70 percent of the Ra-226 and U from both ore and tailings. Greatest extractions of U came with the 1 M acetic-acid-soluble phase in both ore and tailings. Greatest extractions of Ra-226 came later in the extraction sequence with the acid-reducing agent, suggesting an association with iron and manganese hydrous oxides. The resistate character of Th-230 is striking; except for an initial removal of about 3 percent from the tailings with distilled water, total extraction from the tailings differs little from that of the ore. Highest removals of Th-230 (about 20% for both ore and tailings) were achieved with the DTPA extraction, suggesting an association with alkaline-earth sulfate precipitates, organic matter, or both. Further studies are needed to see if the findings reported here are unique to these samples or applicable to a range of paired ore and tailings materials.

A literature and patent search was made of radium ore-processing methods employed in the early 20th century in the United States. A report documented the probable fates of U, Th-230, and Ra-226, drawing parallels with waste materials generated in uranium milling and other modern extractive metallurgical industries. (Landa, 1981).

Reports

Landa, E. R., 1981, A historical review of the radium extraction industry in the U.S. (1906-26) - Its processes and waste products: Proceedings, 4th Symposium on Uranium Mill Tailings Management, p. 3-32.

Landa, E. R., 1982, Leaching of radionuclides from uranium ore and mill tailings: Uranium (in press).