GEOLOGICAL SURVEY CIRCULAR 847

U.S. Geological Survey Research in Radioactive Waste Disposal—Fiscal Year 1979

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By Robert Schneider, E. H. Roseboom, Jr., J. B. Robertson, and P. R. Stevens

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SI UNITS AND INCH-POUND SYSTEM EQUIVALENTS

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

SI unit		Inch-Pound equivalent	
Length			
millimeter (mm)	=	0.039 37	inch (in)
meter (m)	=	3.281	feet (ft)
	=	1.094	yards (yd)
kilometer (km)	=	0.621 4	mile (mi)
	=	0.540 0	mile, nautical (n mi)
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)
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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ABSTRACT

This 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, investigations of specific sites where wastes have been stored, and 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

Since the advent of the atomic age, scientists have known that the release of radioactivity could have harmful effects on the environment and on man. It was also recognized that the potential transport of this radioactivity from buried sources to the human environment would involve water. For these reasons and because the U.S. Geological Survey (USGS) is the principal earth-science agency in the Federal Government, the various agencies concerned with nuclear facilities and the testing of nuclear weapons have requested the advice of the USGS for many years on the relation of geology and hydrology to the isolation of radioactivity from the biosphere.

The research of the USGS includes almost every area of earth science. The specific research activities described in this report are that part of the USGS program that is directly related to radioactive waste disposal. They include geologic and hydrologic research of general applicability to the identification and characterization of waste disposal sites, investigations of specific sites where wastes have been stored, and studies of regions or environments where waste disposal sites might be located. The activities discussed in this report are divided arbitrarily into three categories according to whether they relate most directly to (1) high-level and transuranic wastes,[1] (2) low-level wastes,[2] or (3) uranium mill tailings.

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

RELATION TO PROGRAMS OF OTHER AGENCIES

For about 30 yr, the USGS has provided technical consultation to the Department of Energy (DOE) and its predecessors, the Energy Research and Development Administration and the Atomic Energy Commission; it has also provided consultation to 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, Md., and a variety of regional and detailed geologic and hydrologic studies and generic research related to waste disposal at the Savannah River Plant, S.C.; the Oak Ridge National Laboratory, Tenn.; the Idaho Nuclear Engineering Laboratory; and the Hanford Reservation, Wash. Investigations and research related

[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 >10 nCi/g and generates little or no heat.

[2]The term low-level wastes has carried a changing and imprecise defintion 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 <10 nCi/g. It consists in part of miscellaneous solid materials that have been irradiated and contaminated through use as well as products of reactors and fuel reprocessing plants.

to weapons testing and waste disposal at the Nevada Test Site (NTS) and elsewhere have been carried out. These activities are referred to collectively as cooperative programs, in contrast to those activities supported by direct Congressional appropriations to the USGS.

With regard to high-level and transuranic wastes, the specific responsibility for selection of sites for waste repositories, as well as their design, lies with the DOE. Other agencies, NRC and EPA, are responsible for licensing the facility and establishing criteria for judging its environmental effects. The part of the USGS research on high-level wastes which is funded by its own appropriations is designed to complement and augment the DOE program, thus providing the needed information from an agency that has neither operational nor regulatory responsibilities in waste disposal.

To improve the effectiveness of coordination between the DOE, and the USGS, the USGS and the DOE office of Nuclear Waste Management agreed in August 1978 to prepare an Earth Science Technical Plan (ESTP) for mined geologic disposal of radioactive waste (high-level and transuranic wastes). The objectives were to organize formally the earth-science research tasks directed toward licensing a geologic repository, to show how these tasks address the principal technical questions related to geologic disposal of nuclear waste, to identify technical questions that require additional attention, and to establish the basis for assigning priorities to future work. The initial step in the development of the ESTP was the preparation of a draft report[1] by a Working Group. A revision of this draft was prepared recently.[2]

The low-level waste program, supported largely by USGS appropriations, is closely coordinated with programs of the DOE, NRC, and EPA. This coordination is accomplished through cooperative financial agreements, interagency agreements, and an interagency coordinating committee. It is anticipated that geohydrologic guidelines for low-level waste disposal developed from the USGS studies will form the basis for more formal statements of geotechnical standards and criteria to be prepared by the regulatory agencies and incorporated in forthcoming regulations governing the selection and operation of new disposal sites.

[1]Office of Nuclear Waste Management, U.S. Department of Energy, and U.S. Geological Survey, 1979, Earth Science Technical Plan for Mined Geologic Disposal of Radioactive Waste: TID 29018 (Draft), National Technical Information Service, Springfield, Va.

[2]Office of Nuclear Waste Management, U.S. Department of Energy, and U.S. Geological Survey, 1980, Earth Science Technical Plan for Disposal of Radioactive Waste in a Mined Repository: DOE/TIC-11033 (Draft) and USGS draft report, National Technical Information Service, Springfield, Va.

BUDGET SUMMARY

(in millions of dollars)

High-level and transuranic wastes and related generic research	
USGS appropriation	3.35
DOE transfer of funds	6.2
NRC transfer of funds	0.09
	9.64
Low-level wastes and related research on geologic and hydrologic processes	
USGS appropriation	2.19
DOE transfer of funds	0.57
	2.76
Uranium mill tailings	
USGS appropriation	0.15
	0.15
Total	12.55

HIGH-LEVEL AND TRANSURANIC WASTES

GEOLOGICAL SURVEY PROGRAM FOR IDENTIFYING ENVIRONMENTS SUITABLE FOR LOCATING DISPOSAL SITES

By W. E. Hale, Albuquerque, N. Mex.

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

its characteristics must be considered in conjunction with the types of hydrologic and geologic barriers mentioned above.

The process of selecting potentially suitable sites for repositories is extremely complex and involves social and political factors in addition to those pertaining to hydrology and geology. In view of the fact that the DOE has the responsibility for selecting sites, this USGS study requires coordination with and concurrence of the DOE which has had site selection activities underway for some time. Currently, the DOE effort is focused primarily on salt as the host rock for the waste, as well as on environments at the Nevada Test Site where potential host rocks include quartz monzonite, granite, tuff, and argillite and at the Hanford Reservation, Wash., where basalt is the potential host rock.

The study is part of the USGS high-level waste program, which was started in fiscal year 1979 with direct Congressional appropriations.

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

Approach.—The study stresses the concept of identifying environments with relatively independent multiple barriers to nuclide transport in order to overcome deficiencies in our ability to characterize adequately the masses of rock around a repository and to predict accurately the nature and occurrence of future waste-rock-water reactions, natural events, and nuclide transport (Bredehoeft and others, 1978; Interagency Review Group on Nuclear Waste Management, 1979). A nationwide screening process starting with broad provinces which together encompass the 48 conterminous states, is to be conducted involving the identification and evaluation of successively smaller land units. The provinces in turn will be subdivided into regions, areas, and potential sites (U.S. Department of Energy and U.S. Department of the Interior, 1980).

Progress.—During fiscal year 1979, USGS staff assigned to this project participated in a joint DOE-DOI Working Group to develop the ESTP. The Working Group set up a subgroup to examine plans and methods for the identification and characterization of sites for mined radioactive waste repositories (U.S. Department of Energy and U.S. Department of Interior, 1980). Various approaches to this problem were explored by the subgroup. One approach involved a nationwide screening process with substantial participation of scientists from State agencies concerned with natural resources and (or) earth sciences. If this approach is adopted, the USGS effort under this project would involve working closely with State agencies in its implementation.

The interagency group also considered what types of data would be required for such a nationwide screening process and methods of implementing the process. Probable gaps in the data base were identified, as well as the research needed to fill them.

Pending the resolution of the scope of the site selection process that may be adopted, work was concentrated on developing several alternative plans for identifying suitable environments, primarily using only USGS scientists. One plan would consider a screening procedure which involved the entire conterminous United States. Survey scientists with special knowledge of selected broad regions of the country would conduct the work. Because it would not make use of the entire data base available, this plan would require the use of considerable judgement in the evaluation and ranking of alternative geohydrologic systems. An alternative plan would consider a greatly reduced area, would involve only three or four full-time people, and would focus primarily on Federal lands in the West.

A start was made toward preparing criteria for the selection of environments with suitable multiple barriers to radionuclide migration. Several drafts of proposed criteria were discussed, and a consensus on criteria is beginning to emerge. The criteria for screening broad regional environments are not exactly the same as those for screening specific sites but must be consistent with criteria already published for site selection (e.g., National Academy of Sciences, National Research Council, 1978; Brunton and McClain, 1977).

Regional hydrologic factors received the greatest emphasis in considering the criteria.

Work also began on assembling a data base to support the regional screening process which is ultimately selected. National and regional overviews, useful for preliminary screening, exist for the occurrence of various rock types, mineral resources, and volcano-tectonic features. Hydrology, the keystone for regional environmental assessment, appears to be less well suited to regional definition, and there probably are significant areas with an absence of information on deep water movement.

Preliminary efforts were directed toward identifying ways of recording and processing the large amount of data needed for a national screening process. Progress in developing algorithms for digitizing, storing, and combining areal information of the type needed is well advanced, and the problem is to select the system best suited for this particular application.

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DEPARTMENT OF ENERGY PROGRAM FOR LOCATING AND CHARACTERIZING DISPOSAL SITES

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

NEVADA TEST SITE AND VICINITY

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

SEARCH FOR POTENTIAL SITES

By Gary L. Dixon and Donald B. Hoover, Lakewood, Colo.

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

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

Progress.–Geologic investigations on the NTS were conducted mostly at the following localities in the Jackass Flats area: Wahmonie Flat, Calico Hills, and Yucca Mountain (fig. 1).

A description of each of these and other localities follows.

Wahmonie Flat: The Wahmonie granitic stock is located on the eastern edge of Jackass Flats. At the Wahmonie Flat locality, Tertiary granodiorite is exposed at the surface, but aeromagnetic and gravity data indicated that the largest mass of granodiorite was buried at shallow depth a short distance to the southwest of the outcrop area. Ad-

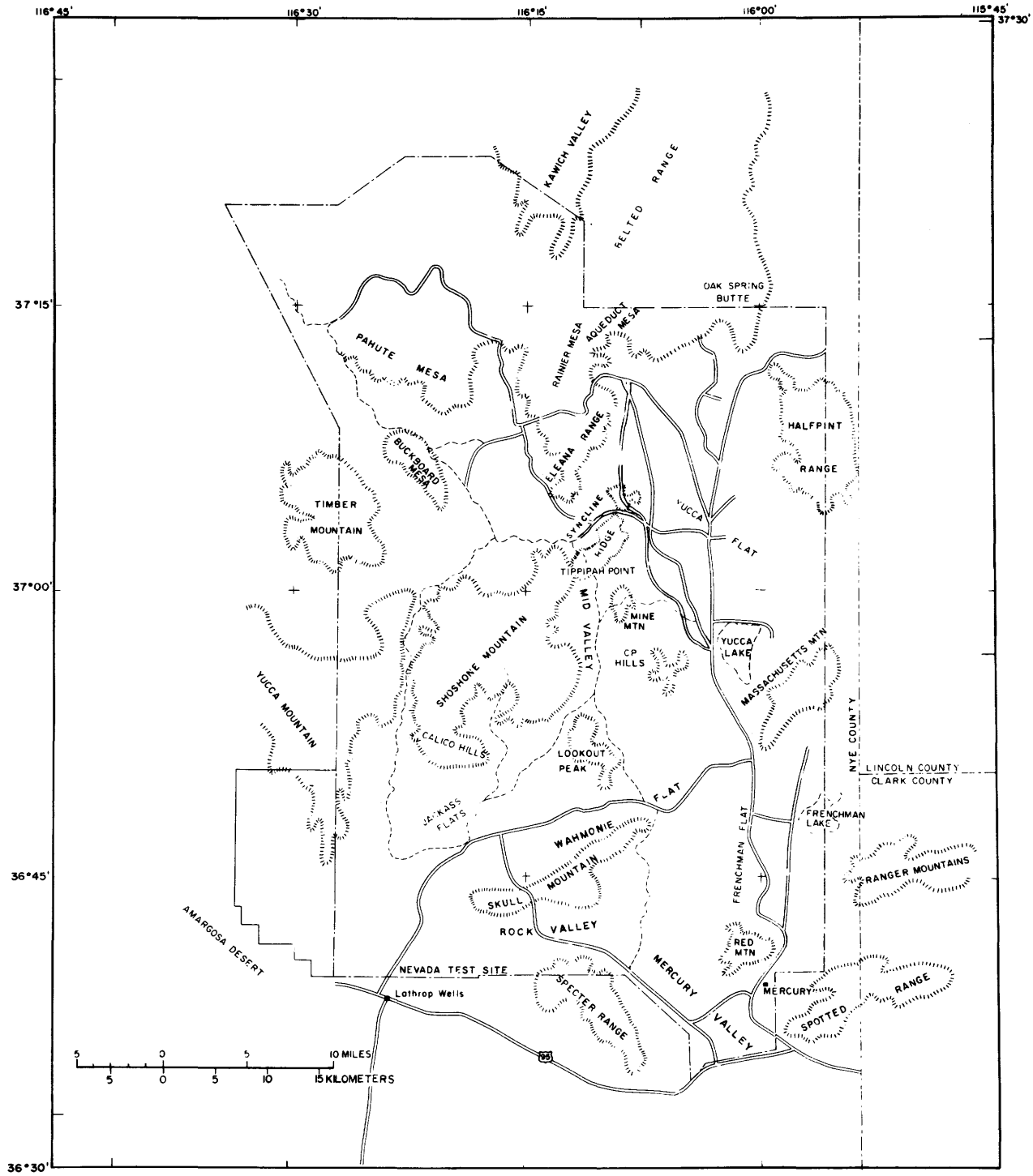

FIGURE 1. – Index map of the Nevada Test Site.

ditional geophysical data support the presence of an intrusive body less than 500 m below the surface. However, the data also indicate major faults cutting the intrusive, a lack of a competent unaltered rock mass in the depth range where a repository could be constructed, and altered and mineralized rock. Nearby faults cut alluvium of Quaternary age. Detailed geologic mapping shows the overlying tuffs and lavas to be highly fractured, faulted, and hydrothermally altered. The surface geophysical studies, which included vertical electrical soundings, induced polarization surveys, gravity, seismic refraction, and aeromagnetic surveys, completed the preliminary evaluation of the Wahmonie Flat area. The DOE has decided to discontinue exploration in this locality.

Calico Hills: The Calico Hills area is a structural dome located in the north-central part of Jackass Flats. The oldest exposed rocks are Devonian limestones thrust over argillite of the Eleana Formation of Devonian and Mississippian age. Both of these rock masses are overlain by Tertiary volcanics. The doming of the Calico Hills was inferred to be caused by intrusion of a crystalline rock mass. Magnetic data had suggested that the intrusive rock was at a fairly shallow depth. An exploratory hole drilled to a depth of 770 m in the central part of the dome penetrated faulted, brecciated, and fractured argillite, limestone, and marble rather than crystalline rock. Part of the magnetic anomaly was found to be due to magnetic minerals in the metamorphosed rocks. Data obtained from the drill hole, surface geologic mapping, and detailed regional and borehole geophysical surveys indicated that the area is highly complex. Additional electrical studies placed the depth to a zone of high resistivity, possibly tight, unaltered intrusive rock, at greater that 1,200 m. This would be the shallowest depth at which unaltered intrusive rock could occur. The geophysical data also showed that the overlying rocks had major lateral discontinuities inferred to be faults, some indication of mineralization, and moderately high temperature (47°C) at 750 m in the drill hole. On the basis of the Survey's findings, DOE decided to discontinue exploration.

Yucca Mountain: Several widespread voluminous ash-flow sheets are exposed in the vicinity of Yucca Mountain, located on the western margin of Jackass Flats. To evaluate the subsurface characteristics of the tuffs underlying Yucca Mountain, an exploratory hole was drilled to a depth of 760 m (Maldonado and others, 1979; Spengler, Muller, and Livermore 1979). Examination of the core showed the densely welded tuffs to be moderately to highly fractured. The fractures were commonly coated with secondary silica, manganese, iron oxides, and calcite. Five minor fault zones were identified in the hole.

A site was selected for a deep (approx 2000 m) stratigraphic hole which is to be drilled in fiscal year 1980.

At Yucca Mountain, gravity and magnetic techniques were found to be unsuitable for defining the size and shape of the thick welded tuff bodies under study. Consequently, the role of geophysics here has been to assist primarily in defining the structural integrity of the site. An electromagnetic technique, Slingram profiling, revealed the presence of shallow electrical conductors in northwest-trending linear valleys cutting the locality. The Slingram signature was the same as that obtained for known faults elsewhere in the area. The nature and extent of the electrical anomalies were investigated further with other electrical techniques and four 150-m holes. These data suggest that the northwest-trending wash which bisects the locality is a zone of fracturing and (or) faulting, but the significance of the electrical anomalies has not been assessed fully. Preliminary curie isotherm analysis and magnetotelluric soundings have been made to identify anomalous hot and (or) conductive regions in the crust. Within the NTS, these data suggest that rocks at temperatures in excess of 500°C may be as shallow as 6 km in the western part of Yucca Flat. Within the areas examined in the southwestern part of the NTS, temperatures at corresponding depths appear to be lower than in the western part of Yucca Flat.

Syncline Ridge: A geologic report for the Syncline Ridge area based on work done in previous years is nearly completed. The report summarizes geologic, hydrologic, and geophysical data from the exploration of the Eleana argillite at Syncline Ridge and at other places on the NTS (Hodson and Hoover, 1978, 1979).

Southern Nevada (off the NTS): A search for potential repository sites in granite (Spengler, Maldonado, Weir, and Dixon, 1979), shale/argillite (Simpson and others, 1979), and tuff was conducted in southern Nevada, on the basis of information in existing reports and limited field reconnaissance. The Nevada Bureau of Mines and Geology is participating in this work through a contract to perform mineral assessments on potential sites identified from the geologic reconnaissance.

Approximately three to five candidate localities underlain by each of the above rock types have been or will be selected for additional geologic, hydrologic, and geophysical exploration. Five granitic sites were selected for detailed field investigations, including geologic mapping to evaluate the character of the granitic masses, such as their lateral and vertical extent, lithology, and internal structural discontinuities. Thus far one site has been investigated.

Shale/argillite areas of potential interest are being mapped and sampled for the USGS by the University of New Mexico.

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TECTONICS, SEISMICITY, VOLCANISM, AND EROSION RATES IN THE SOUTHERN GREAT BASIN

By W. J. Carr and A. M. Rogers, Lakewood, Colo.

Objective.—The objective was to assess the potential for faulting, damaging earthquakes, recurrence of volcanism, and local acceleration of erosion in parts of the southern Great Basin.

Approach.—The following approaches are being used: (1) investigating the rate, intensity, and distribution of faulting during approximately the last 25 m.y., with emphasis on the last 10 m.y., (2) monitoring and interpreting present seismicity, (3) studying the history of volcanism, and (4) evaluating past rates of erosion and deposition.

Progress.—*Tectonics*: Mapping of Quaternary deposits in the southwestern part of the NTS area has been completed for most of two 7½-min quadrangles in the Jackass Flats area and for the Lathrop Wells 15-min quadrangle. Eight trenches were dug and mapped to explore subsurface stratigraphy and to study fault relations. About 25 samples of carbonate minerals from soils and caliche were dated by the uranium-series method. Bishop ash (700,000 yr old), an important time line, was found in alluvium at four localities. Other ash beds, potentially useful for dating, were found in association with lake beds and alluvium.

Two highly significant dates were obtained near the Yucca Mountain locality. Calcite from fractures in three drill-core samples above and below the water table was older than 400,000 yr, the limit of the uranium-series method. An unbrecciated basalt dike cutting a major fault on the west side of the site was dated at 10 m.y., which indicated that there has been no significant movement on this fault since that time.

A preliminary compilation of Quaternary faults in the NTS region has been made (fig. 2); the faults are being categorized as (1) Holocene, (2) Intermediate (middle Pleistocene), and (3) Pleistocene.

Mapping of bedrock for structural studies was done in the Yucca Mountain–Crater Flat area. Work was begun on a NTS regional geologic-tectonic map at a scale of 1:125,000. Structure contouring of the base of the widespread Rainier Mesa Member (11.5 m.y.) of the Timber Mountain tuff was about half completed.

A study of the Death Valley–Furnace Creek–Fish Lake Valley fault zone (fig. 3), the second longest right-lateral strike-slip fault in the western United States, has been completed by George Brogan of Woodward-Clyde Consultants, under contract with the USGS. The study suggests that the maximum length of break on the fault zone during any one earthquake was 25 km. Numerous segments of Holocene faulting have been identified. Late Holocene faulting in central Death Valley is not matched by present seismicity.

Seismicity: A new 45-station seismograph network covering a large area in southern Nevada and a portion of adjacent California (fig. 3) has been completed and is in full operation. The net is configured to study activity on several major tectonic features: (1) the Death Valley–Furnace Creek fault zone, (2) the "east-west" seismic zone that appears to join the California-Nevada seismic zone with the Intermountain seismic belt in Utah, (3) the Walker Lane strike-slip fault system between Tonopah and Las Vegas, and (4) a possible paleoseismic belt in the NTS region. Data from the seismograph network are currently being analyzed to determine

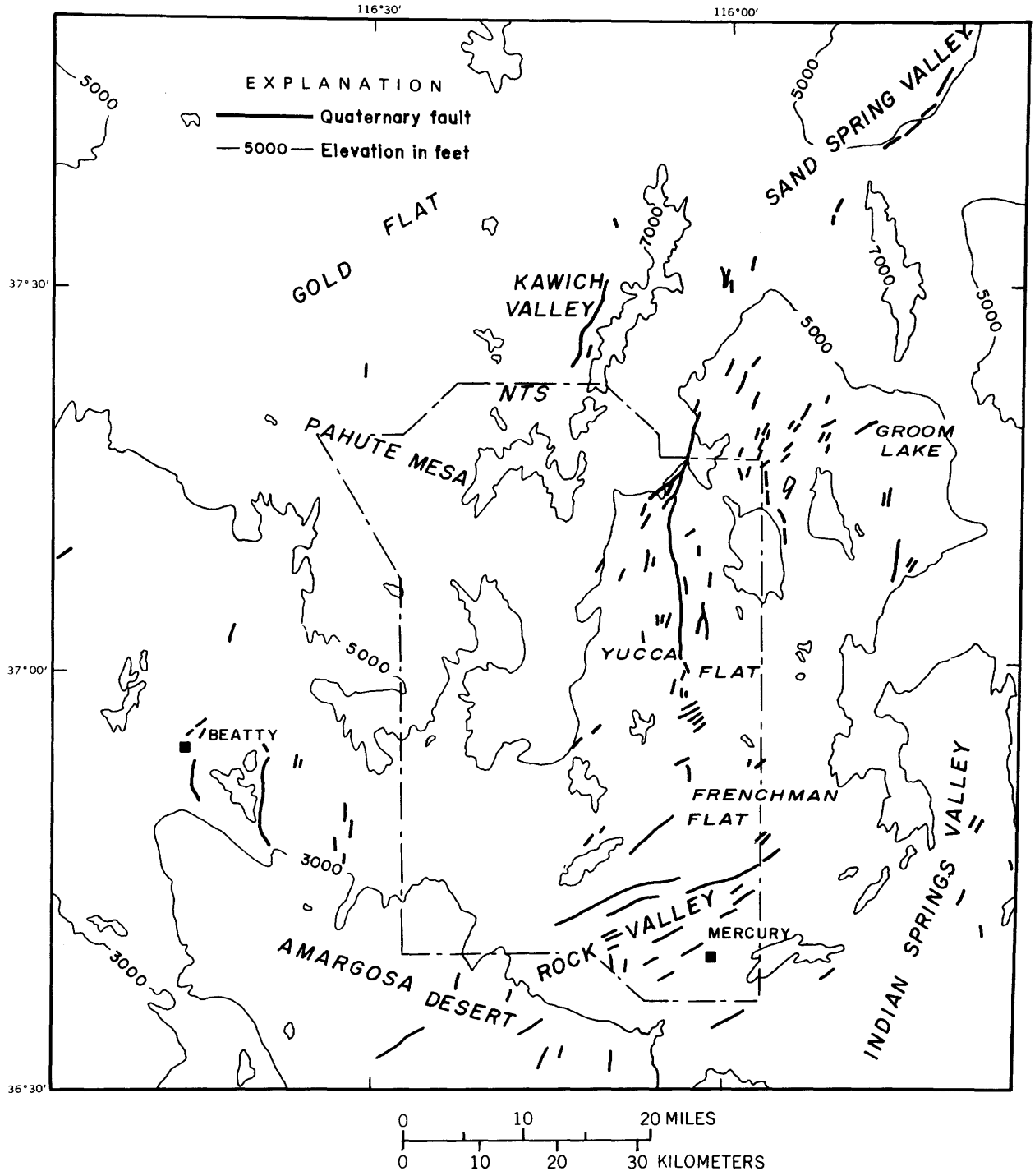

FIGURE 2—Preliminary compilation of Quaternary faults in the Nevada Test Site region.

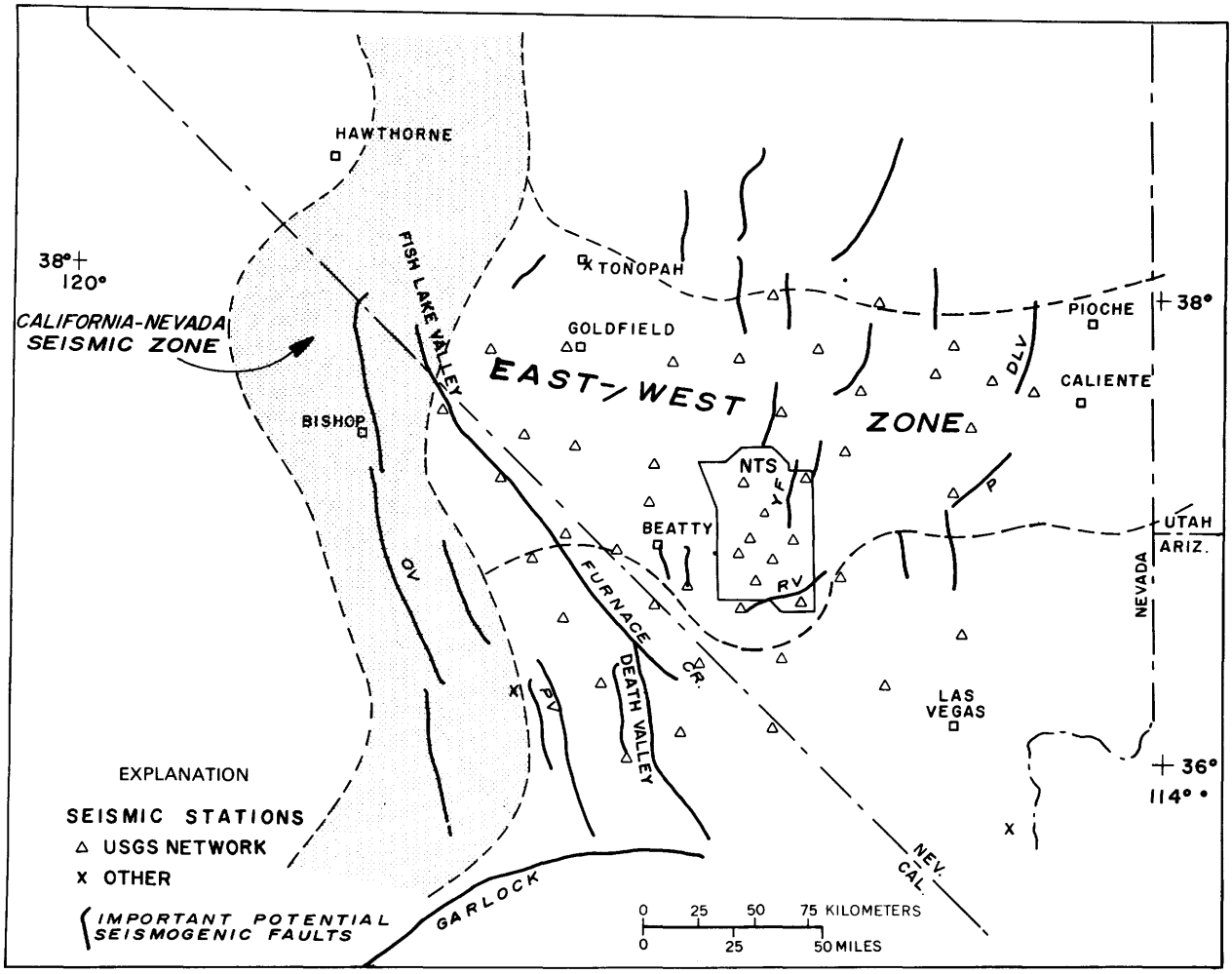

FIGURE 3.—Seismic network and important potentially seismogenic faults in the Nevada Test Site region.

earthquake locations, magnitudes, and direction of slip on active faults. In addition to studies of the seismic hazard, the seismograph network and supplemental portable seismographs will be used to aid in the assessment of volcanic hazard through studies of seismic wave delays which can be used to locate magma chambers in the crust.

A study was begun to understand better and locate past instrumentally recorded earthquakes in Nevada. This work includes relocation of epicenters through re-examination of the records and use of better velocity models. In addition to providing more accurate locations, it is hoped to relate lesser shocks to some of the larger earthquakes over the last 50 yr.

Preparations were begun to install three-component seismometers at the surface and at a depth of about 750 m at Yucca Mountain and Calico Hills to measure subsurface attenuation of ground motion from earthquakes. A similar experiment is already underway at the Climax granite stock in northeastern NTS.

All of the seismological work will eventually lead to a revision of a preliminary evaluation of seismic hazard in the region (Rogers, Perkins, and McKeown, 1977).

Volcanism: About 25 new K-Ar and fission-track dates have been obtained on young (<10 m.y.) volcanic rocks in the NTS region. The most recent basaltic activity in southern Nevada is about 290,000–400,000 yr old. Other basalts were erupted at fairly regular intervals during the period between 1 and 10 m.y. ago. Silicic volcanism ended about 5 m.y. ago (fig. 4).

Quaternary basaltic activity in the NTS region appears to fit three main structural regimes—extensional small rift zones, old caldera ring fracture zones, and intersections of strike-slip and extensional faults.

Volcanic hazard studies, conducted by Los

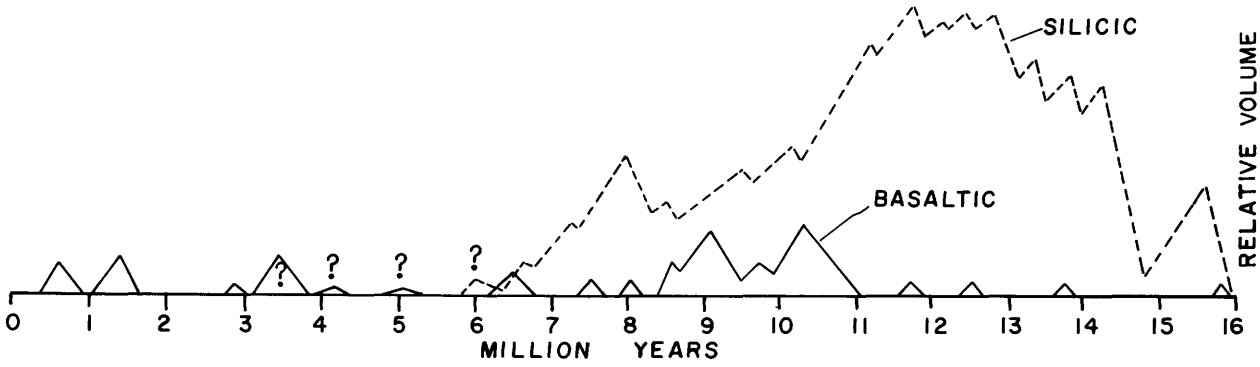

FIGURE 4. – Ages of volcanism in the Nevada Test Site area.

Alamos Scientific Laboratories (LASL) in cooperation with the USGS, focused on Crater Flat adjacent to the southwestern part of the NTS. Mapping of basalt vent areas yielded information that permitted an estimate of the rate of occurrence of volcanism for that area. This was combined with an analysis of disruptive events and considerations of areas involved to yield a worst-case probability of volcanism for the Yucca Mountain area.

Several fission-track ages on apatite, which give the age at which the rock was last above 100°C, indicate a potentially wide variation in local cooling histories. A plot of K-Ar mica ages (which indicates when the rock was last above 300°C) and apatite fission track ages against temperature, for two pairs of samples from exposed metamorphic rocks in the NTS region, give cooling lines that can be extrapolated to present time and ambient temperature. The K-Ar ages are apparently reset by the peak of local volcanism, but one of the samples gave an apatite age of only 3.5 m.y. This age is not compatible with previous inferences regarding the rate of tectonic denudation or with known thermal events. A similar sampling of the ring dike of the Timber Mountain caldera resurgent dome yielded concordant K-Ar and apatite ages, indicating, as was suspected, rapid cooling and thermal stability after 9 m.y. ago.

A report summarizing geochemistry and its application to an assessment of the possibility of renewed volcanism for the Silent Canyon–Black Mountain peralkaline volcanic centers was completed jointly by LASL and the USGS (Crowe and Sargent, 1979). These two centers are about 14 m.y. and 7.5 m.y. old, respectively, the latter representing the youngest major silicic ash-flow eruption in the region. The report concludes that, despite their proximity and chemical similarities, the two centers are spatially and temporally distinct and that no indications of a possible recurrence of such volcanism are evident in the northern part of the NTS area.

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HYDROLOGY

By D. I. Leap, Lakewood, Colo.

Objective. – The objective was to determine present and past hydrologic regimes of the NTS area in order to predict the potential for ground-water transport of radioactive waste to the biosphere.

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

Worldwide changes in climate during the Pleistocene Epoch (glacial and interglacial stages) resulted in repeated changes in the ground-water regime. Future climatic changes are probable in the time frame of significance to a repository for high-level and transuranic wastes. Paleohydrologic studies are being used to estimate water-table

depths, hydraulic gradients, and flow paths to points of ground-water discharge during Pleistocene pluvial cycles in order to assess the differences between present hydrologic systems and those that will prevail under wetter climates in the future.

Geophysical methods are being used to assist in analyzing the regional structure of the southwestern part of the NTS and the ground-water discharge region in the Amargosa Desert.

Progress.—Interpretations of paleohydrologic conditions were made on the basis of the occurrence of spring deposits, the precipitation of certain clay minerals, and the radiocarbon dating of vegetable matter in ancient packrat middens.

I. J. Winograd and G. C. Doty (1980) completed their study of the relation of Quaternary calcitic veins and tufa to former positions of the potentiometric level in the regional carbonate-rock aquifer of southern Nevada. The distribution of tufa and calcitic veins along the periphery of Paleozoic carbonate rocks between Ash Meadows and the Specter Range suggests that the potentiometric level in the carbonate-rock aquifer near Ash Meadows rose no more than 50 m during the pluvial periods of the late(?) Pleistocene. An estimate was also made of water-level rise in this aquifer beneath Frenchman Flat based on assumptions regarding the magnitude of recharge during the pluvial periods and plausible changes in aquifer transmissivity. The rise beneath Frenchman Flat could not have exceeded 90 m and probably was less than 30 m. The maximum rise of water level indicated in the regional carbonate-rock aquifer might, however, have been exceeded in the alluvial and tuff aquifers of Cenozoic age beneath Yucca, Frenchman, and Jackass Flats.

These results do not preclude further consideration of the unsaturated zone at the NTS as a potential repository for high-level, transuranic, or low-level wastes. It was concluded that deep water tables and long ground-water flow paths characterized the region during the Pleistocene Epoch and presumably will characterize it during future pluvials.

A study conducted by B. F. Jones on the mineralogy of clay minerals peculiar to the climate and chemical conditions in the arid southwest, suggests that the amounts of certain clay minerals precipitated may be indicative of past positions of the water table and discharge rates of springs.

W. G. Spaulding (University of Washington), on contract to the USGS, reports that the identification and radiocarbon dating of plant matter found in ancient packrat middens allow an estimation of ancient climates, with special reference to the amounts and seasonal distribution of precipitation. Initial results indicate middens on and near the NTS can yield data on paleoclimatic conditions up to 40,000 yr ago.

D. I. Leap and R. K. Waddell developed a two-dimensional finite-element model of ground-water flow at the NTS and adjoining areas within a distance of approximately 80 km from the site boundaries. Inverse modeling was used to estimate parameters such as transmissivity in areas where subsurface data are sparse.

Gravity, magnetic, and electrical geophysical methods were used to define boundaries of structural elements in the southwestern part of the NTS which appear to coincide with hydrologic boundaries between the two main flow systems in the region.

Reference

Winograd, I. J., and Doty, G. C., 1980, Paleohydrology of the southern Great Basin, with special reference to water-table fluctuations beneath the Nevada Test Site during the late (?) Pleistocene: U.S. Geological Survey Open-File Report 80–569, 90 p.

WASTE ISOLATION PILOT PLANT, NEW MEXICO

The DOE has been investigating an area about 45 km east of Carlsbad, New Mexico, to determine its suitability as a site for the Waste Isolation Pilot Plant (WIPP), a geologic repository for nuclear wastes (fig. 5). The geology and hydrology of the area are being studied in cooperation with Sandia Laboratories to provide the DOE with information on which to base an assessment of the site, particularly with respect to geologic stability, long-term isolation of waste radionuclides, and the potential for the hydrologic system to provide a barrier to radionuclide transport.

The WIPP site is located in the Delaware Basin. The potential host rock is thick-bedded salt of the Salado Formation of Late Permian age. This region is tectonically stable. The dominant structural feature of tectonic origin is a gentle homoclinal dip (fig. 6). Other features include deep and shallow dissolution structures related to the removal of soluble materials (salt, anhydrite, and other evaporites) by ground water and isolated domes and anticlinal ridges containing structurally thickened cores formed by salt flowage in beds near the middle of the Castile Formation, of Late Permian age.

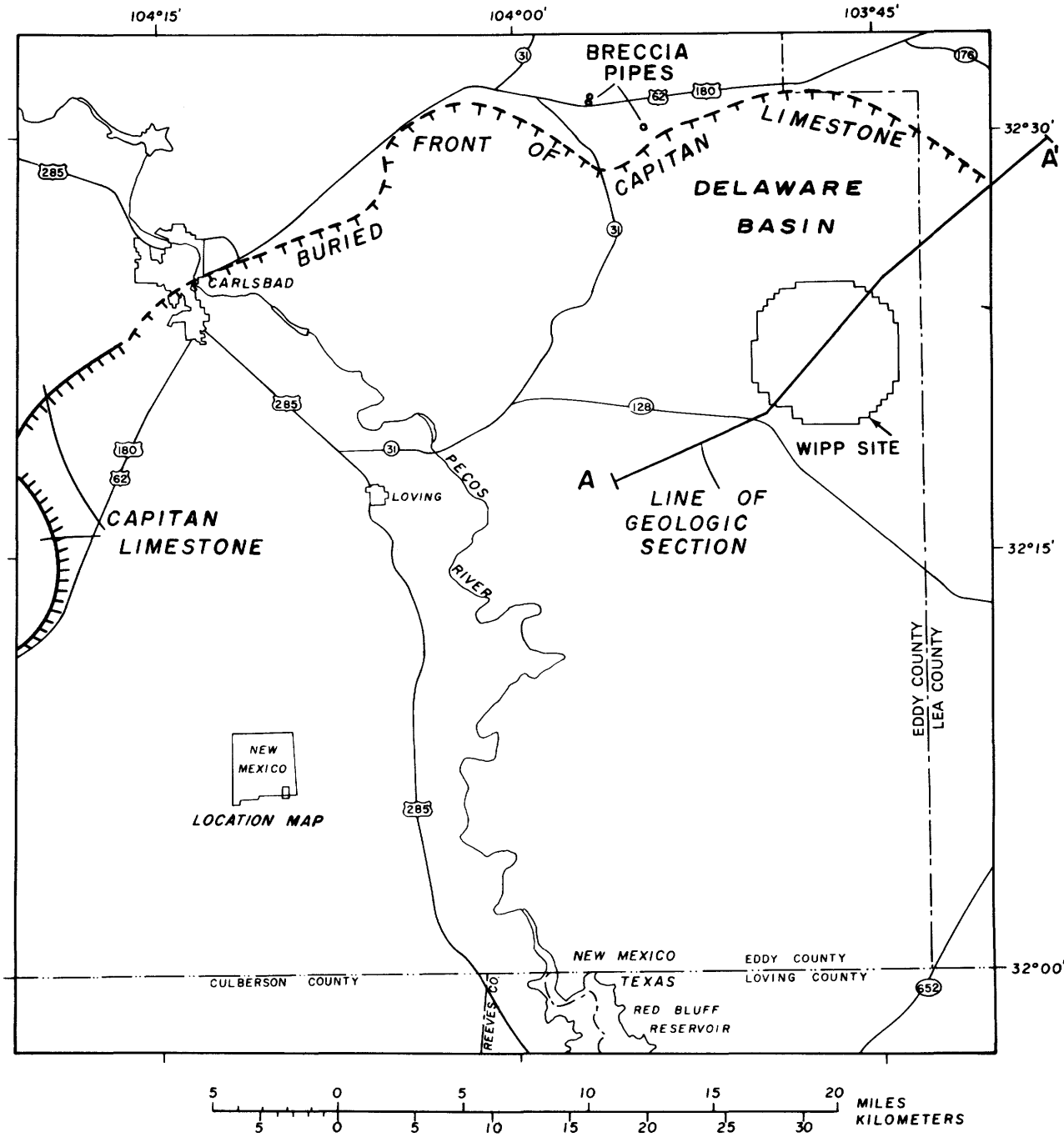

FIGURE 5.—Map showing location of the Waste Isolation Pilot Plant (WIPP) site.

SALT DISSOLUTION AND DEFORMATION STUDIES

By Charles L. Jones, Lakewood, Colo.

Geologic studies in and near the WIPP site are concerned with the identification and evaluation of salt dissolution and salt deformation processes and phenomena in order to determine their possible effect on the geologic integrity of the area.

Among the dissolution features identified in the region, deep dissolution features, known locally as breccia pipes, may represent a potential geologic hazard to a repository. The pipes are nearly vertical chimneys that cut bedded salt of the Salado Formation and extend through overlying rocks to the surface. They are filled by breccia composed of coarse, angular, and broken rock fragments, including salt and polyhalite, that are cemented in a fine matrix of clay and silt. Their origin is

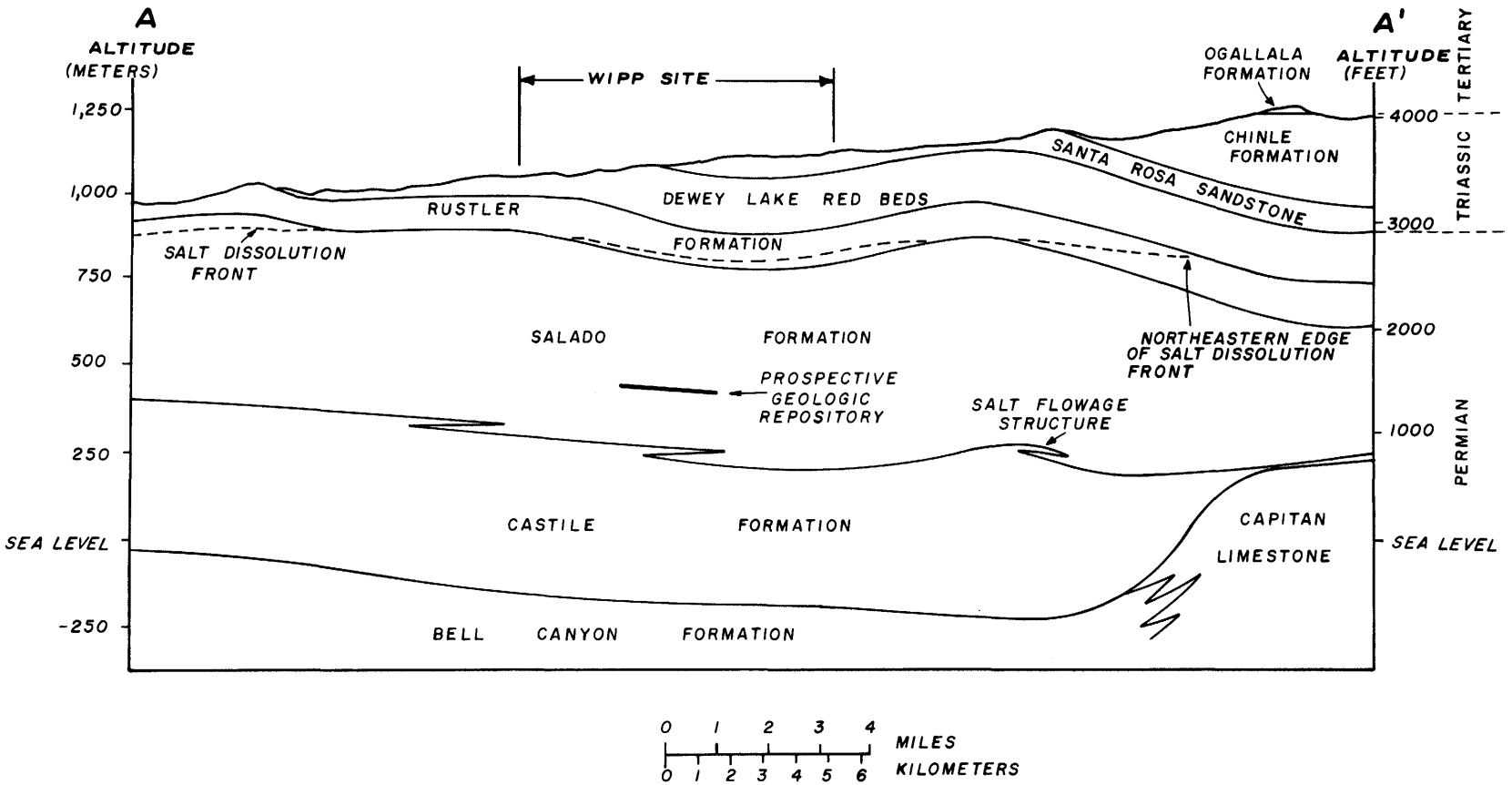

FIGURE 6.—Geologic section through Waste Isolation Pilot Plant site.

unknown, but it seems reasonable to assume a genesis involving the formation of a cavity within or below the bedded salt of the Salado and subsequent collapse of overlying strata into the cavity. The concerns about breccia pipes center on whether they are forming today or may form at some future time at the WIPP site and whether they are sufficiently permeable to provide channelways for ground-water movement into or through a repository.

Other dissolution phenomena identified in the region of the WIPP site have taken place at or near the top of bedded salt in the Salado Formation and throughout the overlying Rustler Formation. These phenomena include sheetlike removal of salt, the conversion of anhydrite and polyhalite to gypsum, and the subsequent dissolution of gypsum, as well as dolomite, along a "dissolution front" that extends across formational boundaries (fig. 6). Accompanying the dissolution of salt and other evaporites is a reduction in formation thickness due to the loss of soluble materials [NaCl, $CaSO_4$, and $CaMg(CO_3)_2$]. The reduction in thickness has triggered a subsidence of rocks above the top of bedded salt in an amount crudely proportional to the thickness of soluble materials removed, and it gives rise to an irregular hummocky structure in the subsided rocks. The pervasiveness of these dissolution phenomena at or near the top of bedded salt in the region of the WIPP site has resulted in considerable speculation that dissolution may also occur at or near the base of the Salado Formation.

From deep drilling (approx 1,200 m) and seismic reflection surveys, a series of salt deformation structures, including isolated domes and anticlinal ridges, have been identified in and near the WIPP site. Most of the structures are concentrated in a "salt deformation belt," 6–9 km wide, that extends around the northern end of the Delaware Basin in front of the Capitan Limestone; other structures are isolated features scattered irregularly through the basin interior. In all instances the structural activity has resulted in thickened salt cores, uplift of overlying strata in domes and anticlines, and salt movement within beds near the middle of the Castile Formation. On some structures, anhydrite beds that have been fractured during salt movement contain reservoirs of geopressured brine carrying H_2S, CO_2, and CH_4 in solution.

Objective. – The objective was to characterize the salt dissolution and salt deformation features and to determine whether they will have a negative effect on the integrity of the WIPP site.

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

Progress. – Preliminary results suggest that the part of the Delaware Basin in which the WIPP site is located is free of deep dissolution phenomena involving the formation of breccia pipes or the removal of salt at or near the base of the Salado Formation. All known breccia pipes overlie the Capitan Limestone, a prolific aquifer which does not extend into the WIPP site. Also, none have been identified by drilling, by geophysical surveys (including electrical resistivity and seismic reflection), and by geologic reconnaissance within or near the WIPP site. In addition, the drilling to date has failed to yield any evidence of deep dissolution in or near the base of the Salado or in the underlying Castile Formation.

Salt deformation structures, consisting essentially of elongated domes, have been identified in the northern part of the WIPP site and near the northeastern and southwestern corners of the area. The salt movement, or flowage, required to form these structures is considered to be the result of stresses exerted by sediment-loading updip. The sediment load may not have been very great because the movement appears to have started during Castile time before dewatering of the salt beds was complete. Locally, the movement was episodic and continued into Salado time. Elsewhere, rocks as young as Late Triassic were uplifted by salt movement.

Some geologic data derived from shallow core tests to investigate dissolution phenomena are tabulated in a series of published reports:

Drellack, S. L., Jr., and Snyder, R. P., 1979, Geologic data, *in* Basic data report for drill hole WIPP-28 (Waste Isolation Pilot Plant–WIPP): Sandia Laboratories Report SAND79-0282, p. 4-31.

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Gonzales, J. L., and Jones, C. L., 1979, Geologic data, *in* Basic data report for drill hole WIPP-25 (Waste Isolation Pilot Plant–WIPP): Sandia Laboratories Report SAND79-0279, p. 4-25.

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Jones, C. L., and McIntyre, A. F., 1979, Geologic data, *in* Basic data report for drill hole WIPP-25 (Waste Isolation Pilot Plant–WIPP): Sandia Laboratories Report SAND79-2081, p. 4-25.

Snyder, R. P., and McIntyre, A. F., 1979, Geologic data, *in* Basic data report for drill hole WIPP-29 (Waste Isolation Pilot Plant–WIPP): Sandia Laboratories Report SAND79-0283, p. 4-18.

CENOZOIC HISTORY OF PECOS RIVER DRAINAGE SYSTEM

By George O. Bachman, Albuquerque, N. Mex.

This project is concerned with the Cenozoic history of the Pecos River drainage system and the influence of this system on erosion and dissolution in the vicinity of the WIPP site.

Objective.–The objective was to determine if presently active geologic processes offer any potential hazards to confinement of wastes at the site.

Approach.–The approach is to identify and understand those geologic processes that have shaped the present land surface and to determine the relative and absolute ages of significant geologic features in the vicinity of the WIPP site.

Progress.–The WIPP site is situated on a rolling geomorphic surface, the Mescalero surface, where caliche and wind-blown sand have accumulated. The average thickness of the Mescalero caliche is about 1–2 m, and it is the product of complex soil processes. As soil products accumulate only under conditions of relative geologic and climatic stability, the age of the Mescalero caliche and the surface it caps offers a measure of the length of time that the present stable situation has endured.

Recent work by John N. Rosholt of Lakewood, Colo., indicates that the Mescalero caliche began to accumulate about 500,000 yr ago. This age determination is in agreement with the age of a volcanic ash fall which underlies the caliche at one locality and was transported by wind from an eruption in the Yellowstone region in Wyoming and Montana about 600,000 yr ago. A younger soil, about 300,000 yr old, rests on the Mescalero caliche at many localities around the WIPP site.

These age determinations show that the WIPP site has been geologically stable in a semiarid environment for the past 500,000 yr.

Nash Draw is a prominent topographic depression about 3–8 km west of the WIPP site area. It is about 26 km long and 10–16 km wide with topographic relief of about 90 m. Although erosion has contributed to the formation of this depression, regional dissolution of gypsum and halite has been the major factor in its formation. Present evidence suggests that much of Nash Draw was a topographic depression at least 500,000 yr ago.

The breccia pipes described in the preceding section indicate that dissolution has extended through the proposed repository horizon, the Salado Formation, at the edge of the Delaware Basin. Recent work indicates that major subsidence of known breccia pipes occurred at least 500,000 yr ago.

SEISMICITY

By A. M. Rogers, Lakewood, Colo.

Although the effects of earthquakes are known to be much less damaging on mines and tunnels than on surface structures, they still must be evaluated both in terms of hazards to the operation of a repository and their possible contribution to breaching the sealed repository through partial collapse of workings, opening of fractures, renewed movement along old faults, or the development of new faults.

Objective.–The objective was to determine the extent of seismicity, the seismic rates, and the relation of earthquake occurrence to geologic structure in the vicinity of the WIPP.

Approach.–A preliminary evaluation of historical earthquake epicenters revealed that the only significant earthquake activity in the region occurred about 80 km southeast of the WIPP site in a portion of the Permian Basin called the Central Basin Platform (CBP). Consequently, a seismograph network of 12 stations was deployed around the historical earthquake locations, over an area of about 3,000 km^2. This network has been in operation since January 1976.

Progress.–Studies of the data gathered from the seismograph network indicate that earthquakes continue to occur in the CBP and also in portions of the Delaware Basin adjacent to the CBP. The largest earthquake recorded during the network operation was about Richter magnitude 3.5. During this period, three earthquakes of magnitudes 3.0–3.5 were felt by the general population at Kermit, Tex.

The earthquakes appear to occur in association with pre-Permian faults that bound the CBP on the west and the east. The earthquakes occur largely at depths shallower than the crystalline basement.

Some events appear to occur at depths where no faulting has been inferred, but the majority of earthquakes are located at oil-producing depths where secondary hydrocarbon recovery is employed; none of the best-located events occur outside this zone if consideration is given to the standard errors in focal depth measurements.

The first earthquake felt in this region was in 1966; it coincided with a rapid increase in the number of projects being operated to improve oil well production by high pressure water injection and the increase in fluid pressures resulting from production improvement projects begun in the early 1960's. These tentative correlations suggest a causal relation between the earthquakes and hydrocarbon production that could be related to increased fluid pressures along faults. The details of this study are given by Rogers and Malkiel (1979).

The results of this study have several implications relating to the seismic hazard at the WIPP site. First, the widespread occurrence of small earthquakes within the seismic network area suggests that additional microearthquake studies in regions closer to the WIPP site are warranted to determine the shortest distance between the seismic zone and the site. Second, the apparent relation between hydrocarbon production and earthquake occurrence indicates that the WIPP site probably should not be included in the same seismic source region as the CBP because the WIPP site is isolated from the major hydrocarbon-producing zones. Third, the maximum magnitude of earthquakes in the active zone may be relatively small if these earthquakes are in fact induced by secondary hydrocarbon recovery operations because the magnitude of artificial pressure increases and the spatial extent of these increases are small.

Reference

Rogers, A. M. and Malkiel, A., 1979, A study of earthquakes in the Permian Basin of Texas-New Mexico: Seismological Society of American Bulletin, v. 69, p. 843–865.

FLUID INCLUSION STUDIES

By Edwin W. 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, the consequences of which 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 or deposition of salt crystals); in the latter case, they provide information on the previous movement of fluids through the rocks.

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

Approach.—Samples are examined by microscope for fluid inclusions and appropriately sized portions are removed for study on microscopes equipped with freezing and heating stages. The temperature of first melting of a completely frozen inclusion provides a measure of the eutectic temperature of the chemical system within the inclusion. The temperature of disappearance of the last solid phase and the composition of that phase, in comparison with appropriate phase diagrams, place some limits on the fluid composition. In the heating stage, the temperature at which the inclusion formed can be inferred from the temperature at which the shrinkage vapor bubble disappears. This determination is somewhat ambiguous because of the possibility of post-entrapment flowage of the host salt crystal. Gas pressure within an inclusion is estimated from the volume of the bubble in an inclusion being examined under the microscope before and after cracking the inclusion or dissolving the host crystal in water. The rate of migration of inclusions in a thermal gradient (by solution at the hotter and reprecipitation at the cooler end) is determined by measurements under the microscope before and after subjecting the sample to a static thermal gradient for weeks.

Progress.—Most of the work has dealt with samples from the ERDA-9 borehole at the WIPP site in New Mexico and is continuing both on this material and on samples from other locations.

Studies of 19 selected samples from the ERDA-9 borehole (Roedder and Belkin, 1979) have shown no evidence of meteoric water; the primary fluid inclusions trapped in the original salt crystals, as they crystallized in the Permian seas, contained highly saline bitterns that have been largely freed, and in part retrapped, during recrystallization of the bulk of these salt beds at temperatures well

under 100°C. This recrystallization of the salt must have taken place at several different times, since the composition of the fluids varies from one inclusion to another. If fresh surface waters had been introduced into these salt beds in the past (as through faulting) and trapped, the resulting inclusions would be simple saturated NaCl solutions and would not have the bittern compositions that were found. Results of studies which used rather large (4–23 mg) samples of H_2O isolated in the laboratory to determine the stable isotopes of hydrogen and oxygen in the fluid of these inclusions (by J. R. O'Neill, Menlo Park, Calif.) also preclude any direct meteoric water source. It is important to note that, at higher temperature, the vapor pressures of bitterns such as those found in the inclusions would be much lower than those of simple saturated NaCl solutions.

In the thermal pulse from a waste canister, fluid inclusions larger than about 1 mm (if not under adequate confining pressure) may burst or "decrepitate" from the high internal pressures (about 12 bars for each 1°C above homogenization temperature for most inclusions in these samples) that result from the heat. Smaller inclusions generally enlarge their cavities by permanent deformation of the host crystals and move toward the heat source at rates that are direct functions of the ambient temperature, the gradient, and the inclusion size (Roedder and Belkin, 1980). Many other factors may influence the movement rates, and several observed movement phenomena remain unexplained, but in salt of 1-cm grain size, the movement rates (e.g., about 1 cm/yr for 1-mm inclusions at 160°C ambient and a gradient of 1.5°C/cm) are such that most inclusions near a canister could be expected to reach at least one grain boundary during the thermal pulse. Their behavior at this point will be controlled by the nature of that boundary; if it is tight, they will simply cross it and continue, but if it contains clay or is otherwise open, the fluid may move preferentially along the boundary. The nature of such intergranular movement under nonuniform thermal and mechanical stress fields is uncertain.

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GEOCHRONOLOGY AND ISOTOPIC STUDIES

By James O'Neil, Barney Szabo, John Rosholt, John Obradovich, and M. Tatsumoto, Lakewood, Colo.

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

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

Progress. – Geochronology and isotopic studies fall into three categories: (1) the use of oxygen isotopes to study brines, (2) hydration and solution of potash and anhydrite, (3) the date of the time of formation of breccia pipes.

Oxygen isotopes (James O'Neil, Lakewood, Colo.): The goals of this investigation are to delineate geologic processes that produced the brines and determine if unique isotopic signatures exist for them; to assist in determining the origin of waters contained in fluid inclusions in evaporite minerals; and to determine temperature histories and possible source materials of various gaseous and solid phases. Samples of ground waters, brines, gases, and minerals have been collected by investigators from Sandia Laboratories and fluid inclusions have been provided by E. W. Roedder (USGS).

The accumulated data continue to show that brines have very distinctive patterns on a plot of deuterium versus oxygen isotopes and may be easily distinguished from ground and surface water. Therefore, it should be easy to tell whether brines are returning to the biosphere at present by examining their light stable isotopes. Initial data on fluid inclusions are similar to those for brines. There is no unique explanation for the unusual isotopic compositions of the brines; one possibility is that the brines formed through a dehydration reaction such as the conversion of gypsum to anhydrite.

Hydration and solution of potash, anhydrite, and other minerals (Barney Szabo and John Rosholt, Lakewood, Colo.): This investigation is aimed at determining the time at which subsurface solution of potash and alteration of anhydrite and polyhalite to gypsum (which develops where

shallow ground waters first interact with the anhydrite formation) have occurred near the WIPP site.

In addition, materials are being dated to determine when free-flowing springs were active in the area as well as the general age of the present land surface. The minimum apparent age of a camel bone embedded in gypsite (ancient spring deposits composed of gypsum) has been determined by Barney Szabo as about 90,000 yr. Preliminary evidence suggests that free-flowing springs existed in the WIPP site area at least 100,000 yr ago. A core and other material from a fossil spring site suggest that active subsurface solution of the gypsum was occurring at least that long ago.

Soils have been dated to help establish the stability of the surface. Initial results on 12 samples indicate the Mescalero caliche may have been formed about 530,000 yr ago and the overlying red Berino soil about 350,000 yr ago.

Dating the formation of Breccia pipes (John Obradovich and M. Tatsumoto, Lakewood, Colo.): These studies are attempting to date the time of formation of breccia pipes and help to determine their origin, as well as dating the times of diagenesis and deformation metamorphism of the evaporite deposits. This is being done through K-Ar and K-Ca dating of samples of sylvite, polyhalite, langbeinite, diagenetic silicates, or other appropriate minerals from breccia pipes. Initial results from a sample of sylvite with tiny blue halite inclusions gave apparent ages on the halite of 5–15 m.y., whereas previous K-Ar ages on sylvite gave apparent ages near 200 m.y. The initial interpretation of these data is that the sylvite in this sample was probably formed less than 5 m.y. ago because the much older ages previously obtained indicate that sylvite can retain much of its argon, although some is apparently lost since the expected age would be a little greater. Although the potassium analysis is not yet completed, the argon content of a sample of polyhalite indicates an age of about 240 m.y. (provided the mineral is stoichiometric); this suggests that the polyhalite is able to retain its argon and has not been subjected to recent mobilization.

A special reaction vessel has been designed and fabricated to permit K-Ar and K-Ca dating to be performed on the same sample.

HYDROLOGY

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

Objective.—The objective was to evaluate the hydrologic systems in the area with regard to their potential for radionuclide transport.

Approach.—Data will be acquired and assembled to define in detail the hydrology of the WIPP site including its relationship to regional ground-water systems. Improvements in digital models, simulating ground-water flow and solute transport, will be required to predict rates and directions of movement of radioactive species and their concentrations in ground water if they should be released from a geologic repository.

Progress.—Water-bearing zones above and below the proposed host formation for the waste, the Salado Formation, include the water-bearing dolomites in the Permian Rustler Formation above the Salado, the brines at the Rustler-Salado contact, and the brines in the Bell Canyon Formation below the Salado (see table that follows). The water-bearing zones in the Rustler Formation require the most detailed definition. This, in turn, should be followed by a detailed definition of the Bell Canyon Formation water-bearing zones.

Calculations of hydraulic gradient and direction of flow of ground water along the Rustler-Salado contact have been hindered considerably because water levels in test wells stabilize very slowly. Preliminary calculations of transmissivity range from 9×10^{-3} m²/d on the western margin of the site to 9×10^{-6} m²/d on the eastern margin. Waters from the Rustler-Salado contact zone contain from 350,000 to 480,000 mg/L total dissolved solids. The

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

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

water chemistry suggests long residence times and extensive fluid-rock interaction, both inversely proportional to permeability.

Water in the Culebra Dolomite Member of the Rustler Formation moves to the southeast, with gradients ranging from 1.3 to 23 m/km. Preliminary transmissivity calculations range from 1.86 m^2/d on the western margin to 9×10^{-4} m^2/d to the east. Total dissolved solids range from 9,700 mg/L along the western margin to 100,000 mg/L to the east. Water chemistry within the Culebra varies from well to well, probably as a function of fracture distribution.

Water in the Magenta Dolomite Member of the Rustler Formation moves to the west at a gradient of about 9 m/km. Preliminary transmissivity estimates range from 0.09 m^2/d to 9×10^{-5} m^2/d. Total dissolved solids range from 12,000 mg/L to 32,000 mg/L.

The extremely low vertical hydraulic conductivity within the Rustler Formation restricts fluid communication between the Magenta and Culebra Dolomite Members and between the Culebra Dolomite Member and the contact between the Rustler and Salado Formations. Water levels are highest in the Magenta Dolomite Member and lowest at the Rustler-Salado contact.

Analyses of the data suggest that varying transmissivity values in the Rustler may be caused by subsidence and fracturing of the water-bearing units due to dissolution of underlying halite and gypsum beds within the Rustler Formation.

To date, three combination hydrologic-geologic test holes have been completed in the Bell Canyon Formation. The test holes vary in depth from 1,324 to 1,443 m. Preliminary values of hydraulic conductivity are on the order of 9×10^{-4} m/d.

Water levels in wells tapping the Bell Canyon Formation near the site are lower than those in wells tapping the Rustler Formation. Bell Canyon fluids contain 189,000 mg/L total dissolved solids. Fluid density and water chemistry indicate long residence times and extensive fluid-rock interaction.

HANFORD RESERVATION REGION, WASHINGTON

The DOE through its contractor, Rockwell Hanford Operations, is investigating the feasibility of and the technology for designing and constructing a repository for commercial high-level radioactive waste in basalt flows of the Columbia Plateau. In support of this effort, the USGS has been requested by the DOE to make reconnaissance geologic maps of the Columbia River Basalt Group and to conduct model studies of ground-water flow in basalt aquifers underlying the Plateau. The USGS is conducting work parallel to the geologic and hydrologic studies by Rockwell within the Hanford Reservation and vicinity.

GEOLOGIC MAPPING OF THE COLUMBIA PLATEAU

By Donald A. Swanson, Menlo Park, Calif.

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

Objective.—The objective was to prepare a geologic map of the Columbia River Basalt group in Washington, Oregon, and Idaho at a scale of 1:250,000. The map will be used in the DOE's evaluation of how regional tectonic and stratigraphic relations might affect the underground storage of radioactive waste.

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

Progress.—Mapping and map compilation in Washington and northern Idaho have essentially been completed. A brief summary of the program and the important results was given by Swanson (1979). Swanson, Anderson, and others (1979) and Swanson, Brown, and others (1979) summarized the results of the mapping and map compilation in USGS open-file reports which will be published later with colored maps. Field work will continue in west-central Idaho, northern Oregon, and southwest Washington, and preliminary maps of parts of these areas will be released to the open file in the winter of 1980–81.

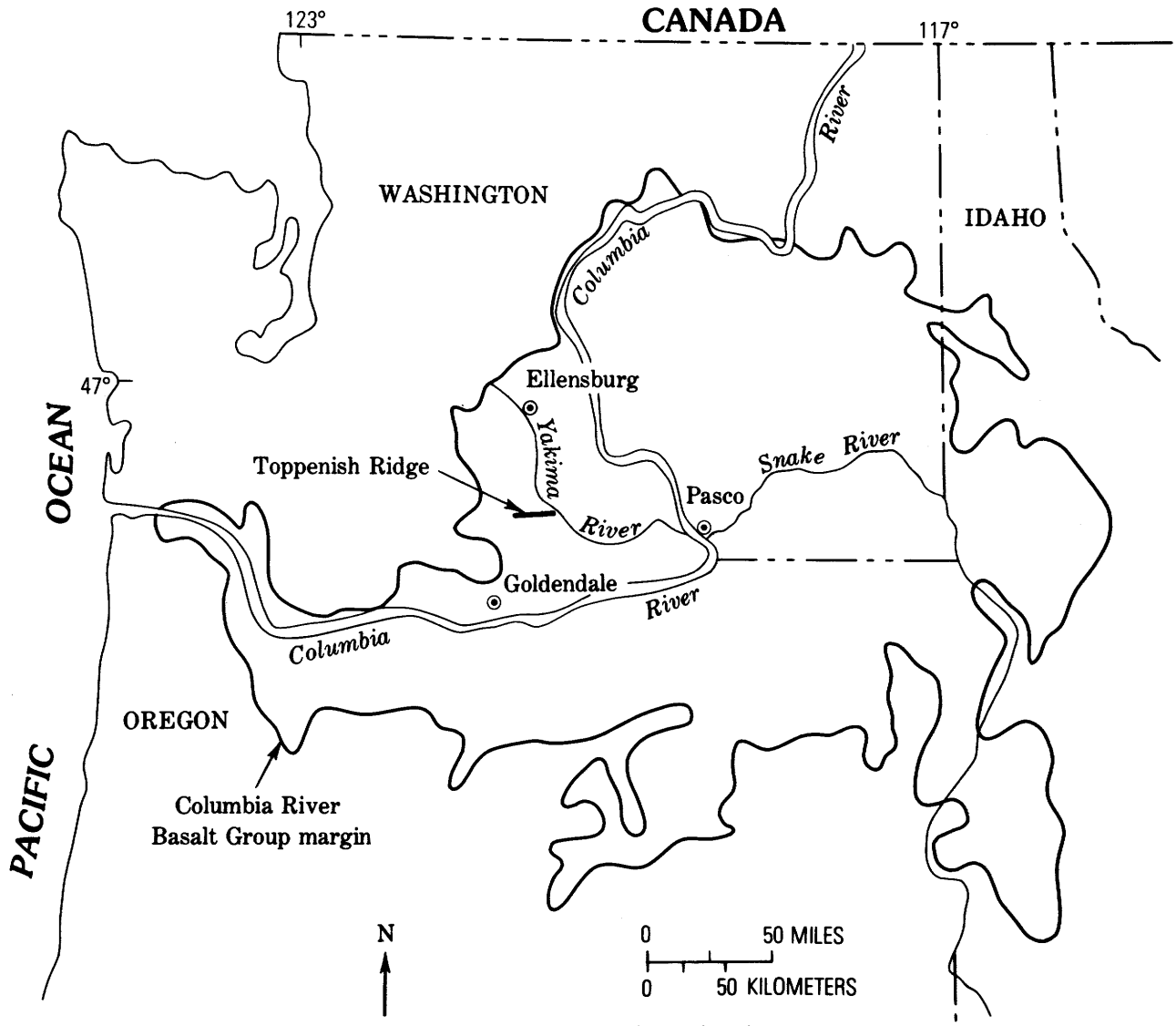

FIGURE 7.–Index map of Columbia Plateau.

Mapping in Washington reveals a much more complex tectonic history than was previously assumed. The basalt of the western one-third of the Columbia Plateau in the State has long been known to be folded, but current mapping shows numerous faults as well. Large thrust faults occur east and southeast of Ellensburg (fig. 7), along the eastern part of Toppenish Ridge, and along several anticlines in the Goldendale area. Northwest-trending faults in the basalt, possibly with right-lateral displacement of a few hundred meters or less, are rather common across the southwest part of the area. Young ground ruptures in sedimentary deposits along Toppenish Ridge are apparently of tectonic origin; they indicate that deformation, at least in this area, is continuing.

The geologic mapping is also delineating the source regions and areal extent of certain flows and the courses of the ancestral Columbia, Snake, Yakima, and other rivers. The Pasco Basin has been found to be a surprisingly young topographic feature, as river courses younger than 10 m.y., and probably younger than 8 m.y., cross the present site of the basin without deflection. Such late development of the basin shows that it must be of tectonic origin; the previously accepted origin, isostatic sinking owing to accumulation of flows within it, is now untenable, as most of the flows are about 15–17 m.y. old and would have triggered subsidence then, not 5–7 m.y. later. Eventual integration and evaluation of this type of information will be helpful in assessing the present and future tectonic situation on the plateau.

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GROUND-WATER MODEL OF BASALT AQUIFER IN SOUTHEASTERN WASHINGTON

By David B. Sapik, Tacoma, Wash.

The Columbia River Basalt Group includes a complex system of aquifers of large areal extent. The principal aquifers have been stressed by pumping at several centers, and models have been constructed for management purposes to simulate the effects of pumping. The complexity and large areal extent of the aquifers, however, have made it difficult to define the boundary conditions realistically.

Objective.—The objective was to calibrate a steady-state, three-dimensional ground-water flow model of the confined basalt aquifers underlying the Columbia River Plateau in southeastern Washington.

Approach.—The work has been divided into three tasks. The first task is to select and verify a suitable computer program for the model. The second is to compile the available hydrogeologic data and to make estimates of aquifer parameter values to be used. The third task is to obtain the additional head and pumpage data needed to calibrate the model.

Progress.—The USGS three-dimensional finite-difference program was selected, and it has been modified to handle a four-layer model of the system and to run on a CDC 7600 computer at Lawrence Berkeley Laboratory. The steady-state model is now operational and can be used to evaluate the adequacy of the data base. Estimates were made for the following parameters:

- Head—maps were completed of head distribution for each aquifer.
- Transmissivity—maps for each aquifer are 75 percent complete.
- Vertical conductivity of confining beds—maps are 50 percent complete.
- Recharge to uppermost aquifer.
- Identification of boundary conditions.
- Leakage rates across boundaries—50 percent complete.

IDAHO NATIONAL ENGINEERING LABORATORY

VOLCANIC HAZARDS

By Brent Dalrymple and Duane Champion, Menlo Park, Calif., and Mel A. Kuntz, Lakewood, Colo.

The eastern Snake River Plain, Idaho, is a lava plain composed of thin basalt flows emitted from fracture-controlled vents located chiefly on volcanic rift zones. The basalt volcanism is Pliocene and Quaternary, and significant areas of the plain are covered by flows younger than 15,000 yr. The Idaho National Engineering Laboratory (INEL), an area of approximately 1,500 km^2 on the plain, is the site of nuclear reactors and radioactive waste storage sites operated by DOE. The USGS, in cooperation with DOE, has been evaluating the recurrence intervals of volcanism on INEL and adjacent areas for the purpose of evaluating the volcanic hazard to reactor and waste-storage facilities.

Objective.—The objective was to determine the rate of recurrence of basaltic eruptions that have flooded the area of the Radioactive Waste Management Complex (RWMC) (contains transuranic and low-level wastes) (fig. 14) and thereby estimate the probability of future disruption or burial of the site by lava flows.

Approach.—Detailed petrographic, K-Ar, and paleomagnetic studies were made of five cores from drill holes that penetrated to depths as great as 200 m on and near the RWMC site. From these studies, the stratigraphy and ages of the various flows were determined.

Progress.—Two studies, recently completed by Kuntz (1978) and Kuntz and Dalrymple (1979), have determined the ages and recurrence interval of basalt lava flows that cover a proposed breeder reactor site and a radioactive waste burial storage facility at the RWMC. The radioactive waste burial facility lies in a shallow topographic depression and has been covered by lava flows emitted from vents located from 5 to 30 km away. K-Ar and paleomagnetic studies show that the burial site has been inundated by lava flows at least 10 times within the last 500,000 yr. The 19 flows and flow

units are arranged in seven groups, each group consisting of one to five flows and flow units that were erupted from a single vent. The average eruption rate is thus approximately one eruption event per 70,000 yr, but the eruptions have been episodic rather than periodic.

The data indicate that there were three major volcanic episodes, each consisting of several groups of flows. The oldest episode occurred about 450,000 ± 50,000 yr ago, and the youngest occurred about 95,000 ± 50,000 yr ago, with an intermediate episode at about 225,000 ± 25,000 yr ago. The study concludes that an eruption in the future from volcanic vents within the topographic basin in which the RWMC is located would pose a threat to the waste burial storage facility but that only about 20 percent of such eruptions are likely to inundate the RWMC with lava. The time of any future eruption is unpredictable, but one could occur at any time from now to 100,000 yr in the future.

The Craters of the Moon lava field, flows from which come within 20 km of the waste facility, covers an area of approximately 600 km² in the eastern Snake River Plain. Stratigraphic, radiocarbon, and paleomagnetic data show that the field was formed in at least five bursts of volcanic activity from vents located along the Great Rift. Major bursts occurred at 14,000–12,000 yr, approximately 11,000 yr, 7,000–6,500 yr, approximately 4,000 yr, and approximately 2,000 yr B. P.

Geologic mapping by Mel A. Kuntz and H. R. Covington suggests that the lengths and orientations of volcanic rift zones, the areal density and types of volcanic vents, and subtle topographic features in lava flows of the eastern Snake River Plain are partly controlled by buried rhyolite calderas. Some volcanic rift zones apparently coincide with buried segments of caldera ring fractures, while others appear to terminate at caldera margins. Areas of sparse or no vents appear to overlie buried calderas. Basaltic cinder cones, low topographic ridges, and rhyolite domes may coincide with ring fractures, whereas arcuate depressions may reflect collapsed "moat" zones.

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PARADOX BASIN, UTAH

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

GEOLOGY

By Robert J. Hite, Lakewood, Colo.

The initial investigations have focused on Salt Valley, one of a series of northwest-trending diapiric salt anticlines along the northeast edge of the Paradox Basin in southeast Utah (figs. 8 and 9). On the basis of a USGS regional survey (Hite and Lohman, 1973) of the salt deposits in the Paradox Basin and two preliminary reports describing the surface (Gard, 1976) and subsurface geology (Hite, 1977) of Salt Valley, the DOE decided that this structure should be examined further. The present investigation began in 1978 with a three-hole drilling program managed by Woodward-Clyde Consultants and geologic, hydrologic, borehole and surface geophysical, and remote sensing studies by the USGS. Two holes (DOE–1 and DOE–2) were drilled to depths of 393 and 374 m, respectively, while DOE–3 was cored almost continuously to 1,242 m. These holes penetrated the top of the first halite bed at depths from 167 m to 196 m. The cores and logs are a key source of data, and the holes are used for both hydrologic and geophysical measurements.

Objective.—The objective was 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.—By using bromine geochemistry, borehole geophysical logs, and detailed lithologic

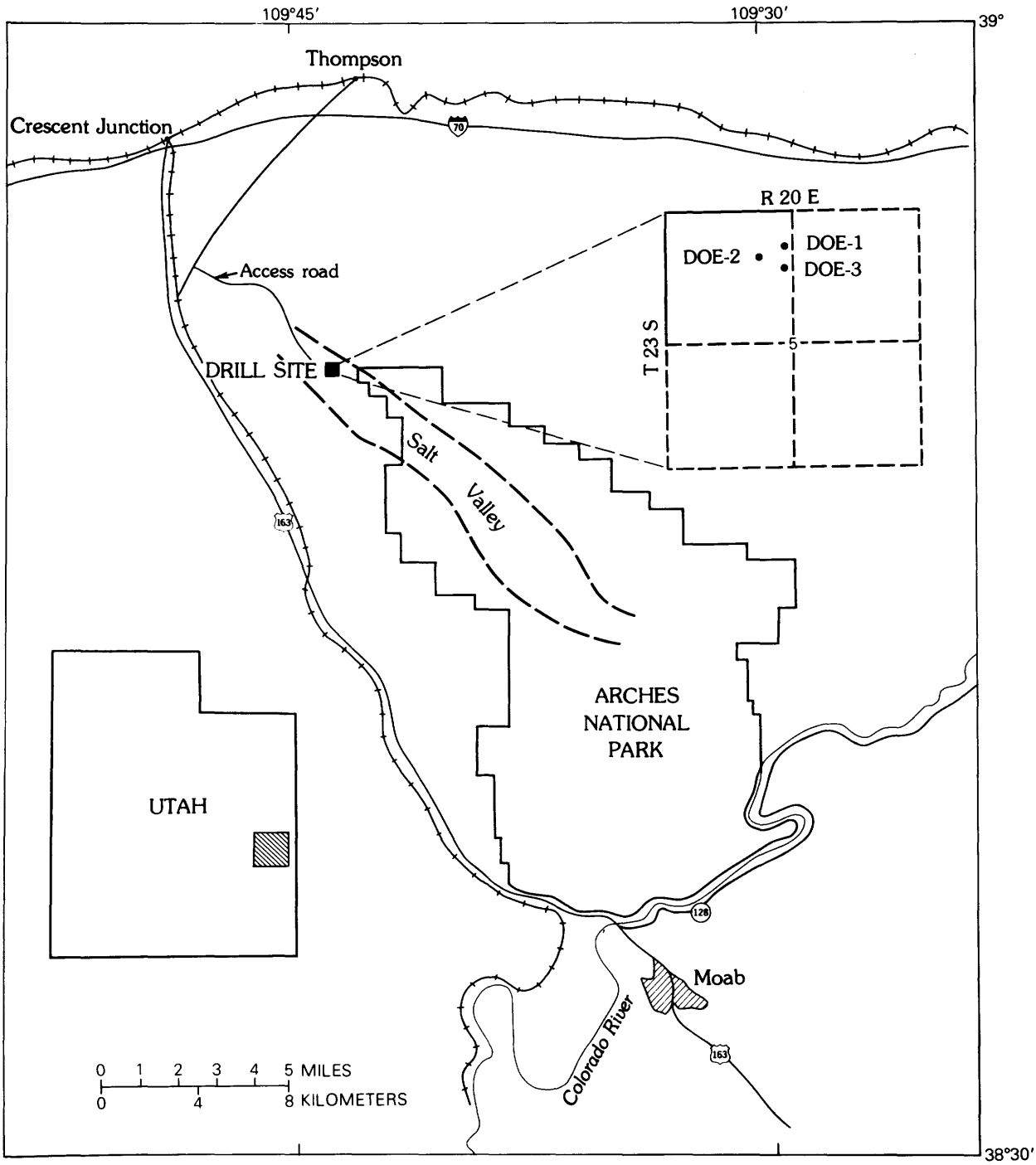

FIGURE 8. – Location of three-hole deep drilling project in Salt Valley, Utah.

logs of the core, the structural configuration of the complexly deformed evaporite sequence intersected by the three holes has been established. Both DOE–1 and DOE–2 penetrated the same halite bed which is overturned and nearly vertical. Core from DOE–3 is being reexamined in greater detail so that overturned sequences of beds can be identified.

The water content of halite samples is being determined by a new technique developed for this study of dissolving the halite in hot methanol and measuring the water content of the methanol ex-

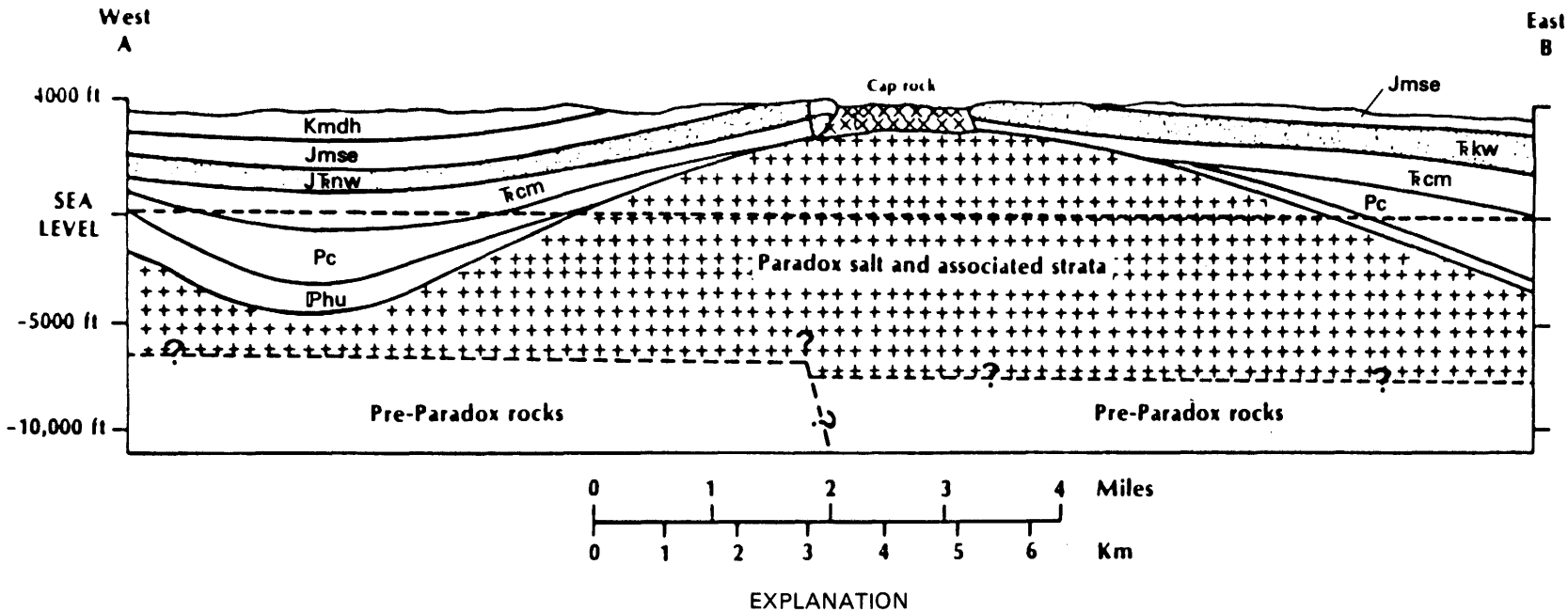

FIGURE 9.—Cross section of Salt Valley anticline, Utah.

tract by Karl Fisher titration. Analyses, thus far, indicate the average water content of the halite rock is very low, about 0.02 weight percent.

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HYDROLOGY

By F. Eugene Rush, Lakewood, Colo.

Objective.—The objective was to evaluate the ground-water flow systems of the basin and their potential as barriers to radionuclide transport.

Approach.—A reconnaissance study using available data is being made to determine the regional hydrogeology of the Paradox Basin. Test drilling at prospective repository sites is required to evaluate the hydrology of the caprock and adjacent aquifer systems.

Progress.—The unsaturated zone of the caprock in Salt Valley is more than 100 m thick. The shallowest indication of water saturation is at a depth of 112 m in drill hole DOE-2. Saturated materials were not identified in drill hole DOE-1 above a depth of 151 m; however, the static water level in this hole is at a depth of 113 m.

Two components of potential ground-water flow were identified in the caprock based on apparent hydraulic gradients: (1) heads decreased with depth within the saturated caprock indicating a potential for downward ground-water flow, and (2) head apparently decreases to the southwest indicating an apparent component of flow in that direction.

The caprock is semi-lithified, and, as a result, there are difficulties in some aspects of drilling, coring, and hydraulic testing. In addition, the presence of dissolved hydrogen sulfide in caprock water presents problems in hydraulic testing.

Ion concentrations of ground water in the caprock vary within the saturated zone. The lowest specific conductance values, as low as 1,900 μmho occur in the upper part of the zone. The specific conductance of deeper samples is generally much higher.

Two pumping tests of the saturated caprock yielded hydraulic conductivity values of 5×10^{-3} m/d and 4×10^{-3} m/d. These values indicate small flow rates through the caprock ground-water system. A ^{14}C age determination of greater than 36,000 yr for a water sample from the caprock supports this conclusion. The $^{2}H/^{1}H$ and $^{18}O/^{16}O$ ratios indicate that the sampled water was derived from atmospheric water vapor by precipitation and infiltration. The $^{13}C/^{12}C$ ratio indicates that the carbon content of the sampled water had a biogenic origin, such as from petroleum.

The thin sedimentary strata interbedded with the salt contain minor amounts of oil and gas, but in general, the rocks have very low porosity and very low hydraulic conductivity. On the basis of pumping tests, the latter generally is about 1×10^{-4} m/d or less.

A reconnaissance study for the part of the Paradox Basin northwest of the Colorado River is nearly complete. Tentative conclusions are:

1. Recharge from precipitation may not be the principal mechanism of recharge to the aquifer systems, rather subsurface inflow may be of greater magnitude.
2. Flow of ground water to the Green and Colorado Rivers may be the principal mechanism of ground-water discharge, followed in magnitude by subsurface outflow to the southwest.

GEOPHYSICS

By Raymond D. Watts, J. J. Daniels, Alfred H. Balch, and Hans Ackermann, Lakewood, Colo.

Objective.—The objective was to utilize geophysical data to characterize and differentiate subsurface lithologies, structural configurations, and inhomogeneities in areas of interest and to evaluate state-of-the-art down-hole seismic equipment for mapping interbeds in salt with vertical seismic profiles.

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

To test the applicability of computer-processed vertical seismic profiling (VSP), which is essentially a new and untried technique, a seismic source is placed in one drill hole and the waveform recorded at many depths in the other (fig. 10). The data are then processed, analyzed, and interpreted to identify, resolve, and profile-map lithologic units of the

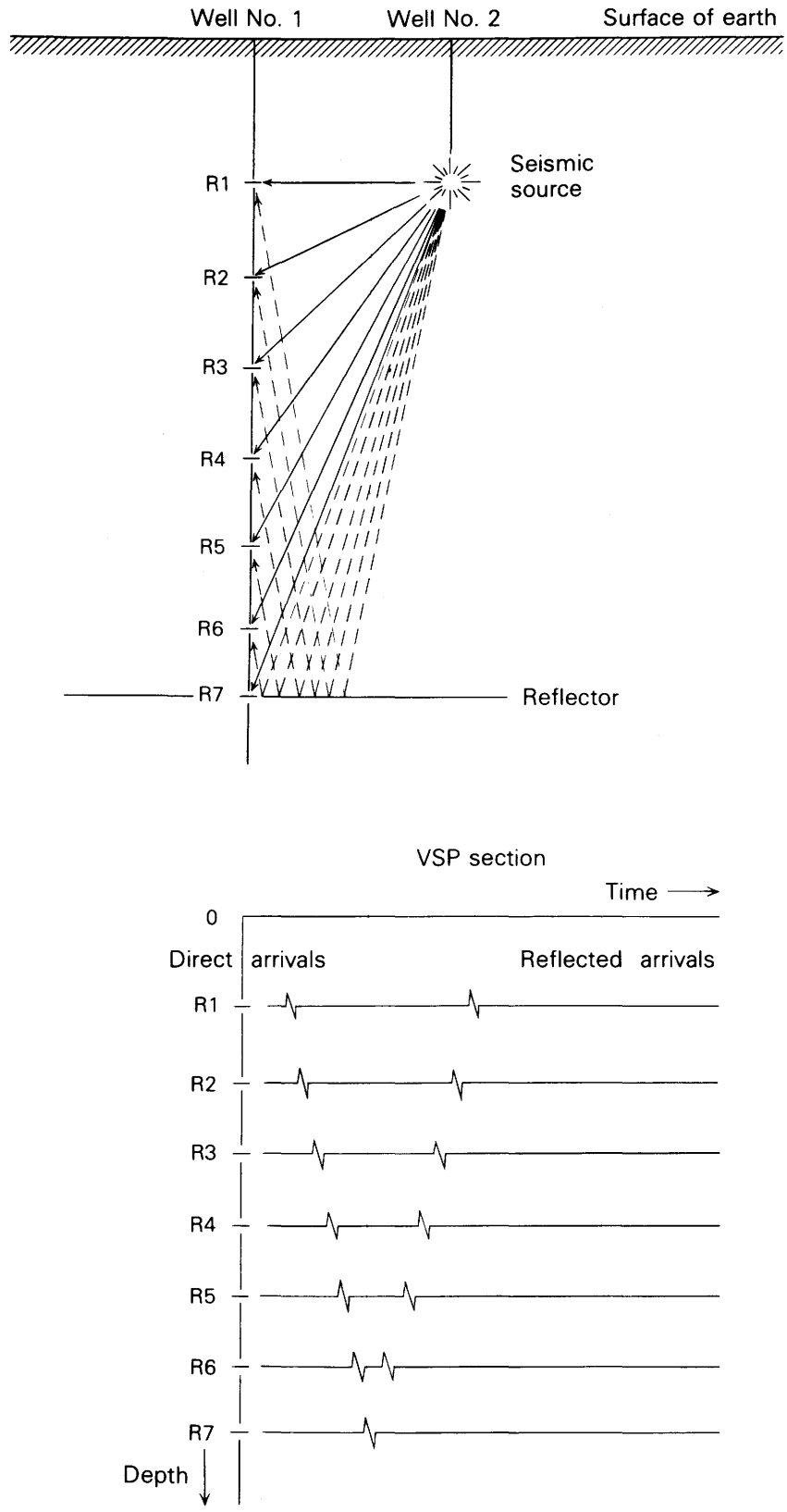

FIGURE 10. – Theoretical seismic paths and seismograms for the vertical seismic profiling method.

geologic section between the source and geophone holes.

Progress.—Two profiles in the immediate vicinity of the Salt Valley drill holes were run by Raymond D. Watts with the "Slingram" system, a loop-loop electromagnetic induction system that operates at five discrete frequencies. The penetration depth of the system is about 100 m. A Slingram anomaly about 200 m long was sensed on both profiles and is believed to be due to the presence of water locally; this was confirmed by drilling. Two vertical electric soundings (VES) of the Schlumberger type were also run. Preliminary results indicate that there is no major conductor (such a conductor would indicate water- or brine-filled rock) in the caprock section overlying the salt. Apparently, water does not have access to the top of the salt deposit at this location and has not formed a continuous brine layer.

Borehole electromagnetic investigations by J. J. Daniels have been concentrated in the deep corehole (DOE-3). A single-coil induction probe gave good resolution of interbedded lithologies and may also be useful for determining the presence of water in halite rock. Studies of the suite of geophysical well logs run at Salt Valley emphasize the difficulty of interpreting complex structural features (Daniels and others, 1979).

A seismic refraction survey in the area of the drill site has revealed an undulating salt surface along the crest of the anticline that has local relief of as much as 80 m. The minimum depth to salt, about 165 m, occurs near the drill site (Ackermann, 1979).

A vertical seismic profiling experiment was conducted by Alfred H. Balch with the seismic source in DOE-1 and recording equipment in DOE-3 to determine if it is possible to map the position of the anhydrite-dolomite-black shale interbeds using this untried technique. The initial effort obtained one complete profile of fair quality. Computer processing should allow eventual interpretation of the location and dip of interbeds.

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REMOTE SENSING

By Jules D. Friedman, Lakewood, Colo.

Objective.—The objective was to acquire, process, and interpret geologically a variety of satellite and aircraft image products of the Paradox Basin region in order to detect and delineate previously unmapped structures which might significantly affect the suitability of a waste repository site.

Approach.—Small-scale multispectral images recorded from satellites and large-scale multispectral data obtained from airborne instruments are used to identify regional and sub-continental scale fault and fracture zones, intrusive and extrusive magmatic centers, collapse structures, buried stream channels, and recent erosional and depositional features that would not be readily detectable through field studies and interpretation of aerial photographs. Features so identified are compiled and digitized. Maps and overlays are prepared at various scales showing the areal distributions of linear features as a function of trend and (or) length; contour maps are made of the areal density of linear features and their intersections, and diagrams are prepared of the azimuthal and length-weighted azimuthal distributions. The origin and significance of the features identified are interpreted.

In addition to the delineation and analysis of individual surface structures, regional structural trends have been compared statistically with linear trends and lines of discontinuity in the regional gravity and magnetic fields which, in themselves, may demarcate profound structural discontinuities in the subsurface rock sequence.

Progress.—Compilation of a lineament map using specially processed and digitally enhanced Landsat images and showing geologically mapped faults and fold axes as well as a heirarchy of problematic structural lines (Friedman and Simpson, 1978) was followed by careful statistical analyses of the problematic line trends and the trends of the previously known structures. At this stage, the geophysical trends were plotted and compared with the geological and remote-sensing data (Friedman and others 1979; Friedman and Simpson, 1980).

The comparison revealed that the dominant strike frequency of the major lineaments (those more than 20 km long) is N. 40°–60° W. This trend coincides with the dominant strike frequencies of the previously known, geologically mapped faults

and fold axes and gravity- and magnetic-field trends and is parallel to the axes of the major salt anticlines and to an inferred boundary fault zone of the Uncompahgre uplift. The dominant strike frequency for all lineaments – including short problematic lines – is N. 40°–50° E., a trend that coincides with 2d order gravity-field and 3d order magnetic-field trends, as well as 4th order mapped fault trends. These coincidences are evidence that many of the lineaments – including many previously unknown – represent faults, fractures, or other geological discontinuities in the Paleozoic and Mesozoic rock sequence that contains the salt diapirs and beds of the Paradox Member of the Hermosa Formation. The stated azimuthal trends are interpreted as representing the dominant tectonic framework, as well as the directions of anisotropy of the fracture pattern within the region.

The enhanced Landsat images have also aided geomorphologic investigations of the Paradox Basin. The major breached anticlinal valleys whose cores are elongate salt diapirs are cross-axial to the Colorado River valley. The floors of the breached anticlinal valleys are at grade with the Colorado River, whose rate of downcutting controls the level and gradient of the anticlinal valley floors. The salt removed through solution by the Colorado and Dolores River is replaced by lateral flow of salt farther up the anticlinal valleys and by concomitant collapse of sandstone and shale of the valley walls sufficient to maintain the valley-floor profiles at grade with the Colorado River.

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GULF COAST SALT DOME REGION

NORTH LOUISIANA

By R. L. Hosman, Baton Rouge, La.

The DOE is investigating the suitability of salt domes in the north Louisiana salt-dome basin as potential sites for the storage of radioactive wastes. The USGS, in cooperation with DOE, is studying the regional hydrogeology of the area. The north Louisiana salt-dome basin includes all or parts of 11 parishes, an area of about 7,800 km² (fig. 11). The basin is a structural depression bounded on the west by the Sabine uplift and on the northeast by the Monroe uplift. The strata of principal concern to this study are of Late Cretaceous and Tertiary age, dip generally southeast, and are less than 900 m below land surface. The general geohydrology of the area, based on available data, and the need for additional data and studies are described by Hosman (1978).

Objective. – The objective was to describe the regional geohydrology and define the ground-water flow system of the north Louisiana salt-dome basin, with particular attention being given to the potential for transport of radionuclides from a repository in a salt dome.

Approach. – A regional, three-dimensional digital model that will simulate flow in the multilayered ground-water system to depths of 900 m or more is to be constructed. The deepest water-bearing unit to be modeled is the Nacatoch Sand of the Upper Cretaceous Series. Other principal units in the model will be the Wilcox Group, undivided, of Paleocene and Eocene age and Carrizo Formation, Sparta Sand, and Cockfield Formation of Eocene age. Maps depicting specific geologic and hydrologic properties of the aquifer systems and confining beds will be needed for input to the model.

Some of the maps that are necessary for the model require data that must be obtained by test drilling. Accordingly, a regional test-drilling program has been planned in cooperation with DOE. The USGS will maintain personnel in the field, as needed, during the entire drilling program to operate a mobile laboratory, conduct hydrologic tests, and provide technical support.

Progress. – A series of 17 regional geohydrologic maps has been completed using available data. The map boundaries correspond to tentative model boundaries and are at sufficient distances from the salt-dome basin that modeled flow in the study area will not be significantly affected by the assumed constant-head conditions at the boundaries.

Records of wells in the vicinity of Vacherie and Rayburns domes have been obtained and the water sampled (Ryals and Hosman, 1980). Flow and water quality of certain key streams in the area were monitored. Miscellaneous flow measurements were made on other streams, and samples were collected for chemical analysis.

In addition to the geohydrologic investigation, a

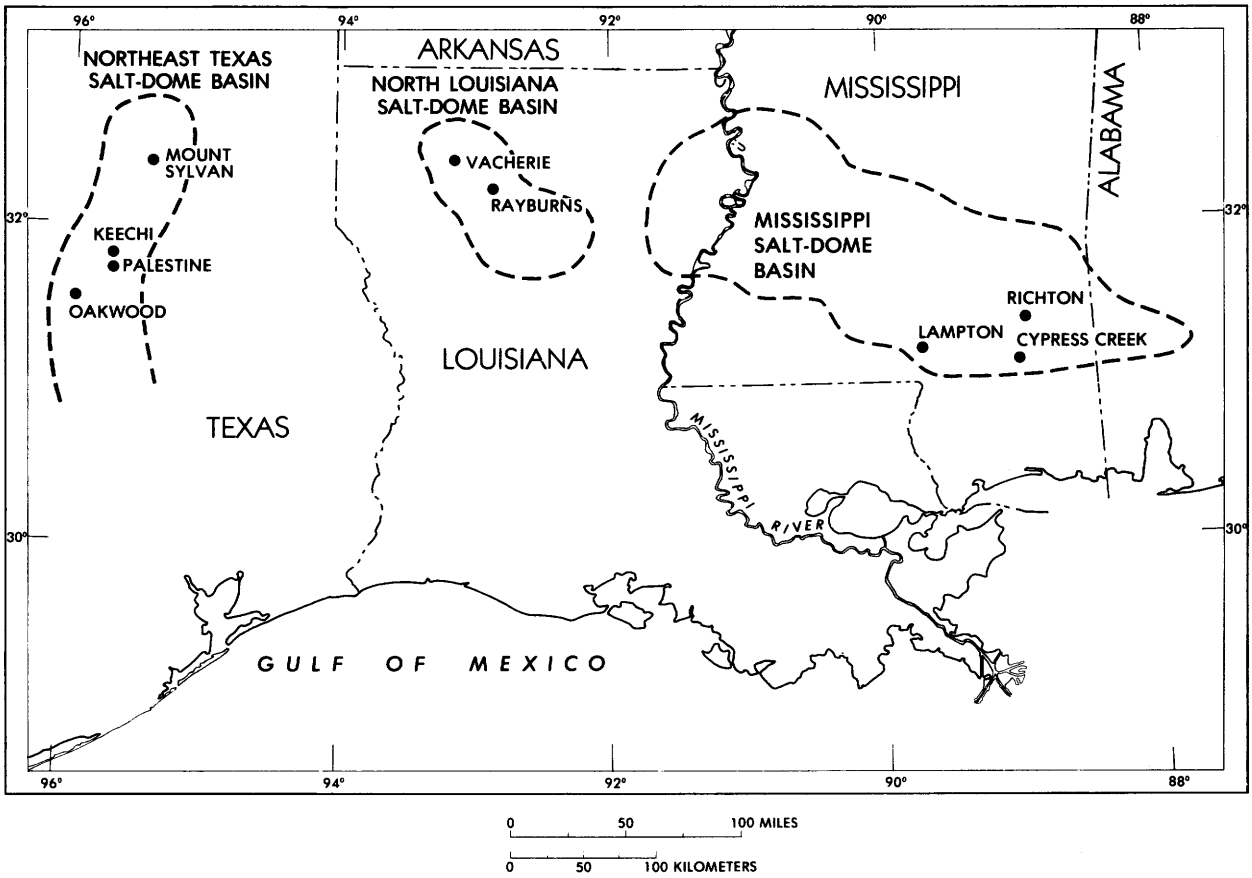

FIGURE 11.–Gulf Coast area showing locations of salt domes being studied.

reconnaissance study has been made by E. W. Roedder and H. E. Belkin (1979) of fluid inclusions in salt from the Rayburns and Vacherie salt domes in Louisiana. Inclusions in these samples, in common with many dome samples, are much less abundant than salt from the WIPP site in New Mexico. None of the inclusions studied, from either dome, contained a bittern; all were close to pure H_2O-NaCl solutions. The simplest interpretation, although unproven, is that, at some time in the past, fresh meteoric water entered the salt beds, presumably via fractures, and some was trapped as inclusions. If this was the origin of the inclusions, it raises a pertinent question regarding the suitability of dome salt as a host rock for high-level wastes. Under what conditions might this happen again?

The effect of migration of fluid inclusions in salt toward a buried waste canister is discussed in the section on Fluid Inclusion Studies at the WIPP site, New Mexico.

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MISSISSIPPI

By C. A. Spiers, Jackson, Miss.

The DOE is investigating the suitability of salt domes in the Mississippi salt-dome basin as potential sites for the terminal storage of radioactive wastes. Knowledge of the ground-water hydrology of the basin and the 50 piercement-type salt domes within it is very limited. The caprock in most of the shallower domes occurs in Tertiary strata ranging in age from Paleocene (lower part of the Wilcox Group) to Miocene (Catahoula Sandstone). The Tertiary strata are composed predominantly of sand and clay with minor beds of marl and limestone and dip about 6 m/km to the south-southwest. The USGS is studying the regional and local ground-water hydrology of the basin in cooperation with the DOE.

Objective.—The objective was to evaluate the ground-water hydrology with reference to the potential for radionuclide transport in ground water.

Approach.—The first phase of the study consisted of a reconnaissance and an analysis of the need for additional data and studies (Spiers and Gandl, 1980). A drilling, testing, and sampling program is needed to determine the significant geohydrologic properties of this multiple aquifer system. The salt domes of principal interest are Cyprus Creek, Richton, and Lampton, in the southeastern part of the basin (fig. 11).

Progress.—Most of the work in 1979 was near the Cyprus Creek dome. Fresh ground water is present at depths greater than 900 m at some places in the basin (Gandl and Spiers, 1980). The deepest fresh water occurs in the Wilcox Group in the northern part of the basin, in the Sparta Sand and Cockfield Formation in the central part, and in Oligocene and Miocene beds in the southern part. In each aquifer the position of the base of fresh water is well marked by a fresh water-salt water interface. Preliminary data suggest that the regional direction of ground-water flow in the Miocene beds is south to southwest at an average rate of about 30 m/yr.

References

Gandl, L. A., and Spiers, C. A., 1980, Results of water quality sampling near Richton, Cypress Creek, and Lampton salt domes, Mississippi: U.S. Geological Survey Open-File Report OF 80-443.

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NORTHEAST TEXAS

By J. E. Carr, Austin, Tex.

The Department of Energy has been investigating the suitability of salt domes in the northeast Texas salt-dome basin as potential sites for geologic repositories for the terminal storage of nuclear wastes. As part of this investigation, the USGS has been studying the regional geohydrology of the basin, including the geohydrology in the vicinity of selected salt domes (phase 1) and has conducted a reconnaissance of surface-water quality around selected domes to identify areas of discharge of saline ground waters (phase 2).

Objective.—The purpose of the phase 1 study was to describe from the available data, the regional geohydrology of the northeast Texas salt-dome basin, to describe the geohydrology of 4 of the 25 salt domes in the basin (Keechi, Palestine, Oakwood, and Mount Sylvan domes; fig. 11), and to make recommendations for further study. The purpose of the phase 2 study was to monitor the quality of surface waters in the vicinity of these four domes in order to identify potential anomalies that may be caused by effluent saline ground water and to differentiate geochemically saline waters resulting from dissolution of salt and saline connate waters.

Approach.—The phase 1 study was concerned principally with formations of Late Cretaceous and younger ages and consisted primarily of compilation and analysis of available data and interpretation of about 800 geophysical logs. The phase 2 study consisted of collecting samples of surface water for chemical analysis and measuring the flow and other stream properties.

Progress.—The salt within Keechi, Mount Sylvan, Oakwood, and Palestine domes presently extends to within 40–260 m of land surface and closely underlies major fresh and saline aquifers within the basin (Carr, Halasz, and Peters, 1980). Regional ground-water flow is mainly to the southeast in the vicinity of these domes, with gradients generally less than 0.80 m/km. Discharge from the artesian aquifers is across confining beds to other aquifers. Dissolution may be occurring at all four of the salt domes. With the exception of Oakwood dome, surface saline waters are reported at all of the domes. It is possible that subsurface saline ground-water plumes are present at all four

domes. Additional problems concerning the hydrologic stability of the Oakwood and Palestine salt domes are related to the disposal of oil-field waters in the caprock and solution mining of salt, respectively. Additional studies are required to determine the hydrologic stability of these domes. (Recently, the Palestine dome was dropped from consideration as a potential repository site.)

Additional geohydrologic studies, including a program of drilling, testing, and sampling, are recommended to evaluate conditions around the domes, to evaluate caprock hydrology, and to define better the regional geohydrology. It is recommended that improvements be made in numerical modeling of fluid flow and solute transport to permit better evaluation of rates of dissolutioning of salt and to estimate travel times for potential nuclide transport from a proposed repository to the biosphere.

The phase 1 studies have been completed and a report is in review. Sample collection and water-quality analyses for the phase 2 studies have been completed (Carr, Halasz, and Liscum, 1980).

References

Carr, J. E., Halasz, S. J., and Liscum, Fred, 1980, Water quality data for aquifers, streams, and lakes in the vicinity of Keechi, Mount Sylvan, Oakwood, and Palestine salt domes, northeast Texas salt-dome basin: U.S. Geological Survey Open-File Report OF 80–2037.

Carr, J. E., Halasz, S. J., and Peters, H. B., 1980, Geohydrology of the Keechi, Mount Sylvan, Oakwood, and Palestine salt domes in the northeast Texas salt-dome basin: U.S. Geological Survey Open-File Report OF 80–2044.

SALINA BASIN, NEW YORK, AND OHIO

The DOE has been investigating the suitability of bedded salt deposits in western New York and Ohio as potential sites for waste repositories. In support of this investigation, the USGS initiated a study of the occurrence of subsurface brines above and below the salt beds and of geologic structures revealed by remote sensing techniques.

INVESTIGATION OF SUBSURFACE BRINES

By S. E. Norris, Columbus, Ohio

Objective.—The objective was to investigate the occurrence, origin, and movement of deep-seated brines in permeable zones above and below the Silurian salt deposits in northeast Ohio and western New York.

Approach.—A two-phased approach was initiated. The first phase was a review of the literature for information on the occurrence, composition, and origin of the natural brines. The second phase was a program to measure hydraulic head, to collect samples for chemical analysis, to determine hydraulic properties of the water-bearing formations as oil and gas wells were drilled, and to collect pertinent hydrologic and hydrochemical data on existing wells.

Progress.—The literature review was completed. In New York, the collection of well data and chemical analyses from oil and gas companies was initiated. In Ohio, down-hole equipment was assembled for implementing work on phase 2 but the project was suspended by the DOE.

REMOTE SENSING

By Lawrence C. Rowan, Reston, Va.

Much of the Salina Basin is covered by extensive glacial deposits, and outcrops of consolidated formations are limited. Thus, interpretations of features observed by remote sensing techniques must be checked against the surface geology, logs of wells drilled for oil and gas exploration, and available seismic profiles. The basic problem is to differentiate features of surficial or near-surface origin from those which indicate major structures and to determine how these structures affect the salt deposits. The area of interest for waste disposal was in southern New York; the study was extended into Pennsylvania only to clarify the relationships among major structural features in the region.

Objective.—The objective was to define the regional tectonic framework of the study area by determining the relationship among lineaments shown on Landsat and other images and surface and subsurface structural features.

Approach.—Digitally and photographically enhanced Landsat images were analyzed to delineate landforms, especially lineaments, that might reflect subsurface structures. In New York and Pennsylvania, subsurface seismic data, oil and gas well data, an airborne magnetometer survey. and joint measurements were used to evaluate the geologic significance of the lineaments.

Progress.—Analysis of enhanced Landsat images of the study area show the presence of numerous lineaments and lineament zones, many of which are tens of kilometers long (fig. 12). Most of the major lineaments are probably related to fracture and fault zones whose morphological expression has been enhanced by glacial and fluvial erosion. Several of the north-south trending lineaments appear to reflect the presence of faults in the Precambrian basement which may have been reac-

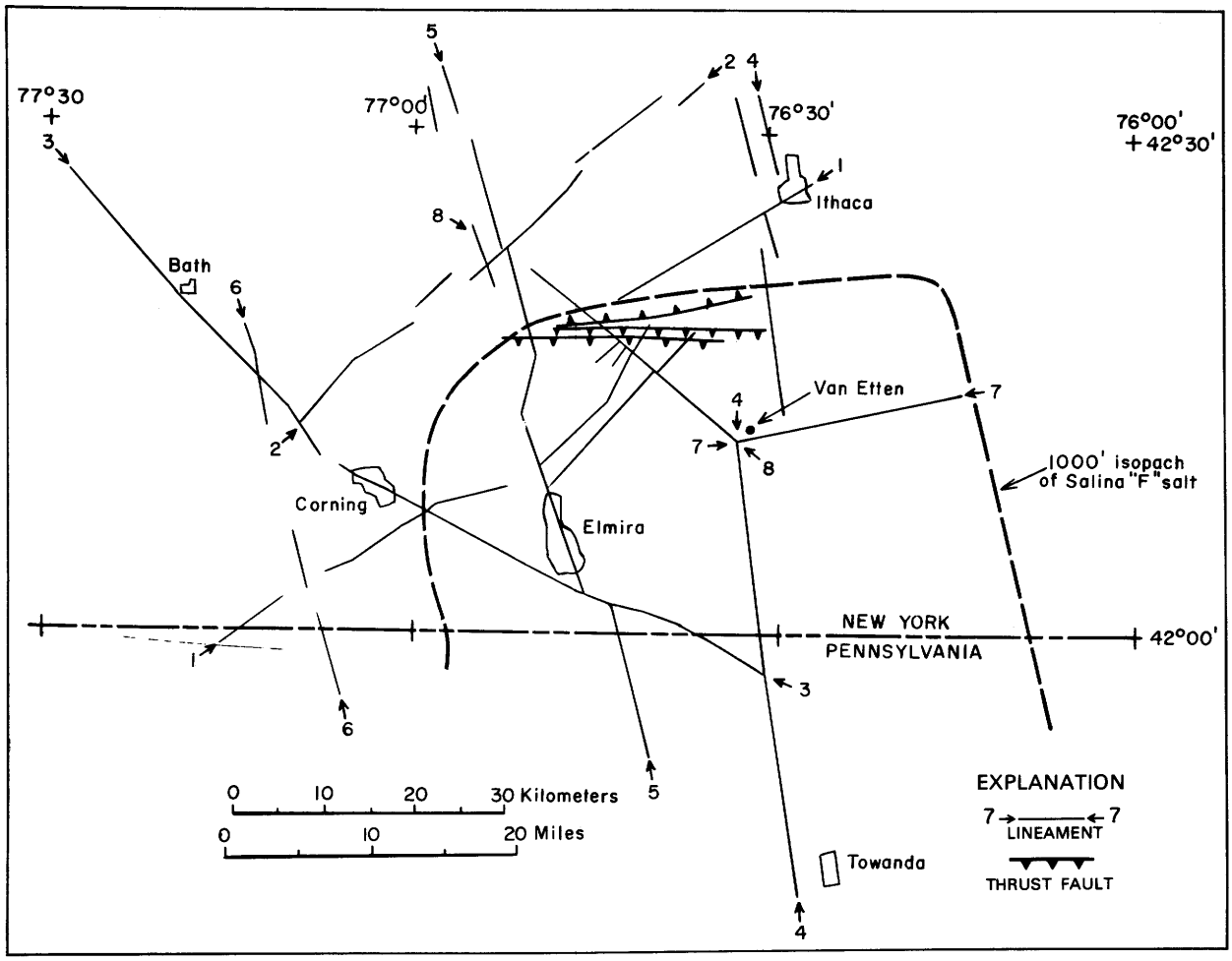

FIGURE 12.—Major lineaments in south-central New York State. Key to lineaments: 1, Cortland-Ithaca; 2, Watkins Glen-Taughannock; 3, Corning-Bath; 4, Van Etten-Towanda; 5, Seneca Lake-Elmira; 6, Painted Post-Blossburg; 7, Van Etten-Candor; 8, Van Etten-Odessa.

tivated at various times. Although joints do not appear to have controlled the development of these major lineaments, departures from regional joint trends along some of these lineaments further support the contention that these features are morphological expressions of faults and fracture zones.

The northeast-trending Cortland-Ithaca lineament system (number 1, fig. 12) correlates well with the projection from Pennsylvania of the northwest margin of the northeast-trending Rome trough, a major regional structure to the southwest of the study area. In Pennsylvania, this margin of the trough served as a depositional hinge line in Ordovician and later time, with the basin deepening to the southeast; the same appears true in New York but with a diminution in the amount of down-dropping as one proceeds to the northeast.

A structure contour map has been compiled on a Cambrian subsurface horizon at or near the basement-Paleozoic contact. Available data indicate that depth to this horizon increases abruptly by about 70 m near the Seneca Lake lineament, one of the north-trending lineaments which coincides with the western edge of the thick salt sequence in the Salina Group at about Elmira, New York. This change, involving a downward displacement of about 70 m to the east is consistent with the hypothesis that the lineament marks a hingeline which controlled salt deposition in the subsiding basin to the east. The east edge of the thick salt sequence in this basin is also the easternmost extent of the north-south trending concentration of lineaments.

Several existing seismic reflection survey lines for the Van Etten, New York, area were purchased from commercial sources and analyzed. From these and well data, structure contour maps were made for an area about 6 × 10 km that crossed two lineaments. These maps, which are for five different horizons, show the three horizons below

the salt to be less deformed than the two horizons above the salt. The fold and fault patterns below the salt differ considerably from those above in both trend and style. Some of the fault patterns in these lower horizons probably continue through the upper horizons to the surface with some lateral displacement. The two horizons above the salt show numerous faults trending both parallel and normal to the Alleghenian folds. The salt itself seems to have no reflecting horizons of any lateral extent, which suggests that it is strongly deformed. The general conclusion is that in this area the salt served as a zone of weakness along which the overlying rocks slid when they were faulted and folded by the formation of a decollement type of structure typical of the "thin-skinned" tectonics found elsewhere along the western margin of the Applachians (Pohn and Purdy, 1979). This detailed "sample" of subsurface structural conditions suggests that complex structures involving the salt may be common in this area.

Reference

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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 wastes, how they may be explored and characterized, and how various geologic and hydrologic processes may affect the integrity of a repository. Some of the work is being done at localities described in the preceding section because they provide convenient and suitable locations and needed supporting studies and data, but the results obtained should be applicable to other localities.

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

With three exceptions, the projects described below were supported by the USGS's direct appropriation; the work described in the sections entitled, "Salt-Brine-Waste-Canister Interactions" and "High-Frequency Electromagnetic Methods" was funded by the DOE and that under "Computer Simulation of Geologic Stability of a Repository" was funded by the NRC.

STUDIES OF ROCK TYPES AND ENVIRONMENTS FOR EMPLACING WASTES

WESTERN CRETACEOUS SHALES

By J. D. Bredehoeft, Reston, Va., and T. C. Nichols, Lakewood, Colo.

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

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

1. Does the low permeability suggested by the hydrologic model analysis indicate flow through the rock matrix, flow through small, closed joints and fractures, or flow through widely spaced, large fractures?
2. What are the problems, particularly rock mechanics problems, associated with putting hot wastes in highly montmorillonitic shales? High temperature wastes would cause a phase change in clay minerals with an associated release of water. Would the physical properties of the shale change during this process?

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

Approach.—The approach will involve completing a hydrologic model analysis of a large region as a prototype for studying the Cretaceous shales. Concurrently, core drilling and in situ testing will be done to obtain laboratory and field data on the permeability of the Pierre Shale. In addition, field measurements will be made to determine in situ stress and other physical and engineering properties of the rock. Constant-strain rate and creep tests will be conducted on the cores

under pressure and temperature conditions to be expected in repositories. Four shallow test holes will be strategically located to sample the entire stratigraphic sequence of Cretaceous shales above the Dakota aquifer.

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

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

Progress. – Test holes were drilled at two sites in South Dakota during the summer of 1978. Extensive in situ hydrologic tests and geophysical well logging were conducted at one site. A complete set of cores was obtained at both sites.

The in situ tests suggest a low permeability for the shale, approximately 1×10^{-10} cm/s.

One suite of cores was analyzed by conventional consolidation tests in the U.S. Army Corps of Engineers Laboratory at Omaha, Nebr. These results indicate a low matrix permeability ranging from 1×10^{-10} cm/s to 1×10^{-11} cm/s.

In view of the low permeability values obtained for the shale, a new approach to direct measurement of permeability in the laboratory is required. A research contract has been given to Terra Tek in Salt Lake City, Utah, to develop the necessary techniques.

Modeling of the regional flow in South Dakota indicates that flow through the Pierre Shale is primarily through fractures. This suggests the need for further work on the density and size of the fractures.

The work to date on the mechanical properties of the shale has been directed toward developing a viscoelastic constitutive stress-strain law for its behavior. This relationship has been developed on the basis of a review of previous investigations along with a limited number of laboratory tests.

Specifically, the following was accomplished as a result of research on the physical properties of the Pierre Shale:

1. A literature search revealed that there is a paucity of pertinent data on the physical properties of the Pierre Shale, especially for the geographic area of investigation. Existing data such as residual shear strength, unconfined compressive strength, elastic moduli, and consolidation-swell tests have been obtained for shallow sites, and they demonstrated considerable variability in these properties. Very few data were available that described creep behavior and the effects of elevated pressures and temperatures on the shale.
2. In connection with the development of field measuring techniques, studies were conducted to evaluate methods for monitoring rebound creep deformations on core sample. Both electronic and mechanical systems were designed and evaluated. Three mechanical systems (micrometers), operated for 2 months have demonstrated maximum standard deviations of 6 μm with operator errors of $\pm$ 7 μm. On the other hand, electronic inductance transducers are monitoring core deformations as small as 5 μm with no operator errors. In addition, these devices can be monitored continuously.

   To ensure that only rebound creep of cores is measured, methods have been developed to keep the cores at a constant weight and temperature while they are being measured.
3. Laboratory equipment has been designed and is being constructed to carry out preconsolidation tests on the shale cores. The preconsolidation tests precede constant strain rate and creep tests that are carried out in the same loading apparatus. Thus, preconsolidation is accomplished under the same temperature and pressure conditions as the constant strain and creep tests, and they can be considered as combined tests. The tests are being conducted at pressures up to 100 MPa and temperatures up to 200°C. The strain-rate tests will vary from 10^{-5}/s to 10^{-8}/s. Three combined tests were run on Pierre Shale cores taken from storage at the University of Colorado; two were tested at 50 MPa, 25°C, and strain rates of 10^{-5}/s, and one was tested at 50 MPa, 200°C, and 10^{-7}/s.

WATER FLUX IN THE UNSATURATED ZONES OF DESERTS

By Jacob Rubin, Menlo Park, Calif.

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

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

Objective.—The objective was to determine, for several types of desert conditions, long-term averages of the downward water fluxes in the unsaturated zone.

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 will be extracted estimates of long-term flux trends. These estimates will be compared with analyses based on isotopic data and with simulation based predictions.

Progress.—The required professional personnel were recruited. The available office space is being remodeled as a laboratory to accommodate especially those laboratory operations concerned with studying samples collected in the field.

Detailed plans were made for the first stage of the study. Special field-sampling equipment and laboratory apparatus are being designed and constructed. Preliminary tests were made of new methods for measuring water flux.

GRANITE AND RELATED CRYSTALLINE ROCKS

By Harry W. Smedes and Zell E. Peterman, Lakewood, Colo., and James D. Byerlee, Menlo Park, Calif.

Crystalline igneous rocks such as granite and some metamorphic rocks such as gneiss are abundant in the Earth's crust and have great strength, structural and chemical stability, heat tolerance, and low porosity. Their water content generally is low and is contained in fractures and in hydrous silicate minerals. Fractures are commonly filled with clays, hydrous oxides, and other minerals with good sorptive properties. In view of these properties, several countries including the United States, Canada, Sweden, and the United Kingdom are evaluating crystalline rocks and their terranes for their suitability, respectively, as host media for emplacing wastes and as areas to locate potential repository sites.

A major problem presented by crystalline rocks is that of characterizing their hydrologic properties. Near the surface of the earth, granites and other crystalline rocks have been fractured through cooling and stresses in the crust. Intercrystalline permeability is generally low, but water flows through interconnecting fractures. At shallow levels, fracture permeability decreases markedly with depth, but the distribution of fractures at anticipated repository depths is poorly known. By selecting areas with appropriate thermal and tectonic histories, it may be possible to identify crystalline rock terranes that have a much lower fracture permeability than others.

Objective.—The objective was to determine where and at what depths crystalline rocks with suitably low fracture permeability could be found.

Approach.—Maps of the United States summarizing geologic data such as active faults, seismicity, heat flow, hot springs, rates of uplift, and major occurrences of crystalline rocks provide a way of screening regions for the identification of areas that may warrant more detailed study. Specific laboratory investigations include the study of naturally occurring isotopic systems to identify the effects on permeability of rock-water interaction, geochronology studies to elucidate the nature and timing of geologic events that may have affected the permeability of rocks in particular terranes, and permeability measurements at temperatures and pressures anticipated at repository depths.

Progress.—A report has been drafted for the DOE by Harry W. Smedes that summarizes the

distribution of crystalline rocks and a number of geologic factors that must be considered in selecting regions for more detailed investigations.

Chemical, petrologic, isotopic, and geochronologic data have been reviewed for several Precambrian terranes including those of the midcontinent region. A synthesis of geochronologic data for Archean rocks identifies some regions that have not been disturbed by major thermal or tectonic events for the last 2.5 b.y., although some younger faulting has occurred. In other regions, Precambrian granitoids have been involved repeatedly in major tectonic events in both Proterozoic and Phanerozoic time. Regions with relatively simple geologic histories and low seismic activity may have a greater probability of containing terranes of suitable granitoids.

Conventional geochronologic methods generally record geologic events for which the temperature exceeded 200–300°C. In an attempt to document and understand lower temperature events better, a fission-track dating study of the mineral apatite is being conducted in the Precambrian shield of the north-central United States. This method depends on the preservation of fission tracks, below 100°C, that are produced by trace amounts of uranium in the apatite. The determined ages indicate the last time the rocks cooled below this temperature. Limited data obtained thus far indicate that some parts of the region were cooled through the 100°C isotherm in the early Paleozoic (400–500 m.y. ago), whereas adjacent parts remained at higher temperatures until the late Paleozoic (ca. 250 m.y. ago). This region is characterized by numerous fault-bounded blocks. A major goal of the study is to determine the nature of the uplift events that resulted in the differential cooling such as regional warping or tilting or movement along ancient faults.

In many granitoids, a major fraction of the naturally occurring uranium is loosely bound in metamict minerals and in other atomic sites in minerals that can be reached by circulating fluids. Research on selected core samples is continuing to evaluate the usefulness of the uranium-decay system in assessing the effects of rock-water interaction that may have occurred in the past. A survey of published U-Pb data indicates that many granitoids have lost uranium in relatively recent geologic time. Limited data suggest that this loss may be more severe in regions that have been disrupted by younger tectonic events than in regions of long-term geologic stability. However, the nature of the hydrologic regimes in these contrasting terranes has not been determined and may account for some of the observed differences in the behavior of the isotopic systems.

James D. Byerlee is studying in the laboratory the intercrystalline permeability of crystalline rocks subjected to a temperature gradient. The initial work is being done on the Westerly Granite of southern New England because it has been well characterized by other research. In the first experiments, permeability decreased with time, probably due to solution and redeposition of minerals as a function of temperature. Alteration of minerals to more hydrous varieties may also have clogged the pores.

ANHYDRITE

By Walter Dean and William Thordarson, Lakewood, Colo.

Anhydrite has been suggested as a possible host medium for emplacement of radioactive wastes. It occurs in thick, relatively homogeneous beds of low permeability in several areas west of the Mississippi River. The thermal conductivity of anhydrite is as high as that of rock salt, both rock types having values near the high end of the range observed in rocks. The thermal expansion of anhydrite is similar to that of most common rock types and is only one-third that of rock salt. It contains very little intercrystalline water, and although it is more soluble than most rocks, it is much less soluble than rock salt. The solubility of anhydrite in either weak or strong brines decreases as temperature is increased up to 230°C, which means that, in contrast to rock salt, intercrystalline fluids would migrate away from a source of heat as long as the rock temperature was below 230°C. Anhydrite is brittle and fractures in the range of anticipated repository temperatures and pressures. Unlike salt, the fractures that develop do not self heal. However, anhydrite hydrates to gypsum ($CaSO_4 \cdot 2H_2O$) in the presence of water of low salinity. This hydration is accompanied by an expansion in volume of 62 percent which possibly could prevent further water penetration by sealing the fractures. Alternatively, the same expansion could cause fracturing and structural damage to the repository if sufficient water continued to obtain access to fresh surfaces of anhydrite.

Objective.—The objective was to inventory the geologic and hydrologic properties and specific physical and chemical characteristics of anhydrite in the United States and to identify apparently favorable areas for more intensive investigation to determine the possibility of locating potential repository sites.

Approach. – On the basis of a survey of available data, all major evaporite deposits within the conterminous United States were evaluated in terms of the statigraphic relationships of anhydrite units to the entire deposit, the thickness of the entire deposit, and the relative abundance of anhydrite. In addition, beds of anhydrite thicker than approximately 30 m and occurring at depths between 300 and 1,500 m were characterized in as much detail as possible.

Progress. – The inventory has been completed and a report is in the review process. All of the major anhydrite deposits within the conterminous United States are contained within 25 structural basins or geographic areas. Within these basins are some 20 areas in which the anhydrite has the requisite thickness and depth described above (fig. 13). The areas underlain by the greatest apparent thicknesses of anhydrite deposits in the specified depth range are in the Picacho Basin, Arizona, and the Castile Formation in the Delaware Basin, Texas and New Mexico.

Test data on the following mechanical and thermal properties were compiled from the literature: density, porosity, thermal conductivity, sonic velocity, Young's modulus, Poisson's ratio, and shear moduli. Ductile deformation of anhydrite occurs at higher temperatures than for halite. Anhydrite's ultimate strength at low confining pressures is two to three times that of halite, and it is ductile under these conditions.

An inventory was prepared on the general hydrologic characteristics, porosity, hydraulic conductivity, and transmissivity of anhydrite, based on published data from outcrops, tunnels, mines, wells, and springs. Data on anhydrite and related phases of calcium sulfate have been evaluated from the available literature for thermodynamic properties, crystallography, phase equilibria, solubility, kinetics of reactions, sorption capacity for radionuclides, and effects of radiation.

The thickest anhydrite beds are in the Castile Formation in the Delaware basin of southeastern Mexico and adjacent southwestern Texas. The entire Castile Formation is up to 600 m thick and contains several anhydrite beds 100–300 m thick interbedded with thick beds of halite. The Picacho Basin of Arizona probably contains the thickest sequence of anhydrite in the world, but knowledge of this sequence is based only on well cuttings and mechanical logs of one well. The sequence of anhydrite and clastics in the Picacho Basin is 1,800 m thick and consists of about 65 percent anhydrite with many beds of anhydrite between 10 and 37 m thick. Unlike most other occurrences of anhydrite, where the anhydrite is interbedded with either car-

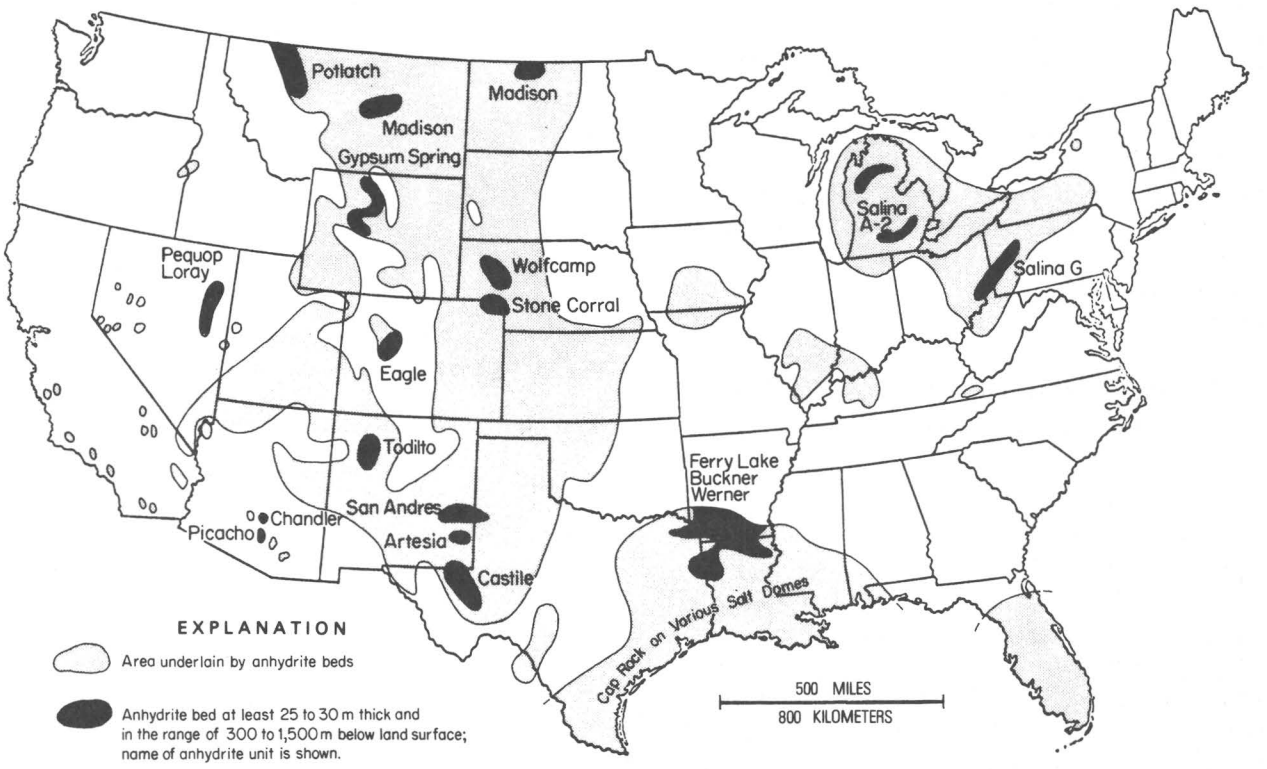

FIGURE 13. – Map showing areas where thick beds of anhydrite are present at moderate depths in the United States.

bonates or halite, the Picacho Basin anhydrite is interbedded with siltstone and claystone which would have a high capacity to adsorb radionuclides. An abundance of data is available on the physical properties of anhydrite, but most of this was obtained on relatively pure materials and under laboratory conditions. The relevance of these tests to natural conditions should be investigated in the field on more commonly occurring forms of anhydrite; it is unclear to what extent laboratory tests on pure anhydrite are applicable to beds of nodular or laminated anhydrite, the most common forms of naturally occurring anhydrite. Some data were inadequate in quantity or quality for thorough evaluation: thermal chemistry and crystallography of the lower hydrates of calcium sulfate, sorption of radionuclides, the effects of radiation on the chemistry of anhydrite, and the effects of pressure on the solubility of anhydrite in bittern brines. Thermochemical and crystallographic properties for the lower hydrates, bassanite and "soluble anhydrite" are unsatisfactory. These lower hydrates are metastable phases but are important in assessing the kinetics of alteration of anhydrite under water saturated conditions. The adsorptive capacity of anhydrite for radionuclides appears to be considerably greater than halite, but this conclusion is based on limited data. Data should be obtained on the effect of pressure on the solubility of anhydrite in bittern brines to make sure that the retrograde solubility that would cause water to move away from a source of heat holds true for these brines also.

A major problem in need of resolution is to identify the conditions under which the conversion of anhydrite to gypsum would help to seal a repository and those under which the conversion might result in damage by the forces generated from the change in volume.

SALT-BRINE-WASTE-CANISTER INTERACTIONS

By R. W. Potter, Menlo Park, Calif.

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

A thermal pulse peaking many tens of years after waste emplacement and lasting hundreds of years is currently being anticipated in the design of repositories. The maximum temperature to be attained over tens of meters of salt in which wastes have been buried will probably be kept below 100°C by the choice of canister spacing or thermal output. However, surface temperatures of the canisters may be as high as 300°C.

The focus of this project is to characterize the physico-chemical properties of the fluids and solids in the system Na, K, Ca, Mg/Cl, SO_4, and Br and reaction products formed by interaction of these components with those of the integrated waste disposal system. These data will help in the design of the waste disposal system, water getters, and radionuclide adsorbers.

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

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

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

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

Progress. – Several workers previously have developed and applied equations for calculating the migration rate of fluid inclusions under a thermal gradient in rock salt. The results vary widely from as little as 7 L to 43 L arriving at a canister in 10 yr. All the models are based on a diffusional mass transport mechanism rather than a mass transport mechanism based on convection, which would yield significantly higher migration rates. Part of the cause for the scatter in the results, based on the diffusional mass transport mechanism, is that much of the data required for the calculations is not available, and the various workers have had to estimate the requisite parameters.

Two of these parameters are the density of the saturated solution (ρ_s) and $\partial\chi/\partial T$, where χ is the concentration of NaCl in the brine. Measurements have now been completed of ρ_s for NaCl-H_2O up to 104°C, $\partial\chi/\partial T$ up to 100°C for a group of brines and up to 270°C for WIPP–A, a synthetic brine used to simulate those at the WIPP site in New Mexico.

The two available literature sets for ρ_s in the NaCl-H_2O system do not agree where they overlap. Our experimental measurements of ρ_s for NaCl-H_2O extended and agreed with the values of Haas (1976) within the tolerances of the measurements. The differences in the ρ_s values would yield migration rates of only a few tenths of a percent faster than the ρ_s data in the literature.

The $\partial\chi/\partial T$ values of some representative brines measured in this study are significantly greater than those of NaCl solutions. These values used in the migration equations will yield significantly greater migration rates than the $\partial\chi/\partial T$ values for NaCl solutions.

Various field experiments were designed to measure the amount of brine that will migrate to a heat source in salt as a function of time and to measure brine movement by collecting steam and weighing the amount of condensate. The weight of condensate is then assumed to be equal to the amount of the brine that has arrived at the heater, but the condensate collected is actually only part of the water because only a fraction of the water in the brines can be converted to steam. As the brine boils off water, it becomes saturated with solid phases that contain structural water, and the boiling temperature of the brine rises to the ambient temperature where boiling ceases.

In the case of a simple salt, the only correction required is that for the amount of salt dissolved in the brine. For example, for sodium chloride solution at 200°C with a solubility of 31.898 weight percent NaCl, the ratio of original brine to condensate is 1.468. However, for bitterns which can have very high boiling points and form highly hydrated salts, the ratio is significantly larger. These ratios were measured directly as a function of temperature and bittern composition by heating a known mass of bittern of specific composition in a sealed autoclave at a known temperature and weighing aliquots of steam that were removed successively until no more steam could be extracted from the autoclave. The ratio was found to range from about 1.7 to 10, depending on the temperature and the composition of the bittern.

Although WIPP–A is not a typical brine of the type to be expected in residual fluids in salt, it has been widely used as a brine for corrosion, sorption, and modeling studies. The following properties were measured for WIPP–A: (1) solubility of NaCl up to 300°C, (2) vapor pressure up to 300°C, (3) vapor pressure of NaCl saturated WIPP–A up to 300°C, (4) the density of WIPP – A up to 102°C, and (5) the amount of water that can be removed from WIPP–A as a function of temperature.

The corrosion of copper in representative bitterns has been measured up to 217°C by standard weight-loss techniques. The results indicate that rates as high as 40 mm/yr are obtained in 24-h runs, while rates of about 1 mm/yr are obtained in 912-h runs. The lower values proved to be deceptive as the solutions are saturated in copper after 72 h at 217°C; the corrosion rate at this time was 10 mm/yr. The lower corrosion values resulted from assuming that the corrosion continued during the whole 912-h period, when in fact corrosion had ceased at 72 h due to the attainment of equilibrium between the brine and metallic copper. Thus, long-term runs can produce misleading corrosion rates if equilibrium between the metal and brine is achieved rapidly.

To develop means of reducing or halting brine movement to the waste canisters, the phase equilibria and crystal chemistry of tachyhydrite, $CaMg_2Cl_6 \cdot 12H_2O$, are being studied. This compound is stable in equilibrium with bitterns up to 150°C and possibly as high as 200°C. Crystallographic studies suggest the possibility of synthetic analogs which may be even more effective water absorbers.

Much work has been done to support the Avery Island, Louisiana, heater experiments being conducted by the DOE. A detailed study of the brines present in the salt dome has been completed and demonstrates the existence of three distinct brine types. A synthetic bittern for the brine migration experiments has been designed and prepared. Its

isotopic composition is so different from the salt-dome brines that as little as 1 ppt of the tagged brine can be identified in a mixture of the native brines and the tagged brine.

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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 geophysical and geochemical techniques are adequate or can be modified to provide the needed information. For other aspects, some new techniques are being developed which can make the task easier, give more accurate results, or provide desirable information that is unobtainable at present.

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

The research in geochemistry involves (1) the development of a method to measure the water content in salt beds indirectly by means of a borehole probe and (2) the improvement of existing methods and the development of new methods of isotopic dating of rocks, soils, and minerals that will allow dating of geologic events and features not possible at present. Improvements in the accuracy of dating geologic events and features will help to refine our knowledge of the geologic history of an area and improve our ability to make extrapolations into the future.

REMOTE SENSING

By Kenneth Watson, Lakewood, Colo.

Previous experience with regional studies aimed at exploration of an area for possible waste repository sites (see sections on Paradox Basin, Utah, and Salina Basin, New York and Ohio) indicates that the combinations of remote sensing techniques with Landsat and other imagery, gravity, and magnetic methods provide a powerful tool for identifying major structural features, discovering unmapped faults and fractures, and generally locating features which need more investigation if the area is to be adequately characterized geologically and hydrologically.

Objective.–The objective was to develop and evaluate remote sensing techniques which can be

used in conjunction with other geophysical and geologic data to determine the presence or absence of structural features of significance to characterization of a potential repository site.

Approach. – Initial emphasis in the remote sensing work is being placed on the use of thermal-infrared techniques to detect structures by sensing density changes and moisture-rich zones and to map geologic materials by their differences in thermal properties. Current studies are aimed at developing an understanding of the different ways in which various types of structures formed by deformation with little or no plastic flow (faults, joints, shatter zones, etc.) affect the thermal properties of the bedrock in which they occur and how these effects can be distinguished in thermal images obtained from aircraft.

Progress. – A preliminary literature search shows that some structures have been detected on thermal images but that a physical explanation for the phenomenon is lacking. Consequently, it is difficult to predict which structures will be detected, when the thermal data should be acquired (time of day, season, etc.), and how the data should be analyzed. Thermal studies indicating or suggesting the presence of folds have been generally better documented and understood than such studies of faults, joints, shatter zones, etc., features especially significant for repository siting. Because folds are recognizable by the contrasting thermal properties of the interlayered rocks, analysis of thermal images has been shown to be a very effective means of detecting structures in terrain with low relief, shallow slopes, and a veneer of weathered materials, areas that are often difficult to evaluate by field mapping or aerial photography.

The physical properties that determine the thermal characteristics of geological materials are reasonably well understood. A thermal model relating surface temperature, physical properties, and the relevant meteorological factors is under development.

PETROPHYSICS

By Kenneth Watson, Lakewood, Colo.

The interpretation of geophysical observations rests on understanding the physical properties of the rocks and their relationship to geologic conditions and the geophysical measurements. Often such measurements will vary by as much as many orders of magnitude as a result of changes in environmental and, thus, observational conditions.

Objective. – The objective was to acquire physical property information from laboratory measurements to aid in the interpretation of surface, borehole, and between-borehole geophysical measurements.

Approach. – Activities in petrophysics have been focused on the measurement of an electrical property (non-linear complex resistivity) which is very sensitive to ground-water Eh and pH as well as to several specific chemical reactions.

Progress. – Results of initial laboratory measurements of non-linear complex resistivity were sufficiently encouraging that a field borehole test was attempted using modified equipment from the laboratory. Preliminary analysis showed that the system was able to log and identify the presence of materials such as sulfides, clays, and relatively non-reactive material such as sandstone. A laboratory system has been developed to study water-rock electrical interactions through simultaneous measurements of hydraulic conductivity, streaming potential, and non-linear complex resistivity as functions of temperature, confining pressure, and differential pore pressure. A file library of the signatures of the non-linear complex resistivity of various geologic materials has been started using computer storage of the signatures.

SURFACE SEISMIC METHODS

By Hans Ackermann, Lakewood, Colo.

Controlled-source seismic methods, both reflection and refraction, are useful tools in exploring for suitable sites for nuclear waste repositories in areas of layered sedimentary rocks with relatively simple structures; these methods generally offer better resolution of subsurface variations in structure and lithology than other geophysical techniques. While surface seismic techniques have been used for many years in petroleum exploration and a variety of equipment and techniques are readily available, the emphasis has been on deep penetration, whereas exploration for waste repository sites will require higher resolution at much shallower depth – from a few hundred to 1,000 or 2,000 m.

Although data processing techniques may be readily scaled to shallower targets, data acquisition techniques may not because of the difficulty in scaling the frequency of the seismic pulse and the surface wave which is a major source of noise. Some improvement has been made during the past few years by using the higher frequency portion of the seismic pulse (Farr, 1976).

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

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

Approach.—Presently used methods of interpreting seismic refraction data assume seismic layers of constant velocity for calculating the depth to these layers. This assumption is invalid and not only results in incorrect depth values but does not permit the delineation of lateral velocity changes which are indicative of lateral changes in physical properties within the layers. However, refraction data contain all the information necessary to calculate both depth variations and lateral velocity changes, and this can be done by means of interactive ray-tracing computer programs.

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

Progress.—The interactive ray-tracing computer programs which will improve the interpretation of seismic refraction data have been written and tested with both theoretical data and a large amount of field data. The results show excellent agreement between computed depths from seismic refraction surveys and depths actually recorded from drilling. Furthermore, lateral changes in the physical properties of the rocks can be delineated on the basis of interpreted lateral velocity changes. There is little doubt that in areas where seismic refraction is applicable to subsurface geologic problems, the new computer interpretation methods will provide greatly improved results. Manuscripts describing the new methods are in preparation.

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HIGH-FREQUENCY ELECTROMAGNETIC METHODS

By Raymond D. Watts, Lakewood, Colo.

Inhomogeneities and structural flaws in a rock mass are potential problems for its use as a host medium for radioactive wastes. Radio waves seem to offer a good means of finding such inhomogeneities and flaws. Unfortunately, radio probing of rock at present is comparable in its stage of development to seismic prospecting in the 1940's and 1950's: some basic capabilities exist, but considerable improvement is needed in (1) instrumentation, (2) understanding of the wave-propagation phenomena, and (3) interpretive tools and techniques.

Electrical properties of rocks are very strongly affected by the water in the rocks. Low porosity, unfractured rocks contain very little water and are quite resistive; porous rocks that contain more water are less resistive. Thus, a rock's electrical resistivity may be, in a gross way, proportional to its suitability as a host medium for wastes. Rock salt and granite are known to be excellent media for radio probing, largely due to their dryness. There is at present a lack of understanding of the fundamentals of radio wave propagation in geologic media. A suitable radar operating frequency cannot be selected without first characterizing radio wave propagation, absorption, and scattering in the various rock types. Because these measurements involve bulk variations in the rocks, the measurements cannot be made in the laboratory.

To be useful in the early stages of repository exploration, radar must be functional from boreholes; mined openings will not be initially available for radio probing activities. The 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.

The work described below was funded by the DOE.

Objective.—The objective was to determine the capabilities and limitations of high-frequency elec-

tromagnetic techniques for evaluating the homogeneity and continuity of salt and to develop and field-test prototype equipment.

Approach. – Preliminary experiments were conducted above ground with the borehole simulated by a plastic tube filled with brine in which the antenna was placed. The strength of the transmitted radio signal was measured after passing through the wall of the tube by an appropriate receiving antenna, amplifier, and oscilloscope. Various combinations of antennas, baffles, and frequencies were tested to reduce attenuation to a minimum and to determine useful operating frequency ranges.

Progress. – An outdoor antenna test range was set up 80 km west of Denver to avoid interference from radio frequency sources. The radiation pattern of a dipole antenna immersed in a plastic pipe filled with brine to simulate drilling fluid was measured. The radiation pattern was measured in the plane perpendicular to the antenna to determine possible effects of an off-center antenna position.

The radiation pattern of the transmitted signal varied only by about 20 percent when the antenna was moved from the center of the tube to the side. However, the most significant problem was the extreme attenuation of the transmitted signal by the brine; attenuation of about 30 dB was observed when an antenna without baffles was immersed in the brine. In an operating situation, both the transmitted and the received signals would pass through the brine, and a net signal loss of 60 dB (reducing the voltage by a factor of 1/1000) would result.

Attenuation of the signals was due to currents flowing in the brine in the opposite direction from the currents flowing in the antenna. Antenna housings were designed to break up the countercurrents. One antenna housing was constructed with baffles that sealed perfectly against the wall of the borehole. At frequencies above the minimum resonant frequency of the antenna in free space, there was a loss of 5–10 dB in comparison to the antenna performance in free space. When the experiment was repeated with baffles that did not completely seal against the tube walls, an additional loss of up to 5 dB was measured. This was an improvement of 30–50 dB in two-way loss in comparison to an unbaffled antenna system in brine.

The experiments indicated that antenna performance, nearly as good as that in air, can be obtained in brine. Consequently, holes would not have to be pumped dry to use this technique. The design using annular baffles has the added advantage that it automatically centers the antenna in the hole, so that the radiation pattern around the hole will be nearly uniform.

There may be other approaches to the problem, such as the use of the brine itself as a radiating element. This could be much easier to implement mechanically, since there would be no need to build baffles that seal effectively against the borehole walls. This concept will also be tested.

BOREHOLE GEOPHYSICAL LOGGING

By W. Scott Keys, Lakewood, Colo.

Test drilling is one of the most useful exploration methods for the identification and characterization of waste-disposal sites and for determining the extent of subsurface migration of radionuclides in ground water. Borehole geophysical logging and measuring devices are an essential part of test drilling.

Of all the factors involved in site characterization, fluid (and waste) flow in rock fractures is one of the most significant and least understood. Borehole geophysical logging can be useful in determining the water transmitting capability of fractures intersected by boreholes.

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

Approach. – The research is subdivided into those borehole geophysical techniques useful in developing site selection criteria and those suitable for monitoring radioisotope migration in ground water. Prominent among the first group are nuclear, acoustic, and resistivity devices that provide information on lithology, porosity, and moisture distribution. In the second group, which may provide data on waste migration, are borehole gamma spectrometry and activation analysis and flowmeter, temperature, and fluid conductivity logging. It is important to apply a complete suite of these logging and measuring devices during site selection and characterization studies and to establish baseline data for periodic monitoring in the future. All logs made at the various waste disposal sites are digitized on magnetic tape so they can be plotted by and analyzed with the computer. A computer data base will aid in future monitoring at the sites.

Progress. – The acoustic televiewer log has been used to determine the location, orientation, and aperture size of fractures in both shallow and deep waste-disposal investigations (Keys, 1979; Keys,

and others, 1979). The televiewer was used to demonstrate that unfractured rocks are very rare even at depths of thousands of meters.

Studies were made of the acoustic wave form. Acoustic logging devices with transmitter frequencies on the order of 30 kHz provide sound waves which can penetrate a few meters into the formation surrounding the borehole, yet the wavelengths are short enough to provide detailed information concerning fracture properties and orientation. Examination of wave propagation in the vicinity of fractures identified in a test well in igneous rock in Canada suggests at least two ways in which the wave form is related to the characteristics of fractures. Enhanced shear energy conversion adjacent to a fracture appears closely related to the hydraulic mobility of fluid within open fractures, while the attenuation of a portion of the wave record, referred to as the tube wave, appears to discriminate between open and closed fractures.

Accurate and dependable borehole gamma spectral probes have been developed and utilized at several sites to identify specific gamma-emitting waste radioisotopes that are migrating in ground water from disposal sites.

A theoretical model has been developed to aid in the quantitative interpretation of borehole gamma spectral data. The geometric and adsorption effects of cylindrical scintillation detector crystals have been calculated theoretically and verified experimentally. A calibration procedure has been developed to determine the efficiency of crystal detectors and photomultiplier tubes through the use of point sources. Also, a computer model of the borehole environment has been developed and tested experimentally. This theoretical model corrects for the effects of the following factors: probe housing, attenuation both above and below the crystal, borehole fluid, drill pipe, borehole size, thickness of a contaminated layer, radius of influence, and porosity and density of the rocks. Experiments have been conducted to test this model using mixtures of quartz, gravel, sand, and liquid contaminant under saturated and partially saturated conditions and for different porosities.

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ACOUSTIC AND ELECTRIC TECHNIQUES

By J. J. Daniels, Lakewood, Colo.

Objective. – The objective was to develop and test new borehole geophysical techniques for locating geologic inhomogeneities that are beyond the range of detection by conventional well logging probes.

Approach. – Hole-to-surface, direct-current resistivity sytems are being developed together with field systems capable of operating to depths of 2,000 m.

Hole-to-hole acoustic surveys have the potential capability of detecting vertical as well as horizontal, structural, and lithologic features such as faults, fracture zones, lenses, alteration zones, and cavities. Multiple sources and receivers are positioned at various depths in vertical holes spaced a few tens of meters to a kilometer apart to detect transmitted and refracted acoustic events originating from a high-power, repetitive, nonexplosive source. The results are interpreted by means of specialized computer modeling procedures.

A magnetic susceptibility probe of high sensitivity is being developed and tested. It will be useful for defining the amount of mineralogic alteration and hence the physical competency of volcanic tuffs, as well as for giving an indication of variation in moisture content in high-resistivity rocks such as salt and granites.

A borehole magnetometer of sufficient sensitivity to be used as a receiver for hole-to-hole electromagnetic measurements is being developed.

Progress. – Hole-to-surface, direct-current resistivity measurements at Salt Valley, Utah, clearly defined the relative variations in the depth of the salt-caprock interface. Similar measurements in volcanics at the NTS clearly defined fracture zones a few hundred meters laterally from a borehole.

An acoustical sparker source has been acquired and successfully tested in the laboratory. It will be used to detect fracture zones and other lateral geologic changes away from the borehole.

A magnetic susceptibility probe approximately 10 times more sensitive than any previously available probe has been developed and successfully tested at Salt Valley, Utah, where its readings correlated with variations in moisture content in the salt. A borehole geophysical truck has been ob-

tained to house a receiver for hole-to-hole electrical and acoustic measurements.

A preliminary study to determine the feasibility of developing a high-sensitivity, superconducting borehole magnetometer to be used as a receiver for hole-to-hole electromagnetic measurements has been completed by a contractor, and a prototype cryogenic dewar was delivered for the initial phases of testing. USGS scientists are working with researchers at the National Bureau of Standards to develop a prototype receiver that will measure three orthogonal components of electromagnetic signals in a dry hole.

NEUTRON ACTIVATION METHODS TO MEASURE WATER CONTENT IN SALT DEPOSITS

By Frank E. Senftle, Reston, Va.

Because of the potential hazards to a repository resulting from the presence of water in salt deposits, a method to measure the moisture content in the range of 0.1–1.5 percent H_2O with a borehole probe would be useful. Though salt has been assumed to be essentially dry, water does occur in cracks and vacuoles and tends to move toward a source of heat because the solubility of salt in water is higher at higher temperatures; the water (or brine) dissolves the vacuole wall on the hotter side and precipitates salt on the cooler side. The composition of such fluids and the amounts that would ultimately move into contact with the canister and backfill are important factors to be considered in the design of a repository system, since the fluids could reduce the mechanical strength of the salt, corrode the canisters, and leach the radionuclides from the waste form.

Objective. – The objective was to test the feasibility of measuring the water content of salt deposits by means of neutron activation and high-resolution gamma ray spectrometry using a borehole probe.

Approach. – For mineral exploration, the USGS has previously developed a neutron activation borehole probe which is now being applied to the problem of measuring the water content in salt. The probe, which is 7 cm in diameter and 2 m long, contains a californium-252 neutron source and a high-resolution gamma-ray detector. The range of penetration and detection into a relatively dry salt bed depends on the energy of the neutrons and will be about 60 cm from the borehole. Measurements could be made every 50–60 cm down a borehole to log the distribution of water. The plan is to test in the laboratory several possible neutron activation techniques which might be used to determine water content. The techniques would be evaluated for their sensitivity, possible gamma-ray interferences, and lower limits of detection. The borehole probe would be calibrated in a laboratory borehole facility and finally tested in the field in a salt deposit.

Progress. – Neutron capture gamma-ray spectra were made in the laboratory in 90-kg samples of dry NaCl and in brines, using a ^{252}Cf fission neutron source, in order to study the relative peak intensities, interferences, and other characteristics of the NaCl spectrum. Spectra were taken using various neutron source-to-detector distances, source intensities, and other conditions affecting sensitivity. Concurrently, rock salt was obtained from four different mines; each sample had a different average water content. Simulated boreholes were constructed from steel casks 1.3 m in diameter and 1.5 m tall, with a 10-cm-diameter pipe along the axis; each cask was filled with about 2,300 kg of fine rock salt and hermetically sealed. Four of the casks were filled with salt just as it was received from the mine. In filling two of the casks, fully hydrated sodium carbonate was mixed with the salt to increase its water concentration. The water concentrations were found by testing samples from each cask by adding a flux, heating above melting temperatures, and measuring the weight loss (the modified Penfield method).

Preliminary spectra have been obtained using both water-filled and dry simulated boreholes. These indicate that the hydrogen neutron capture peak is too weak to be a sensitive measure of water content in the range being considered. However, hydrogen is an effective moderator of fast neutrons and the intensities of gamma rays resulting from fast-neutron inelastic scattering from Na and Cl in the rock formation, and Fe in the casing and probe are functions of the hydrogen concentrations and, hence, of water content. One promising technique uses the intensity ratio of the 438-keV peak due to the Na inelastic-neutron–scattering reaction (where the Na atom captures a neutron and emits a neutron and a gamma ray) to the 789-keV peak due to the Cl neutron-capture reaction (where the Cl atom captures a neutron and emits a gamma ray). The 438-keV inelastic scattering line of Na results from the interaction of non-thermal neutrons with the salt. The 789-keV line of Cl is a deexcitation line that follows thermal-neutron capture. The ratio of the intensities of these lines should be a measure of the moderating effects of the water in the salt. It was found that the ratio decreases with water concen-

tration when the borehole is filled with water and when it is dry. The most rapid decrease occurred in the dry borehole at low water concentrations.

Several other possible reactions will be evaluated prior to field testing in boreholes from which the cores have been analyzed for water content. Since the nuclear methods do not distinguish between bound and free water, nuclear magnetic residence measurements will be tried as a means of obtaining the ratio of the two kinds of water.

ISOTOPE GEOCHRONOLOGY

By Meyer Rubin and Joseph G. Arth, Reston, Va., and Carl Hedge, Lakewood, Colo.

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 occurred between about 30,000 and 1,000,000 yr ago fall in a time range that is not now covered by standard dating techniques. In addition, reducing the size of sample needed for age determinations will allow us to date materials that cannot be dated at present and thus expand the applicability of the techniques involved.

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

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

Work at a number of institutions has suggested that ground waters may be datable up to 200,000 yr by chlorine-36 and krypton-81, and sediments and sedimentation rates up to 1 m.y. by beryllium-10, aluminum-26, and silicon-32. Like carbon-14, these isotopes are generated by cosmic rays in the upper atmosphere; they become incorporated in sediments or ground water and slowly decay with half-lives somewhat longer than carbon-14. In order to make use of these isotopes, very small amounts of them must be measured, and current research efforts are focused on use of cyclotrons or Van de Graaff accelerators. In addition, little is known about the geochemistry of these isotopes and the extent to which they may be selectively fractionated or adsorped through natural processes, which could alter the isotope ratios finally observed. Carl Hedge is closely following the development of these techniques and assessing their usefulness for work on radioactive waste problems. If and when a particular technique becomes sufficiently developed, consideration will be given to acquiring the necessary equipment to apply it.

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

Progress.—Meyer Rubin, in collaboration with a group headed by H. E. Gove at the Nuclear Structure Research Laboratory of the University of Rochester has obtained satisfactory carbon-14 dates on 1-mg samples, a 1,000-fold decrease in the sample size needed by conventional methods (Elmore and others, 1978). A sample of charcoal from a glacial deposit in Michigan gave an age of 41,000 yr (Beukens and others, 1977), and ages of about twice that figure should be possible with the new technique (Rubin, 1979). Experiments are also underway to use this technique to date ground water from its bicarbonate content (Rubin, 1978). This requires the conversion of the bicarbonate obtained from the water sample to acetylene, which is then cracked to produce elemental carbon, which is analyzed in an accelerator. A suitable carbon sample was obtained starting with 0.2 g of $SrCO_3$. With a smaller apparatus, a useable sample could be prepared from about one-tenth that amount of $SrCO_3$.

Carl Hedge has reviewed current developments in new radiogenic dating techniques by visiting

numerous laboratories both in the United States and in Europe and has talked to most of the people working in this field. There appear to be numerous potential applications for these new methods, but the most promising are (1) the dating of young sediments, (2) measuring erosion rates, and (3) the dating of ground water, the most obvious application being to radioactive waste disposal problems. The Swiss in particular are doing much work in developing new ways of dating ground water, and these activities are largely directed toward problems of radioactive waste disposal. The new techniques that are being used for the dating of ground water involve the isotopes argon-39, krypton-85, silicon-32, and chlorine-36. Besides developing the analytical procedures for measuring these rare nuclides, the Swiss are also working on the theoretical aspects and methods of measuring other isotopic and geochemical properties to be used in evaluating the apparent ages that they obtain from the new dating techniques. Hedge concludes that these developments can be of real value to nuclear waste disposal problems.

The USGS initially arranged for construction of a laser microscope argon-40/argon-39 laboratory by the National Bureau of Standards. Subsequently, these arrangements were changed, and it was decided instead to construct the laboratory within the Survey; an argon mass spectrometer is being purchased. A laser microscope unit will be obtained soon, and calibration experiments will begin.

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INVESTIGATIONS AND MODELING OF GEOLOGIC AND HYDROLOGIC PROCESSES

A major objective of the USGS research related to the disposal of high-level wastes is the identification and understanding of the critical geologic and hydrologic properties and processes involved in potential radionuclide migration from a repository to the biosphere. The USGS maintains that a more complete understanding of these properties and processes is essential to improve our predictive capability before specific repositories are made operational.

One group of properties and processes is related specifically to the thermal and mechanical stresses imposed by the emplacement of high-level wastes. The effects of these stresses on the underground flow of fluids (including vapor) and heat cannot be modeled at present for fractured rocks and unsaturated alluvium. To describe accurately the flow of fluids in these media requires an understanding of rock mechanics, heat transport, saturated ground-water flow in fractured rock, nonisothermal water fluxes in the unsaturated zone, and combined unsaturated-saturated zone flow in thick alluvium.

The research described below is supported from USGS appropriations.

FLUID FLOW IN FRACTURED ROCKS

By C. R. Faust, Reston, Va.

Two general conceptual models are available for describing flow in fractured media: discrete and continuum. The mathematical treatment for discrete-type models requires a precise description of fracture geometry, whereas the treatment for the continuum-type model considers meaningful "average" properties of fractures. Both methods have advantages, depending on the type of application considered. The discrete-type model is best for examining local conditions in or near a single fracture or a very few fractures. The continuum approach is more convenient for dealing with applications involving numerous fractures.

Objective.—The objective was to develop an integrated quantitative approach for evaluating fluid flow and thermal-mechanical interactions in the vicinity of a deep repository in brittle rocks.

Approach.—Chronologically, the approach involves: (1) a literature review, (2) testing and evaluation of available theory (through the use of numerical models) with hypothetical, experimental, and field data, (3) development of alternative theoretical and numerical models as needed, and (4) testing and evaluation of alternative theoretical models. In view of the complexity of a general model describing thermal, mechanical, and fluid-flow processes in fractured rocks, specific individual processes will be investigated first. The work will be coordinated with that described in the section on "Geomechanics."

Progess.—A complete literature review of both discrete and continuum models for fluid flow in fractured media has been conducted by P. Hsieh and C. R. Faust. The review, which is being summarized by Hsieh, includes (1) derivations of both types of mathematical models, (2) a classification of various analytical solutions, (3) corrections to and clarification of specific published reports, and (4) a consolidation of many techniques used in different applications with an internally consistent nomenclature.

A numerical model based on a double-porosity continuum has been developed for testing and evaluation with field data. The Galerkin finite-element method, using arbitrary quadrilateral elements, provides the numerical solution. The double-porosity theory assumes that the bulk of the fluid flow is in the highly permeable fracture system and that the rock matrix, which has a low permeability but a high porosity, acts as a source of fluid for the fractures.

NONISOTHERMAL WATER FLUXES IN UNSATURATED ALLUVIUM

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

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

The wastes will have high temperatures and will probably be placed in a medium that is relatively dry initially 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 principles 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.—The objective was 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.—Part of the year was spent in recruiting professional personnel for the work, designing experiments, and equipping the laboratory.

Although much literature has been published on nonisothermal flow in porous media, definitive experiments have not been performed especially at the temperatures anticipated in the vicinity of a radioactive waste repository.

Experimental systems were built to investigate transient, nonisothermal flow in unsaturated soil. Transient vapor-flow tests were run at temperatures up to 150°C. It was found that because the equilibrium vapor pressure of water in the soil was reduced much below steam-table values, the results disagreed with conventional gas-flow theories. A modified flow theory was developed to take into account the effect of lowering the vapor pressure. Experiments are in progress to determine the dependence of vapor pressure in the soil on the extent of liquid water saturation and temperature.

FIELD TESTS OF FLOW IN UNSATURATED ALLUVIUM

By E. P. Weeks, Lakewood, Colo.

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

Objective.—The objective was to develop and field test operational models to simulate combined

saturated-unsaturated flow at a small scale on a precise theoretical basis and to simulate saturated-unsaturated zone interactions at an areal scale on a more empirical basis.

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

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

Progress.—A site for the field tests was selected in the Jackass Flats area of the NTS. A 12-m shaft, 1.8 m in diameter, cased with 1.37-m casing (grouted), was constructed. This installation will permit the lateral emplacement of moisture-tension, thermocouple, and humidity sensors for measuring heat and water flow in the unsaturated zone.

An auxiliary site was needed to conduct generic tests, on a field scale, of the laboratory and theoretical aspects of flow in response to a thermal gradient. In view of the fact that it was underlain by windblown sand which provided relatively uniform and simple conditions, the site selected was in the Sandhills of Nebraska. The site has been instrumented to monitor natural water movement and the thermal transport of water in response to a cylindrical heat source.

A finite-difference model of saturated-unsaturated flow has been developed, tested with laboratory data, and compared with other models. Testing of the model with data for ponded infiltration conditions is in progress.

TRANSURANIUM ELEMENTS IN GROUND WATER

By J. M. Cleveland, Lakewood, Colo.

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

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

Objective.—The objective is to define the chemical and physical form and the chemical and hydrologic behavior of transuranium elements (particularly plutonium) in contaminated ground waters.

Approach.—The approach is to sample leachate from selected shallow disposal sites where there is sufficient plutonium to permit the necessary separations and analysis. Initially, it is planned to run the leachate through a sequence of submicron membrane filters of successively smaller pore sizes to determine the distribution of plutonium among the various particle sizes. Only the plutonium passing through the smallest pore-size filter can be in true solution; therefore, chemical studies will be limited to this fraction.

Progress.—Waters from five trenches at Maxey Flats, Kentucky, were sequentially filtered anoxically through 5-, 1-, 0.4-, 0.1-, and 0.05-μm membrane filters to determine the particle-size distribution of the plutonium. Analyses by alpha spec-

Effect of submicron filtration on plutonium-238 concentrations in trench leachates at Maxey Flats

Trench No.	pH	Eh	Pu-238 concentration, pCi/L*		Ratio, *B*/A
			Unfiltered (A)	0.05-μm Filtrate (B)	
2	6.8	+0.33v.	$1.2(0.11)\times10^{3}$	$1.39(0.17)\times10^{3}$	1.16
26	6.8	+0.64v.	$6.31(1.80)\times10^{5}$	$5.14(1.94)\times10^{5}$	0.81
32	7.6	+0.67v.	$2.59(0.48)\times10^{4}$	$2.56(0.12)\times10^{4}$	0.99
33L-18	2.0	−0.31v.	$1.18(0.38)\times10^{4}$	$7.11(1.02)\times10^{3}$	0.60
35	8.2	+0.10v.	$1.39(0.2)\times10^{4}$	$1.15(0.03)\times10^{4}$	0.88

* Values in parentheses are standard deviations.

trometry of the trench waters before filtration and after passage through the 0.05 μm filter are shown in the table that follows and indicate that only a small percentage of the plutonium is present in particulates larger than 0.05 μm. Since colloids are usually larger than this size, the data suggest that very little of the plutonium is present in colloidal form. This finding, which was altogether unexpected, indicates that the plutonium in these trench waters would be less likely to be removed by filtration and surface adsorption when passing through rock formations than is generally believed. From the composition of the trench waters and the behavior of plutonium in the samples during preparation for analysis, it is tentatively inferred that the majority of the plutonium is most likely present in organic complexes of Pu(III) or Pu(IV), probably the latter. Confirmation must await additional data.

Oxidation state analyses of 0.05 m filtrates collected anoxically are currently in progress. They confirm the absence of major percentages of polymer and indicate the presence of only small quantities of uncomplexed Pu(IV).

The behavior of neptunium, in the few cases where enough was present for meaningful analysis, was similar to that of plutonium, suggesting its presence either as Np(IV) complexes or as the relatively soluble NpO_2^{2+} ion.

These results apply only to Maxey Flats, which may or may not be typical of other shallow land burial sites, and they certainly are not representative of sites for the disposal of high-level calcined waste. Nevertheless, the results should give additional insight into the behavior of plutonium in waters at ambient pH values. Also, they suggest the potential danger of assuming that plutonium is always immobile in ground waters.

REDOX POTENTIALS AND CHEMISTRY OF ACTINIDES IN WATER

By D. C. Thorstenson, Reston, Va.

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

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

Approach.—In the absence of an innovative breakthrough in measurement techniques, the approach to be followed will consist of one or more of the following: (1) the use of electrode materials other than the usual inert metals. For reducing environments, possibilities would include iron, iron oxides or hydroxides, or iron sulfides incorporated in the electrodes, (2) testing the applicability of a wide variety of available chemical redox indicators to natural waters, (3) equilibration with large-volume samples with a small volume of a solution containing a known electroactive and thus measurable redox couple, (4) analysis of electrode responses to electrical or chemical perturbations on the sample. (Since one of the major problems in making standard electrode measurements is the slowness of reaction at the electrode, the more rapid response to initial disequilibrium conditions might provide a more accurate estimation of the true redox potentials), or (5) further work on the estimation of the negative $\log_{10}$ of electron activity from analytical data for multiple redox couples in the same water.

Progress.—A computer program PHREDX (Parkhurst and others, 1978) has been modified to a more general form to make it capable of modeling reactions among a large number of aqueous species and mineral phases. If the data base in the program is not sufficient for a particular problem, the program will now accept as input chemical species and mineral phases of the user's choice, with thermochemical data also provided by the user. An earlier version of this program has been used to model redox and ion-exchange reactions in a natural system (Thorstenson and others, 1979). The current program is being tested by modeling reactions in shallow ground waters and in two regional aquifer systems in the Northern Great Plains.

A survey and evaluation of the literature of hydrated electrons is being carried out.

An automatic titration system has been purchased as a first step in building electrochemical laboratory capability. This system can also be used to maintain constant pH or redox potential in ex-

periments and will be used for studies of redox processes involving the major redox-controlling species in natural waters.

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SOLUTE TRANSPORT IN THE UNSATURATED ZONE

By J. Rubin, Menlo Park, Calif.

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

Objective.—The objective was to develop data-based laboratory- and field-tested mathematical models useful for predicting transport of waste radionuclides in the unsaturated zone.

Approach.—The types of mathematical models needed will require, in the early stages of the project, a combination of laboratory and theoretical work. In later stages, these models will be field tested.

The solute transport models to be developed and tested must be capable of simulating the most significant physical and chemical conditions characteristic of the unsaturated zone. These include wide variations in water content and in water-flow rates as well as a multiplicity of chemical reactions.

Progress.—The professional staff was expanded by recruitment. In addition, the available office space is being remodeled to accommodate the required laboratory operations.

Detailed study plans were made, and special laboratory apparatus is being designed and constructed. Preliminary solute transport tests were carried out with custom-built equipment. The experimental system studied consisted of long soil columns which were partially saturated but of constant water content.

Analysis of mathematical approaches to solute transport systems with different types of chemical reactions showed that the various types of reactions which may be required in certain transport models call for significantly different mathematical formulations and numerical methods. Approaches required by most types of reactions are well known. However, current methods of mathematical treatment of certain potentially important classes of reactions do not seem adequate. Work on improving these treatments is in progress.

Transport experiments with two saturated soils demonstrated, for selected systems, the limits of applicability of mathematical models based on assumptions of localized chemical equilibrium. These models were shown to be applicable only when the solute-carrying water fluxes were very small.

PREDICTIVE MODELS OF RADIONUCLIDE TRANSPORT IN GROUND-WATER SYSTEMS

By David B. Grove, Lakewood, Colo.

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

Objective.—The objective was to develop and evaluate numerical modeling techniques to predict changes in water quality during the transport of radioactive solutes through saturated groundwater systems.

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 systems caused by the introduction of radionuclides.

Progress. – The Survey Waste Injection Program (SWIP), a three-dimensional ground-water transport model, has been revised to account for solute retardation and radioactive decay (INTERA Environmental Consultants, Inc., 1979). These and additional modifications have made this model one of the "state-of-the-art" standards for use on hydrologic problems associated with radioactive waste disposal.

The prediction of solute movement at an artificial recharge site in Lubbock, Tex., served as a verification of the model (Grove and Wood, 1979). The movement and reaction of calcium, magnesium, and sodium through the ground was predicted using ion-exchange parameters evaluated in the laboratory.

An effort has been made to study other field sites where the movement and reactions of solutes in the ground water can be studied. A ground-water contamination problem caused by mining operations in Telluride, Colo., is presently being studied intensively for this purpose. Seventeen wells have been drilled and sampled at various depths in the contaminated area. Both ground and surface water have been contaminated by hexavalent chromium. A report describing the extent and severity of the contamination has been published (Grove and others, 1979).

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GEOMECHANICS

By H. S. Swolfs, Lakewood, Colo.

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

Modeling the thermally induced stress requires knowledge of the initial stress conditions prior to mining. In the absence of such information, it has been necessary to assume zero or lithostatic stress (the increase in weight of the overlying rocks with depth); this assumption has resulted in considerable modeling errors. Some information on the initial stress can be obtained from measurements in boreholes in mined excavations. However, it would be desirable to have data from 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 by such instruments must first be evaluated.

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

Approach. – A large variety of borehole instruments has been developed and marketed during the last several decades that reportedly convey direct information on the state of stress, strength, deformation, various moduli, and other essential properties of the rock mass. Many investigations of individual instruments have been published in the literature, but there has been no attempt to compare the measurements from such instruments or to examine them under laboratory conditions where the imposed stress is known and the significance of the measurements can be evaluated. To this end, a testing facility is being prepared in an experimental mine operated by the Colorado School of Mines near Idaho Springs, Colorado. This facility consists of a rectangular block (3 m long, 1 m wide, and 1.7 m deep) of gneiss partially excavated in the floor of the mine. Flat jacks inserted and cemented in narrow, vertical slots

peripheral to the block will subject it to known stress levels up to 30 Mpa. Holes of different diameters have been drilled vertically into the block and will accommodate the various instruments to be tested. In addition, a borehole device incorporating three vibrating-wire stress meters and designed to monitor long-term stress changes is being developed with emphasis on high reliability and low cost.

From the measurements obtained, the theoretical basis of the instruments will be critically re-examined to determine whether the constitutive laws of rock behavior that they invoke are realistic. In addition, attempts will be made to simplify data reduction procedures, many of which are clumsy and tedious.

To develop an efficient site characterization methodology, a site will be chosen that allows the development of a theoretical model of the distribution of stress. The borehole instruments previously tested will be used to determine the mechanical rock properties at this site, and determination of stress, strength, deformation, and various moduli will be compared with similar information obtained from core samples and derived analytically. Thus, the test site will serve as an additional proving ground in which to test and evaluate existing instruments and to develop modifications, improvements, or new techniques.

Progress.—The borehole instrument testing facility is under construction and should soon be operational. Some of the borehole instruments have been purchased, and others will be borrowed on a short-term basis from other Federal agencies. Construction of the borehole device for monitoring long-term stress changes by means of three vibrating-wire stress meters is proceeding on schedule. A computer program has been written to store and retrieve the instrument test data. Other computer programs for statistical analysis of the data, graphic display of the results, and modeling the response of the instrument test block to loading by flat jacks have been obtained and tested.

A summary report assembling published measurements of the thermal properties of rocks is 85 per cent complete, and the section on thermal conductivities of rocks has been released (Robertson, 1979). The other major sections are Conductivities of Minerals, Pressure Effects, Specific Heats, Expansions, Heat Transfer, and Anisotropy.

Experimental apparatus for studies of elasticity, attenuation, and microfracturing in rock is being interfaced with a mini-computer; circuits and software for a torsion pendulum have been completed and preliminary measurements are being made. The apparatus is being interfaced with a stiff press so that elasticity and microfracturing can be observed under confining pressure.

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SYNTHESIS OF NEOTECTONIC CONDITIONS IN THE UNITED STATES

By Carl M. Wentworth, Menlo Park, Calif.

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

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

Approach.—Evidence of neotectonic deformation and the deformation history through Quaternary time will be gathered and compiled from existing literature and with the help of selected regional and topical specialists. This information will be synthesized into a coherent depiction of the neotectonic behavior of the United States on a map of 1:5,000,000 scale in terms of relative movements and their amounts and rates.

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

Because the results of this project provide basic scientific information useful for a variety of purposes, it is supported jointly by the Radioactive Waste Disposal, Earthquake Hazards, and Reactor Hazards Programs of the USGS. To satisfy the varied interests of the several funding sources, initial emphasis is on (1) a broad, 2°- to 4°-wide band across the southern United States from the southern California borderland to South Carolina (by way of the Southern Basin and Range, Colorado Plateau and Four Corners area, the Rio Grande rift and Texas Panhandle, and the Upper Mississippi Embayment), (2) the balance of California, western Washington, and western Utah, and (3) the upper Mississippi Valley.

Progress.—To enlist the aid of regional experts outside the USGS, a formal request was issued in March 1979 for proposals to prepare analyses of neotectonic history for areas in the conterminous United States. Some 31 proposals were received of which 8 have been funded. These deal with part of the Washington coast ranges; the northern Walker Lane, Nevada; the Ventura Basin, California; Arizona and part of adjacent southeast California; the Bonneville Basin, Utah; southern Montana; and the Precambrian Shield west of Lake Michigan. Preparation of the request for proposals required a careful statement of the ideal contents of a neotectonic map. Included was the argument that the length of geologic record to be consulted must be tailored to the local geologic history and character of the record. In some areas the late Quaternary record may suffice, whereas, in others, the whole Cenozoic or even longer periods must be consulted in order to define reasonably deformation patterns and histories.

Initially, much attention has been devoted to South Carolina and the Southeast. Although evidence of neotectonic deformation there is relatively scant, seismicity and the late Cenozoic record indicate that modest tectonism is underway. Two very different types of Cenozoic deformation are recognized. On a broad scale, the continental margin has subsided and acquired a Cretaceous and Cenozoic mantle of marine sediments that thins westward and grades into continental deposits. This subsidence has not been uniform; broad arches and basins of moderate amplitude have controlled sediment accumulation and produced gentle regional inclinations in the sediments. The distribution of deposits and shorelines during late Cenozoic time indicates continued vertical movement of at least some of these features, at rates on the order of 1 mm/yr.

On a much finer scale, a number of faults have been recognized that offset crystalline bedrock and overlying sediments that variously range in age from Cretaceous to Pleistocene. Most of these faults are known from isolated outcrops along or west of the Fall Line; many are northeast-trending reverse faults. Where well studied—Stafford fault zone along the fall line in northern Virginia (Mixon and Newell, 1977) and Belair fault zone along the Fall Line in northeastern Georgia (Prowell and O'Conner, 1978)—these faults show evidence of progressive offset through Late Cretaceous and Cenozoic time, and maximum cumulative vertical separations less than 100 m. Map patterns suggest that early Mesozoic extensional faults, where appropriately oriented, formed the locus for much of this younger compressional movement. One hundred meters of throw in 100 m.y. yields an average vertical slip rate of 1m/1m.y., a rate so low that any late Quaternary movements may be very difficult to recognize. This, combined with the relatively poor state of knowledge concerning the geology of the Southeast, makes analysis of the neotectonic history of that region difficult.

In order to explore the possible use of gross topography in evaluating tectonic history, a preliminary study of computer simulation of topographic evolution has been made by Larry Mayer (Menlo Park, Calif.). An algorithm was written that relates altitude, slope, and erosion rate, on the basis of the least work to transport material. Rates of erosion and uplift can be varied, and the computer program describes both the three-dimensional form of the topography and its hypsometry, slope, relief, and altitude distribution

through time. The program has been applied to several types of terrain. Preliminary results are reasonable and suggest, for example, that the rate of pedimentation varies with initial relief, steepness of mountain fronts, and with rate of erosion.

Given the capabilities to simulate topographic uplift and erosion, it may be possible to investigate systematically land forms developed under a variety of tectonic and climatic conditions. With geologic constraints where available, land forms may be classified and categorized according to the relative impact of tectonism, as modeled with computer simulation.

References

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COMPUTER SIMULATION OF GEOLOGIC STABILITY OF A REPOSITORY

By Herbert R. Shaw, Menlo Park, Calif.

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

The work described below was done in collaboration with Sandia Laboratories in Albuquerque, New Mexico, with funds transferred from the NRC.

Objective.—The objective was to establish the role of feedback behavior in the analysis of the geological stability of any generic environment considered as a candidate for disposal of radioactive waste materials and to demonstrate the effectiveness of geological simulation methods in describing the ranges of possible release times and transport times of radionuclides from a hypothetical reference repository in a bedded salt environment.

Approach.—Feedback relationships between physical phenomena that may influence the geologic stability of a nuclear waste repository are studied in relation to geometric studies of hydrologic transport paths through the repository environment. The approach uses the simulation language DYNAMO to explore mechanisms that will be adapted to the development of a network flow model by Sandia Laboratories. Conditions of instability, such as the creation of solution cavities in salt or regimes of high chemical transport rates, are identified.

Progress.—Previous work was summarized by Tierney and others (1979). Recent work consisted of expanding the capabilities for computer simulation calculations and expanding the variety of scenarios created to test the performance of a hypothetical reference repository in a bedded salt environment (Sandia Laboratories, Organization 4413, Reference System). A system of scenarios established by Sandia Project 4413 was simulated using DYNAMO; the scenarios represented a variety of modes of breaching the salt layer above the repository horizon of the Reference System (Campbell and others, 1978). Times were calculated for ground water in an overlying aquifer to penetrate the host salt layer and for ground water to overrun the repository completely. These calculations represented a reconnaissance of rate data to be developed for use in statistical consequence analyses by Sandia Organization 4413. Results of the exploratory calculations led to the development by the staff of the Sandia Project of a new simulation code for calculating dynamic interactions of hydrologic conditions and various geometries and properties of flow paths. Another result was the creation of a master system of DYNAMO equations called DISSCC (Dissolutioning With and Without Crack Closure) describing encroachment of ground water through U-tube syphoning mechanisms. DISSCC allows the calculation of dissolutioning rates based on two different schemes for calculating crack permeabilities; it also permits cracks to remain open or to close at prescribed rates and allows the pressure head for brine flow to remain constant with time or to decay with time as a function of brine buildup in the overlying aquifer.

The results of the simulations emphasized the potentially disruptive effects of salt dissolutioning by ground water. Minimum times for wholesale disruption of the overlying salt were reduced from thousands to hundreds of years. Effects incor-

porating rates of crack closure and decreasing pressure head for brine flow became significant only at small crack widths ($< 10^{-3}$ cm. Reconnaissance calculations for other scenarios indicate that the overall range of results tends to be similar to that with dissolutioning rates estimated from the U-tube scenario.

Data on the statistics of faulting for the conterminous United States based on the USGS map of young faults of the United States (Howard and others, 1978), were plotted as histograms of frequencies of fault lengths in different tectonic provinces and age groupings. Rates of change in fault lengths with time in the last 15 m.y. of the geologic record were determined.

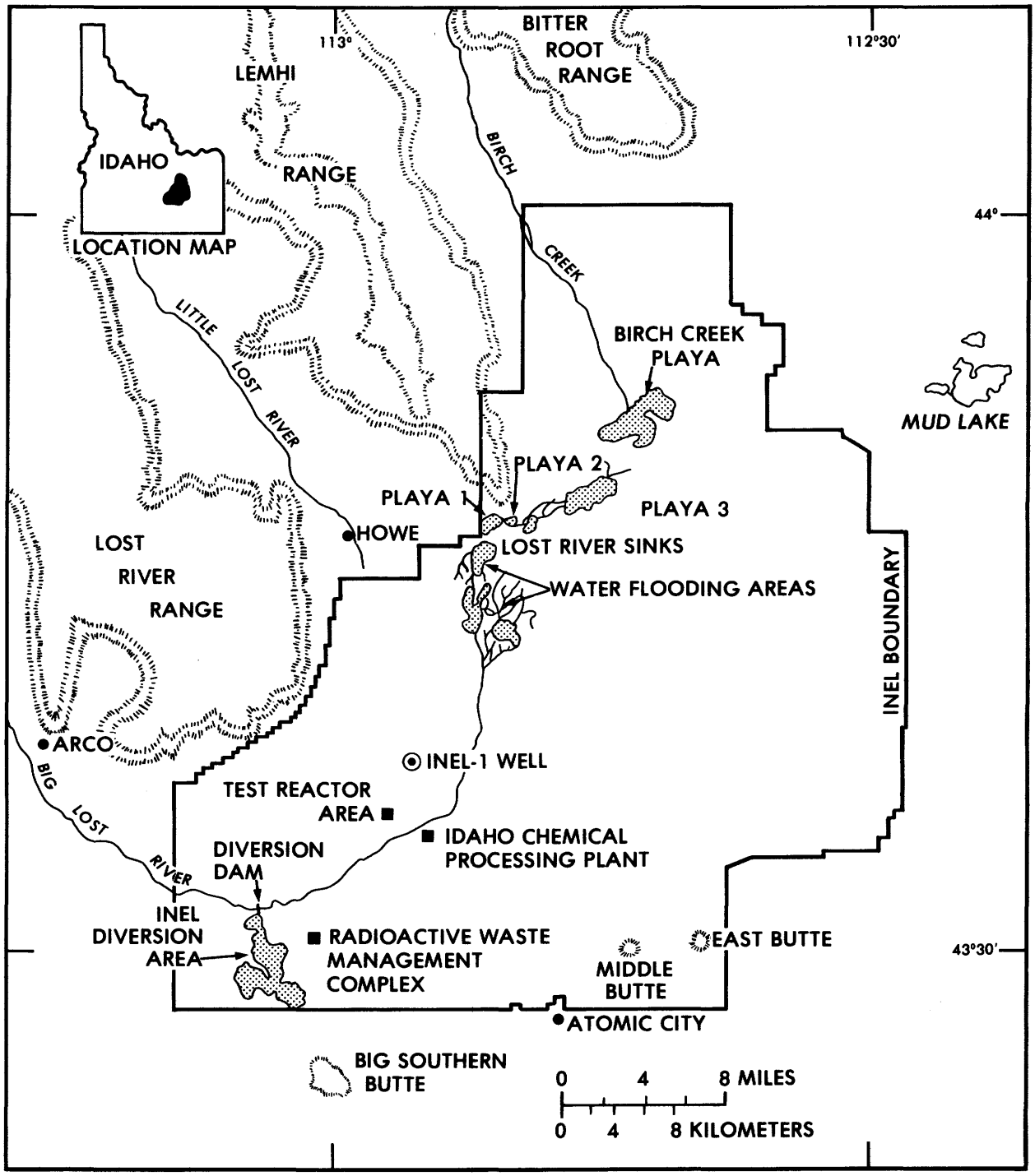

FIGURE 14.—Map showing selected facilities at the Idaho National Engineering Laboratory.

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LOW-LEVEL WASTES

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

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

In 1975, the USGS received direct appropriations to assume a new mission in the area of low-level wastes. The general purpose of this mission is to develop geohydrologic guidelines which can be used to establish technical criteria for selecting, evaluating, licensing, and operating new low-level waste disposal sites. The program was designed to be a 5-yr endeavor, ending in fiscal year 1980. It includes field studies at disposal sites in Sheffield, Illinois; Maxey Flats, Kentucky; Beatty, Nevada; West Valley, New York; and Barnwell, South Carolina. In 1978, the abandoned Argonne National Laboratory burial site in Illinois was included in the study.

INVESTIGATIONS OF DISPOSAL SITES

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

The studies involve the following specific tasks:

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

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

IDAHO NATIONAL ENGINEERING LABORATORY

By J. T. Barraclough, Idaho Falls, Idaho

The Idaho National Engineering Laboratory (INEL), formerly the National Reactor Testing Station, was established in 1949 to test and develop peaceful uses of atomic energy in a remote location on the Snake River Plain in southeastern Idaho (fig. 14).

About 95 percent of the low-level aqueous radioactive waste and about 75 percent of the aqueous industrial (nonradioactive) waste is discharged to two on-site disposal facilities. Liquid wastes are discharged in the southern part of the reservation to ponds at the Test Reactor Area (TRA) and to a 183-m well at the Idaho Chemical Processing Plant (ICPP) which is open to the Snake River Plain aquifer. The aquifer, whose top is about 137 m below these plants, is composed predominantly of basalt with some interbedded sedimentary layers. Solid radioactive wastes are buried at the Radioactive Waste Management Complex (RWMC) in the southwestern part of the reservation.

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

Approach.—The geologic, hydraulic, and geochemical characteristics of the system and the

migration of radionuclides in the aquifer are defined by periodic sampling of wells together with special analyses, various types of drilling, coring, sampling, and borehole geophysical logging.

Progress. – The waste plumes of various constituents in the aquifer have been mapped periodically. The most mobile constituents have migrated downgradient (south) 12.1 km from the ICPP and TRA, covering an area of about 72 km^2 since disposal began in 1952. A plume of low-level iodine-129 was recently discovered and mapped. Because of its very long half-life (1.6×10^7 yr), it is significant in long-range studies of the effects of radioactive wastes on the aquifer. Iodine-129 is dispersed over an area of about 7.7 km^2 and has migrated about 4 km downgradient from the discharge well since 1953. A plume of waste nitrate was mapped for the first time in January 1979. Nitrate is dispersed over about 17 km^2 of the aquifer and has migrated 5.6 km downgradient from the discharge well.

Information on the geology and hydrology of the deeper parts (below about 450 m) of the eastern Snake River Plain has long been limited because deep wells had not been drilled below that depth. This information was needed to answer questions on the possibility of radioactive wastes moving downward in the aquifer and whether radioactive wastes could be injected beneath the aquifer. A 3,159-m well (INEL-1), drilled by the DOE in 1979 to obtain geologic, geothermal, and geohydrologic information, greatly extended knowledge of the geohydrology of the plain. The rocks penetrated by the well were principally volcanic–basalt with interbedded sediments, rhyolite (nonwelded and welded ash-flow tuffs), and rhyodacite(?) (ash flows). Below 488 m, the permeability of the rocks decreases owing to the filling of fractures by secondary minerals. The data suggest that the rocks can be subdivided into three separate aquifers: the near-surface Snake River Plain aquifer (basalt), which is highly permeable by virtue of fractures, fissures, and other voids; the lower basalts of the Snake River Plain aquifer, which are markedly less permeable; and rhyolites beneath the Snake River Plain aquifer. Separating the aquifers are aquitards composed of amygdaloidal basalt, altered clay-rich strata, and

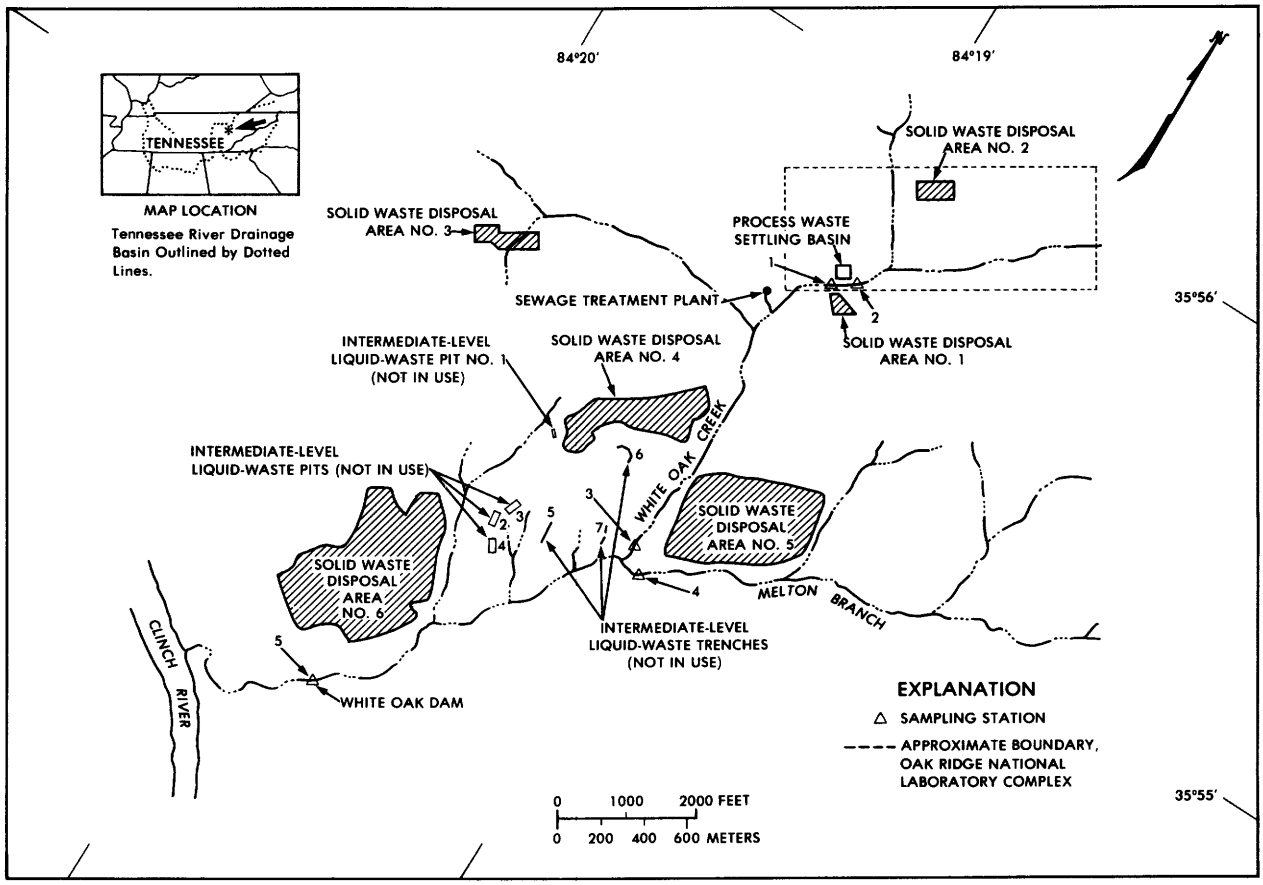

FIGURE 15. – Location of waste-disposal areas and sampling stations at Oak Ridge National Laboratory, Tennessee.

altered tuffaceous sedimentary strata. Hydraulic head increases with depth, being different for each unit. The quality of water also differs for each aquifer, in general the water being more mineralized with depth. The deeper water is of a very soft sodium bicarbonate type. The bottom-hole temperature is 137°C. The data suggest that wastes would not migrate downward to the lower part of the Snake River Plain aquifer. It appears that there are strata below a depth of 760 m that might be suitable for the injection of low-level liquid, radioactive wastes of relatively short half-lives.

Several subsurface studies were made to evaluate the possibility of waste migration through the unsaturated zone from solid radioactive waste buried at the RWMC (Barraclough and others, 1979). Perched water zones were investigated, and samples of sedimentary interbeds and fracture fillings were collected and analyzed. Studies are under way to determine the vertical permeability to air of unsaturated strata by measuring the time lag of barometric pressure fluctuations at different depths.

Samples collected in the sedimentary beds immediately beneath the buried wastes at the RWMC show that waste migration has occurred. Waste solutes have migrated about 2 m downward to the fractured basalt. The waste solutes were carried downward by infiltrating snowmelt, and the concentrations are greatly attenuated with depth.

The principal sedimentary strata interbedded with the basalt are at about 9, 34, and 73 m below the land surface. Analyses of samples collected from these sedimentary beds show a few randomly distributed positive radionuclide values whose activity levels are very low, generally below the fallout levels. Thus, even though waste solutes have probably entered the fractured basalt in places, strong evidence for waste migration in the basalt is not conclusive from the available data. There does not appear to be any danger of radionuclides migrating to the Snake River Plain aquifer from the RWMC if the surface of the facility is maintained to minimize the infiltration of surface water that may percolate through the wastes.

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OAK RIDGE NATIONAL LABORATORY, TENNESSEE

By D. A. Webster, Knoxville, Tenn.

At the Oak Ridge National Laboratory (ORNL), solid low-level radioactive wastes have routinely been disposed of by burial in shallow trenches since the early 1940's. To data, six burial grounds (solid waste disposal areas) have been used (fig. 15). Small but measurable concentrations of radionuclides have been detected in the streams in and near the four largest disposal areas; this leading to the belief that radionuclides are being leached from the waste, transported in ground water, and discharged to those streams.

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

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

Progress.—An inventory has been made of all existing wells in the disposal areas, many new shallow wells have been constructed, and the measurement of water levels was continued generally at intervals of 2–3 weeks. This data base has permitted a determination of the depth to water during all periods of the year, including the magnitude of annual water-level fluctuations, and a definition of some of the areas where waste is buried below the water table. It also has been useful for inferring the direction of ground-water movement in the residuum, documenting present conditions so that the effectiveness of later corrective measures can be evaluated, and providing measurements of parameter values for use in numerical simulation models of ground-water flow and radionuclide transport. The data are useful for determining the hydrologic changes resulting from the increase in surface permeability produced by excavating the trenches. For example, the measurements show that in Burial Ground 5, the water levels in some wells have risen by as much as 3 m in less than 20 yr. As a result, the volume of

unsaturated residuum has been reduced throughout the burial ground, the slope of the water table has increased, and the waste in the lower ends of many trenches has become saturated perennially. These changes are significant to the waste management problems, for each of them has the potential for facilitating radionuclide transport from the disposal areas.

Ground-water tracer tests, using tritium, were conducted near Burial Grounds 4 and 6. These sites, like Burial Ground 5, are underlain by the dipping, interbedded shale, siltstone, and limestone strata of the Conasauga Group (Cambrian). The tests confirmed the hypothesis that weathering of the residuum is sufficient to permit ground-water movement across bedding planes. It was also found, however, that this weathering did not remove entirely the influence of secondary permeability on flow along the bedding planes. Consequently, considerable dispersion occurs in the weathered rock. The direction of ground water movement in the deeper unweathered rock is strongly influenced by partings, joints, and fractures, and it appears possible that water at different depths in the rock can move in quite different directions. Although the results have not been analyzed quantitatively, they suggest a flow system in which some of the water moves through the residuum fairly quickly while the remainder moves much more slowly.

Spectral gamma-ray logs of wells penetrating the Conasauga Group beneath Burial Ground 5 revealed the presence of cesium-137 in a few wells at locations as much as 30 m below the top of the bedrock. This suggests that secondary openings of the bedrock may be conduits for water and the transport of radionuclides. To evaluate the potential for flow through the bedrock, it is planned to install a series of piezometer clusters. Packer and aquifer tests in the first cluster of wells installed indicate that pathways for water movement exist at depths as great as 60 m below land surface, that a significant head difference exists between upper and lower horizons, and that the bedrock has a relatively low transmissivity. The data obtained from these tests, including chemical analyses of water samples from the wells, indicate that the opportunity for the movement of water between the upper and lower zones in the vicinity of this piezometer cluster is poor and that ground-water movement in the deeper zone is principally through small secondary openings where there is minimal opportunity for sorption of radionuclides as a result of contact with the rock.

In collaboration with A. M. Stueber of ORNL, a study of the movement of ground water and radionuclides from Burial Ground 3 has been started. The disposal site is underlain by the Chickamauga Limestone (Ordovician) in which small solution openings have developed. Preliminary results suggest that water and very low concentrations of radionuclides are moving through the solution openings. The solution openings appear to form a high-permeability pathway along the contact between a thick limestone unit and a siltstone member. Overall movement from the disposal site is along this pathway to surface discharge points east and west of the burial ground.

Flow and radionuclide movement in the streams is monitored by automated, continuous sampling devices. Digital recorders at three monitoring stations are used to check occasionally the accuracy of flow measurements made by the sampling equipment. The data show that more water passes stations upstream, within the ORNL complex, than passes the most downstream station near the point of discharge to off-site areas. The difference probably is due to an error in the weir rating for the station farthest downstream, which would mean that a somewhat larger quantity of radionuclides is being released from ORNL than has been calculated.

SHEFFIELD, ILLINOIS

By James B. Foster, Champaign, Ill.

This commercially operated low-level disposal site is located in northwestern Illinois near the town of Sheffield. It covers about 8 ha of rolling terrain with well-established drainage and is bordered on the east, north, and west by strip-mined land. The climate ranges from warm and humid in the summer (average temperature 22.2°C) to quite cold in the winter (average temperature −7.5°C). Average annual precipitation is 890 mm.

Waste burial in the first trench began in August 1967. Twenty-one trenches, comprising all of the usable space, were filled through April 1978. As of March 1978, 83,147 m^3 of waste had been buried.

Objective.—The objective was to study the hydrology and geology of the site in sufficient detail to provide the means of appraising the suitability of this type of hydrogeologic environment for disposal of low-level radioactive wastes.

Approach.—The investigation has been divided into several phases, starting with the use of numerous test wells to define in detail the stratigraphy of the unconsolidated formations and

the hydrology of the unconfined formations. Hydraulic well testing was used to determine hydraulic conductivity of the strata. Numerical modeling is being used to analyze the three-dimensional ground-water flow system. Detailed analysis of geologic and hydrologic conditions directly beneath burial trenches is being accomplished through studies in a specially constructed tunnel. Other approaches being used include special borehole geophysical logging techniques and geochemical analyses.

Progress. – The glacial geology of the site is quite complex. Owing to the variability in the lithology of the stratigraphic units, subsurface mapping is difficult. However, by combining several factors such as grain-size distribution, clay mineralogy, and sequence of deposition, the stratigraphy has been mapped adequately. The lithology of the glacial deposits includes surficial loess (clayey silt); clayey silty till; pebbly silty sand, till composed of sand, silt, and clay; and, in some areas, silty lacustrine deposits. The glacial deposits overlie a thick body of Pennsylvanian shale.

The most significant unit with respect to ground-water movement is the pebbly silty sand which underlies most of the site. Owing to the relatively high permeability of this unit, the upper part and overlying deposits are well drained and the water table is lower than in similar glacial terranes in the region.

Ground water on the site is derived from local recharge supplied by infiltration of rainfall and snowmelt. The water table closely parallels the topography. The apparent direction of ground-water flow, normal to the water-table gradient, has been mapped adequately for this site. Field tests of wells and laboratory measurements indicate the hydraulic conductivity of the deposits ranges from 10^{-1} cm/s for gravelly sand to 10^{-9} cm/s for the more clayey sand. A pumping test of the sand and gravel unit, using observation wells northwest of the site, indicated a hydraulic conductivity of 10^{-3} cm/s. Tritium apparently has moved in ground water from one trench in the southeast corner of the site to nearby USGS monitoring wells at a rate of about 8 m/yr through thin sand lenses interbedded with silt. The hydraulic conductivity required for that flow rate is 2.1×10^{-4} cm/s.

The only radioactive isotope that has been found migrating with the ground water is tritium. Low concentrations have been found in water samples from wells at several locations near trenches along the south side of the site. Since other nuclides have not been found migrating in the ground water, it is assumed that other nuclides are being held by sorption on the clay particles in the strata beneath the trenches. In order to investigate this assumption a 2-m-diameter tunnel was constructed beneath four of the oldest trenches. The tunnel will allow collection of core samples from beneath the trenches for radiometric analysis and for determining hydrologic and lithologic properties.

MAXEY FLATS, KENTUCKY

By Harold H. Zehner, Louisville, Ky.

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

The ground-water system consists of at least eight rock units, each of which has different water-transmitting characteristics and all of which are fractured. Most ground-water flow occurs in the upper 98 m of the rocks underlying Maxey Flats. A sandstone unit is present at a depth of 14–24 m. The remaining rocks are shales containing interbedded sandstones and siltstones. Recharge to the rocks is from infiltration of rainfall on the hilltop.

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

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

Streamflow and water-quality data will be used to describe the surface and near-surface hydrologic systems at a depth of 1–2 m. Water from trenches is also being analyzed for standard and radiometric water-quality properties. Ground-water flow models are being used to test and refine concepts of the flow system.

Progress. – Two clusters of wells have been constructed. One cluster (A) of 4 wells was drilled about 300 m from the burial area, and another

cluster (B) of 5 wells was drilled approximately in the center of the burial area. Wells within a cluster are about 10 m apart and are open to rock strata at various depths. Wells in cluster B are open to rocks similar to those in cluster A. One additional well was drilled at cluster B and is open to a sandstone bed at a depth of 7.3–7.8 m. All other wells are open to rocks deeper than 8 m.

Water-level data from cluster A indicate that rocks from 9 m to about 98 m are probably saturated, but one or two unsaturated zones may be present in this depth interval. The concentration of dissolved minerals in the ground water from 9 m to 43 m is about 1,000 to 2,000 mg/L, and from 43 to 98 m is about 20,000 mg/L. This suggests two distinct flow systems with most flow occurring in the upper system.

Three wells in cluster B are dry. Assuming that these wells are open to saturated rocks (as indicated by cluster A), it is probable that the wells do not accumulate water because they did not intersect fractures in the rocks. This would indicate that nearly all the ground-water flow is through fractures.

Aquifer testing was completed on all wells in the two clusters that yielded water and on several older wells at the burial site. The results of the tests were inconclusive, presumably because most of the flow is through fractures.

Radionuclide contamination was found in each of the four bedrock wells in cluster B, with maximum concentrations in picocuries per liter, as follows: Gross alpha, 2,800; gross beta, 88,700; and tritium, about 290 million. All radionuclide contamination probably came from a sandstone bed at a depth of 7.3–7.8 m, which is the depth of the trenches near the wells.

Water-level data from the well in cluster B that is open to the sandstone bed at 7.6 m indicate that the upper water table is at a depth of about 7 m.

Standard water quality and radiochemical data from streams near the burial site indicate that most surface water during periods of low flow is discharged from alluvial sediments, and little flow is coming from bedrock. Similar data from shallow wells (about 6 m deep) also indicate a near-surface origin for the water. Some water from deeper sources in bedrock undoubtedly enters the adjacent valleys, however, because virtually all water infiltrating the top of the hill eventually moves to the hillside and valley bottoms.

BEATTY, NEVADA

By William D. Nichols, Carson City, Nev.

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

Objective.—The objective was to determine the downward flux (recharge rate) of moisture through the extremely dry unsaturated zone beneath the burial trenches of the site.

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

Progress.—The volumetric soil-moisture content at the study site varies from 4 to 11 percent. In the short term, specifically during winter months, moisture contents of 12 to 15 percent occur at shallow depths. A comparison of the moisture profiles for February and May 1979 strongly suggests the downward redistribution of small amounts of moisture at depths below 3 m.

Soil-water suction and soil temperature are being measured at depths of 3, 4, 5, 6, 7, and 10 m using thermocouple psychrometers and thermocouples, respectively. Soil-water suctions ranging from −50 to −53 bars at 3 m, −38 to −70 bars at 6 m, and −43 to −61 bars at 10 m have been measured. The time relationship between adjacent vertically oriented series of measurements is not well known because of the inherent extremely slow

response time associated with the site environment. Data collected so far indicate a generally downward movement of moisture during most of the year. They also establish the general range of soil-water suctions which must be used in any analysis that is made. Temperature data show seasonally cyclic fluctuations with a minimum time lag of 4 months.

A preliminary analysis of soil-moisture movement based on field data can be made using data thus far collected and data available in the literature. A reasonable value of unsaturated hydraulic conductivity for conditions observed at the study site is about 5×10^{-3} cm/yr, with a range of plus or minus 1 order of magnitude. This value is based on a limited but detailed analysis of the relationships among conductivity, soil suction, and moisture content for a similar soil type. Under equilibrium conditions, this value would represent the long-term steady-state flow rate at depth. Given a depth to water beneath the study site of 85 m, the time needed for moisture to move from the surface to the water table at the prevailing water content would be 1.7×10^5 yr (plus or minus 1 order of magnitude). Using gradients observed in the first 10 m of the unsaturated zone, the flow rate may be as high as 0.3 cm/yr (plus or minus 1 order of magnitude). The significance of the relative amounts of moisture movement in the vapor phase and in the liquid phase at these low values of conductivity and high suctions has not been considered, but it has an important bearing on the question of radionuclide migration.

Preliminary estimates of long-term infiltration also have been made using an evaporation/infiltration model based on U.S. Weather Service data and equations for estimating evaporation; the Jensen-Haise equation is currently being used. Results so far are not reliable quantitatively because the model is poorly calibrated. Qualitative results from the early analysis, however, are consistent with observed field data and also suggest the strong probability of long-term deep infiltration of precipitation at the study site.

WEST VALLEY, NEW YORK

By David E. Prudic, Albany, N.Y.

About 50 km south of Buffalo, New York, near the hamlet of West Valley, are the facilities of the Western New York Nuclear Service Center. Among these facilities is a State-licensed burial ground for commercial low-level radioactive waste. The burial area (4 ha) contains a series of burial trenches that average 6 m deep, 10 m wide, and 180 m long. The site operator, Nuclear Fuels Services, Inc., voluntarily closed the site after water overflowed from two of the older filled trenches.

The site is situated on glacial deposits which blanket Paleozoic sedimentary bedrock. The glacial till and related fluvial-lacustrine deposits range in grain size from clay to gravel and average about 30 m in thickness. The waste-burial trenches are excavated in a clay-rich till with relatively low hydraulic conductivity.

In addition to the USGS study of geohydrologic factors controlling the subsurface movement of radioisotopes, the New York State Geological Survey, under contract with the EPA and NRC, began a complementary study in 1975 to evaluate all other factors related to radiosotope migration at the site.

Objective.—The objective was to describe the three-dimensional characteristics of the ground-water flow system and determine the extent, rate, and concentration of waste radionuclide movement from the trenches.

Approach.—A variety of standard and innovative hydrologic techniques are being applied in this study. Included are the installation and testing of specially constructed wells, the collection and analysis of core and water samples, digital modeling of ground-water flow and radionuclide transport, geophysical borehole logging, geologic mapping, and other techniques.

Progress.—Surficial geologic mapping (LaFleur, 1979) near the site defined the nature and extent of a clay-rich till containing few stones. The till is a valley facies that is widely distributed in Cattaraugus Creek basin below the level of drainage-divide saddles south of the site. This till appears to have been deposited by an ice sheet partially suspended in ponded water. Test drilling near the trenches indicates that the till is about 25 m thick and overlies a 2- to 10-m unit of bedded, lacustrine fine sands and silt. The lacustrine unit is capped locally by gravel and is unsaturated in the upper part. Bedrock at the site may be as deep as 150 m below land surface. Fractures and root tubes with chemically oxidized and (or) reduced soil in their walls extend 3–4.5 m below natural land surface (Prudic and Randall, 1979).

Hydraulic gradients in the till are predominantly downward, even below small valleys. Laboratory and field tests of hydraulic conductivity are in general agreement. Slug tests of several wells indicate that the average horizontal hydraulic conductivity is about 5×10^{-8} cm/s. Preliminary digital model simulations of pressure head suggest that

the upper, weathered till is 1 order of magnitude more permeable than the unweathered till and that in the unweathered till the vertical hydraulic conductivity may be 10–100 times lower than the horizontal.

Peaks of tritium concentration at a depth of about 9 m in two holes 2–3 m from a trench boundary are attributed to lateral migration chiefly along layers of silt and sand. Tritium concentrations in cores collected beneath three burial trenches revealed that tritium had moved downward about 3 m below the trench floors (Prudic, 1979b). Other radioisotopes have moved much smaller distances.

Accumulation of water has been a chronic problem in most of the older trenches in the northern part of the site. Water from several trenches was pumped out and treated from 1975 through 1977. Most of the new trenches to the south had maintained low stable water levels until after the dry summer of 1978, when water levels rose significantly in four of the seven trenches. The water-level rise in the trenches does not seem to be related to ground-water inflow but to increased infiltration of precipitation through the trench cover as a result of the formation of dessication and (or) settling cracks (Prudic and Randall, 1979, and Prudic, 1979a).

Preliminary studies of air-pressure differences between the unsaturated part of the trenches and the atmosphere, using the method described by Weeks (1978), have been completed. Results indicate that, in general, the trenches with a history of rapidly rising water levels had covers of higher permeability, at least seasonally, than those on trenches in which water levels have remained lower and more stable. This observation supports the hypothesis that recharge occurs through the cover.

Hydraulic conductivities of several trench covers, calculated from water-level rises, were 2–3 orders of magnitude less than the values calculated from air-pressure measurements. These differences could reflect the effects of clay swelling during recharge and (or) unsaturated flow through the trench cover.

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BARNWELL, SOUTH CAROLINA

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

The commercially operated low-level waste burial site at Barnwell, South Carolina, is the only operating disposal site in the eastern United States, receiving more than 80 percent of the country's waste. Burial trenches are excavated in relatively permeable, unconsolidated, sandy coastal plain deposits of Miocene age. Precipitation averages about 1,190 mm/yr. The water table is generally at a depth of about 11 m.

Objective.—The objective was to describe quantitatively the ground-water flow system at the disposal site and assess the principal geohydrologic factors affecting radionuclide migration in ground water.

Approach.—Conventional field methods and numerical modeling techniques are being used to analyze the ground-water flow system. Special drilling and sampling techniques will be used to determine the extent of nuclide migration beneath the burial trenches.

Progress.—Soil-core samples were collected beneath the buried waste in two trenches. These cores were collected by driving 100-mm heavy-wall steel pipes through the waste. The leading end of the pipe had a removable solid steel point which was withdrawn once the pipe penetrated the undisturbed soil beneath the waste. The soil cores were obtained with a 0.6-m split-spoon soil sampler which had access to the soil through the open end of the pipe after removal of the steel point. Attempts to obtain similar soil cores at six other trenches were unsuccessful because either the points hit some impenetrable objects or the pipes were deflected at an angle which made removal of the steel points impossible with the equipment available.

Preliminary analyses of the cores indicated that no detectable gamma-ray-emitting waste isotopes were present. However, tritium levels much greater than the background level (about 1–3

pCi/ml) were present in all of the cores sampled. The tritium concentration in moisture from cores collected beneath trench 7 declined from 1.5×10^6 pCi/ml at 0.5 m below the trench floor to 9×10^5 pCi/ml at a depth of 3 m. Similarly, samples beneath trench 8 ranged from 6.4×10^4 pCi/ml at 0.53 m below the trench floor to 1.3×10^3 pCi/ml at a depth of 2.5 m. Judging from the very low moisture content of sand in the bottom of trench 7 (about 6–8 percent by weight), it appears that these soil samples were collected when there was no water in the trenches.

Areal studies of ground-water conditions indicate that there are four aquifer units in the upper 150 m of sediments. Hydraulic head measurements in each of these units indicate a consistent downward gradient.

To determine the hydraulic conductivity of the confining beds between these units, pumping tests were conducted at the north end of the burial site. Two tests of several days duration were made by pumping from the second unit, which is located 21–49 m below the land surface. Preliminary results indicate that the transmissivity of the confining beds between the upper two units is about the same magnitude as that between the second and third units which is about 9.3 cm/d. During the periods of pumping, the fourth, or lowest, unit showed no response to the pumping stress applied on the second unit.

ARGONNE NATIONAL LABORATORY SITE, ILLINOIS

By J. C. Olimpio, Champaign, Ill.

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

Radiometric analyses of unconsolidated glacial deposits and ground water beneath the burial trench (Golchert and Sedlet, 1977) show that tritium has migrated downward through 40 m of glacial deposits to an underlying dolomite aquifer. Tritium concentrations in water from the Palos Forest Preserve wells in dolomite, 360 m downgradient from the waste-burial site, range from 200 to 1,400 pCi/L annually. Samples from these wells have not contained detectable concentrations of any other waste nuclides.

The predominant clay mineral of the drift is illite (Willman and others, 1963), which has a relatively low ion-exchange capacity (Grisak and Jackson, 1978, p. 64–72). Because tritium is probably not significantly adsorbed, its movement from the site would be controlled primarily by the hydrologic characteristics of the glacial deposits.

Objective.–Because of the apparent opportunity at this site to learn more about the long-term mobility of waste isotopes in ground water, a study was initiated to define the geologic and hydrologic properties of the site which control solute transport and to determine the distribution of tritium and other isotopes which might be migrating from the site.

Approach.–The study, which was started in 1978, is based primarily on conventional test drilling, sampling, well testing, and geochemical analyses. Drilling and sampling adjacent to the burial site are underway to determine the extent of the fracture network in both the saturated and the near-surface unsaturated glacial deposits and the influence of the fractures on the ground-water flow and nuclide transport. A simplified digital model has been used to help evaluate factors controlling the ground-water flow near the site.

Progress.–Comparison of geologic and geophysical logs indicate that clayey and silty glacial deposits form continuous strata. Discontinuous lenses of sand and sandy gravel commonly occur within the clay and silt. The upper strata are clay-rich, fractured, and contain numerous thin sand layers and partings. Conversely, the lower strata are silt-rich, dense, and contain a few thick sand layers. Preglacial surface drainage formed narrow, east-west trending valleys in the dolomite bedrock on which the glacial sediments were deposited. There is evidence that one such valley occurs in the Forest Preserve directly beneath the burial site.

The thick, dense, clay-silt strata have extremely low intergranular flow rates, and the clays provide a large effective mineral surface area for ion-exchange. However, fractures have been observed which may provide the principal ground-water flow conduits rather than intergranular pores. Under such conditions, rates of ground-water flow might be orders of magnitude faster than intergranular flow, and the mineral surface area available for ion exchange might be much lower.

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INVESTIGATIONS AND MODELING OF GEOLOGIC AND HYDROLOGIC PROCESSES

GEOCHEMISTRY OF TRACE ELEMENTS IN NATURAL WATERS

By E. A. Jenne, Menlo Park, Calif.

The uptake by biota, the adsorption on solids, and precipitation from solution of radioisotopes and other trace elements is dependent upon the distribution of the individual trace elements or radioisotopes among its various possible solute species (i.e., Co^{2+}, $CoCl^{-}$, $Hg_g(aq)$, etc.). With the exception of physiologically active compounds, such as cobaltamine, for example, the activity of the first hydrolysis product, i.e., $CoOH^{+}$, generally determines the potential for adsorption of radioactive and stable trace metals onto earth materials. The valence of the metals and other trace elements (i.e., Cr^{3+} versus Cr^{5+} and Co^{2+} versus Co^{3+}) greatly affects both their biological potency and adsorption potential. The extent to which a metal such as Fe^{3+} is complexed by Cl^{-}, NH^{4+}, HCO^{3-}, etc., or is reduced to Fe^{2+}, decreases the activity of Fe^{3+} and hence the likelihood of adsorption or precipitation of ferric iron compounds.

Current principal limitations on chemical modeling are (1) the lack of the capability to include the significant organic ligands into the aqueous speciation part of the model, (2) difficulties in addressing redox potential and lack of knowledge of the actual relationships between the various couples, (3) inconsistencies between available adsorption models, and (4) the unavailability of needed thermodynamic data and uncertainty of the adequacy of the available thermodynamic data.

Objective.—The objective was to develop a chemical model appropriate to natural and contaminated waters which will permit prediction of radioisotope bioavailability, sorption on inorganic and organic solids, and precipitation.

Approach.—A variety of laboratory and field experimental techniques are being developed or adapted to measure the parameters needed to overcome present deficiencies in models and to test the reliability of models. A continual comprehensive literature search will be made with the objective of incorporating into the models the latest developments in defining chemical thermodynamic parameters.

Progress.—The published version of the chemical model WATEQ2 (Ball and others, 1978), contains the trace elements Ag, As, Ba, Cd, Cs, Cr, Cu, Fe, Mn, Ni, Pb, Rb, Sr, and Zn, in addition to major elements. Sulfide and polysulfide complexes are contained in the model to the extent that the requisite thermodynamic data are available. Numerous metastable minerals were also added. Redox potentials are calculated for analytically determined Fe^{2+}/Fe^{3+}, As^{3+}/As^{5+}, and S^{2-}/SO_4^{2-} couples.

Low-level ($\mu g/L$) analyses have been developed for S_8^0 and SO^{2-} so that redox potentials for the couples S^{2-}/S_8^0 and S_8^0/SO_4^2 can now be computed. Input data for S^0 increases the accuracy with which the activity of the polysulfides can be computed. The neutral complex NaF^0 and the solid, $Ba_3(AsO)_2$, have also been added to the model.

Resin column fractionation of natural dissolved organics has shown that the quantities of organic carbon in each solubility (hydrophobic and hydrophillic) functional group (acid, neutral, and base) class varies systematically in time and space. Thus, determination of stability constants for radioisotopes and other trace elements with these six classes of solubility-functional group organic compounds from natural waters may provide a rational means of including organic complexation into the model.

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CHEMISTRY OF HYDROSOLIC METALS AND RELATED SUBSTANCES IN WATER

By John D. Hem, Menlo Park, Calif.

Objective. – The objective was 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 may be absorbed by or coprecipitated with such hydroxides.

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

Progress. – Recent emphasis has been on manganese oxide coprecipitation mechanisms (Hem, 1979) and on stability of lead hydroxide complexes (Lind, 1978).

Manganese oxide forms nodules and crusts or coatings on other minerals when dissolved manganese and oxygen are present and the pH is near or above neutrality. When a flux of water containing oxygen and manganese ions impinges upon these oxide surfaces, they are very effective sites for oxidation not only of manganese but also of many other dissolved ions. Redox potentials attained are much greater than those usually encountered in aerated water.

This results in certain metals being coprecipitated with the manganese and held within the thickening precipitate. The accessory metals are not released unless the manganese oxide redissolves. The redox model has been applied to manganese and cobalt. At pH 7.5, a concentration of 17 μg/L of Mn can maintain cobalt solubility at 5.0 μg/L, and a manganese concentration of 1.7 μg/L would limit cobalt solubility to 0.1 μg/L. The theoretical model has been reasonably successful in predicting cobalt concentrations in surface- and ground-water systems where manganese oxide precipitates were forming. The redox mechanism may have some practical potential for use in scavenging or immobilizing radionuclides (e.g., ^{60}Co.)

Stability constants have been determined by anodic stripping polarography for the dissolved lead ions $PbOH^+$, $Pb(OH)_2^0$, and $Pb(OH)_3^-$. A rather wide range of values has been reported for these constants in the literature. It is important to determine the best possible values because lead hydroxide complexes are the predominant dissolved forms of lead in many natural waters. The values obtained for these constants are believed to be the most accurate available for calculating lead solubility in waters of low dissolved solids concentration.

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GEOCHEMICAL KINETICS

By Hans C. Claassen, Lakewood, Colo.

The interaction of the solid and liquid phases in natural ground-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. Values for all of the above properties can be estimated with existing techniques except for the effective surface area of rock material in the aquifer. Quantitative information on the surface-area parameter is required, however, to model mass transport (including pollutants) in a realistic fashion.

Objective. – The objective was to develop a means for estimating the effective surface area of rock material in aquifers through analysis of its influence on geochemical reactions.

Approach. – The approach is based primarily on a detailed study of a natural perched ground-water system in southern Nevada. The aquifer rock material is volcanic glass and the reaction kinetics and mechanism have been determined. The rate-determining process of this reaction is solid-state diffusion of ions from the glass to the solution. The rate of diffusion of each ion species is dependent primarily on the concentration of co-diffusing species (mainly hydrogen ions), the solution concentration of the selected ion, and the sorption properties of the glass surface for that ion. The interrelationships of the variables were combined in a digital computer model. This model was used, together with estimates of initial solution composition, to match the observed ground-water quality.

Allowance was made for precipitation of the clay mineral montmorillonite, since it is observed lining some pores in the ground-water systems. When the computer model reproduced the observed ground-water quality, it was then possible to calculate a value for the surface-to-volume ratio (σ) for the aquifer. This value was then compared with that for σ determined from porosity and surface-area measurements on a number of representative cores from the aquifer system.

Progress.—It was found that the value for σ obtained through modeling water-quality kinetics was only a few percent of that obtained by direct measurement. This is probably because the most rapid flow, and perhaps the greatest quantity occurs in fractures even though a measurable flow occurs though the primary pore spaces. This difference in behavior between flow through fractures and primary pore spaces is responsible for the difficulties in predicting mass transport of pollutants in natural ground-water systems; the water moving through the fractures can travel considerably faster and under conditions of lower values for σ than water flowing through the primary pore spaces. Since smaller effective surface areas provide less opportunity for sorption, pollutant concentrations are attenuated less.

MODELING MINERAL-WATER REACTIONS

By L. N. Plummer, Reston, Va.

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

Approach.—A weight-loss method has been adapted to study dissolution rate of single crystals suspended by platinum wires in known solutions. The solution pH is kept constant using automatic titrations. Numerical simulation techniques are being used to model thermodynamic chemical reactions in aqueous-mineral systems.

Weight loss is measured to within 0.2 μg using an electronic balance. This method has proved to be far more reliable than batch experiments using a suspension of stirred particles.

Progress.—A computer code (PHREEQ) has been developed which can be used to predict the outcome of any hypothetical chemical reaction(s) using a thermodynamic model of the desired mineral-water system. A distinctive feature of this program is that it incorporates aqueous-phase chemical parameters that can be defined by the user. If, for example, the appropriate thermodynamic data for the actinides were compiled, prediction of water-rock reactions involving these elements could be simulated, as could be done for any other chemical system for which thermodynamic data are available. Such thermodynamic data for uranium have been compiled and can now be used with this reaction simulation program. Limitations to the use of PHREEQ are, of course, subject to uncertainties regarding the aqueous model developed by the user and the extent to which homogeneous and heterogeneous reactions actually reach equilibrium in the defined chemical system.

The solution kinetics of eight different dolomite samples were studied in collaboration with E. Busenberg under the following conditions: between 0 and 60°C, 0 and 1 atm CO_2 partial pressure, and pH 0 to 10. The rate of dissolution depends on heterogeneous chemical reactions at the mineral surface and is independent of hydrodynamic conditions at temperatures below 45°C. The $CaCO_3$ component of dolomite reacts faster than the $MgCO_3$ component, leading to apparent nonstoichiometric dissolution, with Ca/Mg ratios in solution greater than that of the solid, when large surface areas are present. The rate limiting step in dissolution is the breakdown of the $MgCO_3$ component which leads to the observed half order reaction dependence on H^+, $H_2CO_3^*$ and H_2O. The rate of backward reaction is proportional to the activity of HCO_3^- *in solution. It is* unlikely that back reaction produces dolomite but instead forms a magnesian calcite or protodolomite on the surface.

The dissolution kinetics of calcite was studied under differing hydrodynamic conditions and showed that while the rate dependence on H^+ is a function of stirring, the $H_2CO_3^*$ and water dependence of the rate are independent of hydrodynamics. This supports an earlier conclusion that the CO_2 and water reactions are surface controlled while H^+ reaction is a transport controlled process.

Calcite dissolution experiments in the presence and absence of dissolved phosphate show that far from equilibrium the forward rate is accelerated when phosphate is present. As the bulk fluid pH approaches the calculated surface equilibrium pH, the effectiveness of phosphate in accelerating the forward rate diminishes. This observation supports the one-mechanism model of Plummer and others (1979) for calcite dissolution and opens the possibility of defining and understanding, as a

whole new class of inhibitors, the weak acids (including organics) which dissociate in the higher pH environment of the calcite surface.

Dr. Michael M. Reddy of the New York State Department of Health spent a month in the USGS laboratory in Reston, Virginia, measuring the rate of crystal growth of calcite at 25°C and constant values of PCO_2. These experiments have been used to test the mechanism of back reaction. Preliminary results of some calcite crystal growth experiments indicate that growth rate can be predicted with a rate model within a factor of two at high supersaturation.

Preliminary experiments with aragonite ($CaCO_3$) and magnesite ($MgCO_3$) indicate that the H^+ dependence of aragonite dissolution appears identical to that of calcite and is probably transport controlled. The rate of water reaction with aragonite appears to be about twice that with calcite. Magnesite dissolution is extremely slow and is observed only at low pH (approximately or less than 3.0), where the H^+ dependence of the forward rate appears to be half order.

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CHEMICAL REACTIONS AT MINERAL SURFACES

By John D. Hem, Menlo Park, Calif.

Objective.—The objective was to determine the effects of the surfaces of common minerals (oxides, silicates, etc.) on reaction rates and on dissolved concentrations of metal ions related to cation exchange and other adsorption phenomena.

Approach.—Current studies entail the development of a theoretical model for quantifying adsorption effects based on the concept of the electrical double layer (EDL) and testing refinements of the existing models in the laboratory. Mathematical fitting is done by means of a computer program.

The EDL theory postulates that an electrically charged solid surface that is immersed in water is covered with a layer of immobilized water molecules and that solute ions with electrical charges opposite in sign to the surface charge accumulate outside the water layer. This system is somewhat analogous to an electrical capacitor.

Progress.—A modification of currently existing EDL models was developed for estimating sign, quantity,and intensity of electrostatic charge on oxide surfaces immersed in water. The equipment needed to measure effective surface areas of sediments was obtained and placed in operation. The EDL model can incorporate the effects of type and concentration of various dissolved species on the adsorption of metal ions and can therefore be used over a wider range of pH and solution composition than can simple adsorption isotherms or mass-law equilibrium models. The silt-size fraction of bed sediment from Colma Creek, south of San Francisco, California, consisting mainly of quartz and feldspar, was characterized using the EDL model, and the adsorption behavior with respect to lead was evaluated in the laboratory. The model successfully predicted the dissolved lead concentration and lead adsorption from pH 2.0 to pH 7.0 (Brown, 1979). Adsorptive properties of mineral surfaces in aqueous systems must be correlated with the effective surface area rather than with weight. The range of adsorptive capacity per unit area of natural sediment and aquifer materials can be expected to be much less than the range of values per unit weight of such materials. Surface area measurements in this study were made by the standard Brunauer-Emmet-Teller (BET) technique of adsorption of nitrogen gas at low temperature and by a wet method for measuring adsorption of an organic dye.

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MICROBIAL REDUCTION OF IRON

By Garry G. Ehrlich, Menlo Park, Calif.

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

It is now commonly recognized that microbes are responsible for the reductive solubilization of these metals, but certain misconceptions about the mechanism of the process are widespread.

The reduced state of the environment in a shallow burial site is a result of microbial activity. Solubilization is not caused by the reducing condition in itself but because some microbially produced reductant reduces the metal compounds. Fe(II) and Mn(II) ions do not appear under sterile conditions unless powerful chemical reducing agents are present. Under low-Eh conditions and at neutral pH, Fe(II) and Mn(II) are stable, and the presence or absence of potential ligands is insignificant.

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

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

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

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

Progress.—High concentrations of iron appear in the presence of organisms that are able to produce hydrogen sulfide under acidic conditions. For example, a strain of *Clostridium cochlearium*, isolated from a fresh-water lake sediment, was able to produce Fe(II) concentrations of 300 mg/L or more when growing on cysteine ($C_3H_6NO_2SH$), an amino acid with a terminal SH group. Only traces of Fe(II) were found in solution when the same organism was grown on non-sulfide containing substrates.

A few other iron-reducing species of clostridia including *C. sphenoides* and *C. bifermentans* were found by Godsy and Ehrlich (1978) in an organically enriched aquifer near an artificial recharge well.

Studies still in progress show that certain nitrate reductaseless clostridia including *C. butyricum* and *C. acetobutylicum* can produce Fe(II) concentrations up to 300 mg/L from hematite (Fe_2O_3) when growing on glucose. The amount of iron produced is proportional to the amount of glucose assimilated. Iron concentrations are highest in media buffered at near neutral pH with solid $CaCO_3$. Glucose assimilation is also greatest under these conditions.

The spectrum of metabolic products produced during the fermentation of glucose is altered in the presence of hematite. Three minor metabolic products, pyruvic acid ($C_3H_4O_3$), oxaloacetic acid ($C_4H_4O_5$), and oxalic acid ($C_2H_2O_4$), which normally appear during fermentation of glucose, are not observed when the fermentation is conducted in the presence of hematite with or without $CaCO_3$. This suggests that these metabolites act as reducing agents in the same manner as H_2S does in the example above. However, when filter sterilized, spent culture media containing pyruvic, oxaloacetic, and oxalic acids is added to hematite under reducing conditions, no Fe(II) appears. The presence of microbes thus seems to be essential for reduction of hematite.

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HEAT TRANSFER IN AQUEOUS SYSTEMS

By Harvey E. Jobson, Bay St. Louis, Miss.

One of the principal factors to be considered in hydrologic studies of low-level waste burial sites is the determination of the amount of precipitation that infiltrates the burial site, percolates downward through buried wastes, and eventually reaches the water table. This amount can sometimes be estimated by subtracting evaporation and surface runoff from precipitation if those components can be accurately measured, calculated, or estimated. Actual rates of evapotranspiration from the ground surface are dependent on many factors controlling the energy

balance of the site and are difficult to measure or calculate.

Objective.—The objective was to improve current techniques for the prediction of energy (heat) transfer between the air and water by evaporation, conduction, and radiation. This information is used to improve the ability to predict both natural and elevated temperature distributions in water systems and evaporation rates from water or ground surfaces.

Approach.—The accuracy of predictions of water temperatures and (or) evaporation rates depends on the ability to model the exchange of energy at the air-water interface as well as the ability to predict water movement and dispersion within the system. The surface-exchange process and evaporation rate are heavily interdependent. The equations describing the processes are being modeled numerically and tested and refined in natural systems as well as under controlled laboratory conditions.

Progress.—A highly accurate thermal model was developed and used to predict successfully the evaporation rate from a flowing stream (Jobson, 1979). The mass-transfer coefficients determined in that study will be extremely useful to future thermal modeling efforts because these coefficients have never before been successfully determined under the conditions of a flowing stream.

The ability to model the movement and mixing of water and heat within a highly transient one-dimensional system has been demonstrated (Jobson and Keefer, 1979). Also, it has been demonstrated how temperature records can be processed in order to estimate natural water temperatures in a thermally altered system (Jobson and others, 1979).

Improvements in instrumentation are important to enhance our ability to monitor energy transfer. A. M. Sturrock, Jr., evaluated various radiation sensors and developed an improved psychrometer.

Assistance was provided to the investigations of low-level waste-disposal sites at Beatty, Nevada, and Barnwell, South Carolina, by setting up instrumentation and developing procedures for measuring properties that will be used to calculate evapotranspiration rates.

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URANIUM MILL TAILINGS

RADIUM GEOCHEMISTRY

By Edward R. Landa, Lakewood, Colo.

In recent years, there has been increasing awareness among scientists and the general public of the radiological hazards resulting from natural radioactivity in the environment and from activities such as the mining and milling of uranium ores which increase the likelihood of exposure to the associated radiation.

Objective.—The objective was to characterize some of the physical, chemical, biological, and mineralogical factors that may influence the mobility of radium in the surficial environment with particular attention to uranium mill tailings.

Approach.—The major initial effort involves examination of the literature relevant to the long-term isolation from the biosphere of uranium mill tailings and their component radionclides.

Samples of mill tailings will be collected at active and inactive sites for laboratory studies to determine the chemical and mineralogical associations of radium in the tailings and the susceptibility of such radium to leaching by water.

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

Progress.—A critical review of the subject, based on the literature survey, was prepared for publication (Landa, 1979). Laboratory facilities for the project were recently installed.

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