U.S. Geological Survey Research in Radioactive Waste Disposal— Fiscal Years 1983, 1984, and 1985

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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^3 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)
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	

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U.S. Geological Survey Research in Radioactive Waste Disposal--Fiscal Years 1983, 1984, AND 1985

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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 would involve water. The movement 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 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 Survey 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 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 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. Similarly, 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 fifth report of progress of Survey research in radioactive waste, the previous one being by Schneider and Trask (1984)[3/].

[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 100 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 100 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., 1984, U.S. Geological Survey Research in Radioactive Waste Disposal - Fiscal Year 1982: U.S. Geological Survey Water Resources Investigation Report 84-4205, 116 p.

RELATION TO PROGRAMS OF OTHER AGENCIES

For more than 30 years, the U.S. Geological Survey, 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 Survey 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; Washington, D.C.; and 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 National 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 Survey.

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 Civilian Radioactive Waste Management (CRWM) program, includes support for cooperative investigations by the Survey. 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 Survey 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 Survey 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.

Starting in fiscal year 1982, investigations of low-level waste disposal were conducted for the NRC at Sheffield, Illinois and West Valley, New York.

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

Basin and Range Physiographic Province

By M. S. Bedinger, Lakewood, CO

A study by the U.S. Geological Survey to evaluate potential hydrogeologic environments for isolation of high-level radioactive waste in the Basin and Range physiographic province was begun in May 1981, with the introduction of the study to the Governors of eight Basin and Range States--Arizona, California, Idaho, Nevada, New Mexico, Oregon, Texas, and Utah--and to respective Indian tribes in those States. Accordingly, these States were invited to participate in the study by designating an Earth scientist to serve on a Province Working Group with the Survey. State representatives provided consultation in selecting guidelines, assembling geologic and hydrologic data, and assessing such information to identify prospective areas for further study.

Objectives: 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.

Progress: Characterization of the Basin and Range province in the States of Oregon, Idaho, California, Nevada, Utah, Arizona, New Mexico, and Texas with reference to factors needed to evaluate favorability for waste disposal was completed by the preparation and assembly of maps containing data on surface occurrence of potential host rocks, Quaternary faulting, Quaternary volcanics, seismic activity, vertical movement, depths to ground water, ground-water flow units, ground-water contours, Pleistocene lakes and marshes, and mineral and energy resources. The first phase evaluation of the province for prospective high-level radioactive waste isolation environments included establishment of guidelines for screening (Bedinger, Sargent, and Reed, 1984), characterization of the province (Sargent and Bedinger, 1984), and evaluation of the province for high-level waste isolation (Bedinger, Sargent, and Brady, 1984). Following the first phase, studies were made of six regions within the Basin and Range province for further evaluation of favorability to isolate high-level radioactive waste.

The regional phase of the study is given in an eight-part report. The first part (Bedinger, Sargent, and others, 1985) describes the guidelines and methods used in characterization and evaluation of the regions. Each region was described in detail with reference to factors established for evaluating the favorableness of geohydrologic environments for isolation of high-level radioactive waste. The regions studied were the Trans-Pecos region of West Texas (Bedinger, Sargent, and Langer, 1985a), Rio Grande region (Bedinger, Sargent, and Langer, 1985b), south central New Mexico and extreme western Texas, the Sonoran region of western Arizona (Bedinger, Sargent, and Langer, 1985c), the Sonoran region of southwestern California (Bedinger, Sargent, and Langer, 1985d), the Death Valley region of southern Nevada and adjacent southern California (Bedinger, Sargent, and Langer, 1985e), and the

Bonneville region of west central Utah and east central Nevada (Bedinger, Sargent, and Langer, 1985f). The evaluation of the regions is given in the final report of the series (Bedinger, Sargent, and Langer, 1985g), which summarizes the favorable and unfavorable factors pertaining to high-level radioactive waste isolation in the regions.

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Buried Crystalline Rocks

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Crystalline rocks buried beneath a relatively thick sequence of sedimentary rocks have been suggested as a suitable environment for the disposal of high-level radioactive wastes because in many such systems water flow can be readily predicted and water use is unlikely because of high salinity (Bredehoeft and Maini, 1981). A panel of the National Academy of Sciences recommended that this concept be explored as to its feasibility (National Research Council, 1983).

The DOE has recently conducted a screening of exposed crystalline rocks in the eastern United States to locate potentially suitable sites for repositories but has not screened buried crystalline rocks.

Preliminary criteria were selected to search for geohydrologic conditions that might be suitable for application of the concept as follows (Davis, 1984):

1. The top of the crystalline rock body should be between about 1,000 and 4,000 feet below land surface. Saline water generally occurs below this minimum depth throughout most of the eastern part of the United States, and depths in excess of 4,000 feet below land surface were excluded for engineering, safety, and cost reasons.

2. The crystalline rock should be overlain by sedimentary strata whose lowermost part, at least, contains saline water (water with dissolved solids concentrations of 10,000 or more milligrams per liter). In general, the saline water will serve as a buffer between any buried crystalline-rock repository and the freshwater-circulation system.

3. Shale or clay confining beds should overlie at least the lowermost aquifer that contains saline water to impede the upward movement of waste nuclides.

4. The ground-water flow system in the lowermost saline-water aquifers should be known reasonably well or be determinable from available data. Ground-water movement would be the major way by which nuclides from a repository could reach the biosphere.

Objective: (1) determine if and where buried crystalline rock environments exist that have potentially suitable geohydrologic characteristics; (2) determine the likely distribution of plutonic and other crystalline rocks beneath the sedimentary cover in regions having potentially suitable hydrologic conditions; and (3) determine if sufficient data are available to define areas where the buried crystalline-rock concept might be applied in any subsequent site-screening program.

Approach: Carry out an initial reconnaissance of the eastern United States using readily available literature sources; carry out more detailed studies of regions which appear to have potentially suitable geohydrologic environments. In the detailed studies, use will be made of data from the Regional Aquifer System Analysis (RASA) Program as well as an integrated analysis of available geophysical data and information from existing wells.

Progress: Davis (1984) concluded that two regions in the eastern United States appear to meet most of the preliminary criteria. One region includes parts of the Atlantic Coastal Plain from Georgia to New Jersey. The other includes parts of western Ohio, eastern Indiana, and north-central Kentucky, which are underlain by the geologic structure known as the Cincinnati Arch.

The northern part of the Atlantic Coastal Plain, from North Carolina to New Jersey, was investigated in further detail in 1984 and part of 1985, by Lloyd and others (1985). Data for the study are from preliminary maps and reports that were compiled by the Northern Atlantic Coastal Plain Regional

Aquifer-System Analysis Group of the U.S. Geological Survey. Four factors were used to make a preliminary evaluation of the geohydrologic suitability of the Coastal Plain environment: (1) the estimated thickness of sediments that contain saline water, (2) the estimated thickness and continuity of the deepest confining beds, (3) the estimated distribution of the hydraulic conductivity of the deepest aquifers, and (4) the inferred direction of ground-water flow in the deepest aquifers.

Daniels and Leo (1985) prepared interpretive maps at a scale of 1:1,000,000 that depict inferred basement rocks, new Bouguer gravity maps of the region at the same scale, and 55 new descriptions of samples of crystalline basement rocks beneath the Atlantic Coastal Plain. Major subsurface lithologies mapped include granitic, dioritic, and gabbroic plutons, low and high grade foliated metamorphic rocks, and rocks of early Mesozoic sedimentary basins. Of these types, granitic and gabbroic plutons are most easily distinguished by using gravity and magnetic intensity maps. In many cases, strong support for these interpreted plutons comes from basement samples.

Part or all of 17 areas identified as probable basement plutons of granitic composition were mapped between the limiting depths to crystalline basement (1,000 to 4,000 feet) suggested by Davis (1984). Most of these occur in South Carolina, North Carolina, Virginia, and Maryland, in terrain similar to the adjacent Piedmont in those States. The inferred plutons range in area from about 150 to greater than 6,000 square kilometers, and were identified by low Bouguer gravity values, sharp gravity gradients, and by associated magnetic character. The smaller areas may be individual plutons, whereas the larger areas may be mixed terranes comprised of plutons intrusive into felsic gneisses and schists of similar density. By analogy with the exposed Piedmont, many of the plutons probably are of late Paleozoic age; two have been dated as such. Others in eastern North Carolina are of latest Precambrian and Cambrian age.

Most of the samples of basement rocks obtained from deep wells are in the form of cuttings. The small size of the individual rock chips does not reveal structural characteristics such as grain size if larger than chip size, metamorphic foliation if coarse, and open fractures. This type of information precludes discrimination between more deformed and less deformed plutons. Many samples described from cuttings as granite may be granitic gneiss. The structural properties of granitic gneisses and gneisses derived from some volcanic and sedimentary rocks may, however, approach those of undeformed granitic rocks and be equally suitable as host rocks.

In contrast with abundant evidence of felsic plutons, bodies of mafic plutonic rocks appear to be relatively less abundant and of smaller size. Diorite was recovered in six wells in eastern North Carolina, but evidence for only two plutons of significant size is reflected in the geophysical data. One of the diorite samples shows the presence of a nearby fault by mylonitic texture. Eight gravity/magnetic anomalies appear to be discrete plutons of gabbroic composition but only three meet the depth requirements. None has been tested by the drill. Other anomalies, particularly a major linear feature east of Richmond, VA, and anomalies east of Baltimore, MD, and Wilmington, DE, are probably mixed suites of gabbro, ultramafic rock, metavolcanic rock, and other lithologies judging from limited well samples

and analogy with Piedmont geology. Evidence for major faults which cut some of these sources is present in the geophysical maps.

In general, this study shows that the geologic nature of the basement rocks of the Atlantic Coastal Plain is similar to that in the adjacent Piedmont. Granitic plutons are as abundant as in the Piedmont, but their positions and areal extent are not as well known.

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DEPARTMENT OF ENERGY PROGRAM FOR LOCATING AND CHARACTERIZING HIGH-LEVEL RADIOACTIVE WASTE 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 Civilian Radioactive Waste Management program is composed of four separate coordinated elements which include many investigations related to locating and characterizing disposal sites: the Nevada Nuclear Waste Storage Investigations (NNWSI) at the Nevada Test Site (NTS); the Salt Repository Project Office (SRPO) in Columbus, Ohio; the Basalt Waste Isolation Project (BWIP) in Hanford, Washington; and the Crystalline Repository Project Office (CRPO) in Chicago, Illinois. This section of the report describes USGS investigations for the NNWSI and SRPO projects. Research in methods of characterizing crystalline rocks, funded in part by the CRPO, is described in a later section that describes generic research on methods of characterizing geohydrologic environments. The Geological Survey is also carrying out geologic and hydrologic investigations related to DOE's Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, which is intended for the storage of defense-generated nuclear waste.

Nevada Test Site and Vicinity

By V. M. Glanzman, Lakewood, CO

The USGS has been assisting the DOE in evaluating the suitability of the Yucca Mountain area, located on and adjacent to the Nevada Test Site (NTS) and about 160 km northwest of Las Vegas, as a possible repository site 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.

As part of the Nevada Nuclear Waste Storage Investigations (NNWSI) project, the USGS is performing multi-disciplinary studies involving projects in both the Geologic and Water Resources Divisions and personnel in the Denver, Colorado; Menlo Park, California; and Flagstaff, Arizona, offices. Studies include detailed surface mapping, surface geophysics, exploratory drilling, borehole geophysics, and topical studies of hydrology, climate, and tectonics. Studies are being performed to assess the potential for faulting, damaging earthquakes, recurrence of volcanism, and local acceleration of erosion in parts of the southern Great Basin.

Hydrologic investigations are directed to determination of present and past hydrologic regimes of the NTS and vicinity in order to predict the potential for ground-water transport of radioactive waste from a repository in Yucca Mountain to the accessible environment. Paleoclimatic studies are also being performed to aid in predicting future climate in the NTS vicinity.

Progress:

The principal borehole (USW G-4) for the Exploratory Shaft was completed on the east side of Yucca Mountain. Results from the borehole, drilled with air-foam to a depth of 914 meters near the proposed shaft site, support the geologic and hydrologic suitability of the location. The repository would be placed in the unsaturated zone which, in the Yucca Mountain area, ranges from about 490 to 760 m thick.

Downgradient and to the east of Yucca Mountain, drill hole UE-25p#1 reached the Paleozoic carbonate pre-Tertiary basement rock at about 1,250 meters. The drill hole was located where gravity and other data indicated that basement rock could be reached at the shallowest depth. Other exploratory holes in the area of interest at Yucca Mountain did not reach basement rocks at depths of as much as 1,830 meters. The aquifer in the Paleozoic basement rock and the complete sequence of volcanic rocks underlying the Yucca Mountain area, including some older tuffs not penetrated by other holes, were sampled in UE-25p#1. The hole also made possible the evaluation of total ground-water production and the identification of water production in all producing zones throughout the complete sequence of volcanic rocks.

Horizontal and vertical plugs from USW G-4 and UE-25p#1 were cored for use in determining hydraulic conductivity, grain density, and porosity. The

hydraulic permeability of the plugs was also determined. In addition, magnetic susceptibility and remanent magnetization measurements were completed on samples from UE-25p#1 core in Paleozoic carbonate rocks.

Regional hydrologic studies were expanded to include studies aimed at understanding the movement of ground water and dissolved chemicals through fractured rock using tracers. To provide supplemental data for the continuing studies, a number of limited-purpose holes were drilled to further define the hydrology around Yucca Mountain. The drilling program included a series of water table holes which were drilled to establish the static water level and to collect water samples around the entire block of interest. Differences in water table elevations suggest that the fault of Solitario Canyon, which is just west of the main ridge of Yucca Mountain, may be retarding the eastward movement of ground water. Chemical analysis revealed that sodium is the most abundant cation and bicarbonate is the most abundant anion in all of the ground-water samples obtained. Pumping and injection tests were performed in test wells UE-25c#1, 2, and 3. These three holes represent a triangular array for hydraulic and transport testing along directions parallel to and across regional fracture sets. Subregional flow modeling was completed to include Yucca Mountain to Alkali Flat and Death Valley.

Three holes were drilled and instruments were installed to measure present water movement at various depths in the unsaturated zone. Twenty-six neutron holes were drilled to monitor water movement in the unsaturated zone and to locate perched water. The one-dimensional model of air and gas flow in the unsaturated zone was completed. A two-dimensional flow model of the unsaturated zone was reviewed to determine what analytical solutions would be appropriate to test its validity. The finite difference model was executed to simulate the unsaturated zone. Realistic rain (flux and period) and evaporation data were developed for use in the model. The run was designed to obtain simulation data for two rain periods separated by a period of evapotranspiration.

Eleven precipitation stations were established to define the effects of storm tracks on the chemical and isotopic composition of precipitation. Two temperature recorders were installed near two precipitation stations located far from existing temperature recorders. Two precipitation samplers, capable of taking six sequential samples during a single storm event, were manufactured and installed on Yucca Mountain and at Kyle Canyon.

Deep trenches were excavated near the centers of Yucca and Frenchman Lakes to evaluate the potential of these playas for paleolimnological and paleoclimatic research. The rationale for pursuing playa studies near NTS began with the need for predicting future climate as near as possible to Yucca Mountain. Cores from Kawich Playa and Desert Dry Playa, taken in the fall of 1983 and spring of 1984 respectively, revealed that some playas, like Kawich, contained an interpretable paleohydrologic/paleoclimatic record, while the stratigraphic record of Desert Dry Playa did not reveal a history of normal lacustrine or marsh sedimentation for the last several hundred thousand years. The reasons for this are still not clear, but the encouraging results for Kawich Playa suggested that it would be appropriate to investigate other playas for suitable records and to attempt to understand the general patterns and processes of Great Basin playa sedimentation. The sedimentary records of both Yucca and Frenchman Playas and probably of other playas in

southern Nevada contain paleoenvironmental information that will be useful to the evaluation of paleohydrology and paleoclimatology in the vicinity of Yucca Mountain.

Sand ramps at Busted Butte and Crater Flat are also being investigated. These landforms resulted from sand blown against hills at lower elevations in the southern Great Basin during Pleistocene climatic episodes that were drier and substantially windier than the present. To date, three distinct volcanic ashes have been identified in three different sand units. These ash beds provide limiting ages for several sand units and soils. It is believed that the sand ramps record Pleistocene episodes of extreme aridity that were unrelated to uplift of the Sierra Nevada and Transverse Ranges. Sand accumulation during extreme aridity is thought to coincide with worldwide episodes of warm temperatures, because studies of local pollen and packrat middens indicate that the Mohave Desert experienced increased effective moisture and denser vegetation cover during Pleistocene episodes of cold temperatures.

Interpretive work continued on the cross sections along and perpendicular to the main ridges of Yucca Mountain. A relationship was developed between thermal conductivity in boreholes for which core is not available. Downhole temperature measurements from Yucca Mountain cross sections were used to develop theoretical models. Temperature logs were reduced from drill holes in the vicinity of Yucca Mountain and entered into disk files. Additional analyses were completed on thermal conductivity data and heat flow distribution for the Yucca Mountain area. The distribution was tabulated and mapped.

A 1:12,000 scale geologic map of Yucca Mountain with cross sections was completed and released. Detailed geologic mapping was extended into the area south and west of Yucca Mountain. Efforts were also focused on the detailed characterization of the geologic setting in the vicinity of the proposed Exploratory Shaft. Detailed fracture mapping and characterization was started at exposed rock pavements near the Exploratory Shaft site. Fracture mapping on two pavements was completed. The concept of fractal geometry was used to quantify the fracture trace patterns for two-dimensional slices through the three-dimensional fracture networks. This is the first time such fracture patterns have been so characterized.

Aerial photo reconnaissance of faults was conducted over Yucca Mountain, and a map was compiled. Various types of photo lineaments in the alluvium were classified and entered on the map. Faults were compiled on the 1:12,000-scale topographic base map of Yucca Mountain. A second map was assembled showing lineaments visible in air photographs of the repository site. In addition, a fault map was compiled of the Beatty 1:100,000-scale quadrangle from published data.

Field work and data compilation for a geologic map of the northwest quarter of the Bullfrog quadrangle were conducted to contribute to understanding the tectonic framework of the Yucca Mountain region. Data compilation of the northwest and southwest quarters of the partially remapped Bullfrog 15-minute quadrangle was completed. Field work was performed to collect data for a 1:24,000 bedrock geologic map of the southwest quarter of the Bare Mountain 15-minute quadrangle.

A 2- to 3-meter section of sediments overlying a disconformity in the Amargosa Desert was sampled to establish the age of these sediments and the underlying disconformity based on magnetic polarities. Numerous widely dispersed outcrops of the Tiva Canyon and Topopah Spring Members were sampled to assess the extent of rotation about a vertical axis in response to movement on lateral shear zones and to different amounts of extension.

Work is continuing on a comparison of fracture orientations obtained by television camera observations of drill-hole walls and those obtained by acoustic televiewer logging of the walls. Cuttings from boreholes were examined to refine detailed correlations of stratigraphic units in the vicinity of the repository site. The stratigraphic and lithologic description of the water-table boreholes was completed.

Rock samples were collected for magnetic property analysis to aid in the interpretation of the Las Vegas 1:250,000-scale aeromagnetic sheet. This work included a preliminary evaluation of the aeromagnetic anomaly map of the Las Vegas quadrangle and the evaluation of background material. Field susceptibility measurements made at the sites of major magnetic anomalies in the NTS region were analyzed in an attempt to relate anomalies to regional structure and hence to the structure at Yucca Mountain. The crustal model of a broad area around Yucca Mountain was refined on the basis of teleseismic and deep refraction results.

Modeling of the Spring Mountains magnetic and gravity anomaly has provided a domal model for the anomaly source. Results are interpreted as suggesting the Spring Mountains are cored by a metamorphic core complex whose central portion is rock of extraordinarily high magnetization and a density somewhat lower than the Paleozoic and later Precambrian sedimentary rocks. The core of the dome possibly is an iron-rich granitic rock of late Mesozoic or Tertiary age which produced the domal uplift of the basement and pre-Tertiary sediments.

The principal results from investigations of natural seismicity indicated that Yucca Mountain lies within a broad "U"-shaped zone of low-level seismicity extending on the west to the Funeral Mountains, on the south to the Black Mountains and Nopah Range, and on the southeast to the Spring Mountains. Through July 1985, three earthquakes have been located within 2 km of the Yucca Mountain seismic network. Magnitudes for these earthquakes range from 0 to 0.5 and represent the latest revised magnitudes for these events based on a recent attenuation study.

A network of 10 tectonic activity measurement stations was established in the Yucca Mountain area to measure crustal deformation. Since crustal deformation can be directly observed, it is a useful indicator of the rate and nature of tectonic activity. Repeated precise distance measurements have proven to be an effective technique for measuring crustal deformation over relatively short time periods (1 to 10 years). By measuring distances with a laser distance measurement instrument and measuring refractivity all along the observing path, precisions approaching 2 parts in 10 million have been obtained.

A new technique to correct sonic logs for cycle-skipping and misidentification errors in the first arrival travel time was developed. Preliminary results of comparison of the technique with previously collected data indicate the

method to be an improvement over existing methods, and one that could possibly be used to identify possible water producing zones prior to pumping tests and to trace some fractured zones between drill holes.

Six topographic maps of the Yucca Mountain area were completed. The photogrammetric compilation is at a scale of 1:5,000 with a contour interval of 2 meters. These maps represent areas 3-km square in much greater detail than the standard USGS 7-1/2-minute quadrangles. These high-resolution topographic maps will support geologic as well as gravity studies.

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Paradox Basin, Utah

The eastern Utah portion of the Paradox Basin 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 has reviewed the mineral-resource potential of the area. Since 1981, exploration efforts

have focused on two locations about 18 km south of Gibson Dome termed Davis Canyon and Lavender Canyon.

Geology

By Robert J. Hite, Lakewood, CO

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: Gibson Dome, which is a small northwest to southeast oriented anticline in the Gibson Dome study area, is located about 18 km north of Davis Canyon. A geologic cross section through the upper part of the salt-bearing Paradox Member of the Pennsylvania Hermosa Formation shows that structure in the evaporite deposits is somewhat more complicated than depicted by previous investigators in the area. For example, in the Belco Petroleum Corporation well, located near the crest of the structure in sec. 2, T. 30 S., R. 20 E., reverse faulting repeats cycles 2, 3, 4, and 5 of the Paradox Member. On the hanging wall of this fault, the halite of cycles 2 and 3 has been dissolved and is represented by solution breccias. The dissolution of halite was apparently brought on as a result of faulting moving the salt bed upward into an active ground-water flow system. Collapse resulting from dissolution caused a later period of normal faulting. Halite is present in the Reynolds Mining Corporation well (sec. 35, T. 29-1/2 S., R. 20 E.) about 1 mile to the northeast of the Belco well. No faulting is present in the Reynolds well, although there is evidence of some thickening of units due to salt flowage. The available evidence suggests that structures in the Belco well are probably the result of Late Pennsylvanian salt tectonics.

Evidence of salt flowage is widespread in the DOE GD-1 core hole. In salt 5, the anhydrite laminae are relatively flat lying; however, the laminae are highly deformed and show as much as 50 percent shortening. Boudinage is common and halite crystals show a strong elongation parallel to the anhydrite laminae. In salt 6, the anhydrite laminae are strongly deformed at the top of the bed and show boudinage gaps of as much as 20 mm. Within the bed, individual laminae dip as much as 30°. The basal contact of salt 6 and the underlying anhydrite dips 45°-50°. Anhydrite laminae in the halite immediately above this contact are nearly flat, which suggests deformation prior to deposition of salt 6. The basal contact of salt 7 dips at about 35°. Halite at the contact has a high content of shale clasts and shows a fibrous habit of crystallization, which suggests the possibility of a shear zone. In general, an analysis of the deformation observed in the halite beds of the GD-1 core suggest a scale of deformation that is probably an order of magnitude less than some of the larger salt anticlines located a few miles to the northeast (Cane Creek and Libson Valley). Nevertheless, it seems quite likely that salt beds in the Gibson Dome area (including the Davis and Lavender Canyon sites) will at least be characterized by gentle folds.

Halite rock in the Paradox Member is characteristically banded, like all marine halites, by anhydrite laminae. These laminae, which range from 0.5 to 5.0 mm in thickness, are believed to represent annual influxes of sulfate-bearing seawater. In addition to the $CaSO_4$ forming the laminae of each anhydrite-halite couplet, some anhydrite is also disseminated as single crystals or crystal aggregates through the halite of each couplet. Studies of the anhydrite-halite couplets in the GD-1 core have shown that in many couplets the amount of $CaSO_4$ present exceeds the theoretical maximum (2.0 mm) that could be deposited in one season by the evaporation of brine saturated for $CaSO_4$ (Hite, 1985). This excess of $CaSO_4$ is believed to represent "reaction" $CaSO_4$, which is precipitated as the result of reaction between influxes of seawater (high SO_4^{2-} and low Ca^{2+}) and inner basin evaporitic brines (low SO_4^{2-} and high Ca^{2+}). Evidence supporting this conclusion comes from high concentrations of Ca^{2+} in brine inclusions in halite rock as well as connate brines associated with the interbeds of dolomite, anhydrite, and black shale.

Considerable concern has been expressed about the problem of brine inclusion migration in halite rock towards heat-generating nuclear waste. However, anhydrite laminae in the halite will act as barriers to this migration. The solubility of anhydrite decreases with increasing temperature so that it is unlikely that brine inclusions could pass through the laminae except where the laminae are broken by boudinage. Thus brine accumulation in a repository would be largely restricted to horizontal migration along halite units of couplets intersected by mine openings.

The evaporite deposits of the Paradox Member were deposited in strongly anaerobic conditions and as a result contain an abundance of organic matter. The black shale units of some evaporite cycles contain over 10 weight percent total organic carbon (T.O.C.). Even some halite samples contain up to 0.51 weight percent T.O.C. Studies of thermal maturation of organic matter in the GD-1 core suggest that hydrocarbon generation began at a depth of about 1,400 feet (609 m) and at a calculated paleo-temperature of 125 °F (51.7 °C) (Hite and others, 1984). At the potential repository horizon (cycle 6), the overlying black shales of cycle 5 had a paleo-temperature of about 142 °F (58.7 °C) and these shales have already generated as much as 2.91 mg of hydrocarbons per gram of rock. At about 2,878-2,880 feet, the black shale of cycle 3 contains about 4.15 weight percent organic matter and 1.17 mg of hydrocarbons per gram of rock. With further heating, this shale produced another 18.11 mg of hydrocarbons per gram of rock. It is a well-known fact that these shales are almost always overpressured throughout the Paradox Basin. Currently, calculations are underway to see what additional heating will add to the already high pore pressures of these rocks.

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Quaternary Geology of the Fisher Valley Area, Utah

By Steven M. Colman and Anne F. Choquette, Lakewood, CO

The geology of the Fisher Valley area, southeastern Utah, 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.

Progress: The project is completed and all required reports are published. Several additional scientific reports are either published or in press.

Geologic mapping and stratigraphic studies have shown that a thick sequence of basin-fill sediments has been deposited in Fisher Valley adjacent to the Onion Creek salt diapir. Numerous dating studies have been done, including those based on the volcanic ashes in the section, paleomagnetic stratigraphy, paleosol development, uranium isotopes, radiocarbon analyses, amino acid compositions of soils, and thermoluminescence of the sediments.

These data show that major geologic and geomorphic changes have accompanied deformation of the Onion Creek salt diapir in the last 1.5 m.y. These changes include major drainage captures and diversions, the formation and filling of a significant sedimentary basin, and major deformation of the basin-fill sediments. Differential deformation of the diapir during this time was at least 140 m, of which at least 70 m was upward movement in an absolute sense. The primary cause of this salt mobility appears to be erosional unloading of the salt mass along the crest of the Fisher Valley anticline.

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Palo Duro Basin, Texas

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: Studies of fluid inclusions in salt at the USGS during the reporting period (October 1982-June 1985) have had a number of objectives. Most important among these are the following:

1) Develop and improve methods of obtaining quantitative data from inclusions and validate their geological and geochemical significance.

2) Determine what information can be obtained from fluid inclusions that may help in determining if, when, and how fluids have moved through the salt in the past and whether this may occur in the future.

3) Determine how much fluid is present in any given site and its distribution properties, and composition.

4) Determine what predictions can be made as to the behavior of known fluid inclusions, as well as other possible sources of migrating fluids (as indicated by fluid inclusion studies), during and following the storage of nuclear waste.

Approach: Specially prepared samples are examined by microscope for fluid inclusions and appropriately sized portions are removed for study and chemical analysis.

Progress:

1) Development of validation of methods

A wide variety of methods have been used in fluid inclusion study in the past, and new developments in many aspects of analytical instrumentation have been applied to fluid inclusion analysis. There is a need to integrate the very widely scattered world literature dealing with inclusion studies. Although some standard retrieval and abstract services such as Georef, Chemical Abstracts, Mineralogical Abstracts, etc., provide an introduction to the literature, these are far from adequate in coverage. The USGS fluid inclusion project has been preparing an annual abstract and citation summary of the world literature on fluid inclusions for 16 years (see, e.g., Roedder, 1985a). In each of the volumes issued during this reporting period, there has been an average of 25 entries specifically on inclusions in saline deposits. In this same connection, a general book on fluid inclusion study (Roedder, 1984a) has also been published.

The gases present in fluid inclusions can, at times, be very informative as to the origin and history of the fluids in a salt deposit. During the report period, several new developments in the use of high-sensitivity gas chromatography for the analysis of fluid inclusions were reported (Andrawes et al., 1984a,b). Similarly, the P-V-T-X properties of brines are essential in understanding the near-field effects of radioactive waste in salt. Several studies have provided important basic new thermodynamic data on the major system $NaCl-H_2O$ (Bodnar, Chou, et al., 1985; Bodnar, Burnham, et al., 1985).

2) Fluid movement through salt

Studies of fluid inclusions in salt from the Palo Duro Basin, Texas, in a cooperative program with the University of Texas, have shown that some are actual samples of Permian salt basin brines, trapped by the primary growth of salt crystals in very shallow brine pools, and even provide a record of the daily cycle of Permian day and night (Roedder, 1982a). Most other inclusions in salt represent fluids present during later recrystallization or diagenesis of the salt beds, and the major problem lies in deciding if these were trapped immediately following the primary crystallization, during diagenesis (perhaps millions of years later), or even in modern times

(Roedder, 1982b, 1984b). Studies of a seemingly trivial mineralogical oddity in the Palo Duro salt (Belkin and Libelo, 1985) may provide some useful evidence.

Study of the isotopes of hydrogen and oxygen in the H_2O in inclusions provide constraints on the possible origin of the fluid, but as many processes can affect the isotopic composition, interpretation of the data is usually ambiguous. This project has cooperated with several groups to provide valid samples for isotopic analysis. Work on Palo Duro samples in cooperation with L. P. Knauth of Arizona State University is still in progress, but that done some years ago on samples from the WIPP site in New Mexico is soon to be published (O'Neill et al., 1986; see also Roedder, 1984b).

3) The amount, distribution, properties, and composition of the fluids
Detailed petrographic and microthermometric studies of the fluid inclusions in salt can provide considerable geochemical data with a minimum of effort. During the report period, brief studies of this sort were made of a few samples from the Gibson Dome No. 1 bore, Paradox Basin, Utah (Roedder, 1984c). These revealed that a major diagenetic recrystallization of these salt beds had occurred, in the presence of very highly concentrated K-Mg brines, at surprisingly high temperatures (98-120°C).

The bulk of the effort during this report period has been in the development and use of procedures to extract and analyze chemically the fluid in inclusions, particularly those from the Palo Duro Basin, in cooperation with the University of Texas. The methods used for extraction are given by Roedder (1984a, 1985b), the analytical procedures by d'Angelo et al. (1984), and the results on a large number of inclusions from the Palo Duro Basin and elsewhere, with some geochemical interpretation, by Roedder et al. (1985, 1986).

4) Behavior of fluids during repository operation

Various aspects of the possible or probable behavior of the fluids in salt during repository operation have been considered during the report period. Some of these are summarized by Roedder (1982c). One of the project activities in this connection has been the review and evaluation of the work of others in the radioactive waste program in light of the data we have developed. Thus, there have been recurring discussions of the migration of fluid inclusions in a thermal gradient (e.g., Roedder and Chou, 1982; Chou, 1983), and numerous discussions and reviews have centered on the problems determining the specific origin of any given inclusion as evidenced by the criteria cited by Roedder (1984a, b, 1985a).

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Waste Isolation Pilot Plant, New Mexico

The DOE has been investigating an area about 40 km east of Carlsbad, New Mexico, to determine its suitability as a site for the Waste Isolation Pilot Plant (WIPP), a geologic repository for nuclear wastes generated by defense activities. The geology and hydrology of the area have been studied in cooperation with Sandia National 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 potential host rock is bedded salt of the Salado Formation of Late Permian age.

Geology

By R. P. Snyder, Denver, CO

Objective: To evaluate the geologic setting of WIPP on a regional and site-specific basis with special regard to the dissolution history and past and possibly future movement (dissolution and flowage) of the evaporite sequence.

Approach: Acquire and refine data to define the geologic history of the evaporite rocks in the northern Delaware Basin using information from existing potash mines, drill holes (both commercial and WIPP-oriented), and surficial mapping. These data will be used to improve the understanding of the subsurface geology and will help in interpreting geologic processes such as dissolution and flowage of evaporite rocks (halite and anhydrite) at or near the repository site.

Progress: Samples from oil seeps that occur above the Permian Capitan Limestone (reef) in a potash mine and in two breccia pipes north of the WIPP site were analyzed by gas chromatograph, carbon isotope, and chemical analysis. Results of the analyses suggest the oil is similar to oil being extracted from wells drilled into the Permian Yates Formation a few miles to the north of the pipes and the mine (Palacas and others, 1982). The Yates also overlies the Capitan but was not deposited inside the Delaware Basin toward the WIPP site. It is believed that the oil moved upward along faults into the Salado Formation when the Salado and other rocks collapsed into cavities formed in the Capitan (Snyder and Gard, 1982).

Drill hole data from hole W-11, 3 miles north of the center of the WIPP site (Snyder, in Borns and others, 1983) indicate that halite in the Permian Castile Formation, underlying the Salado Formation, is much thicker than normal. Data from drill hole DOE-2, 2 miles north of the center of the WIPP site, indicate that halite in the Castile is much thinner than normal and the overlying anhydrite is much thicker. The anhydrite in DOE-2 exhibits flowage, folding, and overturned beds but no apparent fracturing. The anhydrite apparently flowed southward while the halite was flowing northward. No tectonic cause for this has been discovered, and there is no surface expression suggesting recent movement.

Halite-bearing portions of the Permian Rustler Formation, overlying the Salado Formation, show a step-like removal of halite from west to east across the WIPP site. Circulating ground water, unsaturated with respect to NaCl, is removing halite and carrying it south and west toward Nash Draw and then southwest to the Pecos River (Snyder, 1985).

Reports

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Hydrology

By Peter B. Davies, Albuquerque, NM

Objective: To evaluate the ground-water flow system in the WIPP vicinity on a regional and site specific basis with regard to 1) the potential for radionuclide transport and 2) the design of a long term monitor network for the WIPP facility.

Approach: Geologic and hydrologic data are being acquired by means of test drilling, hydraulic testing, water-level monitoring, and water-quality analysis. In addition to the acquisition of field data, numerical modeling is being utilized in the analysis of the ground-water flow system.

Progress: A suite of hydraulic test holes, including several 3-well test complexes, has been completed and tested (Basler, 1983; Drellack and Wells, 1982a, 1982b; Wells and Drellack, 1982, 1983). Analysis of the data from these and other holes has revealed three principal water-bearing zones above the Salado Formation (Mercer, 1983). Of these three zones, the Culebra Dolomite Member of the Rustler Formation is the most persistent and productive in the WIPP site area. Hydraulic testing has shown that transmissivity in this fractured dolomite is highly variable, ranging from 0.001 to 140 feet squared per day at the site and from 18 to 1,250 feet squared per day in the Nash Draw area to the west. A potentiometric surface map (based on equivalent fresh-water heads) suggests a southerly flow direction across the site.

A numerical model of drawdown in the vicinity of a 12-foot diameter shaft has been used to estimate hydraulic diffusivity (transmissivity divided by storage coefficient) in the Magenta and Culebra Dolomite Members of the Rustler Formation (Stevens and Beyeler, 1985). The model results suggest diffusivities of 0.03 and 0.5 feet squared per second for the Magenta and Culebra respectively.

Current modeling efforts are focused on assessing the impact of fluid density variations on ground-water flow patterns in the WIPP area and on characterizing the natural hydrologic boundaries of the regional flow system.

Reports

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Mercer, Jerry W., 1983, Geohydrology of the proposed Waste Isolation Pilot Plant site, Los Medanos Area, southeastern New Mexico: U.S. Geological Survey Water-Resources Investigations Report 83-4016, 113 p., 21 figs.

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Stevens, Ken, and Beyeler, Walt, 1985, Determination of diffusivities in the Rustler Formation from exploratory shaft construction at the Waste Isolation Pilot Plant, in southeast New Mexico: U.S. Geological Survey Water-Resources Investigations Report 85-4020, 34 p., 15 figs.

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. Two of these research projects, High Frequency Electromagnetic Methods and Borehole Geophysical Logging, have been funded partly by the Crystalline Repository Project Office (CRPO) of DOE which is responsible for locating and characterizing sites in crystalline rocks for a second high-level radioactive waste repository.

As 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.

PROPERTIES OF CRYSTALLINE ROCKS

Isotopic Systematics in Crystalline Rocks

By Z. E. Peterman, Lakewood, CO

Crystalline rocks are one of the geologic media currently being evaluated for the containment of radioactive wastes. The emphasis of this project focuses on the naturally occurring radionuclides and the ability of crystalline rocks to retain the resultant daughter products over long periods of geologic time.

Objective: To apply isotope geochemical techniques to the evaluation of a variety of crystalline rocks for the long-term containment of radioactive wastes. To determine the timing of geologic events on regional and local scales for assessing long- and short-term geologic stability. To determine the effects of repeated tectonism on the integrity of crystalline rocks. To determine the source and residence time of fluids and gaseous species in crystalline rocks with the ultimate aim of evaluating long-term permeability of these rocks, the migration of fluids and gaseous species, and their communication with the biosphere.

Approach: The establishment of the geologic framework of areas will involve virtually all phases of isotope geochronology. Conventional methods such as

Rb-Sr, U-Th-Pb, and K-Ar will be used to determine the timing of major rock-forming and metamorphic events and the delineation of major geologic domains. Fission track techniques will be used to determine uplift and cooling histories of particular terranes, and research may be carried out in dating times of faulting. Uranium-series experiments will be conducted to evaluate movement of solutions in selected crystalline rocks during the last 500,000 years. The U-Th-Pb system will also be used on whole-rock samples, particularly those of Precambrian age, to evaluate the integrity of these systems with reference to open- or closed-system behavior. Other methods will be used as required.

Progress: Research during this interval emphasized collaborative work with the Geological Survey of Canada on samples for a deep drill hole in the Eye-Dashwa Lakes pluton near Atikokan, Ontario. Various isotopic systems were used to evaluate the long-term stability and integrity of this pluton as a function of depth. These include Rb-Sr whole rock and minerals, U-Pb zircon, U-disequilibrium, U-Th-Pb whole rock, and apatite fission-track analyses. A Rb-Sr whole rock isochron comprising 16 samples of 2632 $\pm$ 24 million years (Ma) is in close agreement within analytical and decay constant uncertainties to a U-Pb zircon discordia age of 2672 $\pm$ Ma and a whole-rock Pb-Pb age of 2684 Ma. Model ages (Rb-Sr) for the 16 samples, using the isochron IR of 0.70147, show no systematic variations with depth from a few meters to 1,100 meters. Biotite ages from 4, 36, and 993 meters are concordant at 2535, 2575, and 2538 Ma, repectively. These reflect stabilization in the Late Archean. Lower ages are found for fractured rocks and fracture fillings. For example, 10 samples of epidotized whole-rock samples and epidote separates gave a Rb-Sr isochron, although scattered, of 2308 $\pm$ 155 Ma with an IR of 0.7030$\pm$ 6. Fission-track apatite ages of 515 and 506 Ma at 4 and 36 meters, respectively, and 376 Ma and 993 meters suggest an exceptionally slow uplift rate of about 7 x 10^{-3} mm/yr. U-series isotopic studies of cores indicate that unaltered and unfractured material from near surface to 990 meters, are essentially in radioactive equilibrium. Surface samples and fracture fillings have relatively high U contents and indicate some perturbation of the isotopic system.

Report

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Radioactive Disequilibria in Crystalline Rocks

By John N. Rosholt, Lakewood, CO

For geochemical investigations, one of the most common and useful naturally occurring radionuclides is uranium, which is found in minute quantities in rocks. The study of uranium is of particular interest in radioactive waste disposal because when present in similar chemical form its physiochemical properties resemble some of the more harmful actinides (e.g., neptunium, plutonium) that may be discharged into the bedrock following canister leakage.

Objective: One of the multitude of problems to be considered in the storage of high-level radioactive waste is predicting the long-term effects on the geological environment in the event of a slow release of radionuclide material to circulating meteoric waters within the bedrock surrounding the repository.

Approach: It is highly probable that crystalline rocks at repository depths will be fractured, even prior to excavation, and that fracture permeability will be the dominant mode of flow. Much of the work involving both near-field and far-field radionuclide migration has been experimentally based. An obvious complement to the experimental data is to examine naturally occurring radionuclide migration (or lack of migration) within the geological environment of the intended repository. This allows, most importantly, an appraisal of migration on the scale of geological time.

The ^{238}U-^{234}U-^{230}Th-^{232}Th system can reveal geochemical and physicochemical processes that cause open system behavior of U and its daughter products in crystalline rocks, provided the disturbance occurred within the last 0.5 m.y. To the extent that U-series disequilibrium is a product of rock/water interaction, these measurements may help evaluate effective permeability of unfractured and macroscopically fresh rocks, and they can be used to assess geologically recent U mobility in fracture zones.

Progress: The ^{238}U-^{234}U-^{230}Th-^{232}Th system has been investigated in 84 silicic crystalline rocks obtained from drill cores, surface, and near-surface samples in California, Wyoming, Colorado, and Illinois. The study has indicated that (1) only unfractured rock from deep drillholes is in radioactive equilibrium, (2) ^{234}U recoil loss and preferential ^{234}U leach predominates in surface and near-surface rocks, and (3) ^{234}U + ^{230}Th recoil gain and U assimilation occur predominantly in drillcore samples of fractured rocks.

To determine the presence or absence of the natural migration of uranium and its daughter products in a different geological setting, mineralized fractures from the Bjorklund and Pleutajokk uranium occurrences in northern Sweden have been investigated using part of the uranium decay series (^{238}U-^{234}U-^{230}Th). Mineralized fractures from two uranium occurrences were examined mineralogically and isotopically to establish the presence or absence of radioactive equilibrium that may indicate recent rock/water interaction processes based on the natural mobility of uranium (i.e., during the last 0.5 Ma). The results show evidence of radioactive disequilibrium in six of the nine samples investigated. Disequilibria are attributable to solution to solid ^{234}U recoil gain (weakly mineralized zones adjacent to the main mineralization) and solid to solution ^{234}U recoil loss (moderate to highly mineralized zones). The absence of significant ^{238}U loss in the samples emphasizes the reducing conditions at the sampled depths.

Reports

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Smellie, J. A. T., and Rosholt, J. N., 1984, Radioactive disequilibria in mineralised fracture samples from two uranium occurrences in northern Sweden: Lithos, v. 17, p. 215-225.

Rosholt, J. N., Zielinski, R. A., Peterman, Z. E., Evaluation of long-term and short-term integrity of crystalline rocks based primarily on uranium systematics: KBS Technical Report (in press).

Elemental Mobility in Granitic Rocks

By John S. Stuckless, Lakewood, CO

Uranium-thorium-lead isotopic systematics for whole-rock samples can be used to examine the long-term stability of granitic plutons with respect to their interaction with ground water. These investigations provide a natural analogue to the potential release of radionuclide from high-level waste following canister rupture for rock in which the hydrologic rates and directions of movement are difficult to measure or predict.

Objective: Under favorable circumstances, the isotopic approach can be used to identify zones within plutonic rocks that have not interacted with meteoric water. Such zones would be particularly safe from communication with the biosphere in the event of canister rupture. Alternatively, the technique can identify zones that have interacted with ground water.

Approach: Interaction between crystalline rocks and ground water can be identified by disequilibrium between uranium and radiogenic lead. If samples exhibit disequilibrium in the uranium-lead system, the thorium-lead system can be used to assess whether uranium or lead has moved from or into whole-rock samples. If uranium has moved, the amount and timing of uranium mobility can usually be quantified for Precambrian granites.

The data needed to evaluate a potential repository for water-rock interaction are the concentrations of uranium, thorium, and lead and the isotopic composition of lead. These variables can all be determined with high precision; and thus, the limiting factors in application of the technique are geologic. Most important among these factors are (1) the age of the rock unit, (2) the U/Pb value, (3) the number of geologic events that have affected the rock unit, and (4) the existence of a mineral that can be used to measure the isotopic composition of lead at the time the rock formed.

Progress: Studies to date have shown that (1) open-system behavior caused by water-rock interaction is nearly universal for plutonic rocks collected in the surface and near-surface environment, (2) elemental mobility can exist for depths of several hundreds of meters, and (3) elemental mobility is most pronounced in and adjacent to fracture zones. Several variables which influence the amount of element mobility have been identified, including (1) mineralogic sites of uranium and its daughter products, (2) access of ground water to these sites, (3) volume of circulating water, and (4) chemistry of ground water.

Reports:

Smellie, J. A. T., and Stuckless, J. S., 1985, Element mobility studies of two drill cores from the Gotemar Granite (Krakemala Test Site), S. E. Sweden: Chemical Geology (in press).

Stuckless, J. S., 1985, Applications of U-Th-Pb isotope systematics to the problems of radioactive waste disposal (abs.): Proceedings of symposium on High Level Radioactive Waste Repositories in Crystalline Rocks, KBS Technical Report (in press).

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PROPERTIES OF SHALE

Western Cretaceous Shales

By C. E. Neuzil, Reston, VA, and T. C. Nichols, Lakewood, CO

The Cretaceous shales of the midcontinent present a number of intriguing and practical problems with regard to the movement of ground water. Answers to these problems will permit deeper insight into geophysical, geotechnical, geochemical, and geological questions of scientific interest. At the same time, the practical importance of these problems is significant. Tight units such as these shales have important roles in aquifer system response, and the ground-water flow influences movement and occurrence of economically important resources and the geotechnical properties of the rock. A consideration of particular importance is that the low permeability of these shales might be advantageous for disposal of radioactive and other toxic materials.

Certain questions are particularly important in the context of waste disposal and respository design. They include (1) What is the nature of ground-water flow in the shales, and how much vertical leakage occurs through them? (2) What is the nature of transmissive fracture pathways of flow? How frequently and where do they occur? (3) What can be said about long term (up to geologic time scales) flow and the processes which affect it?

Objective: The objective is to delineate, through theoretical, field, and laboratory investigation, the hydrologic behavior of the Cretaceous shales, with particular emphasis on the questions enumerated above. Because of the intimate relationship between transient ground-water flow and geotechnical behavior of the rock, the latter must also be included. Emphasis is to be placed on developing appropriate theory and testing techniques for environments such as the Cretaceous shales, which present unusual difficulties because of their exceptionally low permeability.

Approach: Previous work (Bredehoeft and others, 1983) established the hydrologic framework of the system which includes the Cretaceous shales. An important result is the likely significance of fractures in transmitting flow. Rather than trying to locate transmissive fractures, which has been tried unsuccessfully in the past, work is now being undertaken in specific

locales to determine if the presence of nearby transmissive fractures can be ruled out. The rationale is to seek evidence of relict transient flow conditions which would not exist in the vicinity of transmissive zones. Efforts are also being made to delineate the mechanisms of interaction between compressible pore fluid and deformable matrix which prevail over long periods of time. This will aid projection of long-term flow. Finally, an effort has been made to identify weaknesses in current techniques and approaches to the problems of low permeability; these are approached with the twin objectives of delineating flow in the shales and improving analytical techniques in general for low-permeability environments.

Progress: Analysis. A discussion of the hypothesized fracture leakage in the Cretaceous shales has been published (Neuzil, et al., 1984). The report discusses the densities and sizes of fractures thought possible in the shale. It also discusses the difficulties encountered in attempting to locate transmissive fractures. This issue is central to the problem of waste confinement. The alternative to locating transmissive fractures is to identify regions unaffected by them. This may be possible by identifying transient flow conditions which could not exist in the presence of transmissive fractures. An understanding of the causative mechanisms will aid this approach. In this regard, recent analyses have been completed and published outlining theoretical refinements to the problem of stress induced transient flow (Neuzil, 1985).

Field investigation. To augment previous attempts to accurately determine the undisturbed hydraulic heads within the shale, a special piezometer installation was made in the Pierre Shale. The piezometer was installed in an air-drilled borehole with careful precautions taken to eliminate sources of leakage from the surface. This installation will take much longer to equilibrate than previous tests (using transducers and shut-in with slurry) but promises to provide less equivocal results. It will not, for example, be subject to possible osmotic flow as were previous installations. Results to date, which show no measurable inflow of water over most of a year, suggest that the shale is underpressured or responding to the borehole in a mechanically complex manner.

Geomechanics. Fracture patterns and physical properties of the Pierre Shale were studied at intervals within the weathered zone. Three locations within 20 miles west of Pierre, two along Highway 34 and one along the Bad River Road, were examined in freshly cut highway slopes. Three dominant processes of natural fracture development were observed: (1) faulting or slumping, (2) near surface dessication and hydration, and (3) erosional rebound. Field investigations are continuing on the effect that geomorphic and tectonic processes have on fracture and failure in the shale.

Geotechnical pressuremeter data obtained in a borehole 2 miles east of Hayes, South Dakota, to depths of 550 feet, indicate that the maximum overburden removed by erosion is very close to that determined from geologic evidence.

Theoretical models have been developed by W. Z. Savage to predict conditions under which the uniformity of pore pressure is obtained in samples undergoing constant strain-rate triaxial tests. Consolidation and constant strain rate, temperature, and pressure triaxial tests of samples from the Pierre Shale

are continuing at the University of Colorado to determine long-term deformation characteristics.

Sufficient pore water was extracted from one sample of Pierre Shale showing that pore-water extraction is feasible for the study of pore-water chemistry and oxygen isotopes.

The U.S. Geological Survey 3-D stress probe was field tested to further evaluate its capability as a rock-stress measuring device (Nichols, 1983).

Reports

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Nichols, T. C. Jr., 1983, Continued field testing of the modified U.S. Geological Survey 3-D borehole stress probe: U.S. Geological Survey Open-File Report 83-750, 11 p.

Reference

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PROPERTIES OF THE UNSATURATED ZONE

Water Flux in the Unsaturated Zone of Deserts

By Jacob Rubin, Menlo Park, CA

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 in areally extensive unsaturated zones of arid regions, it has been necessary to develop a new, rapid, steady-flow method for determining hydraulic conductivities of unsaturated sediment cores at low water content. Such a method has been designed and was shown to be feasible by means of a series of laboratory studies.

The method involves high-speed centrifugation. A specially designed apparatus makes it possible to attain steady flow in cylindrical cores of packed sediment spinning in the centrifuge at forces up to 2,000 times normal gravity. Experiments demonstrated that steady one-dimensional flow can be attained relatively rapidly. For certain media the water content is fairly uniform during steady-state flow. When the method was used for determining hydraulic conductivity with relatively dry cores of a precompacted, sandy soil, hydraulic conductivities as low as 7.6×10^{-11} m/sec were measured in a few hours. The results agreed with those obtained by other, much less rapid methods. Darcy's law was tested by measuring hydraulic conductivity in samples with the same water contents for centrifugal driving forces ranging from 216 to 1650 g's. For the sandy soil at a bulk density of 1.82 Mg/m^3 and 27 percent saturation, results confirmed Darcy's law with very high statistical significance (correlation coefficient was 0.9985 and the intercept, ideally zero, was 1.8×10^{-9} m/s). The value of K obtained was 5.22×10^{-10} m/s.

Reports

Nimmo, J. R., Rubin, J., and Hammermeister, D. P., 1986, Unsaturated flow in a centrifugal field: measurement of hydraulic conductivity and testing of Darcy's law: Water Resources Research.

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Paleoclimatology and Paleohydrology of the Southern Great Basin

By Isaac J. Winograd, Reston, VA

An evaluation of the ability of the thick unsaturated zones of the Great Basin to isolate solidified toxic wastes from the hydrosphere for tens of millenia requires knowledge of the paleohydrology and paleoclimatology of

this region. Specifically needed are estimates of regional climate and water-table altitude during the global glacial and interglacial climates of the Pleistocene. Such estimates can then be used as guides for "bounding" future fluctuations of these parameters.

Objectives: a) To develop a detailed and well-dated record of oxygen-18 and carbon-13 fluctuations in ground-water recharge during the late Pliocene and Pleistocene Epochs; b) to compare this isotopic record with marine oxygen-18 and sea-level records in order to test the Milankovich Theory, specifically to determine the lag time of oceanic response to major changes in solar insolation; c) to determine fluctuations of regional water table with climate, an item of major importance to utilization of thick unsaturated zones for disposal of solidified toxic wastes; and d) to determine the time of isolation of the pupfish Cyprinodon diabolis in Devils Hole, Ash Meadows, NV. Knowledge of this isolation time is of major interest to zoologists studying rates of evolution. This research is being done in collaboration with Tyler B. Coplen, Barney J. Szabo, Alan C. Riggs, and Peter T. Kolesar.

Approach: The isotopic record is being developed through uranium-series disequilibrium dating of dense calcitic veins which mark the routes of paleo-ground water flow along fissures. Dated veins are then analyzed millimeter by millimeter for variations of oxygen-18 and carbon-13 in the calcite. Paleo-water levels are being determined by the mapping and dating of a variety of geologic features including: tufa, paleo-spring orifices, calcitic veins, and speleothem.

Progress: A 2-million year record of the variations of deuterium in fluid inclusions in dated vein calcite (Winograd and others, 1985). The record shows a progressive 40 permil depletion of deuterium in ground water recharge during the Pleistocene. This variation is attributed to major uplift of the Sierra Nevada Range and the Transverse Ranges during this epoch with attendant increasing orographic depletion of moisture and deuterium from inland-bound Pacific storms. The deuterium data thus provide a proxy record of progressively increasing aridity in the southern Great Basin during the Pleistocene. The conclusion of progressively increasing aridity is supported by available paleo-botanical and stratigraphic studies. The response of the paleo-water table to increasing aridity is under study, with special reference to Devils Hole, at Ash Meadows, NV, where an excellent record of paleo-water is preserved.

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.

High Frequency Electromagnetic Methods

By David L. Wright, Lakewood, CO

Inhomogeneities and structural flaws in a rock mass are potential problems for its use as a host medium for radioactive wastes. Radio waves offer a good means for finding such features. During the past several years radio probing of rock has made considerable progress but still lags behind seismic techniques in its stage of development. Considerable improvement is needed in 1) instrumentation, 2) understanding of 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. Dry rock salt and crystalline rocks are known to be excellent media for radio-wave probing. There is at present insufficient data on radio-wave propagation including absorption and scattering in various rock types. Because propagation involves bulk variations in the rocks, laboratory measurements are not entirely adequate.

To be useful in the early stages of repository exploration, radar and hole-to-hole probing 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 crystalline rocks, salt, and other low conductivity media, to develop and field-test prototype equipment, and to develop or enhance interpretive techniques.

Approach: Theoretical analysis, experimental scale-model studies, and field tests of single-hole and hole-to-hole systems are being carried out. Improved systems are being developed, and data-acquisition and data-processing techniques for single-hole radar and hole-to-hole geotomographic studies are being developed.

Progress: In August 1983, a 114-mm diameter borehole radar system developed by the USGS was used in studies at the Underground Research Laboratory of Atomic Energy of Canada Ltd. near Pinawa, Manitoba (Wright and others, in press). These tests showed that radar can detect inhomogeneities or fractures in granite tens of meters from a borehole. Other borehole logging techniques missed what appears to be significant fracturing that does not penetrate the borehole wall.

In May 1985, the same radar was used at Oracle, Arizona, in shallow boreholes in a much more highly fractured and conductive environment. As expected, the penetration into the rock was reduced, but useful information is nevertheless evident in the data.

A unique borehole transponder was developed and tested which allows both single-hole and hole-to-hole data to be acquired simultaneously (Wright and others, 1984).

A continuous wave (CW) hole-to-hole system has also been developed which can generate relative attenuation data along a large number of ray paths between two boreholes. Data were acquired using this system at the East Bull Lake, Ontario, site of Atomic Energy of Canada Ltd. during September 1984. Preliminary analysis of these data indicates considerable variation in attenuation. A new computer program has been written for geotomographic inversion of these data. The program is currently being tested on artificial data sets.

Since most of the deep boreholes in crystalline rock in both the Canadian and United States nuclear-waste repository research programs will be approximately 76 mm in diameter, a 57-mm diameter borehole radar system has been developed and is awaiting initial field tests.

A 1,000-m fiber-optic cable has been acquired for development of an all fiber-optic borehole radar and hole-to-hole attenuation and velocity mapping system. The fiber-optic cable has much greater bandwidth than the current cable, greatly increasing information transfer rates and, therefore, data quality and (or) logging speeds. In addition, the fiber-optic cable is nonmetallic which is an advantage in supressing unwanted borehole and cable-guided waves.

A digital data-acquisition system tailored to the two current borehole radar systems and the CW system has been developed by USGS and was first used in the field in Arizona in May 1985. This system greatly increases efficiency in the field by performing real-time data stacking before recording to 9-track digital tape. The system permits the data to be read back and graphics generated in the field, and the recording medium also facilitates data processing on the Branch of Geophysics' VAX computer.

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Hole-to-Surface Geophysical Techniques

By Jeffrey J. Daniels, Lakewood, CO

The development of a nuclear-waste storage facility will require the detection of geologic inhomogeneities (fractures, faults, etc.) without jeopardizing the structural integrity of the rock formation by concentrated drilling. Although surface geophysical techniques can be used to detect near-surface rock properties, borehole methods are needed to improve depth penetration and resolution. Hole-to-hole and hole-to-surface electrical methods have been successfully applied to solving numerous mining and engineering problems. Work is progressing on applying these techniques to depths that will be investigated in the waste isolation program.

Objective: Well-log interpretation techniques will be developed to determine physical and geologic parameters in wells to be drilled for the nuclear-waste isolation program. Hole-to-hole and hole-to-surface electrical and acoustic borehole techniques will be developed and tested for determining geologic inhomogeneities that are located outside of the range of investigation of conventional well logging probes.

Approach: Field studies were conducted at the Nevada Test Site, Salt Valley, and Gibson Dome to determine the feasibility of making hole-to-surface resistivity measurements at proposed nuclear-waste facilities. Theoretical computer models were developed to simulate hole-to-surface resistivity measurements in a complex geologic environment.

Progress: Interpretation of hole-to-surface resistivity field data from Gibson Dome has shown that these measurements can be useful for deep investigations. Specifically, tests show that hole-to-surface resistivity measurements would be very effective in locating large, vertical fracture zones in a salt layer.

A theoretical model has been developed for hole-to-surface and hole-to-hole resistivity studies. The model can be used to simulate the effect of nearly any geoelectric variations in the subsurface on resistivity measurements. Work is continuing to determine the numerical limitations of the model.

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Borehole Geophysical Logging

By Frederick L. Paillet, Lakewood, CO

Test drilling is essential for the investigation of potential host 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 improve the cost-benefit ratio.

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

Progess: The major products of the project are publications. It has been a specific goal to have some sort of publication result from data obtained during each field trip within 1 year of the completion of that trip. A bibliography was prepared by the project that lists references relevant to ground-water hydrology--many of these articles will be very useful to studies connected to waste disposal.

The need for a simple, easy-to-use, nonpolluting, low-velocity, small-diameter, borehole water flowmeter to complement the commonly used spinner-type flowmeter has led to the development of an improved version of a sensitive, low-velocity flowmeter based on the heat-pulse, tag-trace concept originally developed by the Water Resources Centre in England. The flowmeter has a flow-measuring range in water from 0.06 to 6 meters per minute, distinguishes between up-and-down movement, and resolves velocity differences of 0.01 meters per minute. This flowmeter was successfully used to measure water velocities and identify transmitting fractures in granitic rock at a site near Lac du Bonnet, Manitoba, Canada. The latest modification to the heat-pulse flowmeter includes a bladder system to pack off the borehole during the tests. The system is being tested during pump tests, and the results are helpful in quantifying the distribution of fracture permeability. Flowmeter measurements during pumping were made at two sites: The University of Arizona crystalline-rock research site near Oracle, Arizona, and in a set of bedrock wells incorporated in a larger scale ground-water monitoring program at Mirror Lake, New Hampshire.

Two deep boreholes were logged at the AECL site near Atikokan, Ontario. The data were analyzed and publications were produced which relate to radioactive waste disposal.

Acoustic-waveform and acoustic-televiewer logs were obtained for a 400-meter interval of deeply buried basalt flows in three boreholes and for shorter intervals in two additional boreholes located on the U.S. Department of Energy's Hanford site in Benton County, Washington. Borehole-wall breakouts were observed in the unaltered interiors of a large part of individual basalt flows; however, several of the flows in one of the five boreholes had almost no breakouts. The distribution of breakouts observed on the televiewer logs correlated well with the incidence of core disking in some intervals, but the correlation was not always perfect, perhaps because of differences in the specific fracture mechanisms involved. The orientation is consistent with previous estimates of the principal horizontal-stress field in south-central Washington if breakouts are assumed to form along the azimuth of the least principal stress. The distribution of breakouts repeatedly indicated an

interval of breakout-free rock at the tops and bottoms of flows. Breakouts frequently terminate at major, steeply dipping fractures. Unaltered and unfractured basalt appeared to have a uniform compressional velocity of 6.0 ± 0.1 km/s and a uniform shear velocity of 3.35 ± 0.1 km/s throughout flow interiors. Acoustic waveform logs also indicated that borehole-wall breakouts did not affect acoustic propagation along the borehole. Televiewer logs obtained before and after hydraulic fracturing in these boreholes indicated the extent of induced fractures and also indicated minor changes to pre-existing fractures that may have been enlarged during fracture generation.

The project has taken a leading role in acoustic waveform logging research. A comprehensive study on the theory of waveform analyses has been completed. The primary focal point of current efforts is the scale problem: characterizing fractured rocks at different acoustic scales. Recently a joint USGS-MIT experiment was conducted in large and small scale acoustics at Mirror Lake, New Hampshire.

Work on the Cape Cod toxic-waste study has continued. Our experiences in 1984 led to several improvements in logging, along with recognition that disturbances outside of casing had dominated our earlier results. Casings were driven to minimize such disturbances, and cores were obtained for log calibration.

An acoustic characterization method (Paillet, F. L., 1983a) was developed by the project that complements the hydraulic fracture and state-of-stress measurements being made by Rockwell engineers at the Hanford waste disposal site. These results relate breakout character and distribution to local geology.

A cooperative study of the Brule aquifer in the Olegocine Brule Formation (Barrash, W., and Morin, R. H., 1985) was carried out with the University of Nebraska. The results brought together data from well logs, core analyses, and pumping-test data. The findings document the importance and character of secondary permeability that would not be apparent in a more limited data set.

A study of permeability of fine-grained sediments has continued to progress. The theory and application of in situ permeability measurements in the borehole with laboratory measurements have continued. Design for an in situ permeability probe has been started. Upgrading of instrumentation has continued. New digitizing systems have been installed and tested in logging trucks.

A thorough review of calibration procedures for our logging equipment, in conjunction with field trips to calibration facilities in Houston, Texas (American Petroleum Institute, GO Wireline, and WELEX), and Grand Junction, Colorado (DOE), has been undertaken.

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Development of Techniques and Modification of Conventional Wireline-Coring Equipment for Air Coring Purposes

By Warren E. Teasdale, Lakewood, CO

Present geohydrologic concerns and attendant studies show great need for obtaining lithologic samples under in-situ conditions. Studies of flow through the unsaturated zone also require in-situ well instrumentation and field testing under ambient conditions. To minimize core contamination and to approach in-situ conditions of the cores and samples, drilling and coring must be done by dry-drilling methods whenever possible.

Objective: To modify a standard, HQ-size, triple-tube wireline core barrel (designed for use with liquid drilling fluids) for air coring and develop techniques for obtaining satisfactory core using the modified core-barrel system.

Approach: The principal criterion necessary for using the dry-drilling procedures is that the geologic formation to be drilled and cored has to have a negligible moisture content. Too high a moisture content causes bit plugging and mud-ring accumulation (booting) on the drill rods and the dry-drilling technique will not work.

The site chosen to conduct the initial air-coring experiment was located on the Los Alamos National Laboratory, Los Alamos, New Mexico. The drilled and cored formation was the upper member of the Bandelier Tuff of Pleistocene age consisting of ash falls, pumice, and moderately welded to welded tuff.

Wireline-coring equipment designed for circulating liquid drilling media requires extensive modification when used for air coring of rock or sediments. The modifications made to the equipment included reaming of the outer core barrel to provide greater clearance between the inner and outer barrel; milling of air passages in the latch body part of the inner-barrel head assembly; addition of oversized reaming devices to the outer core barrel and the bit; and enlarging the air-discharge parts on the coring bit. To increase the recovery of friable or unconsolidated materials, a basket-type core retainer and ring assembly were used with a conventional spring-type core lifter.

Progress: Approximately 92 percent core recovery was obtained from 160 ft of selected zones within the 210-foot deep hole in the tuff. This included very good recovery of a zone of very fine unconsolidated ash.

A spindle-rotational speed of about 60 to 80 revolutions per minute was maintained throughout the entire coring experiment. Settings of compressor volume and pressure output were adjusted depending on hardness and integrity of the formation encountered downhole in order to optimize quality and quantity of core recovery. During the coring experiment, optimal core recovery was obtained using downhole air pressures ranging from 25 to 75 lb/in^2 and compressor air-output rates ranging from 250 to 600 ft^3/min. Use of the wireline-rotary, air-coring technique and equipment proved to be an effective method for obtaining excellent recovery of uncontaminated cores of the Bandelier Tuff.

Reports

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High Resolution Electromagnetic Sounding Methods

By Frank Frischknecht, Lakewood, CO

Electrical methods are very 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 very 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:

Instrumentation will be improved to increase the depth of investigation without increasing power. Three dimensional computer and scale model studies will continue to help provide information for interpreting results in laterally inhomogeneous areas. Alternatives to non-linear least square inversion for interpretation of one-dimensional data will be investigated.

Progress:

Our ability to interpret TDEM soundings was improved through use of asymptotic methods for calculation of the fields at very late times, double precision

filters, a new, more convenient method for computation and display of results for forward modeling, and development of hardware and software for transfer, processing, and display of data in field (Anderson, 1983 and 1984a; Bradley and Raab, 1983; and Raab and Frischknecht, 1983). An efficient program for calculation of the fields inside and outside of a large rectangular loop was developed (Anderson, 1984b). A number of physical scale models relevant to sounding were completed (Miles, 1985) and limited 3-D computer modeling is underway with the acquisition of a new program from the University of Utah. Reinterpretation of TDEM data from the east flank of Yucca Mountain, NTS, and comparison with resistivity and other electric magnetic results there indicate that the TDEM has a number of distinct advantages over the other methods (Frischknecht and Raab, 1984). As expected, the TDEM method is very effective in sounding to large depths with a relatively small surface configuration and it is less sensitive to lateral boundaries than other electrical sounding techniques.

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Soil Geochemistry

By Milan Pavich, Reston, VA

Understanding of the neotectonics and erosion rates of relatively stable terrains such as the Appalachian Piedmont can be aided by research on the geochemistry of soils that may be indicative of age and residence time.

Objective:

To determine the pedogenic and rock weathering processes operating on crystalline rocks of the Piedmont and sediments of the Coastal Plain.

Approach:

Sampling of regolith in natural exposures, backhoe trenches, and by core drilling was followed by laboratory analyses of particle size, mineralogy, bulk chemistry, and trace element chemistry on selected samples.

Progress:

Soil characterization (in cooperation with the Soil Conservation Service) in the mid-Atlantic region has demonstrated that there are continuing age-related changes in soil characteristics over a 2 ma time-scale (Markewich et al., 1986). In the South Carolina Coastal Plain, back barrier sites also show age-related soil characteristics over the same time scale (Markewich et al., in press).

Study of Piedmont regolith (soil and saprolite) has demonstrated a residence time of about 1 ma in what is a continually weathering and eroding system (Pavich et al., 1985; Pavich, 1985).

One of the promising areas of research is the application of accelerator mass spectometry (AMS) to the study of accumulation of cosmogenic ^{10}Be in clay-rich soils (Pavich et al., 1984) and its subsequent transport on fine-grained sediment in rivers (Brown et al., 1986). This preliminary work is being followed by more detailed studies of ^{10}Be accumulation in soil chronosequences (Pavich et al., in press) and the solubility of beryllium as a function of pH and salinity (Valette-Silver et al., 1985).

This work demonstrates a methodology for more detailed studies of regolith and landscape history in the Appalachian region and the broader area of the humid eastern region of the United States. Of particular relevance to the Radwaste Program are applications to research of late Cenozoic Piedmont faulting along fracture systems such as Mountain Run, Va. (Pavlides et al., 1982), and the history of recurrent earthquake induced liquefaction in areas like Charleston, S.C. (Weems et al., 1986).

Reports

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Isotope Geochronology

By John F. Sutter and John B. Hartung, 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 the dating of 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 Quarternary 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.

Approach: A laser probe mass spectrometer has been assembled for dating the time for 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 make it possible 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: Individual muscovite grains from samples of the tin-tungsten mineralization at Panasqueira, Portugal, supplied by William Kelly (University of Michigan) have been successfully dated by the $^{40}Ar/^{39}Ar$ laser microprobe.

Individual, separated muscovite grains (conventional $^{40}Ar/^{39}Ar$ total fusion age of 290 Ma) from a greisen in the mineralized zone yielded the following laser microprobe $^{40}Ar/^{39}Ar$ apparent ages: 320 Ma (about 1.5 µg); 289 Ma (about 11 µg). Five *in situ* age measurements of single muscovite grains from the same sample yielded a mean apparent age of 307±7 Ma for sample sizes ranging from 8-27 µg (Sutter and others, 1983).

The diameter of the area melted by a single pulse of the laser beam (spot size) can be varied by focusing the beam through a microscope. Spot location can be controlled to about 10 µg using the current system. Based on potassium content and age, a suitable number of spots must be melted to produce a measurable quantity of argon for the age determination. Radiogenic yields have been as high as 98 percent on sample sizes as small as 20 µg.

Laser $^{40}Ar/^{39}Ar$ ages of single mica grains measured *in situ* can aid greatly in understanding the chronology of mineralized zones where micas are present but are not separable mineral phases in quantities needed for conventional age dating (10^4 to 10^5 µg of pure mineral). In addition, *in*

situ dating of superimposed growths of mica in single specimens could help in establishing the minimum duration of various stages of a complex mineralization event.

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INVESTIGATIONS AND MODELING OF GEOLOGIC AND HYDROLOGIC PROCESSES

A major objective of the Survey 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 confidently 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.

Fluid Flow in Fractured Rocks

By P. A. Hsieh, Menlo Park, CA

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 of 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: Cross-hole hydraulic testing methodologies developed in this study were applied to a granitic field site near Oracle, Arizona. Results of the tests indicate that on a scale of 10 m or more, the rock at the site behaves hydraulically in a manner not too different from that of a uniform, anisotropic medium. The principal directions and principal hydraulic conductivities are found to be controlled to a large extent by three near-orthogonal fracture sets in the rock mass. Details of theory and application of the cross-hole tests are given in Hsieh and Neuman (1985), Hsieh and others (1985), and Neuman and others (1985). Methodologies and procedures developed for this field site should provide high transfer value to studies at other similar sites.

Analysis of slug tests in wells surrounded by a finite-thickness skin led to publication of a paper (Moench and Hsieh, 1985a), and a comment (Moench and Hsieh, 1985b). The slug test is a commonly used method for determining the permeability of low-permeability rocks. However, drilling effects on the wellbore often create a region of altered permeability (i.e., a "skin") that complicates the interpretation of test results. The reports describe theoretical analysis of the effects created by the wellbore skin.

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Field Tests of Flow and Transport in Unsaturated Media

By E. P. Weeks, Lakewood, CO

Unsaturated materials are used as the host medium for low-level radioactive waste disposal and are being considered for high-level waste disposal. Techniques are needed to evaluate the potential for radionuclides to be leached by deep percolation from such repositories to the ground-water reservoir and thence to the accessible environment. In addition, methods are needed to evaluate the potential for gaseous radionuclides to diffuse to land surface and the atmosphere.

Objectives: To develop various field methods and modeling techniques for determining and predicting deep percolation under variable climatic conditions in the presence of a heat-producing waste form and to develop methods for characterizing the gaseous-diffusion transport properties of the unsaturated materials.

Approach: Field, laboratory, and modeling studies will be used to achieve the objective. Field studies will include measurement of evapotranspiration for selected periods and of moisture tension, moisture content, soil-gas humidity, soil-gas composition, and temperature to assess driving forces for the movement of water, water vapor, trace soil gases, and heat.

Laboratory studies will be conducted to determine the hydraulic and transport properties of unsaturated porous media, including hydraulic conductivity, specific moisture capacity, and tortuosity and effective porosity for gaseous diffusion.

These field and laboratory data will be used to test and refine numerical models for the simulation of linked water and heat transport and gaseous diffusion transport. These models will allow the simulation of deep percolation using a long sequence of historical weather and will allow evaluation of the effects of extreme weather events or climatic change on the potential flux for leaching radionuclides.

Progress: The field study of transport through the unsaturated zone has advanced in three areas.

Gaseous diffusion. Gaseous diffusion represents a transport process by which radionuclides can escape from repositories in the vadose zone to the atmosphere. Hence, methods for characterizing the tortuosity and effective porosity of the partly saturated materials comprising the unsaturated zone are important to adequately characterize proposed repository sites. Three different approaches for identifying gaseous-diffusion transport properties of vadose-zone materials have been tested. In one approach, the concentrations of the environmental fluorocarbons F11 and F12 (CCl_3F and CCl_2F_2) are determined for samples collected from piezometers open at different depths in the unsaturated zone. The attenuation of the fluorocarbon concentrations with depth can be used in conjunction with the historic atmospheric-concentration buildup in a simulation model to determine tortuosity and effective porosity of materials in the top 50 meters of the unsaturated zone (Weeks and others, 1982).

In a second approach, CO_2 and $^{14}CO_2$ concentrations can be measured at various depths. The seasonal variations in CO_2 concentration with depth can be analyzed to determine gas transport properties of materials in the top 10 meters of the vadose zone (Thorstenson and others, 1983). Also, in theory, $^{14}CO_2$ concentrations can be analyzed in conjunction with the atmospheric buildup resulting from nuclear weapons testing to identify gaseous-diffusion transport properties of materials within the top 50 meters or so of the vadose zone. However, for as-yet unknown reasons, $^{14}CO_2$ diffusion is greatly retarded relative to CO_2 diffusion or to fluorocarbon diffusion, and the method as yet does not provide reliable results (Thorstenson and others, 1983).

In a third approach, trace gases may be released at a constant rate from down-hole permeation devices, and the arrival of the trace gases at various radial and vertical distances from the sources may be determined by sampling soil gas from piezometers. The data may be analyzed using conventional aquifer-test techniques. This method proved useful for determining transport properties of unsaturated materials at the low-level radioactive waste repository near Barnwell, South Carolina (Kreamer and others, 1985).

Evaporation measurement. Evapotranspiration by vegetation at radioactive-waste repository sites limits deep percolation that might leach radionuclides. An eddy-correlation method for determining evapotranspiration has been developed and tested (Weeks and others, 1985). Although some uncertainty exists in the exact magnitude of measured evapotranspiration, the results can be used to bracket actual evapotranspiration.

Unsaturated-zone modeling. A computer code for simulating flow in variably saturated materials has been developed and tested (Lappala and others, 1983). The model may be used to simulate infiltration from rainfall and deep percolation along with evaporation and transpiration, based on user-supplied hydraulic properties of the media comprising the unsaturated zone.

Reports:

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Nonisothermal Water Fluxes in the Unsaturated Zone

By W. N. Herkelrath, Menlo Park, CA

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: Several reports were prepared describing laboratory investigations of nonisothermal flow of water and vapor in partially saturated rocks and soils.

A paper was published which describes measurement of the temperature dependence of capillary pressure in unsaturated porous media (Constantz, 1983). An anomalously high rate of change of capillary pressure was observed as the temperature of the medium was changed from 5 to 95 °C. Results indicate that the surface-tension model of capillarity should not be used in modeling simultaneous heat and moisture flow in the unsaturated zone. In the course of this work, a new laboratory technique for measuring the water content/capillary pressure relationship and the relative permeability of unsaturated porous material at elevated temperature was developed (Constantz and Herkelrath, 1984).

A paper describing laboratory studies of the flow of high-temperature water vapor in a porous medium was also published (Herkelrath and others, 1983). In this work, it was found that water vapor adsorption has a big effect upon vapor flow; a new model was developed which includes a sink term for vapor adsorption. Water-vapor adsorption isotherms were obtained for Topopah Spring welded tuff from Yucca Mountain, Nevada Test Site (Herkelrath and O'Neal, 1985). These isotherms can be incorporated into models of heat and moisture flow in the tuff resulting from emplacement of high-temperature nuclear waste.

A time-domain-reflectometry (TDR) method for simultaneously determining the water saturation and the electrical conductivity of a porous medium was developed (Dalton and others, 1984). This method was successfully used to make large-scale measurements of the water saturation of unsaturated alluvium at the Nevada Test Site near Yucca Mountain. TDR may provide a useful alternative to neutron logging of water content in the deep unsaturated zone.

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Transuranium Elements in Ground Water

by J. M. Cleveland, Lakewood, CO

In view of the long half lives of many of the transuranium elements (plutonium, neptunium, and americium) and uncertainties regarding their geochemistry, it is difficult to predict their transport and distribution characteristics in ground waters. In particular, it is fruitless to attempt to make distribution measurements of the transuranium elements or to model their ground-water transport without first determining their chemical forms and solubilities in the ground waters of interest. This speciation is relatively straightforward for elements with only one common oxidation state such as americium but is somewhat more complex for the multivalent elements plutonium and neptunium.

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

Objective: To define the chemical speciation and the chemical and hydrologic behavior of transuranium elements in ground waters.

Approach: The current approach is in two complementary segments, one applied, and one fundamental:

1) Speciation of plutonium and neptunium in both synthetic and actual ground waters as a function of applied electrical potential.

2) Continuation of studies to determine accurate thermodynamic data for complexes of the transuranium elements with common ground-water anions.

Item (1) is an outgrowth of completed studies of the speciation of the transuranium elements in natural waters, which indicated that the oxidation state of multivalent elements such as plutonium and neptunium is the single most important factor in determining their solubilities--and hence mobilities--in these waters. It is difficult, and perhaps impossible, to obtain meaningful values for the E_h of natural waters; therefore, it has not been possible to establish a direct quantitative relation between the E_h of the waters and plutonium and neptunium solubilities. To overcome this obstacle, a

potentiostat/galvanostat is used to determine the speciation of these two elements at various applied potentials. Initial studies involve synthetic ground water, but actual ground waters will also be used as the work proceeds.

Thermodynamic studies (item 2) are in progress on the americium-citrate system. In addition, both Project members are on the committee formed by the Organization of Economic Cooperation and Development (OECD), Paris, to develop and compile a thermochemical data base for plutonium species relevant to the geologic disposal of nuclear wastes.

Progress: Previous research has been concentrated in three areas: progress in each will be discussed separately.

1) Speciation studies in ground waters. Studies have been extended to an additional eight ground waters (all of some relevance to nuclear-waste disposal) and two surface waters. The results confirm our earlier conclusions that high fluoride concentrations enhance plutonium solubility, whereas high sulfate concentrations retard plutonium solubility, but only in reducing waters. The most important single factor affecting plutonium and neptunium solubility is the oxidation-reduction property of the water. The solubility of americium, which has only one stable oxidation state, was not affected by redox properties but had a strong inverse correlation with the ionic strength of the water.

2) Leaching of plutonium from borosilicate glass cubes. The leaching of plutonium from borosilicate glass cubes by eight ground waters (all of which were also studied as described above) was completed. Ground waters from the Miocene Grande Ronde Basalt (Washington) and from alluvial deposits in the Hualapai Basin in Arizona were the most effective leachants for plutonium. Leaching was incongruent; i.e., plutonium was removed more slowly than the overall glass matrix. All ground waters (except that from tuff at the Nevada Test Site) were considerably better leachants than deionized water, thus casting doubts on the validity of the common practice of using it as a substitute for actual ground waters in leaching studies.

3) Thermodynamic studies. Stability constants and thermodynamic parameters were determined for two systems: plutonium(IV)-fluoride and americium(III)-fluoride. The stability constants of the fluoride complexes of Pu(IV) are not high enough to explain the relatively large solubility of plutonium in high-fluoride ground waters, suggesting that either nonequilibrium processes or mixed-ligand species, such as hydroxyfluoride complexes, are involved.

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Redox Reactions in Ground Waters

By Donald C. Thorstenson, Reston, VA

Redox processes remain one of the least understood controls on natural water chemistry. Errors in measuring and interpreting redox potentials can be large enough to result in incorrect predictions of mineral occurrences and order-of-magnitude errors in solubility or chemical speciation calculations. An understanding of the processes governing redox reactions must be available to permit geochemical modeling of the behavior of multivalent elements such as iron, manganese, or uranium and other actinides.

Objectives: The goals of this research are: (1) Identify controls on redox potential in natural systems; (2) Develop and apply computer models to redox reactions in natural systems; and (3) Evaluate processes responsible for the distribution of oxygen and carbon dioxide in the unsaturated zone. The degree to which ground-water recharge is oxidizing or reducing depends on the presence or absence of dissolved oxygen, which is determined by unsaturated-zone reactions.

Approach: (1) Integration of the fundamental thermodynamics of redox reactions and natural water geochemistry; (2) Application of computer models to specific redox problems in ground-water systems; and (3) Measurement of gas composition and isotopic characteristics of carbon dioxide in deep unsaturated zones. The distribution of oxygen and carbon dioxide in the sub-soil unsaturated zone is virtually unknown.

Progress: A study of thermodynamics of redox reactions has been completed (Thorstenson, 1982; Thorstenson, 1984; Hostettler, 1984). This study provides the basis for a general reevaluation of the theoretical concept of pe as an electron activity and for a more fundamental interpretation of Eh measurements. This work also demonstrates the inherent inability to define a unique redox potential in a disequilibrium system and points up the need for in-situ testing in field studies of redox-active contaminants in natural water systems.

A paper dealing with the thermodynamics of reaction (including redox) path modeling with a detailed example application to a natural ground water system has been published (Plummer and others, 1983). This paper deals in large part with the theory of applying the computer program PHREEQE (Parkhurst and others, 1980) to modeling natural systems. PHREEQE is now being used internationally in nuclear-waste management studies.

The unsaturated zone distribution of major atmospheric gases, including $^{12}CO_2$, $^{13}CO_2$, and $^{14}CO_2$, has been measured over a 5-year interval at sites in the western Great Plains. The data and a theoretical model for the diffusive transport of carbon dioxide have been published (Thorstenson and others, 1983; Haas and others, 1983). This work provides a basis for estimating the depth to which post-bomb $^{14}CO_2$ has been transported into the unsaturated zone, one of the few means of estimating unsaturated-zone transport of volatile constituents. Gas composition measurements from test hole UZ-1, Yucca Mountain (Nevada Test Site) show the unsaturated zone to be fully oxygenated to depths approaching 400 meters.

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Simulation of Radionuclide Transport in Ground-Water Flow

By K. L. Kipp, Lakewood, CO

It is generally agreed that leaching and transport of radioactive wastes by ground water are the most likely mechanisms by which waste radionuclides might enter the biosphere. Mathematical techniques to describe the transport and reactions of these dissolved radionuclides during their flow are necessary to the prediction of resulting chemical changes in ground water.

Objective: The objective is to develop and evaluate numerical modeling techniques to predict changes in water quality during the transport of radioactive solutes below the water table.

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: The Heat and Solute Transport code has been finished and is at the third stage of testing with application to selected studies at the Water

Resources Division district level. A WRI report is at the colleague review stage. This program simulates ground-water flow and associated heat and solute transport in three dimensions. The HST3D simulator may be used for analysis of problems such as those related to radioactive waste disposal, subsurface waste injection, landfill leaching, saltwater intrusion, hot-water geothermal systems, and subsurface energy storage. The solute transport equation is for a single solute species only with possible linear equilibrium sorption and linear decay. The three governing equations are coupled through the interstitial pore velocity, the dependence of the fluid density on pressure, temperature, and solute mass fraction, and the dependence of the fluid viscosity on temperature and solute mass fraction. Finite difference techniques are used to discretize the governing equations using a point distributed grid. The basic source/sink term represents wells and a complex well-flow model may be used to simulate specified flow rate and pressure conditions at the land surface or down in the aquifer with or without pressure and flow-rate constraints. A full selection of boundary condition types is offered, including specified values, specified fluxes, leakage, heat conduction, and approximate free-surface, and two types of aquifer influence functions. A technical note is being published on the last item. All boundary conditions can be functions of time.

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Geomechanics

By H. S. Swolfs, Lakewood, CO

Modeling the thermally induced stress around a repository requires knowledge of the initial stress conditions prior to mining. In the absence of such information, it has been necessary to assume a non-differential or lithostatic stress (the increase in pressure with depth resulting from the weight of the overlying rocks); 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 a large number of 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 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: Site characterization is a fundamental prerequisite in the identification and selection of geologic repositories. Specifically, the problems that still require satisfactory resolution include the definition of geologic structure (i.e., structural discontinuities on all scales), physical and thermo-mechanical material properties, and in situ initial stress, temperature, and hydraulic conditions in brittle rocks. To this end, a testing facility has been constructed and made operational in an experimental mine near Idaho Springs, Colorado, and a surface site on South Table Mountain 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 evaluated at the testing facility underground will be used to determine the mechanical properties at the surface 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 by analytical methods. Thus, the geomechanics observatory near Golden serves as an additional proving ground to test and evaluate existing instrumentation and to develop modifications, improvements, or new techniques as required.

Progress: An effort has been made to examine the size effect on the strength of intact rock (Swolfs, 1983). The issue is of importance because the "concept" of size effect argues against the assumption that strength (compressive and tensile) is a fundamental material property of rock. Indeed, in the absence of stress gradients and external environmental influences, the compressive strength of two rock types, tested in the laboratory as well as in the field, was found to vary little in the size interval spanning some six orders of magnitude in volume. On the other hand, a pronounced size effect results from testing methods that either produce or incorporate a discreet continuous fracture. We have begun to investigate this phenomenon by performing indirect-tensile tests on specimens of latite; these include axial and diametral point-load tests and burst tests on thick-walled hollow cylinders. The preliminary results are that the tensile strength of the latite is about 7 MPa and that the burst pressure exponentially decreases with increasing hole diameter from 1 to 10 cm. Presently, field tests are planned to conduct borehole-fracturing tests using dilatometers to determine the strength distribution in the rock mass at our experimental observatory near Golden, Colorado.

A principal accomplishment has been the derivation of closed-form solutions for the effect of topography on gravitational regional tectonic stress fields. An important result of the analyses is the observation that beneath the crest of a ridge, for example, the horizontal stresses are reduced in magnitude relative to those away from the ridge. This local reduction in the stresses continues to depths several times the height of the ridge and is due to gravitational spreading. The opposite effect is observed under valleys; that is, horizontal stresses are locally enhanced at depth below valleys. We have successfully applied this model to Yucca Mountain, Nevada, where reduced horizontal stresses have been measured beneath the ridge crest in drill hole USW G-3 (Joann Stock, written commun., 1984) at depths between 1 and 1.5 km.

On a continuing basis, we have performed field experiments and block-loading tests at our test facilities near Golden and Idaho Springs, Colorado. Instrumentation has been developed to allow a thorough mapping of the

anisotropic deformation properties of the highly foliated metamorphic rock at Idaho Springs. Laboratory procedures and equipment have been developed to determine the strength properties of right-circular cylindrical rock samples whose length-to-diameter ratios are nonstandard. The technique uses brush platens as loading pistons that significantly reduce the friction between testing sample and loading piston. Tests are being conducted to establish the efficacy of this laboratory procedure.

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Permeability of Hot Rocks

By J. D. Byerlee, Menlo Park, CA

In order to determine the suitability of a potential nuclear waste repository site, the fluid flow characteristics of the host rock must be fully understood. The increase in temperature of the surroundings due to the radioactive decay of the waste material may cause permanent changes in the host rock which could affect the fluid flow characteristics.

Objective: To determine the permeability of a variety of crystalline rocks under conditions likely to exist in the rocks surrounding a nuclear waste repository.

Approach: Carry out laboratory experiments to determine the permeability of rocks as a function of temperature, temperature gradient, confining pressure and water pore pressure. The cylindrical samples 7.6 cm in diameter and 8.0 cm long contained a heater within a central borehole. The heater could produce a constant temperature of up to 300 °C at the center of the sample. Temperature decreased outwards from this heat source so that along the cylindrical outer surface of the sample it was below 100 °C. The exact temperature depends on the rock type and temperature at the inner bore. The discharge fluids were sampled regularly for chemical analysis. The samples from each experiment were examined with a petrological and scanning electron microscope to identify the structural and mineralogical changes that occurred during the experiments.

Progress: The changes in permeability with the time of granite, quartzite, anorthosite, and gabbro were measured while these rocks were subjected to a temperature gradient. Low temperatures ranged from 60 to 100 °C depending on rock type, while the highest temperature (next to the heat source) was fixed at 250 °C. Dissolution of minerals at high temperatures, and redeposition of the dissolved material at lower temperatures caused permeability reductions of up to two orders of magnitude, most notably in the quartzite. Quartz appears to be an important mineral in this self-sealing process. If very low permeability is desired around nuclear waste repository in crystalline rocks, then a quartz-rich rock may be the most appropriate host.

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Postglacial Uplift in Northeastern United States

By Carl Koteff, Reston, VA

The northeastern United States includes extensive areas of exposed crystalline rocks which have been considered possible hosts for high-level radioactive waste repositories. The largest crustal movement in the northeastern United States in the last 13,000 years has been the glacio-isostatic response due to the removal of the Laurentide ice sheet that last overran the region in late-Wisconsinian time. Vertical uplift in northern New England has been at least 250 meters more than in southern sections. The pattern and rate of this uplift is known only generally, and the effects are even less well known. It is presumed that the initial uplift response has been completed, but it has been suggested that there may be present-day crustal subsidence resulting from overcompensation of the uplift. A better understanding of the nature of postglacial uplift is needed to separate this process from any neotectonic activity in the region.

Objective: To establish an accurate postglacial uplift pattern for the northeastern United States and to determine rates and time of cessation of uplift. Localities that depart from the established pattern can then be evaluated as potential areas of modern seismicity. As part of this study, it is necessary to develop a rheologic model of the lithosphere that accounts for what seems to be a considerable lag time between unloading of ice and uplift response.

Approach: The most accurate method available to measure uplift is to obtain altitudes of deltas that were constructed in glacial lakes and in the late glacial sea during deglaciation. The glacial geology is well known in many areas of the northeast, and the altitudes of the topset/foreset contact of the ice-marginal deltas have been determined to be a very precise reflection of water levels (within 1 meter). Thus, tilted former water tables derived from these altitudes will provide a reliable and detailed uplift pattern. At places, however, detailed knowledge of the geology is lacking, and field mapping is required.

Progress: An uplift pattern for western New England has been established by accurate leveling of glacial lake deltas. The uplift gradient there is 0.9 m/km up to the N21W, and the time-transgressive profile of this uplift is so straight that an effective delay to uplift response after unloading is suggested to be on the order of a few thousand years. A computer model of uplift developed by J. A. Clark, Calvin College, Michigan, has been used with the western New England data, and results suggest that the elastic lithosphere in the North American craton is 267 km thick. Comparison of the western New England pattern with that of the glacio-marine areas of Massachusetts, New Hampshire, and Maine, shows a similar uplift gradient in the earlier deglaciated areas (>14,000 yrs B.P.) but a lower gradient in the later deglaciated areas (<14,000 yrs B.P.). This supports the notion of delayed or very slow uplift at the beginning of ice unloading, increasing in rate at about 13,000 yrs B.P. Rates of uplift may have been as much as 10 cm/yr for at least 1,000 years after 13,000-14,000 yrs B.P.

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LOW-LEVEL WASTES

The principal method of disposal for low-level wastes in the United States has been shallow-land burial in 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 sites operated by the DOE.

In 1975, the USGS 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. The initial phase of this program included 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 Barnwell, Sheffield, and Beatty. Included in this phase is the Wood River Junction, Rhode Island, site where a contaminant plume developed in the ground-water system downgradient from a recovery plant for processing cold uranium scrap.

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:

- o defining the geologic and hydrologic conditions at disposal sites that are pertinent to the subsurface leaching and migration of waste radionuclides in ground water

- o 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 Larry J. Mann, Idaho Falls, ID

Idaho National Engineering Laboratory (INEL) obtains its water supply from the Snake River Plain aquifer and disposes low-level radioactive and chemical wastes to the environment. Because of increased concern about water pollution problems, detailed knowledge is needed about the geochemical, hydrological, and geological influences of a nuclear reactor development and testing center on the ground-water resources of the area. In addition, there is concern about migration of leachates from buried radioactive wastes downward through the unsaturated zone toward the Snake River Plain aquifer. Information is needed in deeper zones of the Snake River Plain aquifer to determine if waste water moves downward.

Objective: Describe, evaluate, and assess the effects of radioactive and chemical waste disposal at the INEL on the ground-water resources, contribute to the technology of the effects of waste disposal, and determine principles of water and solute movement in fractured rocks. Map and describe distribution patterns of waste products in the ground water so predictions of future patterns can be made. Evaluate the hydrogeochemical controls on the subsurface migration of solutions from bodies of buried radioactive waste. Evaluate the hydrologic properties of deeper zones in the Snake River Plain.

Approach: The study of the subsurface effects of waste disposal upon the Snake River Plain aquifer compares the current conditions with previous data. Distribution and dispersion patterns, rates of movement, dilution factors, and mass balances of various components are evaluated and compared to several time periods. Radiochemical, geochemical, and hydraulic processes affecting changes are also evaluated. Hydraulic dispersion, radioactive decay, and sorption phenomena are also being studied using digital models. The unsaturated zone, underlying a radioactive-waste burial ground, will be instrumented and studies made to determine the possibility of solute-transport movement toward the regional aquifer.

Progress: Studies of distribution and migration of radioactive and chemical waste products in the Snake River Plain aquifer were continued. Digital models have been revised and updated to provide better waste-prediction capability, provide consultation to the Department of Energy (DOE) in a variety of hydrogeologic topics. Compilation of hydrologic and chemical data sets for

the INEL was completed. The data are applicable to the testing and comparison of solute-transport models used for low-level radioactive waste disposal site performance assessment and prediction of ground-water contamination at arid sites. A test-trench facility, designed to study solute and water transport through the unsaturated zone, was constructed near a radioactive-waste burial ground. Instrumentation of the facility was initiated and is continuing. A weighing lysimeter facility, also located near the radioactive-waste burial ground, was established and is continuing operation.

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Sheffield, Illinois

By Barbara J. Ryan, John R. Gray, Robert G. Striegl, Urbana, IL,
and Richard W. Healy, Denver, CO

The Sheffield low-level radioactive-waste burial site, an 8-ha area located in northwestern Illinois, was operated from August 1967 to April 1978. Wastes were buried in 21 trenches excavated in unconsolidated sediments. A continental climate yields warm summers (average temperature 22.2 °C) and cold winters (average temperature -7.5 °C). Average annual precipitation is about 900 mm of which 660 mm evapotranspires, 200 mm runs off and 40 mm recharges the aquifer. Vegetation at the site consists primarily of brome grass and red clover.

Hydrogeologic studies of the site have been ongoing since 1976. For objectives, approach, and results of the early work (1976 to 1982), see Schneider and Trask (1984). Soil moisture in the unsaturated zone, evapotranspiration, soil erosion, and landform modification are still being studied; gas transport in the unsaturated zone has been added to the scope of work at the Sheffield site.

Objectives: To define the mechanisms that control the movement of water and transport of radionuclides through the trench caps and beneath the trenches; and to determine the effects of the tunnel on flow in the unsaturated zone.

To describe the chemistry of water and geologic materials in the unsaturated zone both onsite and offsite, to determine the naturally occurring geochemical reactions and the effects of buried wastes on pore-water chemistry, and to describe the techniques used to obtain representative water samples from the unsaturated zone.

To identify, quantify, and determine the distribution of gases in the unsaturated zone adjacent to buried low-level radioactive wastes; to estimate the fluxes of waste-generated gases from a waste-burial trench to the surrounding unsaturated zone; and to determine physical and chemical properties that retard the transport of 14- carbon dioxide in unsaturated deposits.

To describe the microclimate and to estimate evapotranspiration at the site.

To quantify runoff and sediment yield at the site; and to determine the relationships amoung rainfall, runoff, and sediment transport.

Approach: A horizontal tunnel 2 m in diameter and 97 m long provides access to the unsaturated zone beneath four waste trenches. Soil cores taken radially from the tunnel were used to define the local stratigraphy as well as mineralogic and hydrologic properties of the geologic materials. Three observation wells within the tunnel and several wells adjacent to the tunnel provided water-level and water-quality data from the saturated zone. Soil-moisture tensiometers were used to determine soil suction. A variably saturated flow model aided data collection and interpretation of the unsaturated flow system.

Three gravity lysimeters and 30 soil-suction lysimeters were installed to monitor changes in water chemistry onsite above the trenches, onsite below the trenches, and offsite.

A two-dimensional gas-piezometer network is being used to determine temporal changes in concentration of radioactive and nonradioactive gases in the unsaturated zone. Fluxes of waste-generated gases are estimated with the use of computer models. Carbon-isotope exchange properties of different geologic materials under various water-saturation conditions is determined through laboratory experiments.

Three methods were used to estimate evapotranspiration: 1) an energy budget, 2) an aerodynamic profile, and 3) a water budget. The energy-budget and aerodynamic-profile estimates were computed from hourly data; the water-budget estimates were computed from weekly or bi-weekly soil-moisture measurements.

Runoff and sediment discharges are monitored in three watersheds comprising two-thirds of the land area of the site, and in a 1.10 ha watershed in undisturbed terrain 0.5 km south of the site. The effects of slope and land use on infiltration, runoff, and sediment yield are being evaluated at four test plots ranging in size from 10.2 to 11.0 m^2, two of which are at the disposal site and two in the undisturbed watershed. Land-surface altitudes are measured at fixed locations at the site to quantify settling and compaction. Periodic photographic surveys from stable reference points are used to study changes of vegetation and other surficial features. Surveys of ground-cover density are also made for assessment of variables affecting the relation between rainfall and runoff.

Progress: The tunnel intercepts both a dense glacial till and a well-sorted, medium-grained sand unit. The sand overlies the till throughout most of the length of the tunnel. Preliminary results indicate hydraulic conductivities range from 4.75×10^{-4} m/d in the till to 5.0×10^{-1} m/d in the sand. Maximum soil suctions are about -1600 mm H_2O in the till and about -800 mm H_2O in the sand. Soil moisture content ranges from 33 to 35 percent in the till and approximately 5 to 35 percent in the sand.

Minimum saturation is 98 percent in the till and ranges from about 15 to 45 percent in the sand.

Water movement through the unsaturated zone is seasonal. Increases in available water in the spring due to snowmelt and rain, combined with low evapotranspiration demands initiate the migration of stored soil water to the saturated zone. The amount of water stored within the soil zone is least in late summer. Soil-moisture tensions decrease during spring, reach a minimum in mid-summer, rise through early fall, and remain fairly constant through late fall and winter. Flow is concentrated along sloping interfaces where more permeable units overlie less permeable units. Vertical leakage from the bottom of the trenches has been difficult to detect, probably because of instrument limitations. Complex flow paths are indicated by the variability of soil-moisture tensions and radionuclide concentrations within and between lithologic units.

The changes in water chemistry which occurred in the unsaturated zone were the result of dissolution reactions involving calcite, dolomite,

montmorillonite, and strontianite; the oxidation of pyrite; cation exchange reactions; sorption of zinc by iron- and manganese-oxides and hydroxides; precipitation of calcite, strontianite, and sulfate; and the transport of organics and tritium from the trenches. Water in the unsaturated zone both onsite and offsite changed from a calcium bicarbonate type near land surface to a magnesium calcium bicarbonate type with increasing depth.

Field sampling of the gas-piezometer network is near completion.

For the period July 1982 to June 1984 annual precipitation (938 mm) and average temperature (10.8 °C) were virtually identical to long-term averages from nearby National Weather Service stations. Solar radiation averaged 65 percent of that expected under clear skies. Net radiation averaged 70.1 watts/m^2, being highest in July and negative for some winter months. Wind speed at the 2-meter height averaged 3.5 m/s and was slightly higher in winter than during the rest of the year. Estimates of evapotranspiration by the energy-budget and aerodynamic-profile methods for March through November were 648 mm and 630 mm, respectively. Daily estimates ranged from 0 to 6 mm. Yearly evapotranspiration by the water-budget method (using data from April through October) was estimated at 655 mm. Seasonal and diurnal trends in evapotranspiration rates mirrored those in net radiation; July generally had the highest rate. The ratio of sensible- to latent-heat fluxes (Bowen ratio) averaged 0.38 from the three methods. Monthly Bowen ratios averaged about 0.35 for late spring and summer and declined reaching zero or slightly negative values during the fall. When the ratio was negative, the latent-heat flux was slightly greater than the net radiation, as additional energy was supplied by cooling soil and air. Evapotranspiration estimates averaged 75 percent of potential evapotranspiration, as predicted by the Penman equation. There was no apparent seasonal trend in the relation between actual and potential evapotranspiration rates.

Annual sediment yield from the site averaged 4.5 Mg/ha and exceeded yields from the undisturbed area by 200 times. Approximately 97 percent of the sediments transported were silt- and clay-particle size. Sediments eroded from bare areas, rills, and gullies composed a disproportionately large part of site yields.

More than 300 surface collapses were recorded at the site from October 1978 through June 1985. Collapsed volumes were distributed log-normally around a median of 0.2 m^3. Ninety-six percent of the collapses were generally cylindrically shaped. Several collapses exceeded 3 meters in width; one collapse was estimated to be approximately 6 m deep. Sixty-two percent of the collapses occurred in swales between trenches or near trench boundaries, and the remainder occurred on trench covers. Two-thirds of the collapses, representing 63 percent of the cumulative collapse weight, were recorded from February through April. Annually, over 3 times more sediment was moved by collapse than by surface transport.

Investigators: M. Peter deVries, John R. Gray, Richard W. Healy, Patrick C. Mills, Charles A. Peters, Barbara J. Ryan and Robert G. Striegl

Reports

Foster, J. B., Garklavs, George, and Mackey, G. W., 1984, Geologic and hydrologic data collected during 1976-1984 at the Sheffield low-level radioactive-waste disposal site and adjacent areas, Sheffield, Illinois: U.S. Geological Survey, Open-File Report 83-926, 261 p.

Foster, J. B., Garklavs, George, and Mackey, G. W., 1984, Hydrogeologic setting east of a low-level radioactive-waste disposal site near Sheffield, Illinois: U.S. Geological Survey Water-Resources Investigations Report 84-4183, 20 p.

Gray, J. R., 1984, Runoff, sediment transport, and landform modifications near Sheffield, Illinois, in Annual Participants' Information Meeting, DOE Low-Level Waste Management Program, 6th, Denver, 1984, Proceedings: Idaho Falls, Idaho, U.S. Department of Energy CONF-84-09115, p. 534-544.

Gray, J. R., and deVries, M. P., 1984, A system for surface runoff and collecting sediment samples from small areas, in Meyer, E. L., ed., Selected Papers in the Hydrologic Sciences: U.S. Geological Survey Water-Supply Paper 2262, p. 7-11.

Gray, J. R., 1985, Erosion and landform modification at a low-level radioactive waste disposal facility near Sheffield, Illinois, in Glysson, G. D., ed., Proceedings of the Advanced Seminar in Sedimentation, August 15-19, 1983, Denver, Colorado: U.S. Geological Survey Open-File Report 85-98, 37-39.

Healy, R. W., Peters, C. A., deVries, M. P., Mills, P. C., and Moffett, D. L., 1984, Study of the unsaturated zone at a low-level radioactive-waste disposal site: Proceedings of the National Water Well Association, p. 820-830.

Striegl, R. G., 1984, Methods for determining the transport of radioactive gases in the unsaturated zone, in annual Participant's Information Meeting, DOE Low-Level Waste Management program, 6th, Denver, 1984, Proceedings: Idaho Falls, Idaho, U.S. Department of Energy, CONF 84-09115, p. 579-587.

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Gray, J. R., Landform modifications at a nuclear-waste burial site: Proceedings, 4th Interagency Sedimentation Conference, Las Vegas, Nevada, March, 1986.

Healy, R. W., deVries, M. P., and Striegl, R. G., Concepts and data-collection techniques used in a study of the unsaturated zone at a low-level radioactive-waste disposal site near Sheffield, Illinois: U.S. Geological Survey Water Resources Investigations Report 85-4228.

References

Schneider, Robert, and Trask, N. J., 1984, U.S. Geological Survey research in radioactive waste disposal--fiscal year 1982, U.S. Geological Survey Water Resources Investigations Report 84-4205, pp. 90-93.

Argonne National Laboratory Site, Illinois

By James R. Nicholas, Urbana, IL, and Allen M. Shapiro, Reston, VA

Low-level radioactive waste was buried during the period 1943-49 on the former grounds of the Argonne National Laboratory in the Palos Forest Preserve about 22 km southwest of Chicago, Illinois. The burial site was decommissioned and capped with concrete in 1956.

Tritiated water has migrated out of the trenches into the underlying 40 m of glacial drift. Concentrations in the drift range from 0.2 to more than 100,000 nCi/L. Tritium is also present in the fractured dolomite beneath the drift. Concentrations in the underlying dolomite range from 0.2 to 30 nCi/L. Tritium concentrations in an ephemeral stream adjacent to the site range from 0.2 to 2,000 nCi/L.

A hydrogeologic study of the site with emphasis on locations, concentrations, and migration directions of tritium in the drift and dolomite was conducted from 1979 to 1984. A 4-year study of ground-water flow and tritium transport in the fractured dolomite began in October 1984.

OBJECTIVES: The objective of the first study was to determine the geologic and hydrologic factors which control tritium migration from the burial site. The objective of the second study is to evaluate the applicability of the discrete-fracture and continuum hypotheses to ground-water flow and tritium transport in fractured dolomite.

APPROACH: The approach of the first study is summarized in Schneider and Trask (1984). The approach of the second study consists of several steps. (1) Determine fracture geometry from borehole geophysical logs and cores from 13 existing wells and 8 new wells. (2) Quantify the hydraulic properties of the fractures and matrix using the cross-hole aquifer-test method developed by Hsieh, Neuman, and Simpson (1983). (3) Quantify the transport properties of the rock using tracers and packers. (4) Evaluate the applicability of the hypotheses. (5) Predict responses over a larger volume of rock. (6) Drill new test wells, repeat steps 1-4, and compare results with predictions.

PROGRESS: Olimpio (1984) summarizes results from the first study. Major findings are noted here. Most of the downward movement of tritium appears to have occurred before decommissioning and the 0.6-m thick concrete cap appears to substantially reduce recharge to the drift. Thin sand layers are the major conduits for tritium migration in the otherwise clayey glacial drift. These layers refract flow, resulting in subhorizontal movement of water and tritium for at least 365 m downgradient. Tritium concentrations in core moisture give an inaccurate picture of concentrations of tritium moving by advective-dispersive mechanisms in the drift. Inaccuracies are related to the fact that extraction of core moisture by heating results in the sampling

of stagnant pores. Stagnant pores typically have higher concentrations of tritium than well-connected pores, probably due to diffusion. Tritium migration in the dolomite is principally through solutionally enlarged subhorizontal joints along bedding planes. The uppermost joints are the major conduits for tritium migration. Seasonal fluctuations in tritium concentration in the dolomite are caused by variations in recharge rates to the dolomite. A steady decrease in seasonal concentration maximums results from radioactive decay. Adjusting concentrations for decay suggests that the concentration of tritium entering the dolomite has been nearly constant from 1973 to 1985.

Predrilling work for the second study included surface geophysics, slug tests, and borehole-dilution tests to aid in locating and spacing new wells. A packer and data-collection system for use in observation wells in the cross-hole tests has also been developed. Surface geophysics indicate the dolomite is karsted and bedrock-surface topography is more rugged than previously thought. Slug tests and borehole-dilution tests in existing wells yielded a wide range of estimated hydraulic conductivities: 0.2 m/dy in apparently unfractured rock; 3 m/dy in a subregional horizontal joint; and 6,000 m/dy in a regional horizontal joint. The packer system consists of a string of five pneumatic packers and six transducer ports. Pressure responses are sent through a datalogger to final storage on magnetic tape, to a strip-chart recorder, and to a small printer. Straddle lengths can range from 0.6 to more than 35 m.

REPORTS

Nicholas, J. R., 1983, Tritium migration at Palos Forest Preserve, Cook County, Illinois (abs.) in Illinois water, planning for the future: Proceedings of Illinois Water Resources Conference, April 1983, p. 31.

Olimpio, J. C., 1984, Low-level radioactive-waste burial at the Palos Forest Preserve, Illinois: Geology and hydrology of the glacial drift as related to the migration of tritium: U.S. Geological Survey Water-Supply Paper 2226, 34 p.

Nicholas, J. R., 1984, Hydrogeologic factors governing tritium migration at a low-level radioactive waste burial site near Chicago, Illinois (abs.): Proceedings of the 29th Annual Midwest Groundwater Conference, October 1984, p. 17.

REFERENCES

Schneider, R. and Trask, N. J., 1984, U.S. Geological Survey research in radioactive waste disposal--Fiscal year 1982: U.S. Geological Survey Water Resources Investigations Report 84-4205, p. 94.

Hsieh, P. A., Neuman, S. P., and Simpson, E. S., 1983, Pressure testing of fractured rock--A methodology employing three-dimensional cross-hole test, NUREG/CR-3213, 176 p.

Maxey Flats, Kentucky

By Mark A. Lyverse, 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.

Until 1980 infiltrating water accumulated in the trenches at a rate greater than the capacity of the site evaporator to keep up with dewatering. In 1980, most of the burial trenches were covered with a polymer membrane (polyvinylchloride) 2 mm thick infiltration barrier. This barrier has limited vertical surface-water infiltration into the trenches, and the site evaporator is now operated only part time.

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 many burial trenches are formed by a 0.5 m-thick sandstone interbed called the lower sandstone marker bed. This bed is fractured and, at places, extends horizontally beyond the trench area to the hill slopes bordering the site. Observation wells outside the burial site have shown that ground-water flow in the shallow sedimentary rocks (sandstone and shale) is controlled primarily by naturally occurring joints and fractures. Wells having relatively high tritium concentrations (up to 3.5 microcuries per milliliter) are associated with the lower sandstone marker bed which probably has a higher density of open joints and fractures than the predominant shales.

OBJECTIVE:

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

APPROACH:

The description of the shallow sedimentary ground-water system will be based on the collection of water-level and water-quality data from approximately 70 wells. Water-level data will also be collected from about 20 burial trenches. Supplementary information from wells drilled in 1962, 1973, and 1979 will also be used.

PROGRESS:

Wells are currently being installed around the perimeter of the burial trenches. At present, the hydrogeologic conditions governing the movement of tritium and other radionuclides are not fully understood. Movement appears to occur primarily in the lower sandstone marker bed where it is present.

REPORT

Zehner, H. H., 1983, Hydrogeologic investigation of the Maxey Flats radioactive waste burial site, Fleming County, Kentucky: U.S. Geological Survey Open-File Report 83-133.

Beatty, Nevada

By Jeffrey M. Fischer and William D. Nichols, Carson City, NV

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.

Field investigations at the site were suspended in June 1980, and data analysis and report preparation were continued into calendar year 1981. As a result of the analysis, it was decided to resume field investigations and to continue the study.

Objective: The objective is 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, soil temperature, and unsaturated hydraulic conductivity. An instrumentation shaft, 14 m deep and 1.6 m in diameter, will contain removable work platforms at 3-m intervals. Psychrometers, thermocouples, and moisture sensors will be installed at selected depths at distances of as much as 4 m from the shaft. Soil-water tension, soil temperature, and soil-moisture content will be collected on a daily basis using digital data loggers.

Meteorological data will be collected at the site to study evaporation processes from bare soil.

Progress: A 14-m deep instrumentation shaft was installed in August 1983. Three-cm diameter holes were drilled out laterally 3 m from the side of the shaft and cased with pvc to allow retrieval of soil psychrometers. The first laboratory-calibrated, thermocouple psychrometers were installed in May 1984. Neutron access tubes were installed in July 1984, and a Penman weather station was installed in August of the same year. Soil matric potential and weather data have been collected on a continuous daily basis since August 1984 via a telephone modem hookup between the Carson City prime computer and the field data loggers. Soil moisture data are collected on a monthly basis.

Preliminary tests indicate that the method used to install the soil psychrometers does not affect natural soil potentials. Measured soil matric

potentials have varied from 33 bars to 56 bars. Volumetric soil-moisture contents range from 2 percent to 10 percent. The data indicate that the dominant form of moisture transport is in the vapor phase.

Plans include determining the unsaturated hydraulic properties of the alluvium both in the field and in the laboratory. Moisture flux will be calculated and modeled.

REPORTS

Morgan, D. S., and Fischer, J. F., 1984, Unsaturated-zone instrumentation in coarse alluvial deposits of the Amargosa Desert near Beatty, Nevada; in Proceeding of the Sixth Annual Participants' Information Meeting, DOE Low-Level Waste Management Program, CONF-8409115, pp. 617-629.

Nichols, W. D., 1985, Geohydrology of the unsaturated zone at the burial site for low-level radioactive waste near Beatty, Nye County, Nevada; USGS Open-File Report 85-198, 87 p.

Wood River Junction, Rhode Island

By Barbara J. Ryan, Urbana, IL, and Kenneth L. Kipp, Lakewood, CO

A recovery plant for processing cold uranium scrap was in operation at Wood River Junction, Rhode Island, from 1964 to 1980. Acid digestion with hydrofluoric and nitric acids and organic separation with tributyl phosphate and kerosene were used in the process. Solid wastes were shipped off-site and liquid wastes were discharged to the Pawcatuck River through a buried drain pipe from 1964 to 1966 and to lined "evaporation" ponds and trenches from 1967 to 1980. The "evaporation" ponds did not function as intended because average annual precipitation (1,150 mm) exceeds average annual evaporation (750 mm). Leakage from the ponds and trenches occurred at least as early as 1967, resulting in a plume of contaminated ground water. Apparently, some irridiated materials were processed along with the cold uranium scrap, accounting for the presence in the wastes of strontium-90 and technetium-99. The U.S. Geological Survey began a 3-year study of the ground-water contamination in June 1981.

Objective: (1) To determine the nature and extent of interaction of radionuclides and solutes with aquifer materials, (2) To develop and calibrate numerical models of ground-water flow and radionuclide and solute transport, (3) To use the model to predict the residence time of selected contaminants in the aquifer, and (4) To use the model to predict the effect of the contaminants on the quality of water in nearby existing and proposed supply wells.

Approach: Observation wells are installed to define the lithology, the direction of ground-water flow, and the horizontal and vertical dimensions of the contaminant plume. Monthly water-level measurements are made and water samples are collected from the observation wells to measure concentrations of radiochemical and selected inorganic constituents in the contaminated water. Hydraulic conductivity is estimated from the lithology

and from aquifer tests at nearby sites. Vertical distribution of porosity is determined from borehole geophysical logs. Seismic refraction is used to determine depth to bedrock. Interaction of sediments and radionuclides is determined from analyses of sediment and water samples taken at the same depths in boreholes.

Progress: As part of the investigation of ground-water contamination at a uranium-scrap recovery plant at Wood River Junction, Rhode Island, laboratory experiments led to the development of a model for predicting the transport of strontium-90 in glacial-outwash sediments based on an approximate mechanism for ion exchange. The multi-component system was simplified to two components by regarding all exchangeable cations other than strontium-90 as a single component. The binary ion-exchange parameter was a function of the variable, total-ion concentration. A one-dimensional solute-transport model was formulated to evaluate the time necessary for natural ground-water flow to remove the strontium-90 contamination plume from the ground-water system to the Pawcatuck River. The finite-difference transport equations were solved sequentially for total-ion concentrations, then for strontium-90 concentrations. Clay-free quartz and feldspar sands at the study site have little potential for strontium-90 sorption, and high calcium, magnesium, and sodium concentrations compete for the few ion-exchange sites. As the total-ion concentration plume moves out of the system, ion exchange of strontium-90 increases, reducing the strontium-90 concentration in the ground water. Cleanout times predicted using the binary ion-exchange mechanism were about two-thirds of those predicted using a constant distribution coefficient. It is suggested that this type of model can simulate solute transport more realistically in many ground-water systems where the total-ion concentration is not constant.

The water-level response to a slug or bailer test in a well completed in a confined aquifer has been evaluated taking into account well-bore storage and inertial effects of the water column in the well. The response range, from overdamped with negligible inertial effects to damped oscillation, was covered employing numerical inversions of the Laplace-transform solution. By scaling the time with respect to the undamped natural period of the well-aquifer system and by using the damping parameter for a second-order damped, inertial-elastic system, a set of type curves was constructed that enables water-level-response data from a slug or bailer test to be analyzed under conditions where the inertial parameter is large. Values of transmissivity and effective static-water-column length can be determined when an estimate of storage coefficient is available. The numerical solution and resulting type curves cover the transition range between the limiting cases of negligible inertial effects and of damped oscillation that have been treated by others. Two examples of slug-test analysis show that precise results depend on accurate measurements of water-level displacement ($\pm$1 percent of initial value).

Reports

Barlow, Paul M., and Ryan, Barbara J., 1985, An electromagnetic method for delineating ground-water contamination, Wood River Junction, Rhode Island; in Subitzky, S., ed., Selected papers in the hydrologic sciences: U.S. Geological Survey Water-Supply Paper 2270, p. 35-49.

Ryan, Barbara J., and Kipp, Kenneth L., Jr., 1984, Low-level radioactive contamination from a cold scrap recovery operation, Wood River Junction, Rhode Island: U.S. Geological Survey Open-File Report 84-066, 31 p.

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Ryan, Barbara J., and Kipp, Kenneth L., Jr., 1984, Radioactive ground-water contamination from a cold-scrap recovery operation, Wood River Junction, Rhode Island, in Proceedings sixth annual participants' information meeting: Department of Energy Low-Level Waste Management Program, p. 562-578.

Ryan, Barbara J., and Kipp, Kenneth L., Jr., 1985, Low-level radioactive contamination from a cold scrap recovery operation, Wood River Junction, Rhode Island, in Subitzky, S., ed., Selected papers in the hydrologic sciences: U.S. Geological Survey Water-Supply Paper 2270, p. 21-33.

Barnwell, South Carolina

By Kevin F. Dennehy, Columbia, SC

Approximately 45 percent of the current national production of low-level radioactive waste is being buried at a 130-ha site in the Coastal Plain physiographic province located about 128 km inland from the Atlantic Ocean in southwestern South Carolina. The site borders the Savannah River Plant and is situated about 8 km west of the city of Barnwell. The burial site is a commercical enterprise operated by Chem-Nuclear Systems, Inc., on property deeded to the State of South Carolina. Solid waste is buried in rectangular trenches that are excavated in unconsolidated Coastal Plain sediments. The burial area presently contains about 50 trenches that average about 7 m in depth, 15 to 30 m in width, and 152 to 305 m in length. The water table at the site is generally at a depth of about 9 to 15 m below land surface. The unsaturated zone consists of 1 to 2 m of eolian surface sand underlain by 10 to 15 m clayey sand. Trenches are excavated in the unsaturated zone, backfilled with sand, and capped by compacted clayey sand. The climate of the area is characterized by warm humid summers and mild winters. Average annual precipitation is 120 cm.

Objective: The potential for migration of radionuclides from the buried waste is dependent on the movement of soil moisture in the unsaturated zone. Therefore, the objectives of the project are to describe the rates, direction, and timing of water movement from land surface into and out of the burial trenches and to determine the principal meteorologic, hydrologic, and trench-design factors that affect water movement.

Approach: The objectives have been met by a data-collection program that focuses on monitoring of soil-moisture migration, estimation of the hydrologic budget, and determination of the effects of two different trench designs on water movement into the trenches.

Soil-moisture movement has been monitored in the vicinity of selected burial trenches with instruments placed in two experimental trenches (monitoring sites 1 and 2) and in two radioactive-waste trenches (monitoring sites 3 and 4). The experimental trenches were constructed using two different trench designs employed at the site in order to examine the influence of trench design on moisture movement. At monitoring site 1, surface sand around the perimeter was replaced by a clayey-sand barrier. At monitoring site 2, this sand was left intact around the trench.

Access to the unsaturated zone was by a vertical metal shaft in each trench. Soil-moisture tensiometers, thermocouples, and conductance probes were installed horizontally at different depths through the wall of the shaft and into undisturbed sediments of fine-grained clayey sand and fine-grained sand used as trench backfill. Conductance probes were also placed vertically at the experimental trench bottoms into undisturbed sediments of fine-grained clayey sand. A tracer test was conducted as part of the monitoring procedure. Data collection at the monitoring sites began in January 1982 and continued until early May 1984.

Estimation of the hydrologic budget involved, in addition to the soil-moisture monitoring data, measurements of precipitation and of the components necessary to estimate evapotranspiration using the Bowen ratio/energy budget and Penman methods. Sixteen different meteorologic measurements were recorded at hourly intervals and used to estimate mean daily evapotranspiration from grass-covered trench caps located on the burial site.

Soil sampling of the unsaturated zone was conducted during instrument installation and upon decommissioning of the monitoring sites. Some of the soil properties examined included grain-size distribution, porosity, saturated hydraulic conductivity, and soil-moisture retention curves. Tritium analyses were also conducted on soil samples at the experimental trenches to examine the variation of concentration with depth.

Numerical modeling of soil-moisture movement in the unsaturated zone at the experimental trenches will be compared with the current hypothesis of moisture flow developed from tensiometer and conductance data.

Progress: The final report on the unsaturated zone study at the Barnwell site has been prepared and is in review. Results are summarized below.

Water movement in the unsaturated zone takes place primarily from late fall to early spring. In the trenches, water moves vertically through the trench cap and into the trench backfill. In the undisturbed sediments adjacent to the trenches, water moves vertically through the surface sand and either continues downward into clayey sand or laterally along the sand/clayey-sand interface into the trench backfill, depending on trench design. Ponding occurs to various degrees above the experimental trench bottoms and is strongly influenced by trench design.

The hydrologic budget for the period July 1983 to June 1984 at the experimental trench monitoring sites included 144 cm of precipitation, estimated evapotranspiration of 106 cm, and negligible storage in the unsaturated zone as indicated by tensiometer data. Mass-balance computations indicate approximately 38 cm of recharge to the water table.

Analyses of the concentration of tritium in water extracted from cores taken during dismantling of monitoring sites 1 and 2 showed an average value of 2980 pCi/L. This value can be considered background. However, the concentration of tritium increased slightly with depth. The maximum value reported was 6390 pCi/L at monitoring site 1 approximately 20 ft below land surface. The direction of water movement determined from the monitoring results is supported by qualitative model simulation of the hydraulic-head distribution associated with each experimental trench design.

Reports:

Cahill, J. M., and Dennehy, K. F., 1983, Monitoring water movement in unsaturated sediments at the low-level radwaste site near Barnwell, South Carolina (abs.): Abstract from NWWA conference on Characterization and Monitoring of the Vadose (Unsaturated) Zone, Las Vegas, NV, December 8-10, p. 31.

Dennehy, K. F., and McMahon, P. B., 1985a, Hydrologic and micrometeorologic data from an unsaturated zone study at a low-level radioactive waste burial site near Barnwell, South Carolina: U.S. Geological Survey Open-File Report 85-476, 32 p.

McMahon, P. B., and Dennehy, K. F., 1985, Water movement in the vadose zone at two experimental waste-burial trenches in South Carolina: Proceedings of NWWA conference on Characterization and Monitoring of the Vadose (Unsaturated) Zone, Denver, Colorado, November 19-21, p. 34-53.

Bear Creek Valley, Oak Ridge Reservation, Tennessee

By Zelda Chapman Bailey, Nashville, TN

Bear Creek Valley, located within the Oak Ridge Reservation, Tennessee, contains the Y-12 Plant, which produces nuclear-weapon components. Several disposal sites are located in and around the plant, which is on the headwaters of East Fork Poplar Creek, but the main disposal areas are located in the Bear Creek watershed. Contaminants, which include oils, uranium, solvents, heavy metals, and nitrates, are leaching into ground and surface water from the hazardous-waste disposal sites. More than 400 wells and test borings, clustered in existing or proposed disposal areas, have been drilled in the 31 Km^2 area by other investigators. However, the regional ground-water flow system and, therefore, the potential dispersion of contaminants, are poorly understood.

The study area, in the Valley and Ridge physiographic province, is underlain by Cambrian- and Ordovician-age rocks that dip southeastward at about 45 degrees. Bear Creek Valley is underlain by the Conasauga Group, primarily calcareous shale containing limestone units. Pine Ridge, on the north side of the valley, is underlain by the Rome Formation, composed of interbedded sandstone, siltstone, and shale. Chestnut Ridge, on the south side, is formed by the Knox Group, primarily massive, siliceous dolomite. The bedrock is generally overlain by regolith, which is composed of soil and weathered rock, ranging from 0 to 15m in thickness.

Numerous site-specific studies are being conducted at the disposal sites to determine the extent of local contamination, to formulate remedial action plans, and to monitor the movement of contaminants in the ground water. The present USGS study, begun in February 1984 and funded by DOE, is to describe the regional ground-water flow system and the potential paths of contaminant migration.

Objectives: The objectives are to describe the regional ground-water flow system in Bear Creek Valley and, thereby, to determine the possible pathways of contaminant transport from hazardous-waste disposal areas.

Approach: Existing lithologic and hydraulic data that have been generated by other investigators were compiled in order to formulate a preliminary concept of the system and to determine where additional data are needed. The data base is derived from 430 wells and test borings. Hydraulic conductivities were available from 277 single-well aquifer tests. Water levels were available for 215 wells in both regolith and bedrock; 110 of those are in bedrock. Their distribution and generally shallow depths limit the interpretation of flow in the bedrock, particularly at the valley boundaries--the Clinch River and the ridges. Although the data base is large for such a small area (12 sq mi), the distribution is not adequate for a regional interpretation of flow.

Logs from existing bore holes and small-area maps were used to map the geology, thickness of the regolith, and the top of the unweathered bedrock. Nine clusters of wells distributed along the valley boundaries are being drilled to provide lithologic and hydrologic information that is not available from the existing data. Discharge measurements along the major streams are used to determine the seepage characteristics of the rock units and the interaction of ground and surface water. Water-quality analyses of surface water and springs have provided additional information on that interaction and on transport of contaminants from the disposal areas.

Cross-sectional and areal ground-water flow models are being used to integrate existing data, to test the conceptualized system, to identify areas of additional data needs, to demonstrate the regional flow pattern, and to estimate a water budget.

Progress: No attempt had been made by previous investigators to integrate data from local studies into a unified concept of the regional ground-water flow system, and no valley-wide maps existed for regolith thickness, geologic units within the Conasauga Group, elevation of the bedrock surface, or water levels in regolith and bedrock. All of these maps have been produced by this study using existing data, and refinements will continue as new data are collected.

The range of measured hydraulic conductivity of the regolith is from 0.003 to 4 m/d, and of the unweathered rock, from 0.003 to 3.4 m/d. Because of the overlap of wide ranges in conductivity, both areally and with depth, no generalizations about conductivity for each geologic unit have been made by other investigators. The data were grouped by formation and then by occurrence in bedrock or regolith. Each group was normalized and plotted on a probability curve (J. F. Connell, U.S. Geological Survey, written commun., 1985). The values of hydraulic conductivity derived from this analysis were used as a

guideline for modeling the system, to show relative differences of hydraulic properties of the formations and of the regolith, and to set reasonable maximum and minimum limits on conductivity during model calibration.

Additional data have been collected during the study to assist in conceptualizing the regional flow system. Seepage characteristics of the geologic units have been shown by analysis of discharge measurements along two major creeks in the valley. Specific conductance measurements in the streams and springs have provided insight into the interaction of ground and surface water and were used as a screening tool to identify sites for more intensive water-quality sampling. Thirty-four sites were sampled during high base flow for physical properties, major constituents, and trace constituents. The sites were resampled during low base flow to verify the results of the initial analyses and to detect any seasonal variations in contaminant concentration and movement.

Several data reports have been published (see Reports) and the following data and interpretative reports are in preparation:

Preliminary evaluation of regional ground-water flow in Bear Creek Valley, Oak Ridge Reservation, Tennessee, by Z. C. Bailey.

Streamflow and specific-conductance data for Bear Creek, August 13, 1985, Oak Ridge Reservation, Tennessee, by R. D. Evaldi.

Reports

Evaldi, R. D., 1984, Streamflow and specific-conductance data for selected sites, February 15 through April 9, 1984, near the Y-12 Plant, the Oak Ridge Reservation, Tennessee: U.S. Geological Survey Open-File Report 84-625, 5 p.

Hoos, A. B., and Bailey, Z. C., 1986, Reconnaissance of surficial geology, regolith thickness, union and structure contours of the configuration of the bedrocks surface in Bear Creek and Union Valleys, near Oak Ridge, Tennessee, U.S. Geological Survey Water Resources Investigations Report 86-4165.

Pulliam, P. J., 1985, Water-quality data for 34 sites, April and June 1984, near the Y-12 Plant, the Oak Ridge Reservation, Tennessee: U.S. Geological Survey Open-File Report 85-165, 13 p.

Pulliam, P. J., 1985, Water-quality data for 35 sites, September 1984, near the Y-12 Plant, the Oak Ridge Reservation, Tennessee: U.S. Geological Survey Open-File Report 85-553, 16 p.

Oak Ridge National Laboratory, Tennessee

by H. H. Zehner, Knoxville, TN, and P. Tucci, Nashville, TN

Low-level radioactive waste has been buried at Oak Ridge National Laboratory (ORNL) since 1943. Most waste is in three burial grounds in Melton Valley;

lesser amounts are in three burial grounds in adjacent Bethel Valley. Both valleys are underlain by shale, siltstone, and limestone. The upper part of the bedrock is regolith, with depth of weathering ranging from about 12 m on hilltops to a few centimeters in valley bottoms.

Surface-water discharge is by Whiteoak Creek and its tributary, Melton Branch. These streams flow into a settling basin called Whiteoak Lake, which discharges to the Clinch and Tennessee Rivers. Dissolved waste radionuclides have been found in Whiteoak Creek and Melton Branch and in ground water in the burial areas. The part of Melton Valley that is of hydrologic interest regarding radioactive-waste disposal is 4.8 Km long, and that part of Bethel Valley is 4.0 Km long.

Water quality is monitored by ORNL at Whiteoak Creek and Melton Branch and at several wells. Collection of stream discharge has been sporadic in the past, and most wells are not suitably constructed for water-quality sampling. Knowledge of the ground-water flow system is insufficient to accurately describe water volume, direction, and flow rate, particularly for the unweathered bedrock.

Objective: The hydrology of the ORNL area is to be described in sufficient detail so that recommendations can be made to the U.S. Department of Energy for establishing ground-water and surface-water monitoring systems. The purpose of the monitoring systems is to accurately evaluate water quality in Melton and Bethel Valleys.

Approach: Continuous discharge is now being collected at two USGS stations installed in 1985 and at three stations recently installed by ORNL. Head data are being collected from existing wells and will be collected from several well clusters soon to be constructed by both the USGS and ORNL. Hydraulic characteristics of the rocks are being determined, and a computer model for describing ground-water flow is being developed for Melton Valley. Plans are being made for developing a computer model for Bethel Valley. Water-quality samples are being collected to provide more information on ground-water flow and surface-water, ground-water relationships.

Progress: Most work done since 1982 has been collection of additional data on head distribution and aquifer characteristics and development of a computer model for simulating ground-water flow. Conceptual analysis of the ground-water system, particularly of the shallow flow in the burial grounds, is described in a draft report "Hydrology of the Melton Valley Burial Grounds" by D. A. Webster.

Computer simulation modeling began in 1984 for the purpose of better understanding the ground-water flow in all of Melton Valley and determining what data are needed for a more detailed description of the flow system. Simulation was by a 3-dimensional, finite-difference model, which contained two layers representing the regolith and bedrock. Model boundaries were surface-water drainage divides (which were assumed to also be ground-water divides), Whiteoak Lake, and the Clinch River. Slug-test data were used for transmissivity input, and base flow analysis of a stream in a nearby valley was used for estimating recharge rate.

The model results indicate that most ground-water flow is within the regolith, and less than 3 percent of the total ground-water flow is between regolith and bedrock. Less than 1 percent of the total ground-water flow discharges to the Clinch River through bedrock. Therefore, it may be assumed that most dissolved radionuclides flowing from the burial areas discharge to Whiteoak Creek and Melton Branch. The modeling work showed that the following additional data are needed: quantity and areal distribution of recharge rates; regolith thickness; head distribution in regolith outside the burial areas, particularly at the model boundaries; head and aquifer characteristics in the bedrock; and long-term, surface-water flow characteristics.

Report

Tucci, Patrick, 1985, Ground-water flow in Melton Valley, Oak Ridge Reservation, Roane County, Tennessee--Preliminary model analysis: U.S. Geological Survey Water Resources Investigations Report 85-4221.

Weldon Spring, Missouri

By M. J. Kleeschulte and Leo F. Emmett, Rolla, MO

Two radioactive waste-disposal sites are located in the Weldon Spring area. One site consists of the Weldon Spring Feed Materials Plant and four disposal pits located on slightly rolling terrain just north of the Mississippi-Missouri River drainage divide. The other site is an abandoned rock quarry in the bluff adjacent to the Missouri River flood plain and about 3 miles southwest of the plant.

The Weldon Spring Feed Materials Plant is located in St. Charles County, Missouri, approximately 24 Km southwest of the city of St. Charles and approximately 48 Km west of the city of St. Louis. The plant was in operation from 1957 to 1966. During that time, the plant converted impure uranium concentrates to pure uranium salts and metal. The metal was manufactured into feed element cores for the atomic reactors at Hanford, Washington, and Savannah River, South Carolina. Residues from the refining operation were disposed of into four pits. The pits have been excavated into the glacial till which overlies permeable limestone. Plant operation also resulted in uranium contamination of the soil adjacent to some of the buildings. The abandoned quarry was used for the burial of radioactive residues from various uranium processing sites. Disposal of radioactive wastes in an area underlain by carbonate rocks has created the potential for contamination of the ground and surface water.

Objectives: To determine the regional extent and magnitude of radioactive contamination of the ground and surface water, to describe the ground-water flow system in the study area, to describe the hydrogeologic characteristics of the aquifers underlying the area, to describe the surface-ground water relationship, and to describe the chemical quality of the ground and surface water.

Approach: Compile and analyze hydrologic information relating to the study area. Collect synoptic water-level data, collect water samples for chemical analysis, install 10 observation wells in bedrock down gradient from the four pits for monitoring purposes.

Progress: Chemical analyses of water overlying the residues in the 4 pits show greater than natural concentrations of calcium, sodium, sulfate, nitrate, fluoride, uranium, radium, lithium, molybdenum, strontium, and vanadium. Analysis of water from a spring located about 2.4 Km north of and down gradient from the plant shows uranium and nitrate concentrations greater than background concentrations. Analysis of water from the quarry shows large concentrations of uranium. Analysis of the water from a slough south and down gradient of the quarry indicates uranium concentrations greater than background.

Report

Kleeschulte, M. J., and Emmett, L. F., 1986, Compilation and preliminary interpretation of hydrologic data for the Weldon Spring radioactive waste-disposal sites, St. Charles County, Missouri: a progress report: U.S. Geological Survey Open-File Report 85-4272, 71 p.

Uraniferous Lignite Mines, Western North Dakota

By Robert L. Houghton, Bismark, ND

Between 1955 and 1967, approximately 268,000 Kg of uranium oxide were recovered from 86,000 mg of lignite mined from the Fort Union Formation in Billings, Stark, and Slope counties in western North Dakota. The lignite, which had a uranium oxide content ranging from 0.001 to more than 2.1 percent, was stripmined in more than 12 pits. The exposed lignite was soaked with waste oil and then burned in pit bottoms or nearby kilns to concentrate the uranium in its ash by approximately a factor of 10. The resultant ash then was transported in open trucks and railcars to uranium processing plants in other States.

Stockpiles of ash and lignite remained in pit bottoms when the mines were abandoned. Most pits have become flooded, because the lignite beds commonly serve as local aquifers and mines are located in recharge areas of the aquifers. Because uranium salts in the overburden generally were not recovered, spoils piles at abandoned mine sites have surface gamma ray exposure levels as high as 500 microroentgens per hour, approximately 30 times local background levels. Infiltrating precipitation leaches spoils and residual ash, introducing uranium and associated elements such as radium, arsenic, molybdenum, and selenium to water in the lignite aquifers or exposed in the pits and facilitating transport of these elements from the mine sites to regions where human exposure is more likely. Aquifer and pit waters have uranium concentrations ranging from 12 to 19,000 micrograms per liter and accompanying radium-226 concentrations ranging from 1 to 73 picocuries per liter, commonly much greater than accepted drinking-water standards. Thick underclays beneath the lignite prevent contamination of underlying aquifers.

More than 800 unreclaimed uranium mines occur throughout the United States. At present, no regulations or guidelines have been formulated to govern

reclamation of these sites. The U.S. Environmental Protection Agency expects to use investigations at the North Dakota mine sites to develop these guidelines.

Objectives: The objectives are: (1) to determine the concentration, distribution, and speciation of radioactive elements and select trace metals in source materials and receiving waters; (2) to determine the physiochemical conditions which promote the mobility of radioactive, select trace metal, and other potentially hazardous chemical constituents from uraniferous lignite mines throughout the hydrologic system; (3) to predict the mobility of these constituents at representative abandoned mine sites; (4) to compare predicted and observed ground-water, pore-water, and surface-water compositions affected by mine-derived solutes; (5) to develop reclamation methods which might limit hazardous waste mobility from the sites; and (6) to evaluate the effectiveness of reclamation practices adopted by regulatory agencies to restore the mine sites to maximum safe usefulness.

Approach: The study consists of four phases. Phase 1 is designed to provide geohydrologic and geohydrochemical data necessary to determine the concentration and distribution of radioactive and associated elements in relation to the hydrologic flow system. Phase 2 will determine chemical speciation and the geochemical processes controlling radiochemical mobility in the hydrologic system. Investigations during Phase 2 will concentrate on a representative uranium mining and ashing site which intersects the water table, a second uranium mining and ashing site remote from the water table, and a kiln site. Phase 3 will determine the transference value of information gathered in Phase 2 to the remaining North Dakota mining sites and similar sites in South Dakota and Montana. Phase 4 will develop and evaluate effective reclamation practices for restoring the sites to safe use.

Progress: In the fall of 1983, piezometer networks were installed at nine mine sites. Since that time, water levels have been monitored on a monthly basis and water-quality samples analyzed quarterly for uranium, radium-226, and associated constituents. Pressure-vacuum lysimeters have been sampled concurrently to determine the quality of unsaturated-zone waters. Stage staffs have been used to determine water levels in mine ponds, and water and biota from mine ponds have been analyzed for radioactive constituents and associated trace metals. Ground-water flow and solute-transport models are being developed using these data. Calibration of the solute-transport model has been aided by the illegal disposal of concentrated hydrochloric acid and oilfield wastes in one of the unflooded pits. Chloride and oil migration to adjacent pits have provided excellent tracers for the transport system.

Core material recovered from and adjacent to mine sites has been analyzed by x-ray diffraction and fluorescence and subjected to various extraction procedures to determine the mineralogic and chemical phases in which radioactive constituents and associated trace metals reside and the conditions under which they become mobile. The preliminary results of these studies are reported by Houghton and others (1984c).

Radon degassing rates have been calculated for several mine spoils and undisturbed environments. Radon concentrations at various depths in the soil column have been determined using Track-Etch detectors. Gas diffusion rates have been determined using soil-gas probes and injection devices.

Combined data for radon concentrations and inert gas diffusion rates permit calculation of theoretical radon degassing rates. Measurement of radon surface accumulation rates has been used to confirm these calculations.

Preliminary procedures for reclamation of uranium-mine sites have been developed based on the results of these investigations. Pilot reclamation of one mine site followed collection of uranium, radium, and metal concentration data on a 15m horizontal grid and a 0.6m vertical spacing in the mine spoils to be returned to the pit. Post-reclamation monitoring to determine the success of reclamation procedures is underway.

Reports

Houghton, R. L., Wald, J. D., and Anderson, Garth, 1984a, Hydrogeochemical controls on the mobility of radiogenic constituents in mine spoils and uraniferous lignite ash in southwestern North Dakota, in, Moreland, J. A., and Van Voast, W. A., eds., Abstracts of the 13th Annual Rocky Mountain Ground-Water Conference, April 8-11, 1984, Great Falls, Montana: Montana Bureau of Mines and Geology Special Publication 91, p. 26-27.

Houghton, R. L., Wald, J. D., and Anderson, Garth, 1984b, Hydrogeochemical controls on the mobility of radiogenic constituents at uraniferous lignite mines in southwestern North Dakota: Proceedings of the North Dakota Academy of Science, Vol. 38, p. 59.

Houghton, R. L., Wald, J. D., and Anderson, Garth, 1984c, Distribution and hydrogeochemical mobility of radioactive and associated constituents in the coal-bearing Fort Union Formation of western North Dakota, in, Houghton, R. L., and Clausen, E. N., eds., Proceedings of the 1984 Symposium on the Geology of Rocky Mountain Coal, October 2-4, 1984, Bismarck, North Dakota: North Dakota Geological Society Publication 84-1, p. 89-113.

INVESTIGATIONS AND MODELING OF GEOLOGIC AND HYDROLOGIC PROCESSES

Geochemistry of Trace Elements in Natural Waters

By D. K. Nordstrom, Menlo Park, CA

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 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 nonexistent. 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, and redox species, the compilation and evaluation of thermodynamic data used in speciation calculations, and the investigation 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 respository, will be used to develop concepts and methodology for studying trace-element behavior in granitic rock masses and their application to the origin and evolution of granitic ground waters.

Progress: Research has continued on the relationship between fluid inclusions and the deep ground-water chemistry at Stripa, Sweden. Major ion chemistry is dominated by carbonate geochemistry, and a general model for hydrochemical processes in the Stripa ground waters has been formulated. Co-workers have completed extensive isotopic analyses of both the water and the fracture minerals. A first comprehensive report on the subject has been completed (Nordstrom et al., 1985) that presents the most detailed work on ground-water geochemistry in crystalline bedrock sponsored by a radioactive waste management agency.

Research has also continued on trace element speciation techniques and chemical modeling has led to the publication of papers on both analytical speciation methods (Moses et al., 1984), computational approaches to speciation (Nordstrom and Ball, 1984), and evaluation of basic thermodynamic data (Nordstrom et al., 1984; Nordstrom and Munoz, 1985).

Reports

Carlsson, L., Olsson, T., Andrews, J., Fontes, J.-C., Michelot, J. L., and Nortstrom, K., 1983, Geochemical and isotope characterization of the Stripa groundwater--Progress report, Stripa Project Internal Report 83-01, 130 p.

Moses, C. O., Nordstrom, D. K., and Mills, A. L., 1984, Sampling and analyzing mixtures of sulfate, sulfite, thiosulfate and polythionate, Talanta 31, 331-339.

Nordstrom. D. K., 1983, Geochemical characteristics of Stripa groundwater, in OECD/NEA Workshop on In Situ in Granite Associated with Geological Disposal of Radioactive Waste, 143-153.

Nordstrom, D. K., and Ball, J. W., 1984, Chemical models, computer programs and metal complexation in natural waters, in International Symposium on Complexation of Trace Metals in Natural Waters, Nijhoff/Junk Publishers, 149-164.

Nordstorm, D. K., Valentine, S. D., Ball, J. W., Plummer, L. N., and Jones, B. F., 1984, Partial compilation and revision of basic data in the WATEQ programs, U.S. Geol. Survey Water Res. Invest. 84-4186, 40 p.

Nordstrom, D. K., Andrews, J., Carlsson, L., Fontes, J.-C., Fritz, P., Moser, H., Olsson, T., 1985, Hydrogeological and hydrogeochemical investigations in boreholes--Final Report of Phase I geochemical investigations of the Stripa groundwater, Stripa Project Internal Report, 250 p.

Reference

Nordstrom, D. K., and Munoz, J. L., 1985, Geochemical Thermodynamics, 447 p.

Geochemical Kinetics

By Hans C. Claassen, Lakewood, CO

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: A detailed mass balance of aqueous chloride for the dacite-andesite tuff watershed revealed the utility of that ion in partitioning precipitation input to a watershed among its various hydrologic components: evaporation, recharge, and runoff. The method requires a knowledge of chloride input from precipitation, chloride concentration of vadose-zone recharge, and amount of precipitation. The rocks in the watershed must not contribute significant amounts of chloride to the ground water compared to precipitation. The mass balance model was used to predict runoff in the watershed for a 3-year period, a period which spanned unusually dry, unusually wet, and average conditions. Runoff was predicted within 2 cm, of the amount measured, which in an average year is less than 5 percent of precipitation. The method is being applied to other watersheds to demonstrate its widespread utility.

Perhaps one of the more interesting applications of the chloride model is determination of climatic conditions and locations associated with recharge of paleogroundwater, such as is found in the Great Basin. Because the chloride concentration in ground-water recharge is determined by not only amount of precipitation but also vegetation type and density, slope and aspect of watershed, it is a sensitive indicator of climate scenarios. In those climates which are presently arid, the ground water reflects conditions associated with past recharge, and. therefore, maybe those conditions expected to be associated with future recharge as well. It is primarily these climates which will be associated with transport of contaminants stored at waste-disposal sites.

Other indicators of climatic conditions associated with recharge are the isotopes of hydrogen, carbon, and oxygen present in the ground water. These isotopes provide information on temperature and seasonal distribution of precipitation as well as type and density of vegetation present in the recharge area. These principles are continuing to be developed and applied; published examples may be found in the reports list which follows.

The aforementioned isotopes were used to determine the range of climatic conditions associated with recharge of ground water found in the west-central Amargosa Desert, Nevada. The most probable conditions were different for the range in time of 17,000 to 10,000 years before present (yr B.P.) represented by ground-water age determinations. At 17,000 yr B.P., winter and summer precipitation both contributed to recharge; mean annual temperature was about 8 °C below present. By 10,000 yr B.P., only winter moisture was effective in contributing to recharge; mean annual temperature was about 1 °C below present. These temperature shifts from present are in agreement with those determined from fossil packrat-midden studies.

Reports

Claassen, H. C., 1982, The application of chemical kinetics to defining the source of ground water in the west central Amargosa Desert, Nevada:

38th Southwest and 6th Rocky Mountain Combined Regional Meeting of the American Chemical Society, abstract no. 109, p. 50.

----- 1982, Guidelines and techniques for obtaining water samples that accurately represent the water chemistry of an aquifer: U.S. Geological Survey Open-File Report 82-1024, 49 p.

----- 1984, Paleohydrology of the Amargosa Desert, Nevada, Abstracts with Programs, 97th Annual Meeting of the Geological Society of America, Reno, Nevada, p. 471.

----- 1985, Sources and mechanisms of recharge for ground water in the west-central Amargosa Desert, Nevada--a geochemical interpretation: U.S. Geological Survey Professional Paper 712-F, 31 pp.

----- 1985, Paleohydrology of the west-central Amargosa Desert, (to be published in Isotope Geoscience).

Claassen, Hans C., Reddy, Michael M., and White, Art F., 1983, Relationship between precipitation and vadose-zone chemistry in a high-altitude watershed in Colorado: in Proceedings of the fifth annual participants' information meeting DOE low-level waste management program, CONF-8308106, p. 726-736.

Claassen, Hans C., Reddy, M. M., and Halm, D. R., 1985, Use of chloride ion in determining hydrologic basin water budgets--A three-year case study in the San Juan Mountains, Colorado, (to be published in Journal of Hydrology).

Reddy, Michael M., and Claassen, Hans C., 1985, Estimates of average major ion concentrations in bulk precipitation at two high-altitude sites near the continental divide in southwestern Colorado, Atmospheric Environment, v. 19, no. 7, p. 1199-1203.

Reddy, M. M., Benefiel, M. S., and Claassen, Hans. C., 1985, Cadmium, Copper, Lead and Zinc determination in precipitation: A comparison of inductively coupled plasma atomic emission spectroscopy and graphite furnace atomic absorption spectroscopy, Analytical Chemistry (in press).

Chemistry of Hydrosolic Metals and Related Constituents in Water

By John D. Hem, Menlo Park, CA

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: Chemical, thermodynamic, and other basic data are obtained from published literature 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: The crystal form and oxidation state of manganese precipitated by aeration of dilute solutions of divalent manganese at pH 8-9 can be predicted when the temperature and predominant anion species are known. At 25 °C the initial oxide formed is hausmannite (Mn_3O_4), and at temperatures below 5 °C the product is predominantly feitknechtite (βMnOOH), if the anion is chloride, nitrate, or perchlorate. In sulfate solutions, the product is manganite (γMnOOH). The first two oxides alter during aging to form manganite, which is the most thermodynamically stable of the Mn^{3+} oxides. All are capable of disproportionation to form Mn^{4+} oxides (Hem and Lind, 1983). When manganese oxidations are carried out in the presence of other transition metal ions such as iron, cobalt, nickel, copper, or zinc the other metal tends to be scavenged from solution by incorporation into the growing manganese oxide crystal lattice. The efficiency of scavenging depends on compatibility of the accessory metal with the crystal form of the manganese oxide precipitate. The stability of the coprecipitate toward recrystallization and accompanying partial release of accessory metal depends on similar compatibility factors. A coprecipitate of cobalt with βMnOOH formed at 1.0 °C is a relatively stable mixed phase in which CoOOH was identified (Hem et al., 1985). Coprecipitation of copper with βMnOOH gives a less stable oxide. In this oxide the charge deficiency caused by Cu^{2+} ions substituted in the hexagonal crystal lattice of βMnOOH is compensated by adjacent Mn^{3+} converting to Mn^{4+}. If the Cu/Mn ratio exceeds about 1/10, the structure decreases in stability (Hem, 1984).

Hausmannite has a spinel structure. Zinc ions may substitute for Mn^{2+} in this oxide. The pure zinc manganese spinel $ZnMn_2O_4$ (hetaerolite) can be synthesized at 20 °C by coprecipitation. Solid solutions containing lower proportions of Zn are more stable toward recrystallization than is hausmannite and can decrease dissolved Zn to levels as low as $10^{-8.0}$ molar (less than 1 µg/L) (Hem and Roberson, 1985). Metal coprecipitations may be an effective means for immobilizing radionuclides.

Aluminum solubility can be controlled by equilibria involving kaolinite. Simple equilibrium solubility concepts, however, are not readily applicable for evaluating stabilities of smectite type clays. Stabilities of these minerals can be estimated by considering their formation to be an irreversible process (May, 1985).

The kinetics of dissolution of aluminum hydroxide polyions show strong pH dependence. The fundamental reaction mechanism involves simultaneous encounters between two H^+ ions and the two OH's bridging between Al^{3+} ions in the polymer structure (Hem, 1983). Knowledge of the stabilities of clay minerals and $Al(OH)_3$ is needed in designing waste-storage facilities.

References:

Hem, J. D., 1983, Kinetics of dissolution and structure of aluminum hydroxide polymers: in Augustithis, S. S., Ed. Leaching and diffusion in rocks

and their weathering products. Athens (Greece) Theophrastus Publications S. A., p. 51-62.

Hem, J. D., and Lind, C. J., 1983, Non-equilibrium models for predicting forms of precipitated manganese oxides: Geochemica et Cosmochimica Acta, v. 47, p. 2,037-2,046.

Hem, J. D., 1984, Coprecipitation of metal ions with manganese oxyhydroxides (abs.): EOS, v. 65, p. 890.

Hem, J. D., Roberson, C. E., and Lind, C. J., 1985, Thermodynamic stability of CoOOH and its coprecipitation with manganese: Geochimica et Cosmochimica Acta, v. 49, p. 801-810.

Hem, J. D., and Roberson, C. E., 1985, Synthesis and stability of divalent-metal manganites (abs.): American Chemical Society Annual Meeting, Sept. 8-13, 1985, Chicago, IL.

May, H. M., 1985, Smectite geochemistry and the estimation of clay mineral stability (abs.): Eighth International Clay Conference, July 28-Aug. 2, 1985, Denver, CO.

May, H. M., Kinniburg, D. G., Helmke, P. A., and Jackson, M. L., 198--, Aqueous dissolution, solubilities and thermodynamic stabilities of common aluminosilicate clay minerals: kaolinite and smectities: Geochemica et Cosmochimica Acta, (in press).

Chemical Reactions at Mineral Surfaces

By James A. Davis, Menlo Park, CA

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 mechanisms 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 complexation for well-characterized, clean hydrous oxides (Davis and Leckie, 1979), 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 which has been modified to include surface reactions in the computation of equilibrium.

The surface complexation model is based on the coordination chemistry of surface-OH groups which are present at many 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: The research effort has focused on a study of the mechanism of surface reactions of cadmium ions with a calcareous, sandy aquifer material. The results have demonstrated that cadmium binding is dominated by patchy deposits of secondary minerals (iron and manganese oxides and calcite overgrowths), which are deposited on the surfaces of the primary mineral grains (quartz, feldspars, and calcite). Through studies with pure calcite, it was shown that cadmium reacts with the calcite surface in three stages. Stage I is an adsorption reaction which reaches completion in minutes, and the reaction rate is controlled by diffusion. Stage II involves the formation of a solid solution in a surface microlayer where cadmium ions substitute for calcium in the solid phase. This reaction reaches completion within 24 hours. Stage III involves the incorporation of cadmium into the calcite crystal structure, which is a very slow reaction controlled by the rate of dehydration of cadmium ions. Adsorbed cadmium can be readily desorbed from the surface such that an instantaneous equilibrium is maintained with the Cd^{2+} concentration in water. However, the release of cadmium from the solid solution is very slow and allows the surface to exist in a non-equilibrium state for an extended period. Similar non-reversible behavior was observed for cadmium reactions with the aquifer material.

The results impact directly on the common methods used for determining distribution coefficients (K_D). These empirical parameters have no meaning when surface binding involves a series of consecutive reactions occurring on the surface of the material. The chemical scenario summarized above may be relevant to the binding of many toxic metal ions and radionuclides.

Reports

Chang, C. C. Y., Davis, J. A., and Kuwabara, J. S., 1985, The Study of Metal Ion Adsorption at Low Suspended Solid Concentrations, Estuarine and Coastal Shelf Science, in press.

Davis, J. A., 1984, Complexation of Trace Metals by Adsorbed Natural Organic Matter, Geochimica et Cosmochimica Acta, v. 48, 679-691.

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URANIUM MILL TAILINGS

Radium Geochemistry

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Radium appears to be the most important nongaseous radioactive contaminant associated with uranium mill tailings. Therefore, research will be aimed at assessing its chemical state in the tailings, and its potential mobilization and retention in natural aqueous systems. In order to investigate the behavior of radium in comparison with other radioactive and toxic elements, and in association with a range of earth materials, the studies underway are addressing (1) uranium, thorium, and selected stable elements, as well as radium associated with tailings and (2) nontailings materials including uranium ore, sediments receiving radium-rich brines, and residues from the radium extraction industries of the early 20th century, as well as uranium mill tailings.

Objective: To study the chemical form in which radium, its parent radionuclides and selected stable elements are retained in surficial earth materials, particularly uranium mill tailings, and to identify processes operating in natural aqueous systems that may influence the transport of radium and other elements from these earth materials.

Approach: (1) Selective chemical extraction techniques (e.g. water-soluble, exchangeable, hydrous-oxide associated) and particle-sizing are used to determine the partitioning of nuclides and elements of interest in tailings, ores, and sediments; (2) Factors (e.g. kinetics, brine strength, sediment properties effecting the sorption of radium-226 from brine by sediment are investigated by (i) analysis of core samples taken in the vicinity of an actual brine outfall, and (ii) exposing well-characterized sediments to the brine in the laboratory, and measuring radium sorption; and (3) Uranium mill tailings produced by a sulfuric-acid leach process are incubated in an anaerobic aqueous media with sulfate-reducing microorganisms, and the release of radium-226 compared with that observed from sterile controls.

Progress: A sequential, selective extraction procedure was used to assess the effects of sulfuric acid milling on the geochemical associations of molybdenum and arsenic in a uranium ore blend, and the tailings derived therefrom. The milling process removed about 21 percent of the molybdenum and 52 percent of the arsenic initially present in the ore. While about one-half of the molybdenum in the ore was water soluble, only about 14 percent existed in this form in the tailings. The major portion of the extractable molybdenum in the tailings appears to be associated with hydrous oxides of iron, and with alkaline earth sulfate precipitates. In contrast with the pattern seen for molybdenum, the partitioning of arsenic into the various extractable fraction differs little between the ore and the tailings.

Sparingly soluble sulfate precipitates appear to be a major host for radium in sulfuric acid-treated, uranium mill tailings. The dissolution of such precipitates by natural processes, such as metabolism by sulfate-reducing bacteria (SRB), creates the potential for the release of radium to the contacting waters. Significant leaching of radium by SRB was achieved in the laboratory during the anaerobic incubation (1 to 119 days) of uranium mill tailings with pure cultures of Desulfovibrio desulfuricans and mixed cultures containing SRB isolated from the tailings, all grown on a lactate medium at room temperature. While the maximum ^{226}Ra concentration reached in a sterile media control was 12 pCi/L, that in the SRB systems was 1640 pCi/L or about 20 percent of the total radium inventory in the original tailings sample. The leaching of radium in SRB systems was accompanied by a decrease in soluble sulfate concentration, an increase in total sulfide concentration, and an increase in the number of SRB. The observed leaching effect does not appear to be due to the action of microbial chelates or to binding to cell walls.

In a study of the effect of montmorillonite on the dissolution of $BaSO_4$ (barite), $SrSO_4$ (celestite), and ^{226}Ra from uranium mill tailings, it was found that: (1) More of these substances dissolve in an aqueous system that contains montmorillonite than dissolve in a similar system without clay, due to the ion exchange properties of the clay; and (2) Na-montmorillonite is more effective in aiding dissolution than is Ca-montmorillonite.

Radon concentration in the indoor air of six residential and three non-residential, earth-sheltered buildings in eastern Colorado were monitored quarterly using passive, integrating detectors. Average radon concentrations during the 3-month sampling periods generally ranged from about 1 to 9 pCi/L; although one building, a poorly ventilated storage bunker, had concentrations as high as 39 pCi/L. These radon concentrations are somewhat higher than those typically reported for conventional buildings but are of the same order of magnitude as radon concentrations reported for energy efficient, non-earth sheltered buildings. Radium contents and radon emanation coefficients of soils at the building sites and radon concentrations in water supplies did not correlate linearly with indoor radon concentrations.

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