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OAK RIDGE NATIONAL LABORATORY

OPERATED BY

UNION CARBIDE CORPORATION

NUCLEAR DIVISION

POST OFFICE BOX X

OAK RIDGE, TENNESSEE 37830

December 17, 1981

Mr. Hubert J. Miller, Chief
High-Level Waste Technical Development
Branch
Division of Waste Management
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Dear Hub:

As a follow up to our recent telephone conversation, I am enclosing an informal report which we prepared on the Palo Duro and Paradox Basins, the leading candidates for locating a high-level waste repository in bedded salt. The report summarizes the background and current status of geologic and hydrologic knowledge about these two basins, identifies areas where additional information and/or data is needed, and suggests plans for further investigation. After you and your staff have had an opportunity to review the document we would like to meet with you, at your convenience, and explore avenues where ORNL could provide technical assistance to the NRC in developing the necessary information required to evaluate the potential of these basins for use as a waste repository.

I am also including along with the report, a resume for T. F. Lomenick who would be the principal investigator for any technical assistance work that we would undertake for the NRC in this area.

Best wishes for the holiday season.

Sincerely,

E. J. Frederick
Manager of Regulatory Programs
Chemical Technology Division

EJF:msb

Enclosure

RESUME

Name: Thomas F. Lomenick

Employer: Oak Ridge National Laboratory, Union Carbide Corporation — April 1959 - Present

Address: P. O. Box X, Oak Ridge, TN 37830

Phone: 615-574-4949

Education: B.S., M.S., PhD degrees

Work Experience:

Includes 22 years of research, development, and management work on radioactive wastes storage/disposal programs. Geotechnical work in most all facets of low-level, as well as high-level storage/disposal has been accomplished. Includes burial ground siting and assessment, surface and subsurface water monitoring, hydraulic fracturing technology, repository siting and evaluation in rock salt, granite, argillaceous sediments, etc. and the development and implementation of stabilization and containment and control programs for uranium processing and storage sites.

Initiated site exploration for high-level waste repositories in the Permian Basin (Kansas, N. Mexico, and W. Texas), the Gulf Coast domes, the Salina Basin (Michigan, Ohio), and the Paradox Basin (Utah).

Conducted original creep tests on Model Pillars of Rock Salt for Repository Design.

Papers, Publications:

Includes more than 40 scientific publications in such journals as <u>Health Physics</u>; <u>Soil Science Society of America Proceedings</u>; <u>Rock Mechanics</u>; <u>Nature</u>; <u>Southeastern Geology</u>; <u>Nuclear Engineering and Design</u>; <u>Encyclopedia of Materials Science and Engineering</u>; <u>OECD/NEA Proceedings IAEA Bulletin</u>; etc.

Lectures:

Frequent (2 - 4 times/year) guest lecturer to Oak Ridge Associated Universities.

Special Assignments:

- Expert witness - Gorleben International Hearings on Entsorgungszentrum, Federal Republic of Germany

- Consultant to IAEA for preparation of documents entitled "Site Selection Factors for High-Level Radioactive Waste Repositories" and "Site Investigation for the Disposal of Solid Radioactive Wastes in Deep Continental Geological Formations"

INTRODUCTION

As a potential host medium for the repository disposal of high-level radioactive waste, rock salt has remained at the forefront of the U. S. program ever since its recommendation in 1957 by a National Academy of Sciences panel. In the mid to late 1960's, verification of many of the favorable geological and physical properties of salt was established from studies conducted on bedded deposits near Lyons, Kansas under Project Salt Vault. Oak Ridge National Laboratory designed and administered that program. Assistance to the then-existent U. S. Atomic Energy Commission was also provided by the U. S. Geological Survey through a compilation of general data on domestic salt deposits (Pierce and Rich, 1962).

Even though Project Salt Vault did not lead to the selection of a repository site, interest in salt nonetheless persisted into the 1970's. This rock type remained as the principal potential host medium under investigation by the programs of the Office of Waste Isolation (OWI), a distinct organization created in 1975 by the Union Carbide Corporation and headquartered at Oak Ridge National Laboratory to direct the waste program for the U. S. Energy Research and Development Administration (ERDA). A significant contrast to earlier efforts was that the OWI program was designed to include studies of salt domes in the Gulf Coast region. Pioneering work on these domal deposits was performed by the Institute of Environmental Studies at Louisiana State University, Netherland, Sewell and Associates, Inc., and the Texas Bureau of Economic Geology, all under contract to OWI.

A comprehensive study report on all domestic salt deposits, which included recommendations on their regional waste-disposal potential, was also undertaken by OWI (Johnson and Gonzales, 1978). Figure 1 here indicates the salt-bearing basins considered in that report.

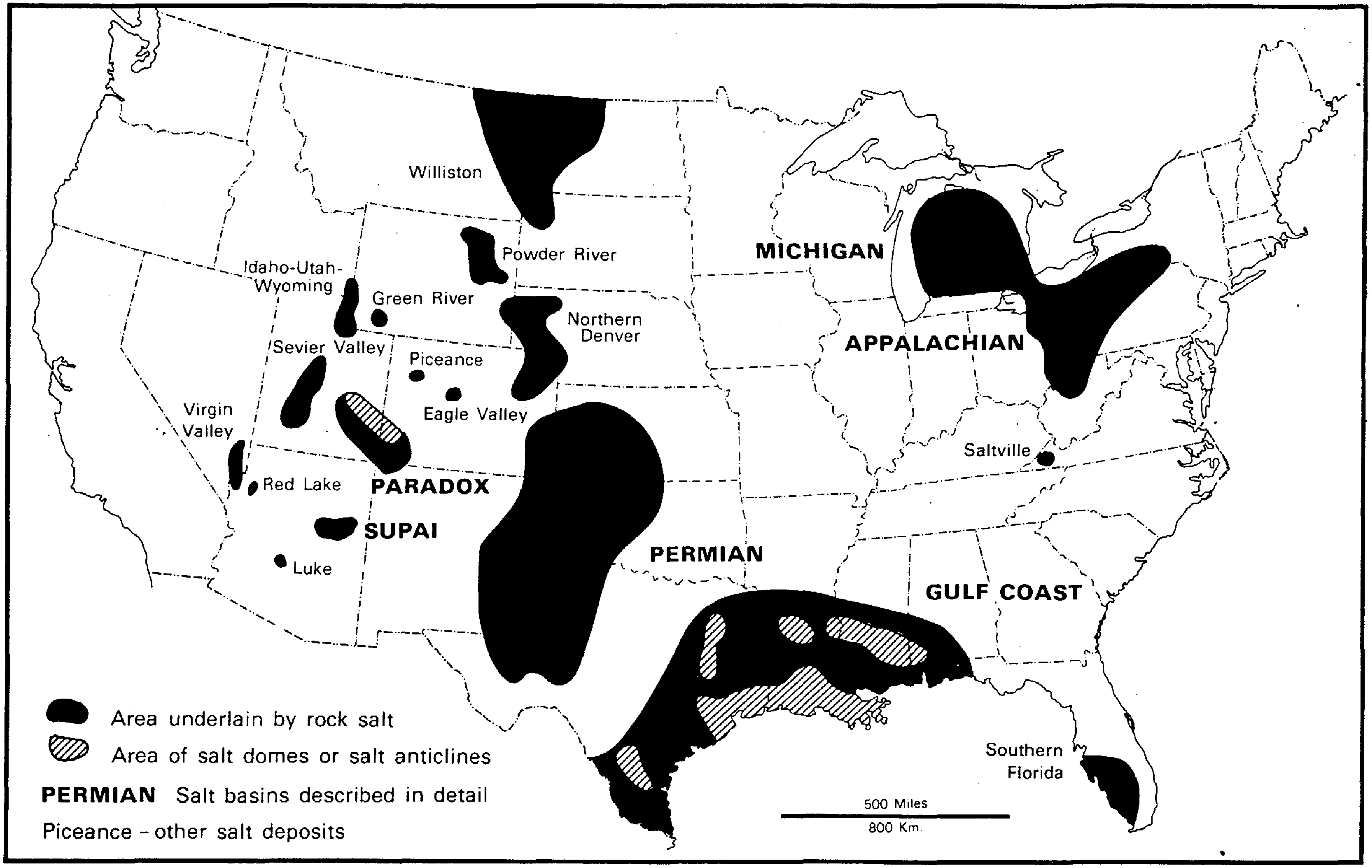

Figure 1. Map showing the distribution of principal salt-bearing basins within the conterminous United States (modified after Johnson and Gonzales, 1978).

Although the Silurian-age salts within the Michigan and Appalachian Basins were also evaluated as promising in another OWI study (Johnson and Gonzales, 1976), lack of concurrence with the affected states precluded further detailed investigation. In another OWI-sponsored study (Johnson, 1976), the potential of the Permian-age salt sequence within the Palo Duro Basin of west Texas was clearly established. This led to the eventual involvement of the Texas Bureau of Economic Geology to extend the studies on this basin under the OWI program.

Geologic and hydrologic investigations of the Pennsylvanian-age salts within the Paradox Basin of Utah and Colorado were also underway as part of the participation of the U.S. Geological Survey within the OWI program. Studies by Hite and Lohman (1973), Gard (1976), and Hite (1977) were instrumental in establishing firm interest in these salts.

In early 1978 when the corporate decision to dissolve OWI was reached by the Union Carbide Corporation, the significant involvement of several other organizations had been accomplished through the assignment of Geologic Project Managers (GPM's) for various salt deposits. Thus, Stone and Webster Engineering Corporation was supervising work on the Silurian salts in the Northeast, Woodward-Clyde Consultants were directing the Paradox Basin work, and Law Engineering Testing Company was coordinating activities on the Gulf Coast domes. When the national waste program was transferred to the newly created Office of Nuclear Waste Isolation in the Battelle Memorial Institute, all the GPM's originally established under the OWI program were maintained. Two years later, a GPM for the Palo Duro Basin studies was established and awarded to Stone and Webster Engineering Corporation.

This brief paper summarizes the background and current status of geologic and hydrologic knowledge about the two leading candidate basins, namely Palo

Duro and Paradox, that contain promising bedded salt. Reviewed here are thus the results of studies begun under the auspices of Oak Ridge National Laboratory, continued and expanded by the Office of Waste Isolation, and refined toward more specific site identification under the Office of Nuclear Waste Isolation. Although the more than a decade of investigations so summarized have greatly increased the level of geotechnical understanding on these two basins, unanswered questions, unresolved technical problems, and data deficiencies still remain. Therefore, at the end of each discussion, some of these issues are briefly outlined and possible plans for investigation suggested.

GEOLOGIC STRUCTURE AND STRATIGRAPHIC FRAMEWORK

The Palo Duro Basin is the dominant structural feature in the southern part of the Texas Panhandle. It is a large asymmetrical basin between the Matador Arch on the south and the Amarillo Uplift and Bravo Dome on the north (fig. 2). The basin has a length of about 280 km, a width of about 100 km, and an axis about 10 km north of the Matador Arch.

Initial development of the Palo Duro Basin as a structural and depositional feature began in Pennsylvanian time, while the adjacent uplifts were being raised. As much as 3,300 m of sedimentary rocks overlie the basement complex of igneous and metamorphic rocks in the deep part of the basin: pre-Pennsylvanian and Pennsylvanian stratigraphic sequences are each about 300 m thick, Permian strata are about 2,100 m thick, and Triassic and Tertiary strata combined are about 600 m thick. Although the Palo Duro Basin became a distinct structural feature during Pennsylvanian time, the principal episode of down-warping and sedimentation occurred later, during the Permian Period. All Permian units are thicker in the southern part of the basin, and they are thinner northward toward the Amarillo Uplift. Permian strata, which include the thick salt beds that are a potential repository host, dip gently to the south and southwest over most of the basin, and the rate of dip is typically 5 to 10 m/km (about ¼ to ½ degree).

Since Permian time there has been some continued minor downward movement in the Palo Duro Basin, in comparison to the adjacent uplifts. Thus, although the pre-Permian rocks are locally faulted and complexly folded in and near the uplifts, the Permian and younger strata in the Palo Duro Basin are virtually free of structural deformation.

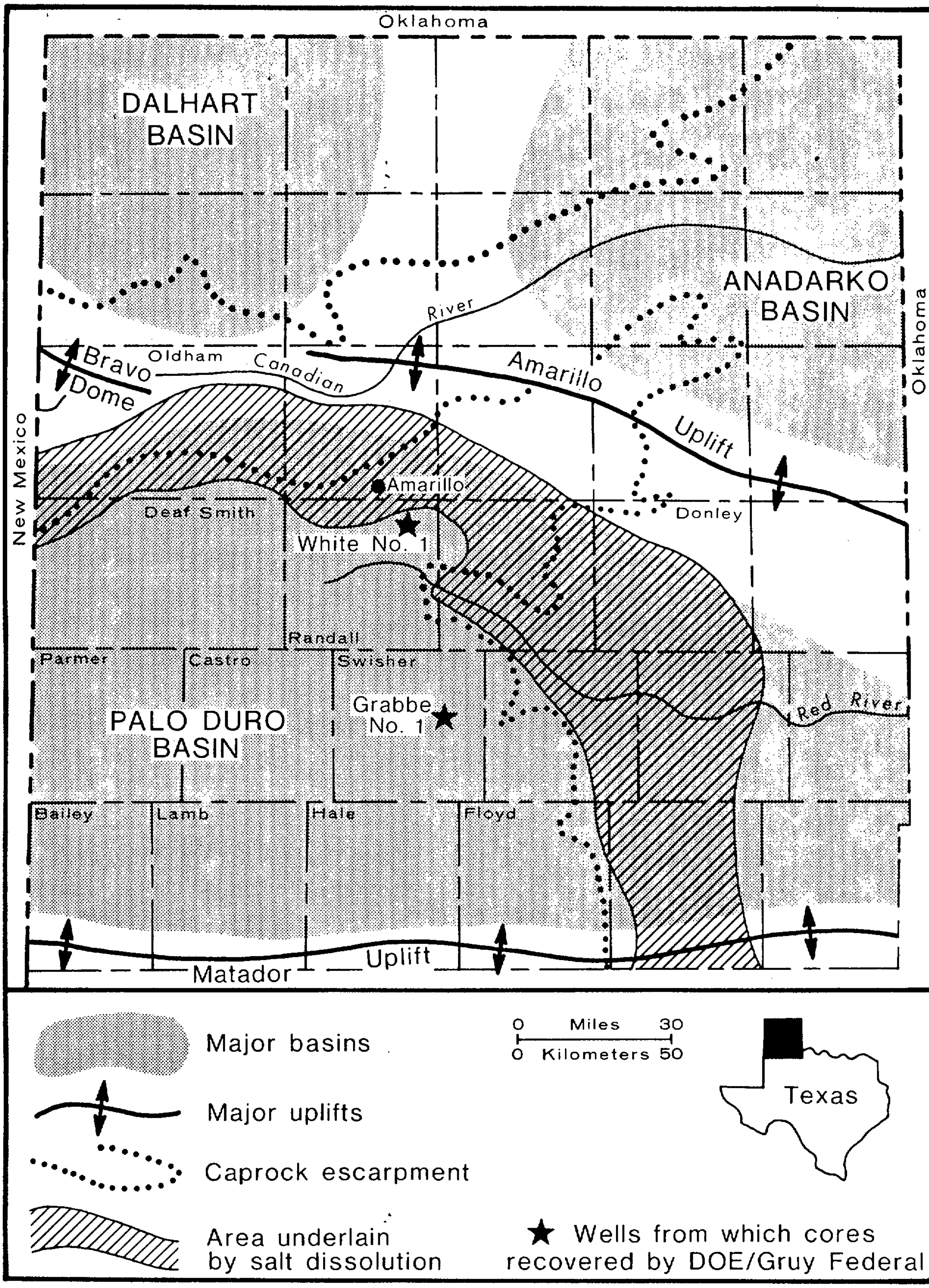

Figure 2. Map of the Texas Panhandle showing major structural features, salt dissolution area, and region in main part of Palo Duro Basin where salt has not been affected by dissolution (modified after Gustavson and others, 1980).

SALT GEOLOGY

Salt deposits in the Palo Duro Basin and nearby areas are Permian in age and occur as part of a thick redbed-evaporite sequence (fig. 3). Seven salt-bearing units in the basin have been of interest as potential hosts for nuclear-waste isolation, and these include (in ascending order) the Lower Clear Fork, Upper Clear Fork, Glorieta, Lower San Andres, Upper San Andres, Seven Rivers, and Salado salt beds (Dutton and others, 1979; Gustavson and others, 1980). Each salt-bearing unit is typically between 30 and 250 m thick in the basin, and each unit contains more than 15 m of net salt at depths between 305 and 915 m below the land surface in some portion of the Palo Duro Basin.

Two deep holes (each about 1,200 m deep) were continuously cored in order to obtain rock samples and to perform hydrologic tests on subsurface formations in the Palo Duro Basin. These stratigraphic tests, drilled in 1978, are the DOE/Gruy Federal, Inc., Rex White No. 1, in northeastern Randall County, and the DOE/Gruy Federal, Inc., D. M. Grabbe No. 1, in northeastern Swisher County. Data from these cores show that 4 major lithologies can be recognized in each of the salt-bearing units: these lithologies are (1) siliciclastics, (2) salt, (3) anhydrite, and (4) dolomite. Siliciclastics are predominantly redbed sandstones, siltstones, mudstones, and claystones that may be loosely cemented with halite and minor silica. Salt occurs as two basic types: (a) banded to massive salt that generally is clear to gray and consists of crystals several millimeters to 5 cm in diameter; and (b) chaotic mudstone-salt that consists of clear halite crystals up to 4 cm in diameter set in a matrix of red mudstone and claystone, where the amounts of halite and matrix are highly variable. Anhydrite is typically blue to gray, may be nodular, massive, or laminated, and normally underlies salt beds in the evaporite sequence. Dolomite beds are mainly gray, laminated to thin bedded, and consist of a

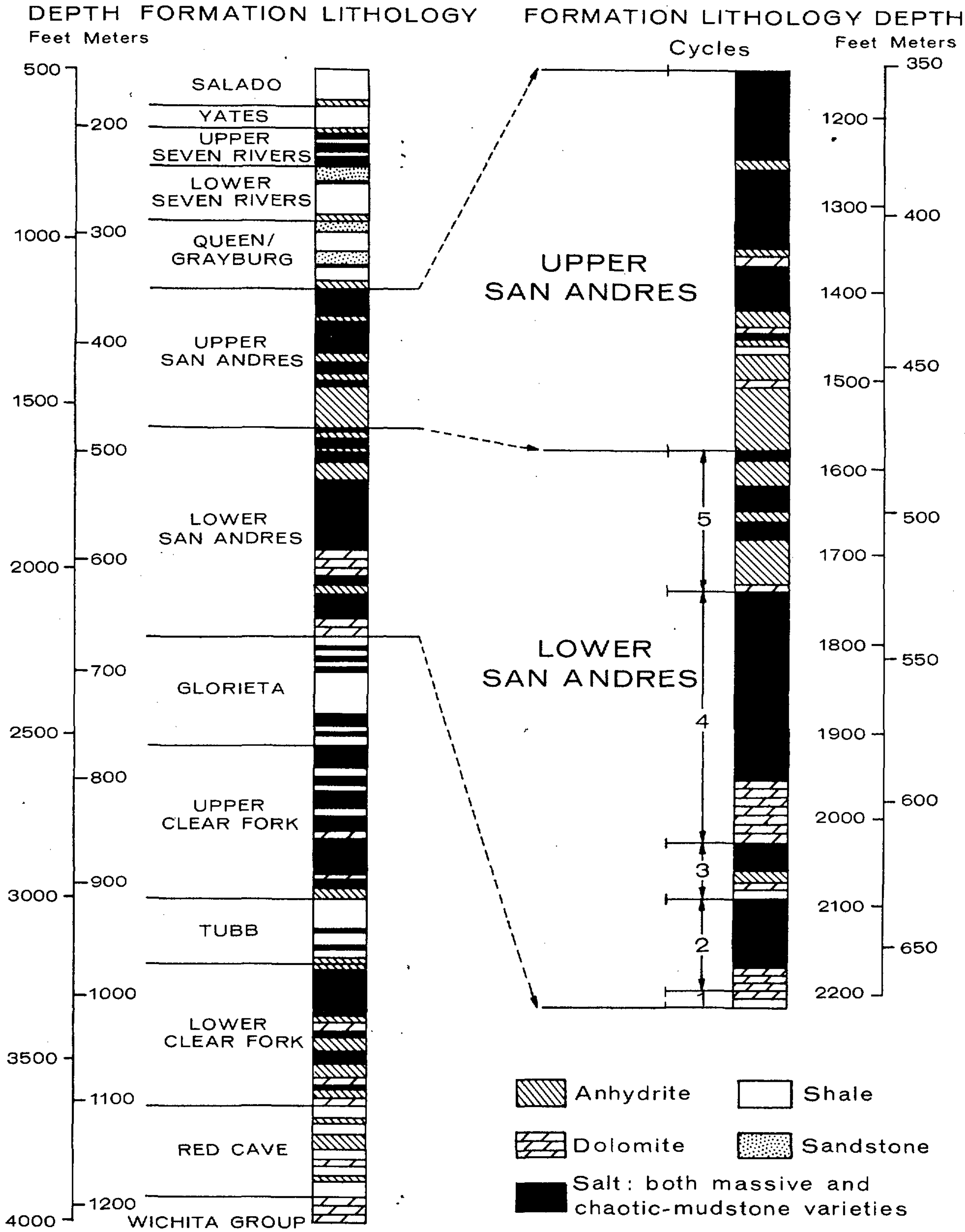

Figure 3. Lithologic column of Permian salts and associated strata in DOE/Gruy Federal, Inc., Rex White No. 1, in northeastern Randall County (modified after Gustavson and others, 1980). Column at right is an expanded section of Lower and Upper San Andres salt units.

wide variety of textures.

The 7 salt-bearing units typically consist of interbeds of all four of the major lithologies. Sequences consisting chiefly of one or another of the major rock types commonly are 10 to 75 m thick in the two coreholes, with the principal thick salt sequences being in the Lower and Upper Clear Fork and the Lower and Upper San Andres salt units. Each of these four units contains a predominantly salt sequence (more than 85 percent halite) that is 35 to 65 m thick in one or both the cores.

The salt sequence that appears to be thickest and of highest purity within the two cores is the cycle 4 salt in the Lower San Andres unit; this salt is 65 m thick and 530 m deep in the Randall County well, and is 50 m thick and 765 m deep in the Swisher County well. The cycle 4 salt consists almost entirely of banded to massive salt, with few thin interbeds of chaotic mudstone-salt and siliciclastics. Of similar thickness, but not quite as pure, is the salt sequence in the Upper San Andres unit; this salt is 60 m thick and 355 m deep in the Randall County well, and is 50 m thick and 555 m deep in the Swisher County well. The Upper San Andres salt consists mainly of banded to massive salt, but it also contains numerous interbeds of chaotic mudstone-salt as well as some interbeds of siliciclastics and anhydrite. Salt sequences in the Lower and Upper Clear Fork appear to be moderately thick and of high purity in the Randall County well, but lack these properties in the Swisher County well; in Randall County the main Lower Clear Fork salt is about 40 m thick at a depth of 985 m, and the main Upper Clear Fork salt is 35 m thick at a depth of 860 m.

Although the above-mentioned salts are thickest and of highest purity in the 2 cores that have been drilled so far, studies by Johnson (1976), Johnson and Gonzales (1978), Dutton and others (1979), Gustavson and others (1980), and Stone and Webster (1981) show that each of the 7 salt-bearing units may also be thick enough, pure enough, and at a desirable depth for a repository in a number of localities within the Palo Duro Basin. Also, it is possible that the Upper Clear Fork salt may also be suitable in parts of the Dalhart Basin, in Dallam and Hartley Counties of the northwestern part of the Texas Panhandle.

HYDROGEOLOGY

The main part of the Palo Duro Basin is drained by Red River and its tributaries, whereas a small portion of the northwestern part of the basin is drained by the Canadian River. Principal fresh ground-water aquifers include Quaternary alluvium and aeolian deposits and the Tertiary Ogallala Formation. Quaternary aquifers are composed of unconsolidated, well-sorted sand, gravel, silt, and clay in beds that range from about 5 to 60 m in thickness. Though not as prolific as the Ogallala, the Quaternary aquifers locally yield as much as 1,900 lpm (liters per minute) to irrigation wells.

The Ogallala is the major source of ground water in the Texas Panhandle and nearby areas; over 90 percent of the water used for irrigation purposes is pumped from the Ogallala. In the Palo Duro Basin area the thickness of the Ogallala is commonly 10 to 150 m, and the depth of the water table below land surface is typically 30 to 60 m (Stone and Webster, 1981). Wells drilled into the Ogallala generally yield about 400 to 9,000 lpm of water that typically is fresh, somewhat hard, and contains between 300 and 1,000 ppm of dissolved solids. Ground water in the Ogallala is recharged locally by precipitation, is usually under water table (or unconfined) conditions, and flows toward the east-southeast (Gustavson and others, 1980; Stone and Webster, 1981).

In addition to the major aquifers mentioned above, small amounts of lower quality water are locally produced within the Palo Duro Basin from rocks of Cretaceous, Triassic, and Permian age.

Studies of deep-basin hydrology have been conducted by the Texas Bureau of Economic Geology and summarized by Stone and Webster (1981). Deep-basin strata (those below the Permian salts) contain strongly saline water within the Palo Duro Basin, and this deep ground water flows from west to east at very slow seepage rates. The low permeability of the overlying Permian evaporite sequences effectively limits the vertical movement of ground water between the shallow and deep aquifers. Aquifers beneath the salt sequences have a lower potentiometric head than those above the salt, and this would lead to a net downward movement of ground water if communication between shallow and deep aquifers should develop across the evaporite units at some time in the future.

Dissolution of salt is occurring at shallow depths along the eastern and northern margins of the Palo Duro Basin (Gustavson and others, 1980; Gustavson, Finley, and McGillis, 1980; Stone and Webster, 1981; Johnson, 1981). This peripheral dissolution occurs where fresh ground water percolates downward through shallow strata to salt beds, dissolves the salt, and then the brine moves laterally to the east until it is emitted in a series of brine springs and salt flats in the eastern part of the Palo Duro Basin. Salt dissolution takes place at depths ranging from about 100 to 300 m in the basin. The most active zones of dissolution appear to be parallel to the Caprock Escarpment in many places, with the salt beds generally remaining undissolved underneath the Caprock and the Ogallala Formation. Gustavson and others (1980) suggest that the rate of dissolution may be directly related to the rate of retreat of the Caprock Escarpment. They determined possible slope-retreat rates of 1 km per 5,500 to 9,000 years for the eastern Caprock Escarpment, and 1 km per

24,000 to 32,000 years for the escarpment above the Canadian River Valley on the north side of the Palo Duro Basin. Preliminary studies also indicated minimum salt-dissolution rates of 250 to 350 m per 10,000 years along the eastern Caprock Escarpment (Gustavson and others, 1980).

SEISMICITY/SEISMOLOGY

Recorded seismic activity in the Texas Panhandle and nearby areas is low, compared to most other parts of the United States. Earthquakes of Modified Mercalli Intensity V (MM V) or greater are sparse in the region. Most of the earthquake activity in the Texas Panhandle appears to be along the Amarillo Uplift and farther north in the Anadarko Basin.

Stone and Webster (1981) compiled an earthquake catalog for a large region embracing the Texas Panhandle. They also prepared an epicentral map of the region, and a survey of seismic-wave propogation and of the history of seismological instrumentation.

A total of 14 earthquakes have been reported with epicenters in the Texas Panhandle (Stone and Webster, 1981). Seven events occurred on the Amarillo Uplift or in nearby parts of the Anadarko Basin, two events occurred on the Bravo Dome, and one event occurred on the north flank of the Anadarko Basin. Three earthquakes are reported for the Palo Duro Basin: two in 1925 had intensities of MM IV and MM V; one in 1951 was of intensity MM VI. A single earthquake reported in the Dalhart Basin was a MM VI event in 1948. Seismological instruments operating continuously since 1961 (Lubbock Station) do not give any evidence of earthquakes with m_b values of 3.5 or more in the vicinity of the Palo Duro and Dalhart Basins (Stone and Webster, 1981).

The low seismicity of the Texas Panhandle is reflected in the published seismic hazard maps. Algermissen (1969) included the region in zone 1, with the possibility of only minor earthquake damage. A later study of seismic hazard in the United States by Algermissen and Perkins (1976) shows that peak acceleration corresponding to a 10 percent probability of exceedance in 50 years (return period 475 years) is less than 0.04 g for the Texas Panhandle.

BACKGROUND STUDIES

Few geologic studies of the Palo Duro Basin and its salt beds were made prior to 1976, mainly because the province was not a significant producer of petroleum or other minerals and because the bedrock geology of so much of the basin was masked by unconsolidated Tertiary and Quaternary sediments. Nicholson (1960) summarized earlier work and provided an analysis of the structural and stratigraphic framework of the region. This was followed by a stratigraphic study of the post-San Andres evaporites by Tait and others (1962) and a brief discussion of salts in the Texas Panhandle by Pierce and Rich (1962).

McKee and Oriel and others (1967a, 1967b) presented a nationwide survey of the geology of Permian rocks, including the salts and other evaporites of Texas Panhandle and surrounding regions. The U. S. Geological Survey, on behalf of the U. S. Atomic Energy Commission, compiled data (Bachman and Johnson, 1973) on the stability of bedded salt in the Permian Basin as an aid in making decisions on the suitability of parts of the basin for emplacement of nuclear wastes. The latter report led to intensified studies in the Carlsbad district of southeast New Mexico for the proposed WIPP (Waste Isolation Pilot Project) site.

STUDIES SPONSORED BY OWI

The Office of Waste Isolation (OWI) at Oak Ridge National Laboratory began studies of the Permian Basin on behalf of the U. S. Energy Research and Development Administration (ERDA) late in 1975. A brief overview of the entire Permian Basin was prepared by OWI and these general data were then released by ERDA as part of a comprehensive document on alternatives for managing radioactive wastes (U. S. Energy Research and Development Administration, 1976).

The first study of the salt deposits in the Texas Panhandle and their potential use for storage of radioactive waste was conducted by Johnson (1976). His investigation summarized the general character, thickness, distribution, depth, structure, and dissolution of the salt deposits in the Palo Duro, Dalhart, and Anadarko Basins of the Texas Panhandle and western Oklahoma. Johnson (1976) concluded that the Palo Duro Basin appeared to be the most suitable of these basins for underground storage of radioactive wastes. He identified five major salt-bearing units, each 60 to 485 m thick at depths of 300 to 900 m beneath some 30,000 sq. km of the basin. He also noted that the basin lacks a history of earthquakes or petroleum production, is structurally simple, and has few boreholes drilled through the salt units.

Johnson (1976) also established that the Dalhart Basin was of secondary interest, because it contained only one thick salt-bearing unit at moderate depths and also contained a few small oil fields. The Anadarko Basin was of least interest because, although it contained three thick salt units at moderate depths, it is a major petroleum province that has many boreholes drilled through the salt units, and several earthquakes have occurred in the eastern and western parts of the basin.

Data presented in the report by Johnson (1976) were subsequently incorporated in a comprehensive OWI-sponsored evaluation of salt deposits throughout the United States and their suitability for storage of radioactive wastes (Johnson and Gonzales, 1978).

Early in 1977, as a result of Johnson's study (1976), OWI invited the Texas Bureau of Economic Geology (TBEG) to assemble and evaluate all available geologic data on the Palo Duro and Dalhart Basins, and representative geologic data on the Anadarko Basin. TBEG entered into a long-term program of basin analysis, salt studies, surface studies, and basin geohydrology.

Arrangements were made early in 1978 to recover continuous cores at two drill sites in the Palo Duro Basin. Gruy Federal, Inc., was selected to provide drilling management, coordination, and technical services for the two boreholes that would provide geologic and hydrologic data on the suitability of bedded salts in the basin for nuclear waste disposal. The DOE/Gruy Federal, Inc., Rex White No. 1 well was drilled to a total depth of 1,220 m in northeastern Randall County from July 26 through September 28, 1978. The second well, DOE Gruy Federal, Inc., D. M. Grabbe No. 1, was drilled to a total depth of 1,283 m in northeastern Swisher County from October 1 through November 22, 1978. Cores recovered from these boreholes were turned over to TBEG for determination of lithology, fluid content, porosity, permeability, and hydrocarbon potential.

STUDIES SPONSORED BY ONWI

During the summer of 1978, the Office of Nuclear Waste Isolation (ONWI) was established at Battelle Memorial Institute to assume management of the Nuclear Waste Terminal Storage program for the U. S. Department of Energy (DOE). At this time, responsibility for the Palo Duro Basin studies were transferred to ONWI from OWI.

TBEG continued their DOE-sponsored studies and released annual reports for FY78, FY79, and FY80 (Dutton and others, 1979; Gustavson and others, 1980, 1981), as well as a series of topical reports discussing various geological aspects of the Palo Duro and Dalhart Basins. The TBEG studies form the basis for some of the detailed data presented previously here.

Environmental studies of the Texas Panhandle region were conducted for ONWI by NUS Corporation (1979a, 1979b, 1980). Parameters addressed in these reports include demography, economics, societal factors, ecology, meteorology, air quality, and the uses of land, water, energy, and mineral resources. These environmental data were obtained from available sources only, with no field studies being conducted.

In July, 1980, Stone and Webster Engineering Corporation (SWEC) assumed the role of Geologic Project Manager (GPM) for the Permian Basin salt program, and is working as a subcontractor to ONWI. As GPM for the Permian Basin, SWEC is to plan and execute the geological, technical, administrative, managerial, and related tasks, under the general direction of ONWI, that are required to identify, characterize, and support licensing of one or more radioactive-waste repository sites in the Palo Duro and Dalhart sub-basins of the Permian Basin.

SWEC has prepared a report (Stone and Webster, 1981) that summarizes the geologic and hydrologic setting of the bedded salts in the Palo Duro and Dalhart Basins. This area characterization report is intended to provide sufficient data to allow screening based upon a number of geologic factors, including depth and thickness of salt beds, active dissolution zones, and location of oil and gas fields. The data will be used to support the identification of one or more potential repository locations within the Texas Panhandle.

Two additional boreholes are currently planned in order to provide information on salt stratigraphy and salt dissolution at the perimeter of the main salt deposits of the Palo Duro Basin. One borehole, near Clarendon in Donley County, is currently being drilled, and the other borehole, in southeastern Oldham County, will be drilled later this Fall. Upon completion of these boreholes, attention should focus on areas that probably have the greatest potential for waste disposal, particularly in and around parts of Deaf Smith, Randall, Swisher, and Castro Counties. Also, attention should focus on the thick and fairly pure salt units in the Upper San Andres and in cycles 4 and 5 of the Lower San Andres (fig. 3); one or more of these salts appear to be at least 30 m thick and at depths of less than 1,000 m in much of the four-county area referred to above.

OTHER FEATURES

Other characteristics of the salt beds and associated strata have been determined largely from study of the two deep cores drilled by DOE/Gruy Federal, Inc. In addition to establishing the quality of various salt units in the basin, the cores have enabled calibration of geophysical logs of oil and gas tests for lithologic interpretation. Dominant clay minerals in the salt sequence are illite, chlorite, chlorite-vermiculite, and chlorite-smectite. Other tests showed that the _in situ_ free-water content of the San Andres salts ranges from 0.15 to 0.53 percent, whereas samples from the Upper Clear Fork and Upper Seven Rivers salts range from 1.83 to 2.44 percent.

Significant types and quantities of important mineral resources are not known to underlie or be interbedded with the salt beds of the Palo Duro Basin. Oil and gas have been discovered in small quantities only at and near the margins of the basin, i.e. on the Amarillo and the Matador Uplifts, and the Palo Duro Basin is not regarded as an important petroleum province. Potash minerals, which are present in some of these salt units in the Carlsbad district of southeastern New Mexico, have been detected only in trace amounts in the Palo Duro Basin and are not believed to be an important resource in the Texas Panhandle. Thus, aside from salt, there are no known mineral deposits in the Palo Duro Basin whose development would be in conflict with siting of a waste-disposal facility; and with the great abundance of salt resources throughout the Palo Duro Basin and nearby areas, the exclusion of salt resources around a repository will have no adverse impact on the available resource base.

Other features relating to possible development of a repository in the Palo Duro Basin include the fact that few boreholes, and no mine shafts, have penetrated the salt units. Also, the region is sparsely settled cropland and rangeland, with annual precipitation ranging from 40 cm/year in the west to 50 cm/year in the east. The basin is crossed by several railroads and a good network of Interstate, Federal, and State highways. Two Standard Metropolitan Statistical Areas are adjacent to the Palo Duro Basin: Amarillo SMSA, with a population of 144,396 (1970 census), is to the north, and Lubbock SMSA, with a population of 179,295, is to the south.

PROBLEMS AND DATA-DEFICIENT AREAS

Hydrogeology

Chemical characteristics and ages of both the shallow- and deep-aquifer waters are needed to evaluate the source of these waters and their potential to dissolve salt and to interact with materials in a waste repository. Tests can be performed on water samples collected from wells now producing fresh water, or from petroleum test holes before they are plugged and abandoned.

Recharge and discharge areas for both the shallow- and deep-aquifer waters must be ascertained, along with the hydraulic head of each aquifer. The regional and local flow paths of these waters must be established, and the velocity of such ground-water movement should be determined. These data can be collected by measuring the potentiometric surface in shallow wells and by conducting drill-stem tests in deep wells during or after completion of the drilling phase. Regional potentiometric-head data on the deep aquifers have already been gathered and presented by Gustavson and others (1981).

The porosity, permeability, and transmissivity of shallow- and deep-water aquifers must be better understood, as well as those same properties in aquitards and in other strata that are between the aquifers. These data are especially critical, inasmuch as they are a measure of an aquifer's ability to conduct water toward and away from a repository area, and also measure the capability of an aquitard to inhibit ground water from reaching or leaving the repository itself. Porosities and permeabilities can be measured in core samples collected from boreholes drilled in the area, and transmissivities can be determined by conducting pump tests on various aquifers and (or) aquitards.

The water content in salt units that are prospective repository units is little understood. These data are important in the ultimate design of a repository in order to protect the waste from invasion by brines derived from fluid inclusions in the salt. Free water in samples from the Lower and Upper San Andres salts ranges from 0.15 to 0.53 percent in Karl-Fisher titration tests, and from 0.09 to 0.76 percent when heated to temperatures of 150 to 650 C (Gustavson and others, 1981). Additional large core samples should be analysed and the results compared with the optical estimate of free water in fluid inclusions. Other potential sources of fluid in the salt units include hydrated minerals, clay minerals, and oxyhydroxides.

Salt Dissolution

Studies to date have indicated the broad areas where each salt unit has been, or is being dissolved (Gustavson and others, 1980). Refinement of these data is necessary, particularly for the candidate repository horizons in the north-central part of the Palo Duro Basin. Rates of dissolution have been estimated for the entire salt sequence in several parts of the Texas Panhandle, but more precise determinations of rates are needed for the candidate repository horizons. Also, there is a need to distinguish between dissolution that occurred in the geologic past (and has now ceased) and dissolution that is going on at the present time, and to determine if paleodissolution can jeopardize the present or future operation of a repository.

Breccia pipes are known around the margins of the Palo Duro Basin and parts of the Anadarko Basin. Whether there are any such features in the north-central part of the Palo Duro Basin that could compromise a waste repository must also be ascertained.

Host-Rock Characteristics

The purity of rock salt in the Palo Duro Basin is accurately known only at the two coreholes drilled by DOE/Gruy Federal, Inc., and much more data are needed to characterize each of the potential repository units. Salts of both the Lower and Upper San Andres typically are massive and well bedded, although there are layers and zones in both units that are chaotic mudstone/salt.

Not clear, however, is how important it is to have high-purity salt in the repository unit. A certain amount of clay minerals (several percent, up to perhaps 15 to 20 percent) admixed in the salt might possibly improve the salt's performance as a host rock. Additional cores of the potential repository salt units are needed, and both physical and chemical tests should be run on them in order to characterize them as repository units.

The mineralogy of the salt beds is known only from the two coreholes, and more must be known about the various evaporite minerals and clay minerals in prospective repository units. These data will enable predicting reactivity with fluids, sources of water, potential for swelling, and the capacity for host-rock minerals to absorb radionuclides that might escape from canisters within the repository. Additional data can be obtained by testing cores from additional test holes in the area.

Little is known about the rock-mechanical properties of the prospective repository units in the Palo Duro Basin. Properties such as elastic moduli, friction, compressive and tensile strength, creep, thermal conductivity, thermal expansion, and effects of radioactivity have not been adequately established for the San Andres salts. Preliminary determinations of some of these properties can be made on cores recovered from boreholes, whereas other tests are best conducted as in situ tests in a mine that may be opened for site characterization.

Structural and Tectonic Features

The Palo Duro Basin is not structurally complex, but there are some faults and gentle folds near the basin margin that must be more completely understood. These structural features probably originated during Pennsylvanian time (prior to deposition of the Permian salts), but they may have been reactivated at later times and may be the focus of small-scale modern movement. No evidence of capable faults has yet been reported in the Texas Panhandle, and clearly a comprehensive search for such evidence must be made before a repository site is selected.

Joints and other fractures are known in various parts of the Palo Duro Basin. They are known through field studies and have been detected on aerial photos and other remotely sensed data. The orientation, spacing, length, and depth of these joint sets need to be determined, and their relationship to deep-seated structures, salt-dissolution zones, and (or) other features must be evaluated. The joints may reflect zones of weakness that penetrate down as deep as a potential repository unit, and they may represent possible avenues for vertical migration of ground water and other fluids.

Geomorphic Processes

Surface investigations by TBEG have been underway for several years now in order to characterize the meteorology, landforms, erosion, and surface geology of the Palo Duro Basin and nearby areas. Additional study is needed to firmly establish rates of erosion and escarpment retreat, and to determine if there is a direct relationship between these phenomena and subsurface dissolution of salt.

Shaft Design and Construction

The stratigraphic sequence of sediments and sedimentary rocks overlying the prospective repository units is fairly well understood, but the special problems that might be encountered in sinking a shaft through these strata in the Palo Duro Basin have not been addressed. No mines, shafts, or other excavations have been dug to depths of more than a few tens of meters anywhere in the Texas Panhandle. Experience gained in sinking a shaft at the WIPP site and in sinking shafts in the potash-mining district around Carlsbad, New Mexico, should be extremely valuable in planning a shaft in the Palo Duro Basin, and much can be learned from the experiences of drilling companies that have been exploring for petroleum in the Palo Duro Basin.

Land Ownership and Access

Almost all lands in the Palo Duro Basin are privately owned, and thus access to land for further testing and acquisition of land for a potential repository will require purchase of surface and mineral rights, or may require condemnation proceedings. There are no large blocks of Federal lands within the Palo Duro Basin, although public lands in excess of about 10,000 acres are the Palo Duro Canyon State Park (in eastern Randall County) and Buffalo Lake National Wildlife Refuge (in southwestern Randall County).

GEOLOGIC STRUCTURE AND STRATIGRAPHIC FRAMEWORK

The Paradox Basin is a major sedimentary basin within the Colorado Plateau province and occupies more than 30,000 sq. km in southeastern Utah and southwestern Colorado. The basin is elongated in a northwestern direction, extends for a length of 320 km, and reaches a maximum width of about 160 km. Along its northern and northeastern margin it is bounded by the upfaulted Uncompahgre Uplift, whereas to the west, southwest, and south are situated the more gently upwarped San Rafael Swell, Monument Uplift, and Defiance Uplift respectively (fig. 4). Within the eastern Utah portion of the basin are found the Abajo and La Sal Mountains which are localized centers of Tertiary igneous activity.

A wedge-shaped sequence of sedimentary rocks unconformably overlies a Precambrian granitic basement such that the thickness is greatest along the northeastern margin near the Uncompahgre Uplift. Here, more than 5,000 m of strata remain. Toward the southwestern portion of the basin, the sequence thins to about 2,000 m. Although the age of the strata range from Cambrian to Quaternary, there are several significant stratigraphic gaps. Ordovician and Silurian rocks are apparently absent and no post-Cretaceous marine units are present. From 500 to 1,000 m of marine strata, mainly carbonates, were formed prior to Middle Pennsylvanian time, when the Paradox Basin became the site of significant evaporitic deposition. During repeated marine transgressive-regressive intervals under renewed basin subsidence, a total of 29 evaporite cycles were formed to become the Paradox Formation. Around all the basin margins, except the northeast, this salt-dominated sequence is less than 300 m thick. In this trend adjacent to the Uncompahgre Uplift, the salt deposits exceed 2,000 m. Some of the numerous salt-cored anticlines which occur

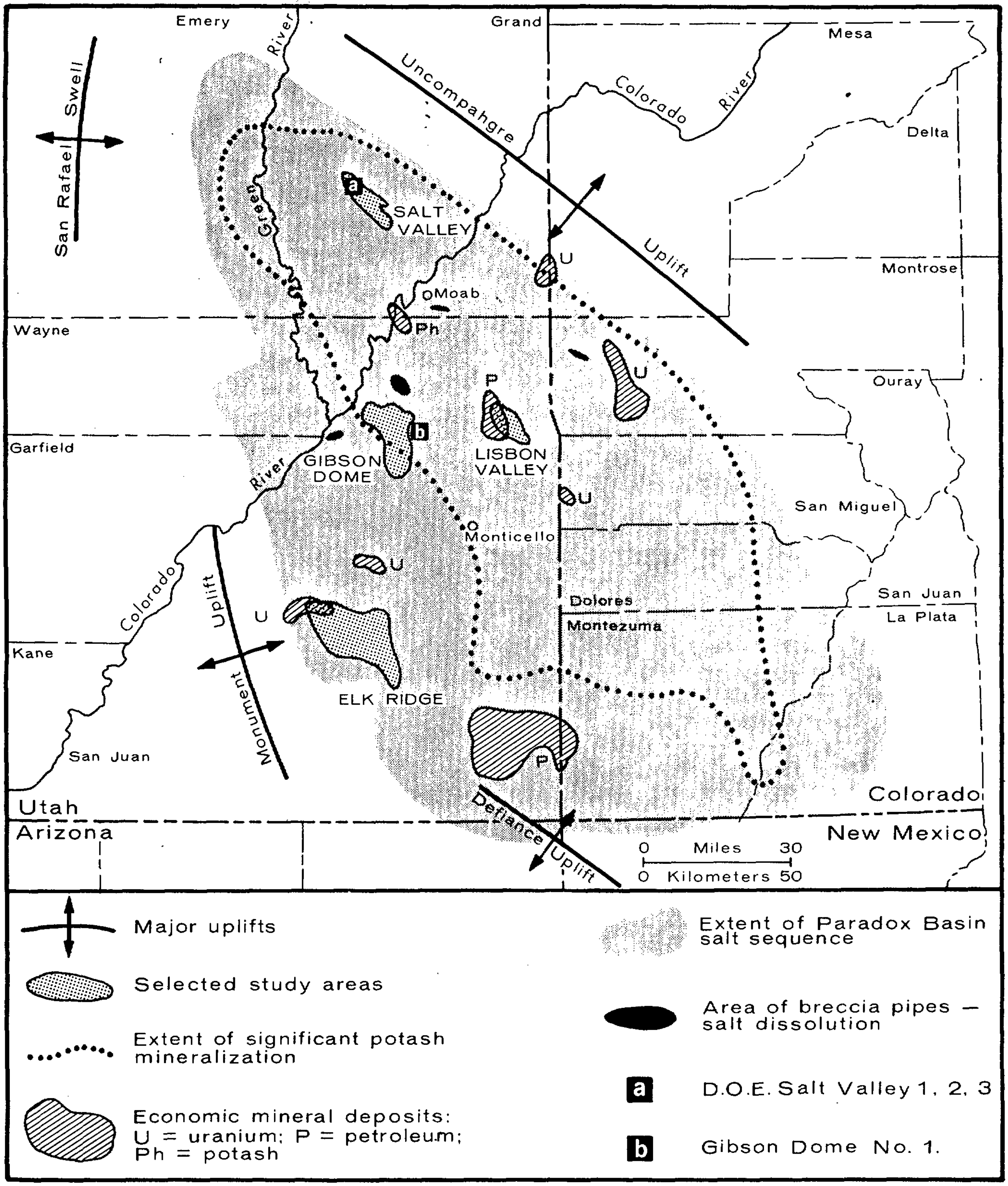

Figure 4. Map showing extent of the Paradox Basin in Utah and Colorado, adjacent major structural features, salt-dissolution areas, and location of economic mineral resources. Four designated study areas, and exploratory coreholes are also shown (modified in part after Bechtel National, Inc. and Woodward-Clyde Consultants, 1980).

within the northeastern and central parts of the basin contain salt sequences in excess of 4,000 m in thickness.

Post-Pennsylvanian strata are represented by mainly non-marine clastic units of Permian through Jurassic age, although much of the Cretaceous sequence consists of gray marine shale. Since the Cretaceous, the basin has been uplifted and subjected to continued erosion which has led to the spectacular and typically rugged topography characteristic of the entire Colorado Plateau province.

Salt movement to form the ten principal salt-cored anticlines is believed to have commenced in Pennsylvanian time and persisted throughout the Permian as evidenced by thinning in post-Permian strata along the flanks (Shoemaker and Elston, 1968). Movement along deeper, northwest-aligned faults associated with the Uncompahgre Uplift is thought to be the cause of initial flowage; recurrent fault movement and the natural buoyancy of the lower density salt extended the upward growth of the anticlinal cores. Although the internal structure of the more diapiric anticlines, for example Salt Valley, is complex, and the dip of the younger strata can be steep along the flanks, there are areas to the southwest where the dips within domal features are less than a few degrees.

SALT DEPOSITS

The salt deposits in the Paradox Basin are Middle Pennsylvanian in age and are restricted to the Paradox Formation of the Hermosa Group (earlier literature treats the Paradox as a member and the Hermosa as a formation). The evaporite sequence is underlain and overlain by stratigraphic intervals dominated by carbonate lithologies and known respectively as the Pinkerton

Trail and Honaker Trail Formations (fig. 5). A thin red-bed sequence termed the Molas Formation represents the basal Pennsylvanian strata which in turn overlie an extensive Mississippian carbonate unit, the Leadville Limestone.

Throughout most of the basin, the top of the salt sequence is deeper than 1,200 m, but it is shallower than 300 m in the central portions of several of the salt-cored anticlines. Along a north-south trend toward the west-central and southwestern part of the basin, however, is a moderately large area where the top of the salt sequence is shallower than 900 m even though diapiric, salt-cored anticlines are not present (Bechtel National, Inc. and Woodward-Clyde Consultants, 1980).

As estimated by Hite and Lohman (1973), the original thickness of the entire evaporite interval (= Paradox unit) was on the order of 1,500 to 1,800 m; subsequent lateral flowage and diapiric movement have created a modern-day thickness which ranges from zero to more than 4,000 m. In some of the salt-cored anticlines and their adjacent synclinal structures, the thickness change is abrupt, ranging again from zero to more than 3,000 m within horizontal distances of only a few kilometers.

The Paradox Formation evaporites are clearly cyclic; a total of 29 individual cycles, numbered 1 (youngest) through 29 (oldest), have been recognized (Hite, 1960; Hite and Liming, 1972). The principal lithology in each cycle, where well developed, is rock salt (halite), while non-salt interbeds (also termed marker beds) separate the halite of adjacent cycles. The typical interbed sequence consists of a thin basal anhydrite, with dolomite and black shale above, and additional anhydrite directly beneath the salt which is the last-formed unit in each cycle. In most cycles, black shale is the most abundant non-salt lithology present. Individual cycles range from 30 to 100 m in thickness, while the salt units within them commonly are from 20 to 80 m thick.

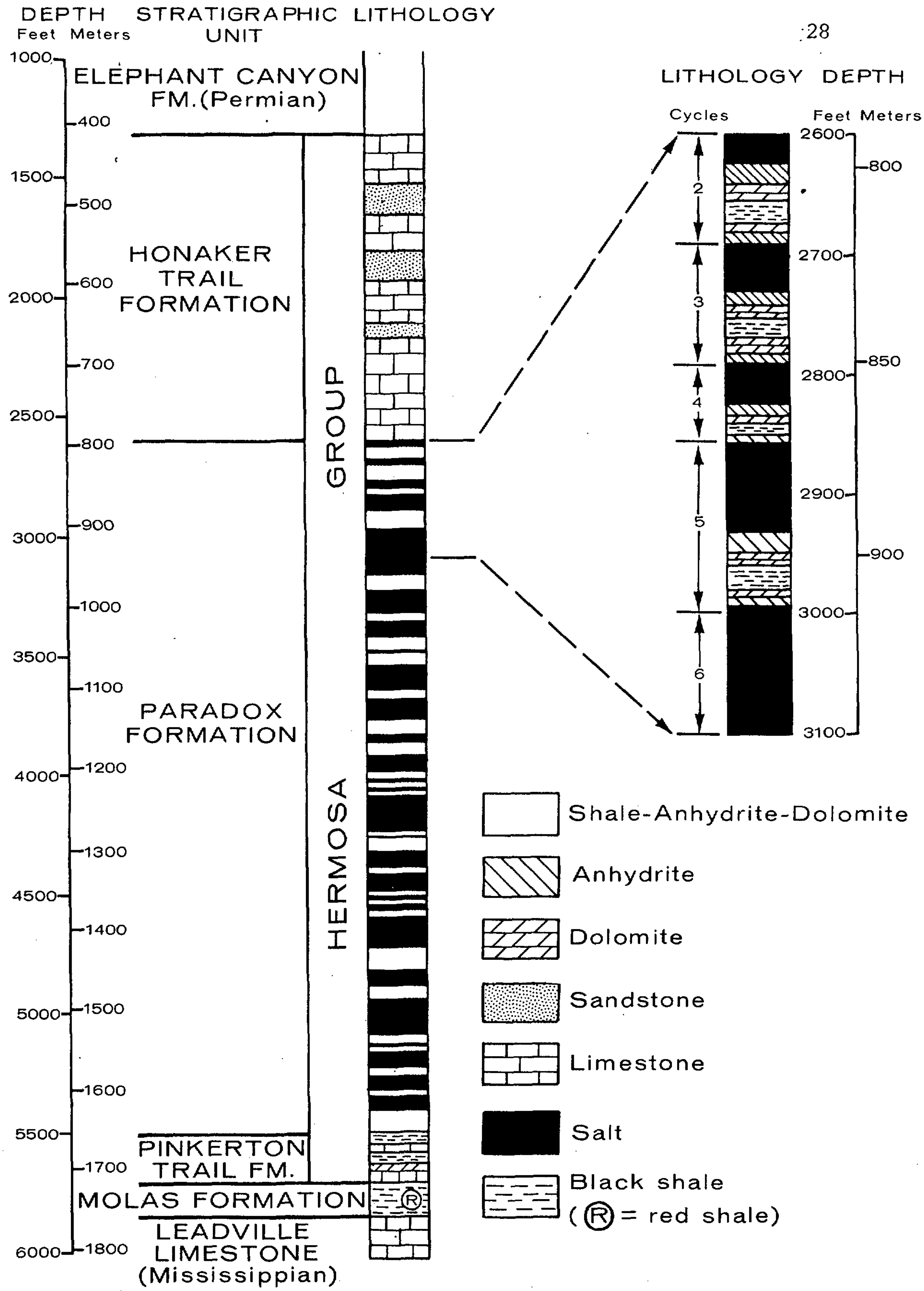

Figure 5. Lithologic column of Pennsylvanian salts and associated strata as projected for the general Gibson Dome Study Area in San Juan County, Utah. Column at right is an expanded section showing the more promising cycle 6 salt as projected off the central part of Gibson Dome.

Although halite is the dominant evaporite mineral, several cycles also contain potash minerals such as sylvite and carnallite. This potash mineralization is invariably concentrated near the top of the halite interval in those cycles. Cycles 6 and 9 of the shallower intervals and 16, 19, and 24 in the deeper section contain more regional distributions of potash mineralization (Hite and Liming, 1972). Hite (1977) has also shown that the percentage of the total evaporite sequence containing more than 15% potash increases rather uniformly in a northeasterly direction or toward the linear trough where the entire stratigraphic sequence is thickest.

Because of the cyclic pattern of lithologies, distinct contrast at the upper contacts of the halite units, and the favorable response of the black shales on gamma-ray logs, the lateral persistence of these evaporite cycles has been determined and good correlations have been established over large distances. Lateral lithologic changes (= facies changes) are however known and are best demonstrated in a northeast to southwest direction across the basin. Also, where the internal structure due to flowage within the salt-cored anticlines is complex, correlation of the cycles becomes very difficult. Hite (1977), using core material from a commercial borehole (Tenneco Oil Company Redd Ranch No. 1), showed that detailed determinations of bromine in halite could be used to identify where evaporite cycles have been structurally overturned due to diapiric movement. Later studies conducted by Hite on cores obtained from boreholes DOE 1, 2, and 3, as drilled on the Salt Valley anticlines revealed that bromine analyses also helped to identify overturned beds in that salt-cored feature.

Hite and Lohman (1973) reported that generally the content of insoluble minerals in the Paradox halite units is less than 2 or 3 percent; more recent analyses of core material from the DOE boreholes at Salt Valley reveals an average value of 1.5 percent by weight. Anhydrite is the dominant insoluble constituent; minor amounts of quartz, calcite, dolomite, and illite are also present. One interesting aspect about this anhydrite is that much of it comprises thin laminae within the salt, and that different salt beds may actually have different, and thus recognizable, microstratigraphies (Bean and others, 1981).

The characteristics of these salt-bearing cycles are significantly modified in the central areas of several salt-cored anticlines where dissolution at the upper salt surface has created a localized cap rock of insoluble material (Hite and Lohman, 1973). Cap rock here is composed of insoluble anhydrite, typically hydrated to gypsum now, as well as the insoluble material from the associated, collapsed marker beds. Commonly these zones of dissolution residue are very porous, and several contain brines.

A basin-screening procedure (Bechtel National, Inc. and Woodward-Clyde Consultants, 1980b) led to the selection of four study areas within the Paradox Basin for more thorough investigation. These areas (fig. 4) are: (1) Salt Valley, a diapiric, salt-cored anticline; (2) Lisbon Valley, a non-diapiric salt anticline; (3) Elk Ridge; and, (4) Gibson Dome. The last two areas entail non-diapiric domal structures where the strata are nearly horizontal, or dip very gently. As the result of coreholes drilled at all four areas, salt conditions are known to vary considerably between these features. From an evaluation of the data obtained through coring, both Lisbon Valley and Elk Ridge have been dismissed as not promising. Salt Valley has been temporarily deferred, and Gibson Dome has been recommended for further study (Frazier, 1981).

HYDROGEOLOGY

The Colorado River and several major tributaries, namely the Green, San Juan, and Dolores Rivers, drain the Paradox Basin. Much of the area that contains salt-cored anticlines is drained by the Dolores River. There are no surface-water impoundments (reservoirs) within the Utah portion of the basin.

Most stream flow is supplied by precipitation and runoff (much of that from outside the basin), although some volume is furnished by ground-water discharge. With the exception of the La Sal and Abajo Mountains, annual precipitation is generally less than 30 cm throughout most of the basin, while runoff is typically less than a few cm per year. Only in the central part of the La Sal Mountains does annual runoff exceed 25 cm; thus, most tributaries to the larger streams cited are clearly ephemeral.

Ground-water discharge is known from the La Sal Mountains, an irregularly shaped belt to the west of the Abajo Mountains, and along the steep-walled valleys of the Colorado, Green, and San Juan Rivers (Bechtel National, Inc., 1980). There is also minor ground-water discharge from springs at various other individual locations; as well, narrow elongate belts of ground-water discharge are located along the Paradox Valley and Gypsum Valley. Where the Dolores River transects the Paradox Valley, this discharge is saline and represented by numerous seeps (Thackston and others, 1981).

Thackston and others (1981) have reported on the preliminary results from the study of the ground-water circulation from essentially the Utah portion of the basin. This study has involved a review of the rather scant existing literature, chemical analyses of water samples, and hydraulic testing in several boreholes. These investigators recognize three hydrostratigraphic units, namely an upper zone which lies totally above the salt-bearing Paradox Formation, a middle interval which includes the evaporite sequence and associated aquitard strata of the Paradox Formation, and a deeper zone of extensive regional flow contained within the underlying Mississippian Leadville Limestone. Principal among their findings are that: (1) ground-water flow in the upper hydrostratigraphic unit is controlled by topography, moves generally downgradient toward the major river valleys where some discharge occurs, and the water is mainly a Ca-Mg-HCO_3 type although there is a significant Na-Cl component; (2) ground-water flow in the Leadville Limestone is generally toward the southwest, no discharge from this unit is known within the basin, and the water is high in its content of total dissolved solids, being mainly a Na-Cl type; (3) to the west, where the salts of the overlying Paradox Formation are absent, water in this deeper zone becomes less saline, suggesting that downward movement of dissolved salt derived from the Paradox Formation is a plausible explanation for the high salinities found in these deeper waters, and the inference is made that vertical communication is provided by several zones of faulting and other structures; (4) the strata within the Paradox Formation are very low in permeability and act as effective aquitards except where structurally disturbed or positioned close to near-surface dissolution as was (and is) the case in some of the salt-cored anticlines; and (5) in addition to the paleodissolution that has created cap-rock zones in several salt-cored anticlines, there is other evidence of salt dissolution within the Paradox Basin.

Probably the most noteworthy of these areas of dissolution is Lockhart Basin which lies to the south-southwest of Moab and north of Gibson Dome (fig. 4). Huntoon and Richter (1979) have described the remnant features and related structure in this area, and postulated that downward flow along a prominent fault zone caused the obvious dissolution and localized brecciation. Because the potentiometric surface of the deeper Leadville hydrostratigraphic unit is commonly above the top of the Paradox Formation, an alternate explanation, patterned after that advanced by Anderson and Kirtland (1980) to explain dissolution features in the Permian Basin of New Mexico, has been suggested by Thackston and others (1981). They propose that upward flow, resulting in a density convection cell, could actually have dissolved the salts from below, as opposed to from above as viewed by Huntoon and Richter (1980).

There is cited evidence (Sumsion, 1969) that modern-day dissolution is active along the Spanish Valley salt-cored anticline; moreover, the saline discharges known along Paradox Valley also appear attributable to present dissolution of the salt there, or at least communication with brines formed sometime in the past.

Because much of the subsurface ground water in the Paradox Basin contains more than 3,000 mg/l total dissolved solids, relatively little application of it is made (Bechtel National, Inc. and Woodward-Clyde Consultants, 1980b). A few small areas are however identified where very localized use is made of the ground water.

Near Moab, the Cane Creek potash mine of Texas Gulf, Inc., is operated as a solution-mining facility developed within the salt-bearing Paradox Formation. Also near Moab, Williams Brothers Energy Company has developed a small subsurface hydrocarbon-storage facility by dissolving space within the soluble salt interval (Richard Langill, 1981, personal communication). Both these operations of course represent localized, man-made dissolution.

SEISMICITY AND SEISMOLOGY

Bechtel National, Inc. (1980) has compiled the known data on earthquakes in both the general Colorado Plateau region and portions of Utah to the west of the Paradox Basin. Previous studies cited in that report have demonstrated that the Colorado Plateau, near whose center the Paradox Basin is located, has been seismically inactive during historic times, with the possible exception of a cluster of moderate-magnitude events related to normal faulting near Dulce, New Mexico, near the southeastern border of the province. From a regional viewpoint, the principal trends of seismicity are centered along well-known belts of faulting (Tertiary or younger movement) such as the Sevier, Elsinore, and Hurricane fault zones in central to southwestern Utah, some distance to the west of the Paradox Basin. Less prominent seismicity exists along other borders of the Colorado Plateau where it abuts other geologic provinces.

Seismic activity within the Paradox salt basin proper has been very modest in both frequency and level (magnitude). The few events which have been recorded within the basin are widely scattered, of intensities less than Modified Mercalli V, and do not appear associated with any geologic structural features (Bechtel National, Inc., 1980). Only along the extreme northwestern corner of the basin (but in part actually outside the basin) is there a small cluster of recorded earthquakes. Here, one event with an intensity of V was recorded in May, 1961, while a magnitude of 4.3 was detected for another event in March, 1965. Wong and Simon (1981) ascribe some of these events to underground coal extraction in this Book Cliffs area. To the northeast of this minor concentration of activity lies another small cluster of low-magnitude events, but these are even more removed from the margins of the basin.

Given these regional and basin-specific characteristics, assignment of the Paradox Basin to seismic-risk zone 1 (expected minor damage) of Algermissen (1969) is understandable. The more statistically significant seismic-hazard assessment by Algermissen and Perkins (1976) similarly forecasts that peak ground-acceleration corresponding to a 10 percent probability of exceedence in 50 years (return period 475 years) is 0.04 g or less for the Paradox Basin.

Because the seismicity reported above may however represent a historically incomplete record, more recent microseismic study has been undertaken in the Paradox Basin since mid-1979 (Wong and Simon, 1981). Observations obtained to date reveal a belt of microseismic activity (M_L = 1.0 to 2.4) coincident with the Colorado River north of its confluence with the Green River. These researchers interpret the data to indicate that a fault zone within the underlying Precambrian basement is serving as the zone of weakness by which strain is released; annual ten-fold fluctuations within the river's discharge is postulated as the cause of seismic-strain buildup. Despite delineation of this localized zone of microseismicity, there were no other findings that refute the low level of seismicity typical of the Paradox Basin.

BACKGROUND STUDIES

Previous geologic investigations of the Paradox Basin have in part been directed at that area because of interest in the economic potential for petroleum (Baars, 1966; Wengerd, 1970), for uranium ore (Lewis and Campbell, 1965; Chenoweth, 1975), or for potash mineralization (Evans and Linn, 1970; Hite, 1978). Additional geologic interest has centered directly upon the Paradox Formation salt sequence and the salt-cored anticlines which were developed from it (Shoemaker and Elston, 1968; Hite, 1968; 1970).

More regional studies which have addressed the basic structural and stratigraphic framework of the Paradox Basin and the Pennsylvanian System within it include those by Wengerd and Strickland (1954), Wengerd and Matheny (1958), Kelley (1958), and Szabo and Wengerd (1975).

Prior to the detailed study on the ground-water systems in the Paradox Basin (Thackston and others, 1981), the leading data source on this important topic was the work by Hanshaw and Hill (1969).

In addition to the studies cited above, the Paradox Basin and surrounding areas in the Four Corners Region have also been the subject of various investigations conducted by the U. S. Geological Survey, the petroleum industry, and local geological societies. These and other references are tabulated by Bechtel National, Inc. (1980) and Bechtel National, Inc. and Woodward-Clyde Consultants (1980), and are not recounted here due to the large number of citations involved.

STUDIES SPONSORED BY OWI

Interest in the salt deposits of the Paradox Basin is mainly attributable to the work by Hite and Lohman (1973). From their study, which was initiated at the request of the U. S. Atomic Energy Commission, the Salt Valley anticline was recommended as having definite potential for waste emplacement.

In 1975, the Office of Waste Isolation (OWI) began various studies, data from which were incorporated within the comprehensive document on alternatives for managing radioactive wastes (U. S. Energy Research and Development Administration, 1976). Because mined geologic repositories and rock salt as a disposal medium remained foremost among these alternatives, interest in the bedded to diapiric salts of the Paradox Basin persisted. The U. S. Geological

Survey, under subcontract to OWI, continued its studies on the Salt Valley anticline, concentrating upon evaluations of the geology, hydrology, mineral resources, and geothermal regime there, especially along the northwestern end of this feature (Gard, 1976; Hite, 1977). In their comprehensive regional study-evaluation of all domestic salt deposits, Johnson and Gonzales (1978) also concluded that there were areas within the Paradox salt basin where conditions appeared suitable for further investigation.

OWI and the U. S. Geological Survey also worked cooperatively with regard to the drilling of two boreholes (DOE 1-TD of 394 m; DOE 2-TD of 380 m) as part of a vertical seismic profiling study on the Salt Valley anticline. As well, a third borehole (DOE 3-TD of 1,243 m) was drilled and continuously cored. From a study of the cores recovered from this third hole, compared to data obtained from the first two seismic holes and nearby exploration wellbores, it was learned that the internal structure of the Salt Valley anticline is extremely complex. Strata within the Paradox Formation are overturned and locally offset by faults; some units appear vertical. Although thick salt is present at moderate depths, there is a very low reliability that any given salt cycle can be accurately projected elsewhere within this anticline, given limited subsurface control.

Under the OWI/USGS research, only the Salt Valley anticline was studied in any detail, although an investigation on the potash resources at another structure (Lisbon Valley anticline) was initiated (Hite, 1978). To facilitate better technical management of the Paradox Basin studies, especially the test drilling and geophysical studies, OWI awarded the Geologic Program Manager (GPM) to Woodward-Clyde Consultants of San Francisco.

STUDIES SPONSORED BY ONWI

In mid 1978, the Office of Nuclear Waste Isolation (ONWI) was established by Battelle Memorial Institute to assume management of the radioactive-waste-disposal program for the U. S. Department of Energy (DOE). Responsibility for the studies within the Paradox Basin and continuance of the GPM (Woodward-Clyde Consultants) were transferred to ONWI at that time.

Geologic studies, remote sensing, additional borehole drilling, geophysical surveys, microseismicity monitoring, and ground-water hydraulic testing conducted since 1978 have been performed jointly by the U. S. Geological Survey, Woodward-Clyde Consultants, and subcontractors to them. As the result of various screening efforts, three study areas, Lisbon Valley, Elk Ridge, and Gibson Dome, were selected in addition to Salt Valley, and designated to receive more detailed investigation and evaluation by borehole methods (Bechtel National, Inc. and Woodward-Clyde Consultants, 1980).

Regional environmental studies of the Paradox Basin and surrounding territory have been conducted for ONWI by Bechtel National, Inc. (1980). The standard parameters addressed in these environmental studies were addressed from data available from existing literature.

Test boreholes have now been drilled in the Elk Ridge and Gibson Dome areas, and additional data evaluated for all four study areas. Lisbon Valley has been rejected due to the large number of boreholes, extensive uranium exploration and shaft development (shaft areas are typically wet), nearby petroleum production, and evidence of recent (Quaternary) fault movement (Frazier, 1981). Similarly, Elk Ridge appears doubtful due to the thinness of and significant depth ($>$ 1,050 m) to the prospective salt cycles, and proximity to environmentally sensitive areas (archeological and natural habitat) (Frazier, 1981). Its distance from a railroad haul route is another negative factor. Because of the structural complexities already cited, salt dissolution that has produced a shallow caprock, and possible conflict with potash resources there, further work on the Salt Valley anticline has been indefinitely deferred (Frazier, 1981).

Based upon geologic mapping, data from existing exploration boreholes, and the core information from the Gibson Dome No. 1 (drilled to below the Leadville Limestone; TD of 1,952 m), Gibson Dome appears promising and will be the focus of ongoing detailed studies (Frazier, 1981). Proximity to the Canyonlands National Park, the need to visually screen the area by natural topography, the nearby dissolution area at Lockhart Basin, and the Shay Graben zone to the southwest remain as problems which these future studies are planned to address. The cycle 6 salt, estimated to be more than 80 m in thickness and less than 1,000 m deep on the south-central part of the dome, is the principal salt horizon of interest.

A five-volume area characterization report is expected to be released by ONWI in early 1982. Site characterization on the Gibson Dome Study area is also underway at this time (Frazier, 1981).

OTHER FEATURES

Unlike the Palo Duro Basin, the Paradox Basin is known to contain various mineral resources of commercial importance. Potash recovery, via solution mining, has been underway on the Cane Creek anticline since the mid-1960's by Texasgulf, Inc. (Evans and Linn, 1970). Additional large potash resources are known, especially in the northeastern part of the basin, but their depth may make recovery a fairly distant eventuality. Hite (1977), however, showed that the potential potash resources on the Salt Valley anticline alone might amount to 555 million metric tons per square kilometer. The Lisbon Valley structure also contains potash mineralization (Hite, 1978).

Uranium ore, as found in Triassic-Jurassic strata above the prospective salt sequence, is another mineral resource which has been produced within the Paradox Basin. Although most of the commerical production (includes coproduct vanadium) has been from the Uravan belt in western Colorado, commercial recovery has also been made from deposits surrounding Elk Ridge in Utah. Numerous abandoned mines and small workings dot much of the central part of the basin.

Petroleum production has also been established within the basin. Most noteworthy for this discussion is the large Lisbon field on the Lisbon Valley anticline; production here is principally from the Mississippian Leadville Limestone. In the far southeastern part of the Utah portion of the basin also lies the large Greater Aneth field. Within this same general area are a number of smaller petroleum (mainly gas) fields. Several newly discovered fields in this same area are Bug, Patterson, and Squaw Valley, all of which produce from carbonate facies of the Paradox Formation.

Petroleum exploration can also be expected to continue with renewed interest within the Paradox Basin, given the recent trends in the oil industry to drill prospects based upon reprocessed old data, to drill deeper and possibly more marginal prospects, and to drill more speculative wildcats.

Also of import here is the fact that gas and minor oil are known to occur in interbedded marker beds of the Paradox Formation (Hite and Lohman, 1973). Some production has been realized from small fields where the shales are fractured (Johnson and Gonzales, 1978).

Other mineral resources known to occur within the Paradox Basin include gypsum, salt, copper, gold, silver, and various industrial minerals. There does not appear at present to be any indication that sizeable deposits of non-evaporite minerals exist. There is no economic reason to mine the huge salt resources, and the gypsum found in several cap rocks is too impure to currently warrant recovery.

As previously noted, one small LPG-storage facility has been sited in the Paradox Formation salt interval near Moab, Utah. Originally developed by the Suburban National Gas Company, the facility is currently operated by Williams Brothers Energy Company.

The Paradox Basin is very sparsely populated; no Standard Metropolitan Statistical Areas exist within the basin. Within Utah, the only urban areas are Green River, Moab, Monticello, and Blanding, all of which are somewhat removed from the Gibson Dome study area. Each has a population of less than 10,000 people. One railroad crosses the northern part of the basin in an east-west direction; from it a spur extends to the Cane Creek potash mine. In the eastern Utah part of the basin, there are good state and federal highways; toward the west, dirt and gravel roads and terrain traversable by trails handled best by four-wheel-drive vehicles becomes the rule.

Annual precipitation averages 21 cm. Some rangeland exists, but the bulk of the area is sparsely vegetated arid land. Most of this land is administered by the U. S. Bureau of Land Management, although the Departments of Agriculture and Interior administer National Forests and National Parks located there. The Arches and Canyonlands National Parks lie within the area encompassed by the Salt Valley anticline and Gibson Dome, as does the Dead Horse Point State Park.

PROBLEMS AND DATA-DEFICIENT AREAS

Hydrogeology

Although considerable studies have been made in the knowledge of the hydrogeologic system of the Paradox Basin, much is still to be learned and several questions remain unanswered. With more of a focus being directed at the Gibson Dome Study Area, detailed hydrologic data on this more localized area will be needed. With the exception of data from the Gibson Dome No. 1 borehole, there are very little nearby potentiometric or water-quality data for any of the three hydrostratigraphic units in this part of the basin. To improve the quality of the data, it may be necessary to drill and test several boreholes solely for hydrologic purposes, not attempting to make them serve a dual role of also providing cores and related stratigraphic data.

Other problems in need of resolution include: (1) whether the Mississippian Leadville Limestone aquifer was (is) involved in salt dissolution by a convection-density mechanism; (2) whether this same aquifer is directly connected to saline discharges from its stratigraphic equivalent (Redwall Limestone) within Marble Canyon in Arizona, and if so, whether the salinity is related to dissolution of Paradox Formation salts; (3) the degree to which the water chemistry of the lower hydrostratigraphic unit has been caused by dissolution of shallower salts, and secondly the degree of interconnection which has facilitated the downward movement of dissolved material; (4) the extent to which zones of structural deformation, such as the Shay Graben and Needles Fault zone and other structures, serve to interconnect the several recognized hydrostratigraphic units; and (5) more detailed examination of the geochemical evolution of the ground water in all three hydrostratigraphic units.

Salt Dissolution

There is clear evidence that the salts within the Paradox Formation have been dissolved in the geologic past and continue to be dissolved today in certain areas. Outside of the shallow dissolution which has resulted in the formation of cap-rock zones within the upper portions of several salt-cored anticlines, the exact mechanism(s) involved in other dissolution is (are) not clearly understood. Suqiura and Kitcho (1981) have shown that there are several collapse features in addition to those at Lockhart Basin for which salt dissolution appears to be involved. Even though the features at Lockhart Basin have been studied (Huntoon and Richter, 1979; Thackston and others, 1981), there is disagreement on the causal mechanism, namely whether the dissolution was downward and structurally controlled or upward and hydrodynamically controlled. If zones of faulting are involved in salt dissolution as suggested for the Lockhart Basin, a related question is the degree of salt dissolution near other structurally disturbed zones, but for which surface collapse features are not evident. The timing of fault movement and the relationship or lack thereof to salt flowage appears different for different fault zones; hence, the relative role of salt tectonics to the development of structures which may have influenced ground-water access to salt beds becomes an essential topic as well.

A petroleum test well drilled into the Shay Graben, for example, penetrated absolutely no salt at that location (Frazier, 1981). Unanswered is whether this absence of salt is due to flowage removal of the salt, or dissolution of the salt due to the presence of a structure which facilitated downward ground-water circulation. There are no collapse features here, which represents a contrast to Lockhart Basin where both faulting and dissolution collapse features are present. In essence, there needs to be a better understanding of localized structures, their relationship, if any, to salt flowage, their relationship in turn to salt dissolution, and why apparently some structures have been genetically involved in salt dissolution and others have not been.

Sugiura and Kitcho (1981) also suggest that the dissolution and upward stoping of limestone may be related to the formation of certain collapse features. Because dissolution within a salt-bearing basin is usually associated with the removal of salt, this suggestion needs to be pursued in more detail to ascertain if carbonate dissolution is partly or wholly involved in any specific collapse features. Detailed shallow to intermediate-depth drilling appears mandated to provide data to answer this and other questions on dissolution here.

Because Lockhart Basin, Gypsum Canyon-Beef Basin, the Needles fault zone, and the Shay Graben are all within the general vicinity of Gibson Dome, the importance of better understanding the origin of these features and the mechanisms of salt (and possibly carbonate) dissolution assumes even greater importance.

Host-Rock Characteristics

More detailed mineralogic analyses of the cycle 6 salt needs to be done to fully characterize its purity, insoluble mineral content, clay-mineral composition, and the overall distribution of anhydrite for the designated Gibson Dome Study Area. Preliminary indications are that at least 95 percent of the insoluble fraction consists of the mineral anhydrite; but, unlike other salts in which the anhydrite occurs as disseminated grains, much of the anhydrite in the cycle 6 salt is present as discrete thin lamina. Further work on anhydrite band microstratigraphy and log plots of insoluble residues, as outlined by Bean and others (1981), appears warranted.

An assessment of the localized depth and thickness variation for the cycle 6 salt is a related need.

Because the depth to the cycle 6 salt is anticipated to be more than 900 m within the Gibson Dome Study Area, investigation of the rock-mechanical properties for this salt unit is another area in need of attention. Preliminary data suggest that the anhydrite lamina add to the overall strength of the salt, but the spatial distribution of these lamina, and in turn the salt's rock-mechanical properties, remain to be established beyond the single Gibson Dome No. 1 borehole. What effect thermal loading will have on a microlayered salt unit also needs study.

Also important to the Gibson Dome assessment is the specific nature, hydrocarbon and/or non-hydrocarbon fluid (if any) content, rock mechanical properties, and physical dimensions of the several marker-bed assemblages which are shallower than the cycle 6 salt. Just as the spatial distribution of salt characteristics must be investigated, so too must be the properties of these associated marker beds. Because several non-salt lithologies (namely black shale, dolomite, and anhydrite) are involved, the rock-mechanical properties of these assemblages assume greater importance given the somewhat greater depth.

Structural and Tectonic Features

Although field mapping, remote sensing, geophysical surveys, and borehole evaluations have elucidated much on the regional and local geologic structures in and around the Paradox Basin, a full understanding of the evolution of various structures is not yet at hand. Some of the more critical topics to be addressed here are: (1) the exact nature, including the degree of control on younger structures, of Precambrian (basement) structures, especially those having a pronounced northeast orientation (rejuvenation of Precambrian structures has already been demonstrated by Kelley (1958) and Baars (1966)); (2) the extent to which structures with surficial expression are involved in salt tectonics, or which structures initiated or caused salt flowage versus those caused by salt flowage; (3) better placement of the youngest displacement on certain fault systems, several of which appear to offset Quaternary-age gravel terraces and soil horizons; (4) a detailed explanation for the alluvium-filled or open faults within the Needles fault zone which contrasts to faults found in other zones; (5) the depth of stratigraphic penetration by several fault zones, and related to that, the degree to which ground-water influx has been facilitated along such zones, and in turn the impact on deeper salt dissolution; and, (6) a clearer understanding, as already noted under the section here on dissolution, on the role of structure in the formation of recognized collapse features.

There similarly needs to be a better comprehension about faults which affect (offset) the salt sequence (with or without extension to deeper horizons), but which lack expression at the land surface. More work using data from boreholes which cut such faults and geophysics appears needed in this case. Cross-sectional interpretations (Baars, 1966; Hite, 1978), for example) commonly show faults (with or without surface expression) terminating downward within the Paradox salt sequence. Is this really the case, and if so, is it possible that some of these faults represent décollment surfaces in which the salt/marker bed interfaces acted as glide surfaces? While this specific topic is not directly related to the gently flexed Gibson Dome Study Area, an investigation of it may be germane to understanding the overall tectonics within the basin.

Geomorphic Processes

Work by Woodward-Clyde Consultants to date has characterized Quaternary gravel terraces, calcic soil horizons, displaced alluvial deposits, and evaluated climatic-induced erosional cycles and erosion rates. Some remaining problems include an inability at present to establish an integrated Quaternary history over the entire basin, and related to that, an insufficiency of material which can provide absolute dates by which to better establish the desired chronology.

Also in need of additional investigation is whether the offset deposits adjacent to salt-cored anticlines were affected by remobilized salt flowage or salt dissolution or both. Also unanswered is whether climatic changes influenced the ground-water system's ability to dissolve shallow salt, or whether this dissolution proceeded merely because of the shallow, diapiric position of the salt. Alluvial fill within certain fault zones, adjacent to other faults, and deposits offset by others obviously are clues to the tectonics in post-Tertiary times. Although these Quaternary sediments have been studied in some detail already, more localized investigations with trenching and better absolute-age determinations can aid in solving some structural-geology problems.

Shaft Design and Construction

All the normal considerations under this topic pertain to the Paradox Basin as well. The most noteworthy contrasts with other areas would appear to involve the shallow marker beds within the Paradox Formation, the greater depth of the cycle 6 salt, the different nature of the associated anhydrite in the salt, and the lack of any experience from the mining or construction industry relative to deep shafts in this basin. Some knowledge does, however, exist for shallower shafts from the uranium mining industry in the Colorado part of the basin, as well as additional data from the original Cane Creek potash mine.

Land Ownership and Access

Inasmuch as much of the acreage in the Paradox Basin is controlled by federal government agencies, ownership per se may not be as much of a problem as elsewhere. More significant is the concurrence of the State of Utah relative to the use of an area adjacent to a scenic national part (Canyonlands) and the resolution of citizen opposition to a repository in this part of that State. Related factors are the perception against a railroad line being constructed adjacent to that park, concealment of surface operations (at a shaft for example), disposal of other use of the excavated rock, and mitigation of numerous socio-economic impacts in a sparsely populated region. Impact assistance and clear resolution of many environmental (including visual-esthetic) factors, including proper adherence to the NEPA review process, appear as more significant problems than land ownership. Related factors involve the proximity of a state park (Dead Horse Point) and the maintenance-preservation of recreational-wilderness values.

Although these issues are clearly peripheral to the technical arena, their intrinsic importance to people requires careful study on how to address them and the reaching of prudent solutions.

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