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Background Information Presented to the Expert Panel on Inadvertent Human Intrusion into the Waste Isolation Pilot Plant

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W. D. Weart, S. G. Bertram-Howery, R. V. Guzowski,
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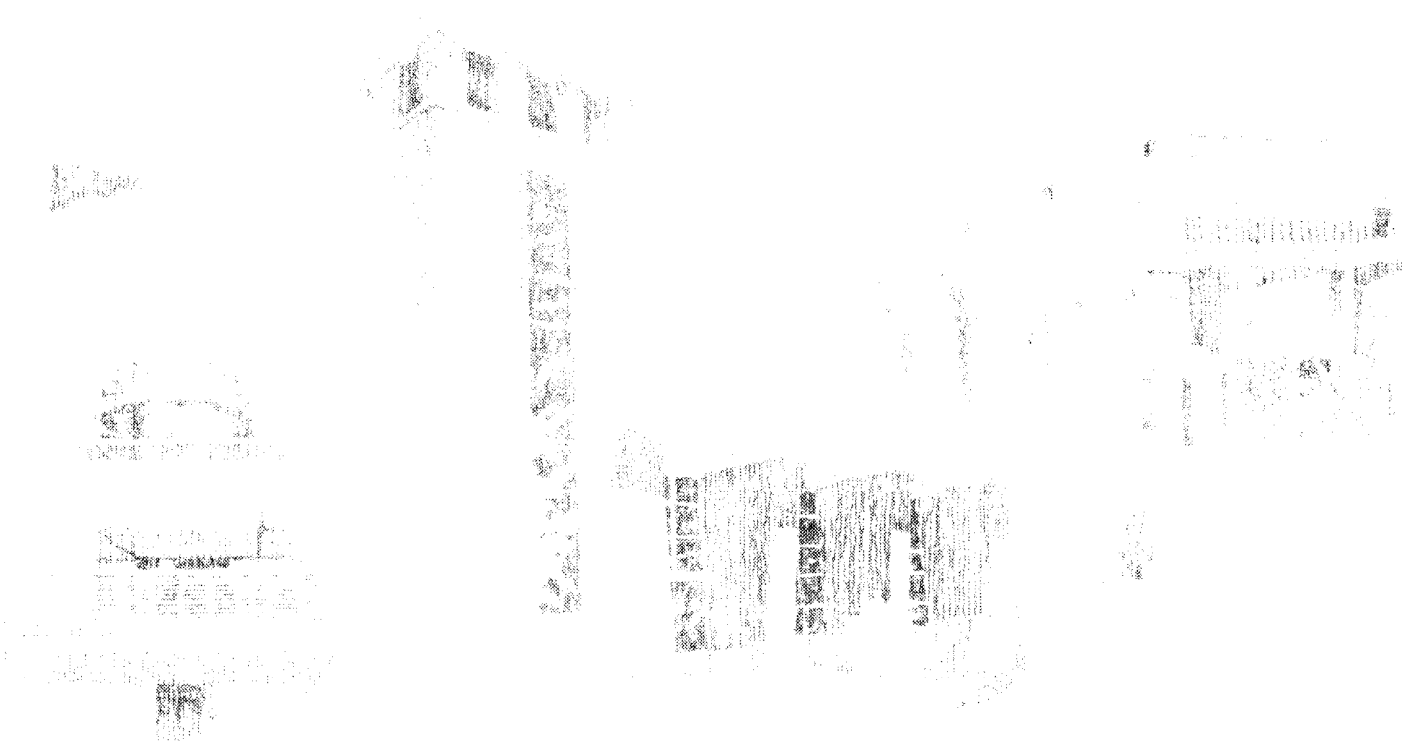

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BACKGROUND INFORMATION PRESENTED TO THE EXPERT PANEL ON INADVERTENT HUMAN INTRUSION INTO THE WASTE ISOLATION PILOT PLANT

R. V. Guzowski[1], M. M. Gruebel[2], Editors

W. D. Weart, S. G. Bertram-Howery, R. V. Guzowski[1],
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ABSTRACT

The Waste Isolation Pilot Plant (WIPP) is planned as a mined geologic repository for the disposal of transuranic (TRU) radioactive wastes generated by defense programs of the United States Department of Energy. One of the criteria for evaluating the suitability of the WIPP for disposal of TRU wastes is compliance with the United States Environmental Protection Agency's (EPA) standards for such facilities. The Containment Requirements of those standards require calculating cumulative releases of radionuclides to the accessible environment by all combinations of events and processes (scenarios) that may affect the escape and transport of radionuclides from the repository for 10,000 years after decommissioning of the facility. Because the release limits established by the EPA are probabilistic, scenario probabilities are also required. A panel of experts was convened to estimate the probabilities of occurrence of the events used in scenario development and to identify additional human-intrusion events for inclusion in a safety assessment of the WIPP. This report documents the background presentations that were made to the panel about the WIPP program, regulatory guidelines, the performance-assessment program, and site-specific and regional geologic and hydrologic characteristics that may affect the WIPP disposal system.

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I. INTRODUCTION

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The Waste Isolation Pilot Plant (WIPP) is a research and development facility being used to determine whether a bedded-salt formation in southeastern New Mexico is suitable for the deep geologic disposal of transuranic (TRU) wastes generated by defense-related programs within the U.S. Department of Energy. If the selected location is determined to be suitable, the WIPP will be enlarged and used for the permanent disposal of TRU wastes.

One of the criteria to be used in the evaluation of the WIPP is compliance with the requirements of the U.S. Environmental Protection Agency's (EPA's) standards for the management and disposal of spent nuclear fuel, high-level, and transuranic radioactive wastes (40 CFR Part 191) (U.S. EPA, 1985; referred to as the Standard in this chapter). Chapter III of this report provides a detailed discussion of the contents and legal status of the Standard. Addressing the Containment Requirements in Subpart B of the Standard requires completion of performance assessments of the disposal system (§191.13[a]). A performance assessment requires the calculation of cumulative releases of radionuclides to the accessible environment by all combinations of events and processes (scenarios) that may affect the escape and transport of radionuclides from the waste-storage panels for 10,000 years after the decommissioning of the disposal facility (Cranwell et al., 1987). Probabilities of occurrence of the events and processes are necessary for screening purposes and for plotting the cumulative radionuclide releases of the scenarios in a complementary cumulative distribution function (CCDF) for comparison to the radionuclide release limits defined in Subpart B of the Standard.

Whereas probabilities of occurrence of the events and processes are necessary to address the requirements of the Standard, the Standard contains no guidance as to how these probabilities should be determined. Appendix B of Subpart B of the Standard states that passive institutional controls consisting of both markers and records can be assumed to deter systematic or persistent exploitation of the disposal area and to reduce the likelihood of inadvertent, intermittent human intrusion by an amount to be determined by the implementing agency.

A preliminary scenario analysis of the WIPP (Guzowski, 1990) identified potentially disruptive scenarios consisting exclusively of human-intrusion events. Based on the guidance of Appendix B of Subpart B of the Standard, exploratory drilling for resources at the location of the waste panels was considered to be the most severe type of human intrusion that needed to be included in scenario development, although additional human-intrusion events beyond the boundaries of the waste panels were included in scenario development. Estimation of the probabilities of occurrence of the events in the scenarios was beyond the scope of this particular scenario-development effort. An evaluation of the applicability of various probability techniques to human-intrusion events (Guzowski, 1991) indicates that expert judgment is the dominant technique for estimating probabilities.

In order to estimate the probabilities of occurrence of the events used in scenario development and to possibly identify additional human-intrusion events for inclusion in a safety assessment of the WIPP (Department 6340, 1990) requested by the WIPP Panel of the National Research Council's Board of Radioactive Waste Management, the WIPP Performance Assessment Program proposed the formation of three panels. Each panel would be multidisciplinary with each panelist being a recognized expert in a particular subject area pertinent to the issues to be addressed by the particular panel. The first panel (futures panel) would identify possible future societies and human activities associated with these societies that could affect the integrity of the WIPP disposal system. This panel also would estimate the probability of occurrence of the possible societies and any event identified for each society. A second panel (markers panel) would consider the form, composition, and message for the markers required by the Standard to indicate the presence of the disposal location and assumed to discourage human intrusion. An additional task would be to estimate what effect these markers would have on the probabilities of occurrence of the events identified by the futures panel. A third panel (barriers panel) would investigate possible physical barriers to human intrusion that could be incorporated into the disposal system and estimate the effect of these barriers on the human-intrusion events identified by the futures panel.

The first meeting of the futures panel was August 13 through 15, 1990. A series of presentations was made to the panelists to define the problem to be considered, and to provide background on the WIPP performance-assessment program, the opinion-elicitation process, the geologic and hydrologic setting of the WIPP, and how the results of the elicitation procedure will be used in the performance assessment. On the first day of the meeting, presentations were made to the panel on the goals and overview of the WIPP performance-assessment program, the process of eliciting expert judgment, the history of the WIPP, performance assessment and the Standard, and the procedure for identifying potentially disruptive scenarios for use in consequence analyses.

A training session to familiarize the panelists with probabilities and possible unrecognized biases also was conducted. On the second day of the meeting, the experts were taken to the WIPP. Topics presented to the panelists on the third day were an overview of the geology and hydrology, geochemistry of the ground water, natural resources in the WIPP region, climatology, and a review of the cultural history of southeastern New Mexico.

A second meeting of the futures panel was held on October 10 and 11, 1990. At this meeting, each of the four teams within the panel presented conclusions on possible evolutionary pathways of future societies and possible modes of human intrusion at the WIPP associated with these societies. A separate probability-elicitation session was held with each team so that probabilities of occurrence of the future societies and modes of intrusion could be assigned. The first meeting of the markers panel was originally scheduled to meet at the same time as the second meeting of the futures panel. This arrangement would have allowed the markers panel to have direct access to the results of the futures panel. Budget restrictions resulted in a delay of the first meeting of the markers panel until November 1991.

This report contains documentation that summarizes the presentations on the WIPP program, regulatory guidelines, the performance-assessment program, and site-specific and regional geologic and hydrologic characteristics that may affect the WIPP disposal system. Background material on the ground-water geochemistry will be published as a separate report. A summary of the elicitation procedure will be included with the conclusions of the futures panel and the probability elicitation in an additional document (Hora et al., 1991).

With two exceptions, the individual papers in this report are reproduced in their original form with only minor editorial revisions. Chapter V, "A Summary of the Hydrology and Geomorphology of the Northern Delaware Basin near the Waste Isolation Pilot Plant," was orally presented to the expert panel at its first meeting, but no paper was provided at that time. Portions of Chapter IX, "A Historical Perspective of Cultural Development in Southeastern New Mexico," have been revised for clarification.

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II. HISTORY AND OVERVIEW OF THE WASTE ISOLATION PILOT PLANT*

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In 1972 the bedded-salt location in Kansas, which had been suggested as a repository site, proved to be unacceptable for a repository because of indications of extensive drilling for oil, and because solution mining of salt had taken place in the area. A nationwide search for suitable bedded-salt deposits was conducted by the United States Geological Survey, and in 1973 four locations in New Mexico were identified as promising. The best of these, located in the northern Delaware Basin, was selected for on-site investigation, and initial exploratory holes were drilled in early 1974. In 1975, an exploratory hole (ERDA-6) (Figure II-1) encountered steeply dipping salt beds at the proposed repository horizon. Because of this relatively unpredictable geology, the repository location was moved about 10 km toward the interior of the basin, to an area more suitable for nuclear-waste disposal for a number of reasons. For example, the host rock, the Salado Formation, is thick, deep, relatively dry, areally extensive, nearly flat-lying, and extremely uniform laterally. This location, now the location of the Waste Isolation Pilot Plant (WIPP), was selected in December 1975 and has subsequently been evaluated using more than 100 exploratory holes emplaced for geologic and hydrologic data. In 1980, on the basis of borehole information and extensive geophysical data, the U.S. Department of Energy (DOE) considered this site satisfactory to proceed with a program of underground validation. This subsurface investigation required two shafts to a depth of about 655 m and mining of drifts roughly 1.6 km north/south and 1.4 km east/west to outline the area of potential waste emplacement (Figure II-2). The DOE concluded in 1983 that the site was suitable (U.S. DOE, 1983), and construction of the WIPP began later that year. Since 1983, extensive in-situ experiments have been conducted at the WIPP to better understand the behavior of salt and the interactions that can occur between wastes and the salt

* Extracted from Lynch, R. W., R. L. Hunter, D. R. Anderson, F. W. Bingham, J. M. Covan, G. F. Hohnstrieter, T. O. Hunter, R. D. Klett, E. E. Ryder, T. L. Sanders and W. D. Weart. 1991. *Deep Geologic Disposal in the United States: The Waste Isolation Pilot Plant and Yucca Mountain Projects*. SAND90-1656. Albuquerque, NM: Sandia National Laboratories.

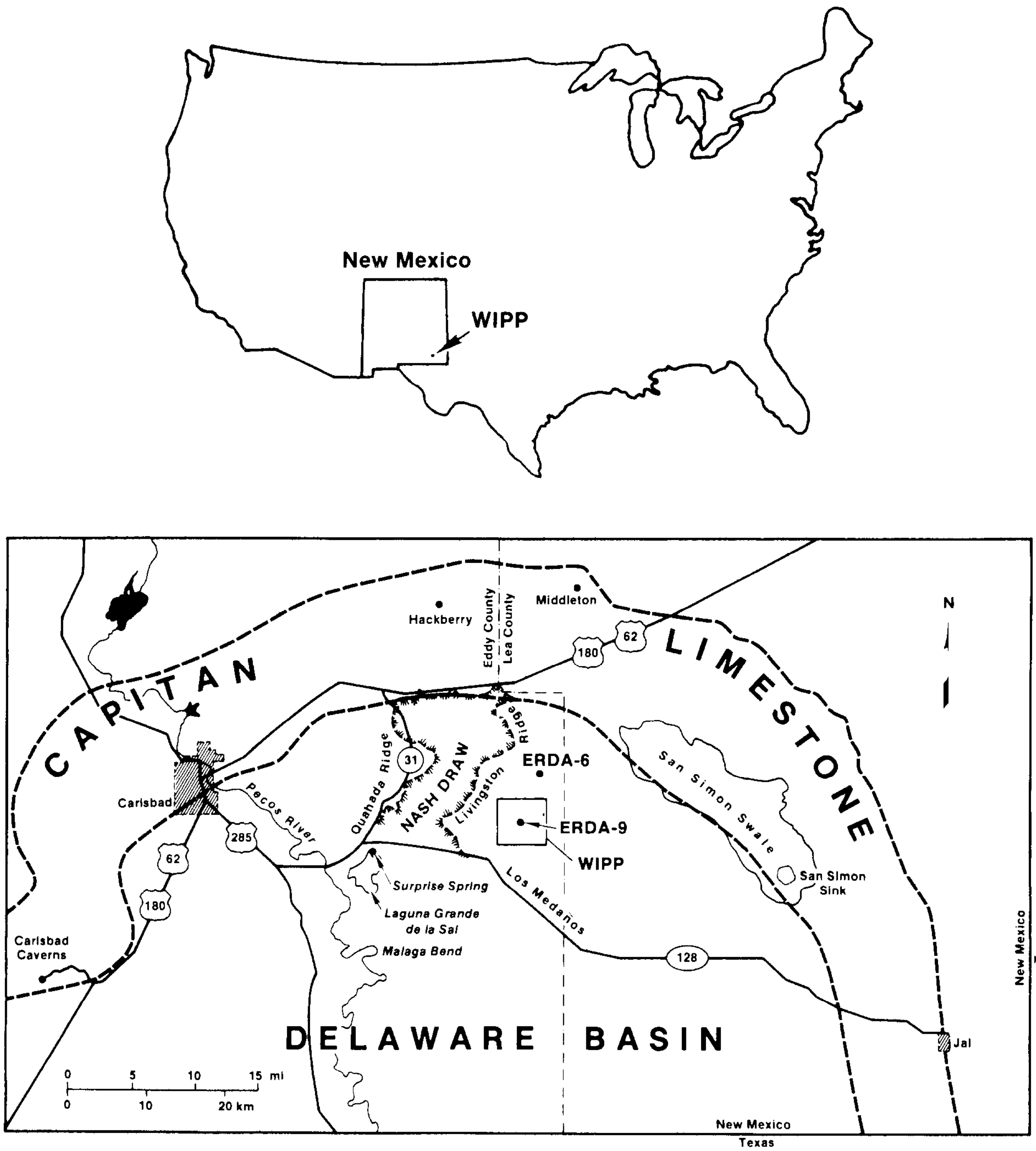

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Figure II-1. Location of the WIPP in the Northern Delaware Basin.

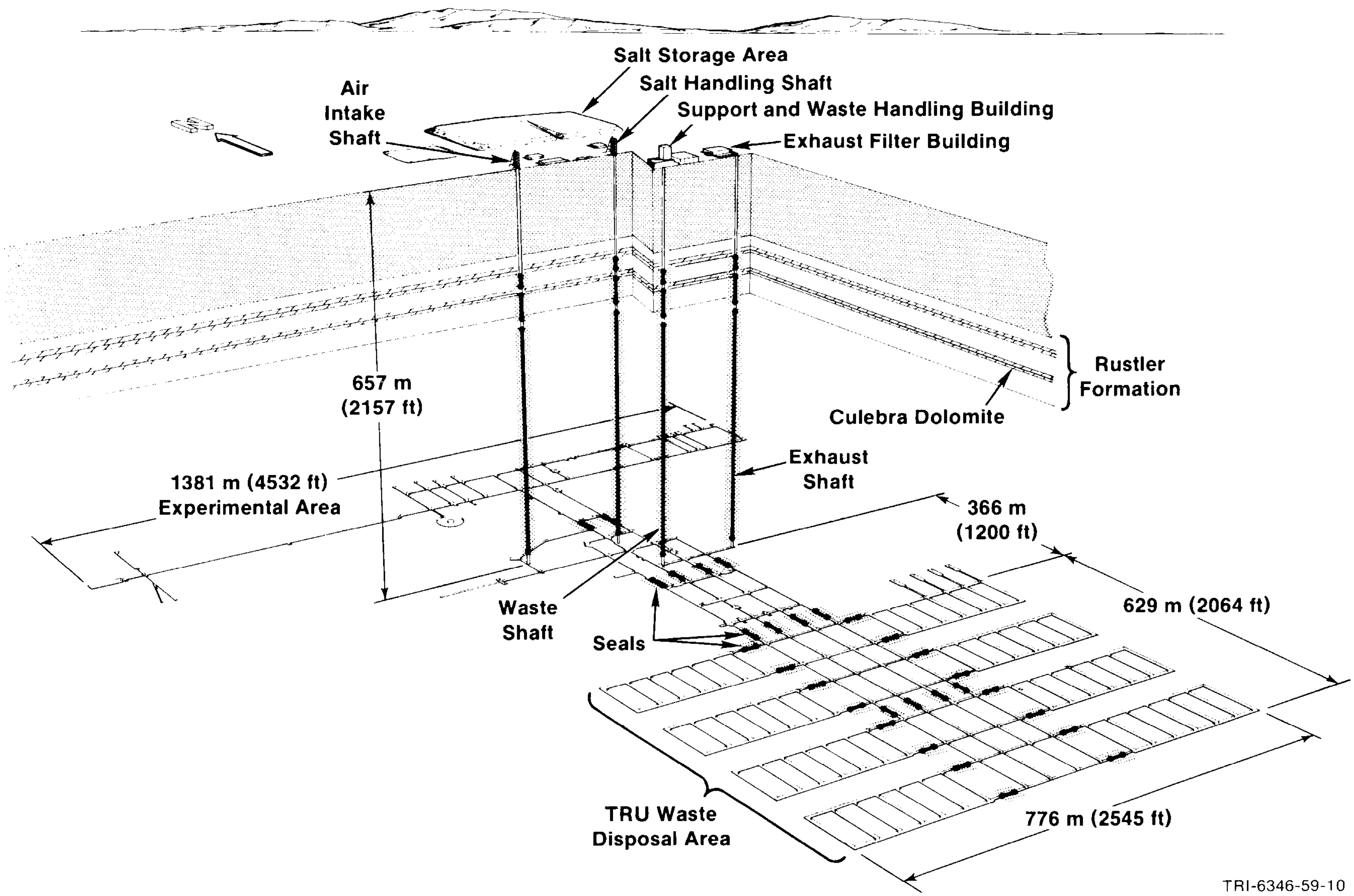

Figure II-2. Schematic Diagram of the Waste Isolation Pilot Plant (after Nowak et al., 1990).

environment. The experiments to date have not used radioactive waste but will be extended to do so when institutional barriers to waste receipt at the WIPP are resolved.

Mission of the WIPP

The WIPP was designated by Public Law 96-164 in December 1979 for the express purpose of providing a research and development facility to demonstrate the safe disposal of radioactive wastes resulting from the defense activities and programs of the U.S. exempted from regulation by the U.S. Nuclear Regulatory Commission (NRC).

The transuranic (TRU) waste to be disposed of at the WIPP is defense-generated waste produced by the United States government since 1970. Typically, the waste is made up of laboratory and production trash like glassware, metal pipes, disposable laboratory clothing, cleaning rags, solidified sludges, and so on that is contaminated with transuranic elements. In the United States, TRU waste is defined as material contaminated with radionuclides having atomic numbers greater than 92, half-lives greater than 20 years, and concentrations greater than 100 nCi/g. Much of the waste is packaged in 55-gallon metal drums; large metal boxes are also common.

Transuranic waste is classified according to the radiation dose at the package surface. About 97 percent of the waste by volume can be contact handled (CH) because the external dose rate is below 2 mSv/hour, and people can handle the properly sealed drums and boxes without any special precautions. These drums and boxes are vented through high-efficiency particulate air filters to prevent the buildup of gas inside the containers. Most of the CH-TRU waste has a much lower surface-dose rate, and the average rate is $\leq$0.14 mSv/hour. About 3 percent of the waste has a surface-dose rate greater than 2 mSv/hour and must be remotely handled (RH); that is, it must be handled and transported in specially shielded casks. All containers for CH-TRU and RH-TRU waste are thoroughly inspected and certified before being shipped to the WIPP to ensure that they meet the WIPP Waste Acceptance Criteria (WEC, 1985). Under current plans, most TRU waste generated since 1970 will be disposed of at the WIPP; a small amount will be disposed of at other DOE facilities because the wastes cannot meet either the Waste Acceptance Criteria or shipping regulations.

About 60 percent of the TRU waste to be shipped to the WIPP is also contaminated with hazardous chemical constituents as defined under the Resource Conservation and Recovery Act of 1976 (RCRA). These hazardous chemical constituents include metals like lead, cadmium, chromium, uranium, and barium and organic solvents like methylene chloride and toluene (U.S. DOE, 1990a).

Although only about one third of the waste destined for the WIPP has been generated, the best estimate is that about 400,000 containers containing about 9.0×10^6 Ci, about 1.6×10^5 m^3, of radioactive material will be emplaced in the WIPP repository. The design capacity of the WIPP is larger, 1.8×10^5 m^3 of waste.

The WIPP Waste Acceptance Criteria place a number of limitations on the containers of TRU waste that will be accepted for disposal. For example, no free liquids may be included except minor residues remaining in drained containers. No more than 1 percent of the waste in a container may be made up of particulates less than 10 microns in diameter. RH-TRU containers are limited to a total of 600 g of fissionable material and to a thermal power of 300 watts. The concentration of total radioactivity in a container is limited to 23 Ci/l averaged over the volume. CH-TRU containers are limited to 5 g of radioactive material per cubic foot (178.6 g/m^3). The sites that generate or store the waste are responsible for implementing the Waste Acceptance Criteria.

Framework of Major Regulations Governing Deep-Geologic Disposal in the U.S.

The disposal of spent fuel and high-level and transuranic radioactive waste in the United States is regulated under a complex of laws, standards, and implementing regulations. The three principal applicable laws are the Nuclear Waste Policy Act (NWPA) and its amendment, the Nuclear Waste Policy Amendments Act, the Resource Conservation and Recovery Act of 1976 (RCRA), and the National Environmental Policy Act (NEPA). Other laws, such as the Safe Drinking Water Act, Clean Air Act, and Mine Safety and Health Act, also apply.

The National Environmental Policy Act (NEPA, Public Law 91-190), our basic national charter for protecting the environment, requires that federal agencies explicitly consider the environmental impacts of their actions. The results of the investigation are published in environmental statements. Public involvement as appropriate is addressed in various NEPA documents. Three environmental impact statements (EIS) have been issued for deep-geologic disposal: the so-called generic EIS, ***Final Environmental Impact Statement, Management of Commercially Generated Radioactive Waste*** (U.S. DOE, 1980a); the original EIS for WIPP, ***Final Environmental Impact Statement, Waste Isolation Pilot Plant*** (U.S. DOE, 1980b); and a supplemental EIS for the WIPP, ***Final Supplement, Environmental Impact Statement, Waste Isolation Pilot Plant*** (U.S. DOE, 1990a).

Three important regulations have been promulgated under the Nuclear Waste Policy Act: a primary standard, a regulation covering licensed repositories, and siting guidelines. Table II-1 compares some of the requirements of these

TABLE II-1. REGULATORY FRAMEWORK

	Congress
Makes policy and law	National Environmental Policy Act, Nuclear Waste Policy Act, Nuclear Waste Policy Amendments Act, Resource Conservation and Recovery Act, Safe Drinking Water Act, Clean Air Act, etc.
	Environmental Protection Agency
Sets primary standards	Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (40 CFR 191)
	Nuclear Regulatory Commission
Regulates commercial repositories and transportation	Disposal of High-Level Radioactive Wastes in Geologic Repositories (10 CFR 60) Packing and Transportation of Radioactive Material (10 CFR 71)
	Department of Energy
Sites, builds, and operates repositories	General Guidelines for the Recommendation of Sites for the Nuclear Waste Repositories (10 CFR 960)

three regulations. The primary standard regulating the disposal of spent fuel and high-level and transuranic waste in a geologic repository is the Environmental Protection Agency's "Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes," referred to as the Standard (U.S. EPA, 1985). Although the Standard has been remanded to the Environmental Protection Agency (EPA) by the First Circuit Court of Appeals, the EPA expects to propose the revised Standard in December 1990. The DOE does not expect the basic requirements of the Standard to change significantly. The Standard is divided into two subparts. Subpart A limits annual radiation doses to members of the public from waste management and storage operations at disposal facilities. Subpart B limits cumulative releases of radioactive materials for 10,000 years, radiation doses to members of the public for the first 1000 years, and radioactive contamination of certain sources of ground water for the first 1000 years, as a result of waste disposal. Appendix A of the Standard specifies how to determine the release limits, and Appendix B provides nonmandatory guidance for implementation of Subpart B. The DOE will assess compliance with Subpart A primarily by means of an extensive monitoring program. The DOE will assess compliance with

Subpart B primarily using performance-assessment techniques developed specifically for the evaluation of the performance of high-level-waste repositories, although compliance with some sections of Subpart B will be assessed using other techniques.

Two Federal agencies are responsible for implementing the EPA Standard. The NRC is the implementing agency for repositories for commercially generated spent fuel and defense high-level waste (HLW), and the DOE is the implementing agency for repositories for defense-generated transuranic waste. In either case, the DOE selects the sites and builds and operates the repository. For spent fuel and high-level waste, the DOE must obtain a license from the NRC to construct and operate a repository. For defense transuranic waste, the DOE determines directly whether a proposed repository meets the EPA Standard. Thus, the DOE's WIPP Project will evaluate compliance of a deep geologic repository directly against the EPA Standard because it is not subject to the NRC's rules for licensing repositories.

The EPA has also promulgated regulations under the Resource Conservation and Recovery Act, e.g., *Land Disposal Restrictions*. This sharply limits land disposal of hazardous chemicals, such as solvents and heavy metals. To dispose of such chemicals in a geologic repository, the DOE must obtain a "no-migration variance" to the RCRA regulations. Such a variance is only issued if the EPA determines that public health and safety will not be endangered by the disposal facility, because any migration of hazardous chemicals will be below health-based standards. The DOE has petitioned the EPA for a no-migration variance for the WIPP.

Characteristics of the WIPP

The WIPP is located in the northern portion of the Delaware Basin near Carlsbad, New Mexico (Figure II-1). The WIPP underground workings are being constructed at a depth of about 655 m in bedded salt in the lower portion of the Salado Formation (Figure II-3). In the vicinity of the WIPP, the salt beds dip eastward with a slope of only about 1 degree. The mine is below the McNutt Potash Zone and south of the Capitan Limestone. The region is semi-arid, receiving about 30 cm of precipitation annually, and there are no perennial streams nearer the WIPP than the Pecos River, 22 km away at its closest point. Ground-water circulation in the Salado Formation is extremely limited. Water-bearing units of the Rustler Formation overlying the Salado Formation produce only small amounts of brine. The underground workings will remain dry while they are ventilated, but slow seepage of interstitial brine does occur. The most recent discussion of the geology and hydrology of the WIPP was prepared by Lappin et al. (1989). This section is taken largely from their work.

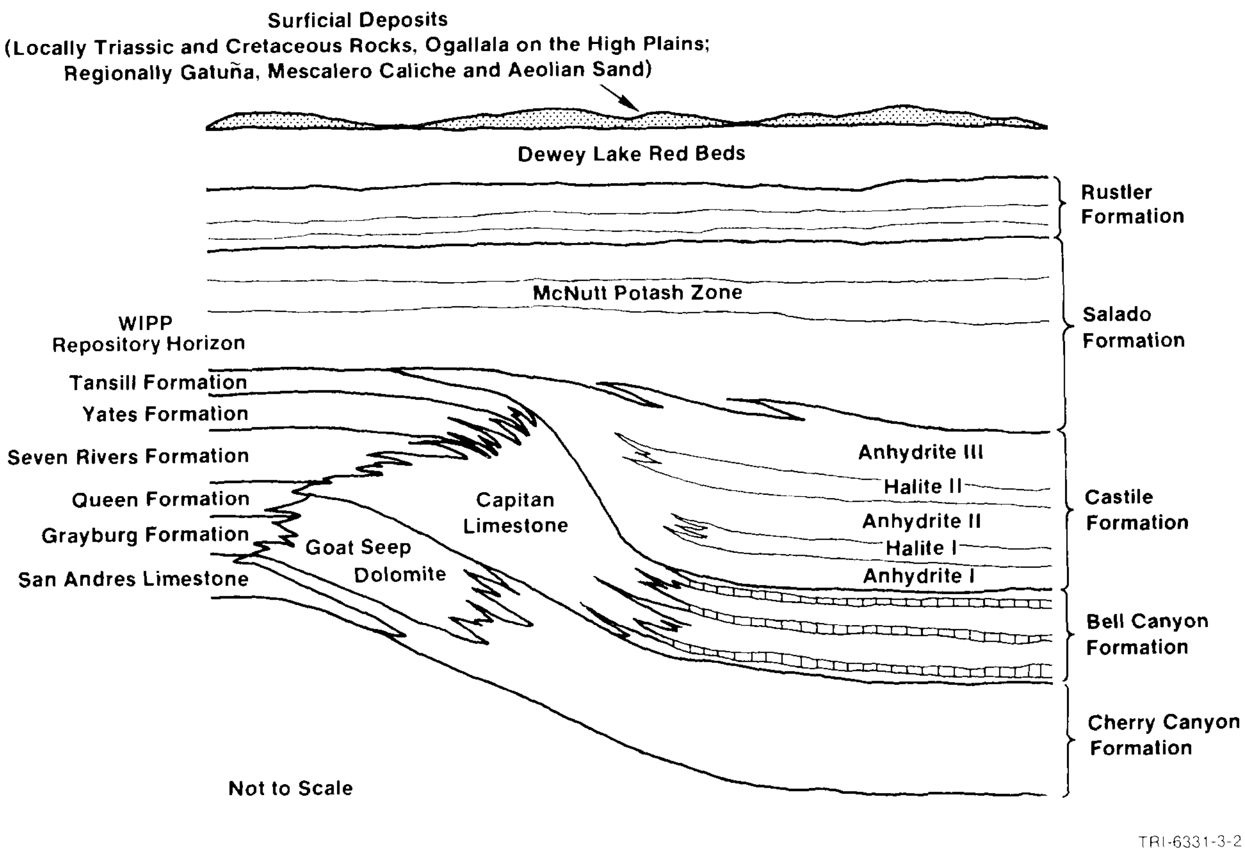

Figure II-3. Diagrammatic Cross Section of the Northern Delaware Basin (after Lambert, 1983). North is to the left.

The Delaware Basin became a distinct structure by the late Pennsylvanian Period or early Permian Period, about 280 million years ago. As the basin subsided, the reef now represented by the Capitan Limestone began to grow around the margins of the developing basin, and the sandstones, shales, and carbonates now making up the Delaware Mountain Group were deposited within the basin (Figure II-1). Although some portions of the Capitan Limestone are hydrologically active and locally support karst hydrology, including the formation of large cavities like Carlsbad Caverns, the Capitan is about 15 km from the WIPP at its nearest point. The basinal Delaware Mountain Group contains three major subdivisions, the Brushy Canyon, Cherry Canyon, and Bell Canyon Formations (in ascending stratigraphic order). The Bell Canyon Formation is the first regionally continuous water-bearing formation beneath the WIPP underground workings. The hydraulic behavior of the Bell Canyon Formation is assumed to be more important to the long-term performance of the WIPP than that of any underlying unit. Near the WIPP, the Bell Canyon Formation consists of a layered sequence of sandstones, shales and siltstones, and limestones 300 m or more in thickness (Powers et al., 1978).

The sandstones and shales of the Bell Canyon Formation are overlain by thick-bedded anhydrite and halite units of the Castile Formation, also of Permian age. The Castile Formation near the WIPP normally contains three anhydrite/carbonate units and two halites. The thickness of the Castile Formation near the WIPP is approximately 400 m. During hydrocarbon exploration in the Delaware Basin, a number of boreholes have encountered pressurized brine reservoirs in the Castile Formation, usually in the uppermost anhydrite. These pressurized brine reservoirs have caused some concern that human intrusion through the repository and into the Castile could lead to both immediate and long-term releases of radionuclides from the repository. In the absence of human intrusion, these brine reservoirs are not expected to interact with the repository in any way.

The Salado Formation, of Late Permian age, is 530 to 610 m thick near the WIPP. It generally contains beds 0.1 to 1 m thick, with 45 anhydrite marker beds of variable thickness. Between marker beds, the Salado Formation consists of layered halite of varying purity and accessory mineralogy. Anhydrite, clays, and polyhalite are the dominant accessory minerals. The halite contains about 1 percent brine, which seems to be immobile under undisturbed conditions. When a new drift is mined, however, small weeps develop on the walls of the excavation. Growth of these weeps generally stops within a year of mining. In-situ, brine-flow experiments have been used to estimate permeabilities in the Salado Formation of 10^{-21} to 10^{-20} m^2 using a poroelastic Darcy-flow model. It is not yet known whether the Darcy model is appropriate, however, and there may be some threshold below which no flow occurs.

The Salado Formation is overlain by the Rustler Formation, also of Late Permian age. The Rustler Formation contains five members. Two, the Magenta and Culebra Dolomites, are gypsiferous dolomites with a variable concentration of vugs and fractures and local occurrence of silty zones. The other three members of the Rustler Formation consist of varying proportions of anhydrite, siltstone, claystone, and halite. The Rustler Formation ranges from 83 to 130 m in thickness at the WIPP. The Culebra Dolomite is the first saturated, laterally continuous unit above the repository horizon to display significant permeability. Barring direct release to the surface, the Culebra Dolomite provides the most likely pathway between the repository and the accessible environment. According to the EPA Standard, the accessible environment consists of the atmosphere, land surface, surface water, oceans, and all the lithosphere beyond the controlled area. Whereas the controlled area has not been defined for the WIPP (Bertram-Howery and Hunter, 1989), the distance to the proposed withdrawal boundary down the ground-water flow gradient from the waste panels is approximately 3 km. The hydrology and fluid geochemistry of the Culebra Dolomite are complex. The unit displays wide ranges in hydraulic properties, local flow and transport mechanisms, and geochemistry. As a result of these factors, the Culebra Dolomite has received much study during WIPP characterization.

The Rustler Formation at the WIPP is overlain by the Dewey Lake Red Beds, roughly 30 to 170 m of siltstones and claystones with subordinate sandstones. The ages of the Castile, Salado, and Rustler Formations and Dewey Lake Red Beds range from about 255 million to 245 million years. Over approximately the eastern half of the WIPP, the Dewey Lake Red Beds are overlain by the (undivided) Dockum Group of sandstones and shales of Triassic age. The shallowest and youngest stratigraphic units at the WIPP proper, except for recent surficial sands, range in age from 600,000 years to 250,000 years (Bachman, 1985). Together, these younger units indicate the relative structural stability of the WIPP over the past 400,000 to 500,000 years. The WIPP is located in an aseismic region. The nearest Quaternary fault is located about 100 km to the west.

Oil and gas are produced in the Delaware Basin from several geologic units below the Castile Formation. In addition, potash is produced in the McNutt Potash Zone within the Salado Formation above the level of the repository. The DOE plans to acquire all mineral rights at the WIPP before waste is permanently disposed there.

Receipt Schedule for the Wastes

Unlike the repository at Yucca Mountain, the WIPP will receive waste for experimental purposes before disposal begins. The plans for the Test Phase at the WIPP (DOE, 1990b) call for the use of about 0.5 percent by volume of the design capacity of waste in experiments. The Test Phase is expected to last for five years after the first receipt of waste, which is tentatively scheduled for 1991.

If the WIPP becomes a disposal facility, waste will be emplaced at a much higher rate than during the Test Phase. Assuming that all waste arrived in drums (which is not the case), the design-basis rate for handling CH-TRU waste is about 130 drums per day. The waste would arrive in TRUPACT-II shipping packages (discussed below). Each truck trailer is capable of carrying three TRUPACT-IIs (Figure II-4), and each TRUPACT-II can contain 14 drums. Eight hundred ten shipments are expected per year, for a total waste volume of 7000 m^3 per year.

Characteristics of the Shipping Packages for the WIPP

TRUPACT-II, which was developed by Nuclear Packaging, Inc., is a reusable Type B container that will be used to transport the majority of the CH-TRU waste to the WIPP. TRUPACT-II provides two levels of containment for the payload during both normal and hypothetical accident conditions, as required by the applicable NRC regulation for shipments containing more than 20 Ci of plutonium.

TRUPACT-II was designed to be both rugged and lightweight to benefit operator and public safety. The use of a rugged, yet deformable, package provides abundant capabilities to ensure no release of the contents when the package is subjected to typical transportation accidents. The lightweight design allows the transport of a maximum payload per legal weight vehicle, thereby reducing the total number of radioactive shipments.

A TRUPACT-II unit is approximately 2.4 m in diameter and 3.1 m high and when fully loaded weighs about 8700 kg. It is composed of an Outer Containment Assembly (OCA) and an Inner Containment Vessel (ICV) (Figure II-5). The OCA consists of an exterior 304 stainless steel shell, a relatively thick layer of insulating and energy absorbing polyurethane foam, and an inner stainless steel boundary which forms the Outer Containment Vessel (OCV). The ICV is fabricated primarily of 304 stainless steel and is used to provide a secondary level of containment.

Four test series were conducted at Sandia National Laboratories (SNL) on full-scale units, each including multiple drop and puncture tests. The package was chilled to -29° C for several of the drop tests. Following the drop sequences, three of the four damaged units were each subjected to fully engulfing jet fuel fire tests where temperatures exceeded 800° C for

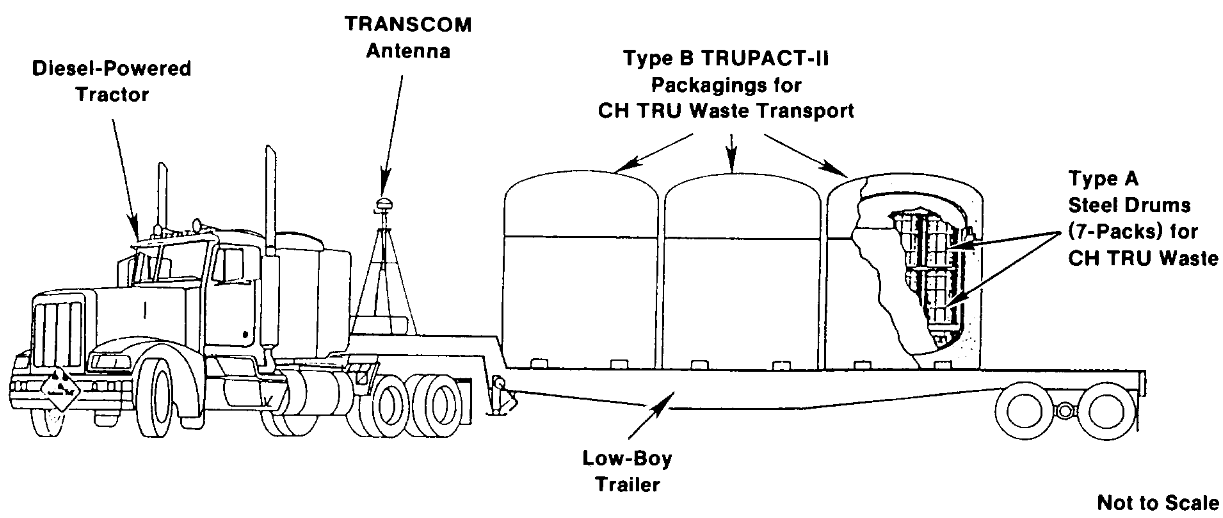

Figure II-4. TRUPACT-II Shipping Containers on a Trailer (DOE, 1990a).

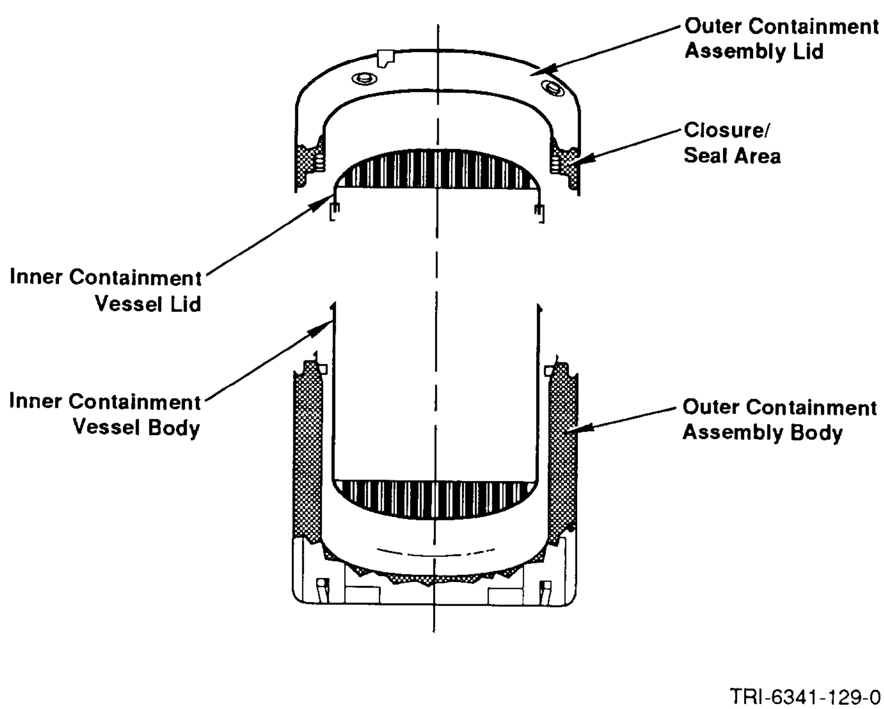

Figure II-5. Cut-away View of a TRUPACT-II Showing Container-within-a-container Construction.

30 minutes. A leak check successfully demonstrated that the TRUPACTs remained leaktight. A satellite-based tracking system (TRANSCOM) will enable the Department of Energy and all affected states and Indian tribes to pinpoint the location of trucks that are in transit at any time. No deviation from agreed-upon routes will be allowed. Stringent qualifications will be required for all drivers, who, in addition, will receive special training before transporting the defense-generated transuranic waste to the WIPP.

Surface and Subsurface Facilities

The waste handling building is the principal surface structure at the WIPP (Figure II-6). This building includes areas for the receipt, inspection, and transfer of TRU waste to a common waste shaft. The waste is received through air locks that permit the maintenance of interior air at a lower pressure than outside air, preventing the unfiltered release of radioactive contaminants to the outside. Other buildings are the exhaust filter building, the maintenance building for shipping packages, and miscellaneous support buildings. A large tailings pile stockpiles salt for backfilling the mine after waste disposal. Following waste delivery, any TRUPACT-IIs found to be contaminated are decontaminated on site. Uncontaminated or contaminated but overpacked CH-TRU containers will be stacked on pallets for transportation underground. RH-TRU waste will be handled in a hot cell and will be transported underground in special facility casks.

Four shafts connect the surface and subsurface facilities (Figure II-2): the air-intake shaft, the salt-handling shaft, the waste-handling shaft, and the exhaust shaft. The underground facilities at the WIPP are divided into two sections. The northern section of the mine is devoted to nonradioactive experiments. The southern section is the waste-disposal area and will also contain any experiments conducted using TRU waste. The disposal area is configured as a room-and-pillar mine with a low extraction ratio, less than 25 percent. The underground workings are being mined at a depth of 655 m. At this time, only one of the eight waste-storage panels (northeastern panel) has been mined. Pallets loaded with CH-TRU waste will be transferred to the hoist cage and lowered to the underground waste-receiving station. Waste containers are then transported to disposal rooms and stacked in three layers (Figure II-7). The facility casks, each containing one RH-TRU canister, will be transferred to the hoist cage and lowered to the underground waste-receiving station. RH-TRU waste canisters will be emplaced in horizontal boreholes in the disposal rooms and sealed with shielded steel plugs (Figure II-8). During operations, panels will be filled with waste, backfilled, and sealed in sequence; salt from each newly mined panel will be used in backfilling the previous panel. In the event of a radioactive release, air from the mine will be routed through high-efficiency particulate air filters in the exhaust

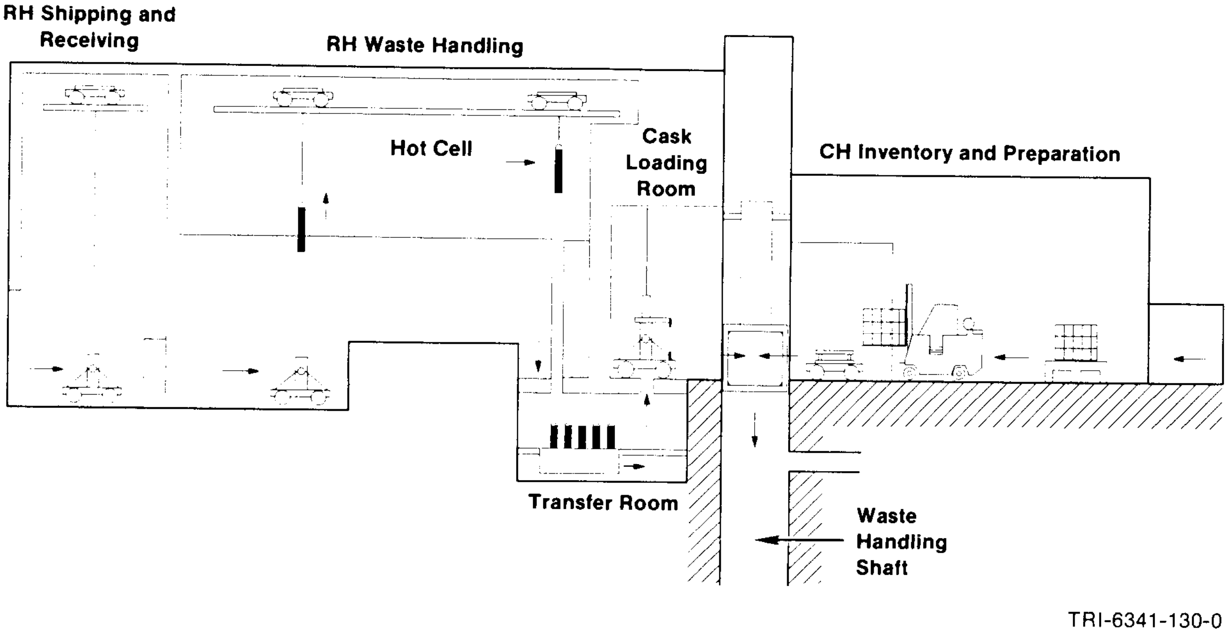

Figure II-6. Waste-handling Building.

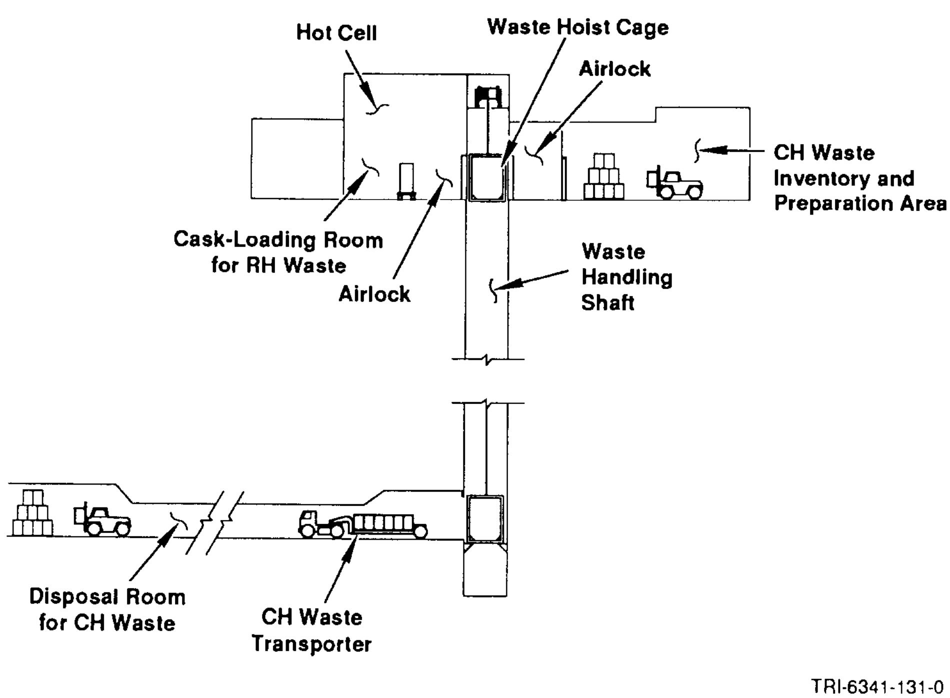

Figure II-7. Transportation of Contact-handled Transuranic Waste from the Surface to the Underground Waste-Disposal Areas (after DOE, 1980a).

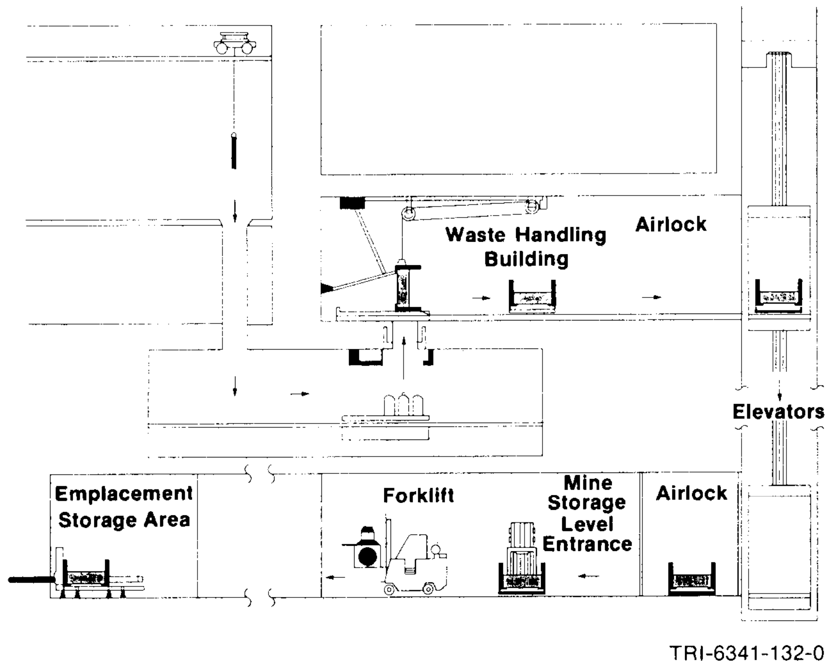

Figure II-8. Transportation of Remotely Handled Transuranic Waste from the Surface to the Underground Waste-Disposal Areas.

filter building. After the panels are filled, the entrances will be sealed. In addition, the accessways will be sealed at the northern end of the panels, between the panels and the shafts. During operations, air will flow through the mine in such a way that workers are upstream of the air that flows through filled waste rooms, thus reducing occupational exposures to radiation. Totally separate air flow will be provided to the nonradiation areas being mined for new waste rooms.

Performance Assessment Issues to be Resolved*

In October 1980, the DOE published the Final Environmental Impact Statement (FEIS) for the WIPP to provide information for the decision on whether the WIPP should be constructed and operated at the current site (DOE, 1980b). At that time, there were no environmental standards for disposal of transuranic waste. Predictive calculations for the FEIS analyses used the best available data, conceptual and mathematical models, and computer codes. Radionuclide transport through the Rustler Formation was believed to be by porous flow only, and the sorption coefficients of the radionuclides were interpreted to be high in that formation. The Salado Formation was believed to be dry

*[*Editors' Note: As of mid-1990.*]

(except for a few brine inclusions), as was the compacted room after final closure and passage of time; radionuclide migration through the compacted room and the formation was assumed to be by diffusion through the solid salt. The calculations predicted that any one of the three main barriers (the Rustler Formation, the Salado Formation, and the compacted waste room) was adequate to contain the waste for over a million years. The FEIS showed that the WIPP disposal system was very robust and that the Project should proceed to the construction phase.

Subsequently, shafts have been dug, drifts have been mined, and the underground experiments necessary to validate the assumptions made in the FEIS have been initiated. Underground disposal rooms have been mined and above-ground facilities have been constructed to prepare the WIPP for disposal operations. The WIPP Project has proceeded with the necessary in-situ and laboratory validation experiments. In 1985, the EPA promulgated its Standard. The Project expected to complete a final set of calculations using the new data and show compliance with the Standard, so that disposal operations could begin.

In 1990, the calculations required by the EPA Standard are considerably different from those presented in 1980, and more data are available for calculations as a result of the intervening experimental work. For these reasons, the 1980 calculations have proven to be less conservative than previously believed. The Culebra Member of the Rustler Formation is a poorer barrier than predicted because fracture flow predominates in critical areas. The approximate 5 km ground-water travel distance to the accessible environment is of regulatory concern, rather than the 25 km to the Pecos River originally assumed. The sorption coefficients for radionuclides in the Culebra are now conservatively interpreted to be low because of fracture flow, thus decreasing the effectiveness of this barrier. In addition, the EPA Standard requires that human intrusion be considered in ways that differ from the 1980 calculations. Human intrusion, as described in the guidance to the Standard, effectively eliminates the encapsulating Salado Formation as a barrier in important scenarios. The EPA suggests in its guidance that an intruding borehole should not be considered to be carefully or permanently plugged (i.e., current oil drilling technology should be assumed). With that technology, the plug probably would begin to degrade after 75 years, resulting in a rubble-filled hole to the surface within another 75 years. Furthermore, pressurized brine in the Castile Formation appears to underlie part of the repository. Borehole intrusion through the repository and into a pressurized brine reservoir, coupled with inadequate borehole plugging, could lead to radionuclide releases that, under some sets of assumptions, would violate the Standard.

The current experimental program within the WIPP Project is designed to provide information necessary to determine whether the WIPP can meet the long-term performance goals set forth in the EPA Standard. Several fundamental questions are raised by the considerations set forth above:

1. How much brine is likely to enter the underground openings, and how rapidly will it enter?
2. TRU waste is heterogeneous and contains organic materials and bacteria. What are the potential effects of gas generation on the repository?
3. How rapidly will the underground openings close, and what will be the condition of the rooms and the waste after closure?
4. How rapidly will the panel and shaft seals become effective, and what will their long-term performance be?
5. If waste leaves the repository as a result of natural processes or human intrusion, how will it travel through the geologic and hydrologic system surrounding the WIPP?
6. What is the most appropriate way to model these processes?

Aspects of the experimental program are directed toward answering each of these questions (DOE, 1990b).

Some brine will flow in from the surrounding host rock before room closure occurs. Permeability measurements of the host rock are being made, and brine inflow in vertical and horizontal boreholes of various diameters is being used to investigate the effects of opening-scale and small-scale variations in rock type. In addition, a large room (Room Q), circular in cross-section, has been constructed to produce data on brine inflow (Figure II-9). These experiments will allow calibration of the predictive models for brine flow through the host rock and into the waste rooms. Previous brine-inflow data come from boreholes and seeps in rooms. Room Q's circular cross section will provide high-quality data on large-scale excavations by minimizing rock fractures and maximizing the fraction of inflowing brine that can be collected. The predictive models will include a three-dimensional mechanistic hydrologic transport model of the repository. Current information indicates that brine inflow will be limited by very low salt permeabilities and will not exceed about 40 m^3 per waste room in 100 years, by which time the room will have closed to final dimensions by virtue of salt creep. This amount of brine will not prevent compaction of the waste and backfill into a rigid, solid mass. There will be sufficient brine, however, that anoxic corrosion of iron could generate appreciable quantities of hydrogen gas.

Gases generated by bacterial action, corrosion, and radiolysis may locally degrade the effectiveness of the Salado Formation as a barrier, because the

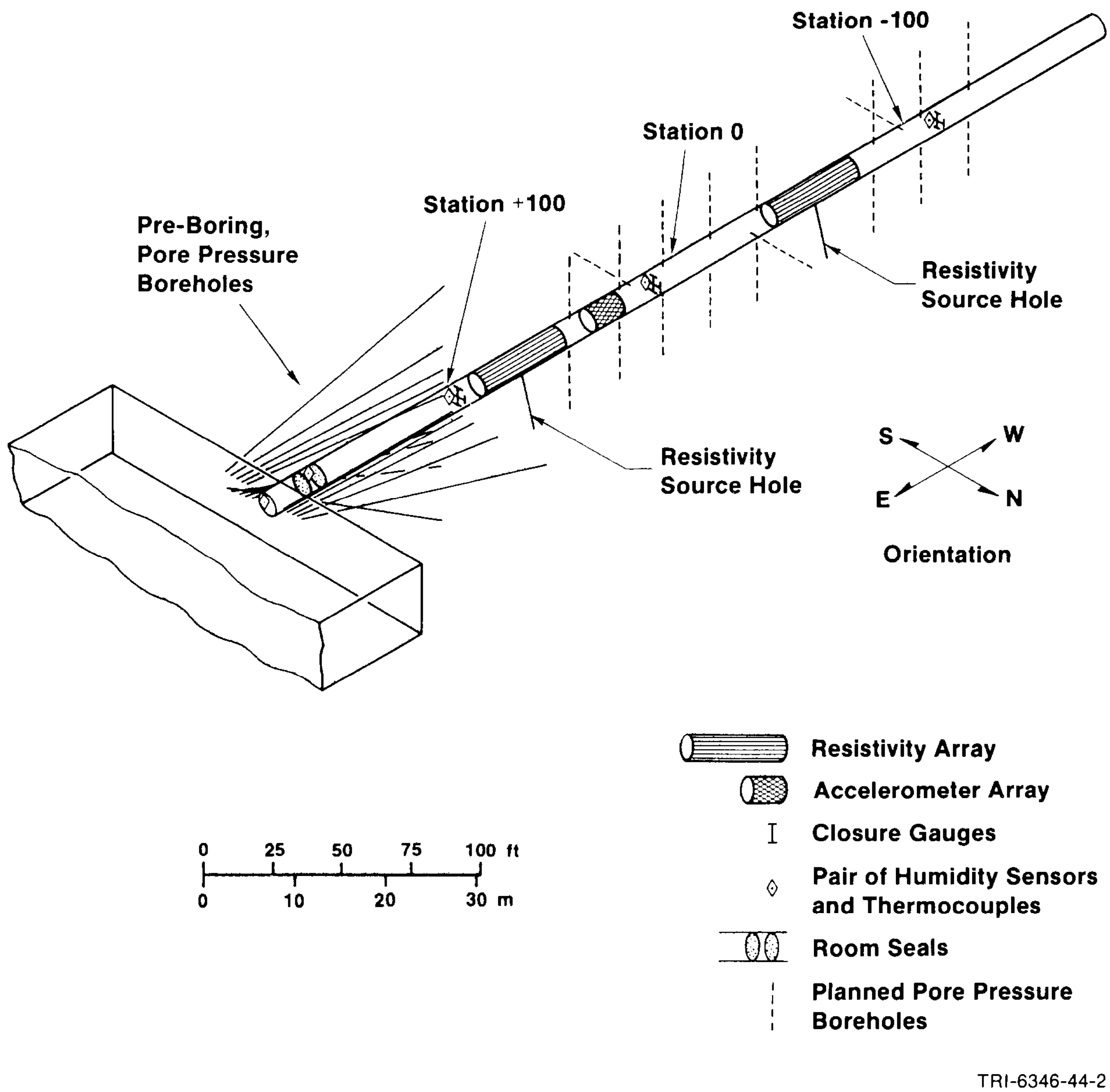

Figure II-9. Schematic Diagram of Room Q.

low permeability of the intact rock may prevent or delay gas diffusion out of the room (Figure II-10). In a hypothetical sequence of events following room closure, all access drifts and experimental areas are backfilled (Figure II-10a). The disturbed rock zone (DRZ) is at its maximum extent. Fractures in an anhydrite bed directly below the floor of the excavations (MB139) are filled or partially filled with brine. As closure occurs, containers are crushed. Brine flows from anhydrite layers above and below the repository into the DRZ and remaining voids in the rooms and drifts. Consolidation is nearly complete before large amounts of gas are generated (Figure II-10b).

In the hypothetical sequence, gas generation by anoxic corrosion, radiolysis, and microbial action pressurizes remaining voids and reverses the flow of brine at later times until equilibrium conditions are reached. Continued gas generation saturates the brine with gas in the anhydrite layers. Some enlargement of the closed rooms may occur if gas pressures approach lithostatic pressure (about 15 MPa) (Figure II-10c). Undisturbed conditions result in gas-filled rooms with gas-saturated brine in the anhydrite layers (Figure II-10d). In case of human intrusion at any time during this process, gas and brine are released through the borehole. After sealing of the intruding borehole and subsequent degradation of the seal (Figure II-11b), remaining gas and brine are released from the anhydrite layers, brine from the Castile brine reservoir can flow through a small portion of the room, and any brine released from the Salado Formation between the confining anhydrite layers may also flow through the waste and up the borehole, which is concurrently creeping shut (Figure II-11c).

The gas buildup could interfere with reconsolidation of the room and disturbed rock zone and therefore affect room permeability, increasing the potential for dissolution of the wastes and transport to the accessible environment in the event of human intrusion. The WIPP Project will investigate the generation of gas by the waste in laboratory, bin-scale, and room-scale experiments. The laboratory experiments will use simulated waste and will investigate specific processes in a well-controlled and well-understood setting. For bin-scale experiments, several waste types will be tested in volumes equivalent to about six drums. Each waste type will be combined with various backfills, gas getters, and moisture conditions to determine the effects of differing repository conditions on gas generation. Most bins will be initially flushed with argon and made anaerobic. Data will be collected over a period of five or more years, although some usable data are expected in less than one year. Data from bin-scale tests will be combined with data from laboratory experiments and alcove tests to refine the understanding of gas-generation processes, rates, and volumes (Figure II-12). Room-scale experiments will examine for the first time the interactions among the host rock, gas and brine released from the host rock, and gases generated by the waste. Because they

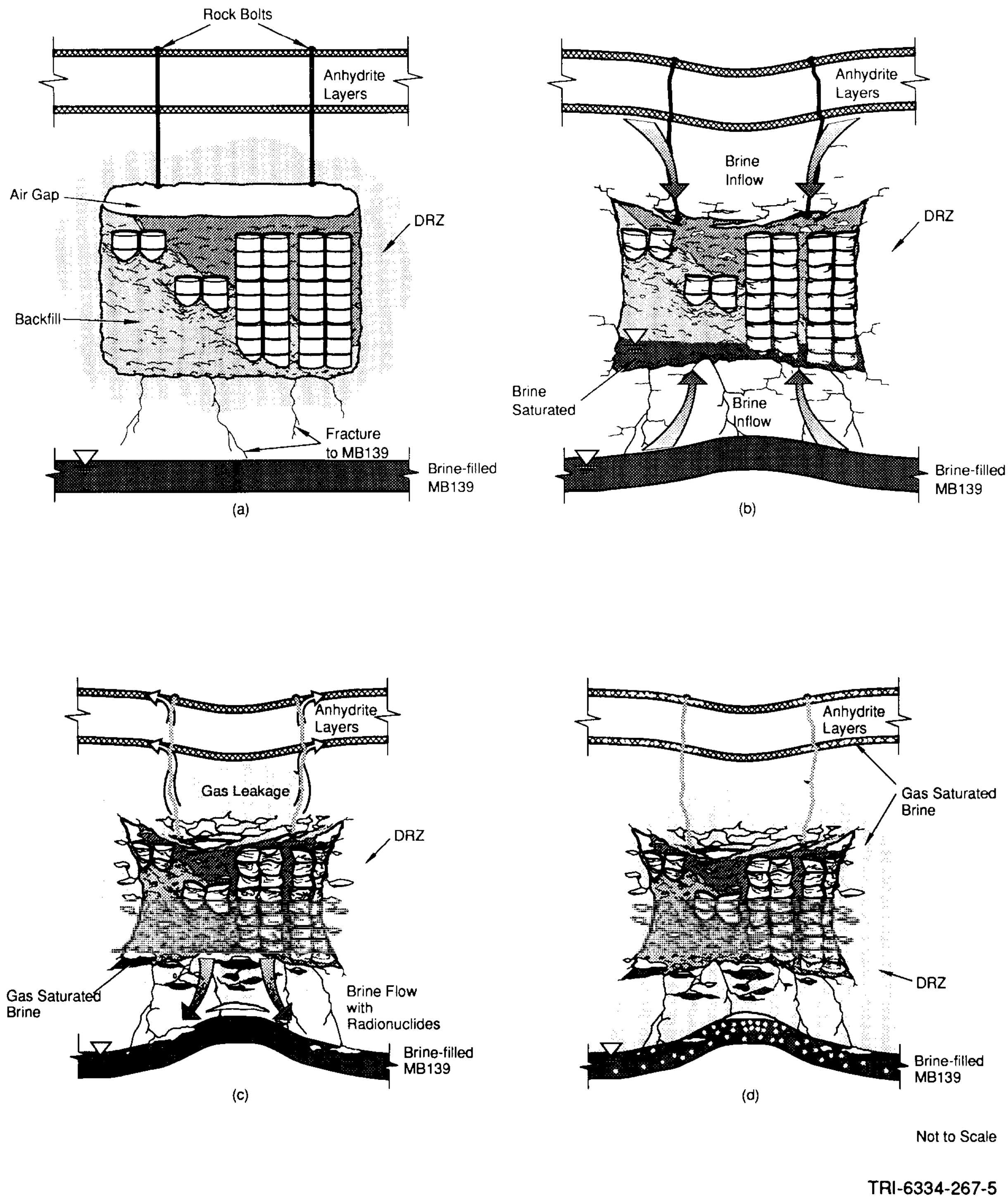

Figure II-10. Hypothesized Episodes in Disposal Area Leading to Undisturbed Conditions (Rechard et al., 1990). This drawing shows (a) initial conditions after decommissioning; (b) room creep closure and brine inflow; (c) gas generation, brine outflow, and room expansion; and (d) a gas-filled room surrounded by gas-saturated brine.

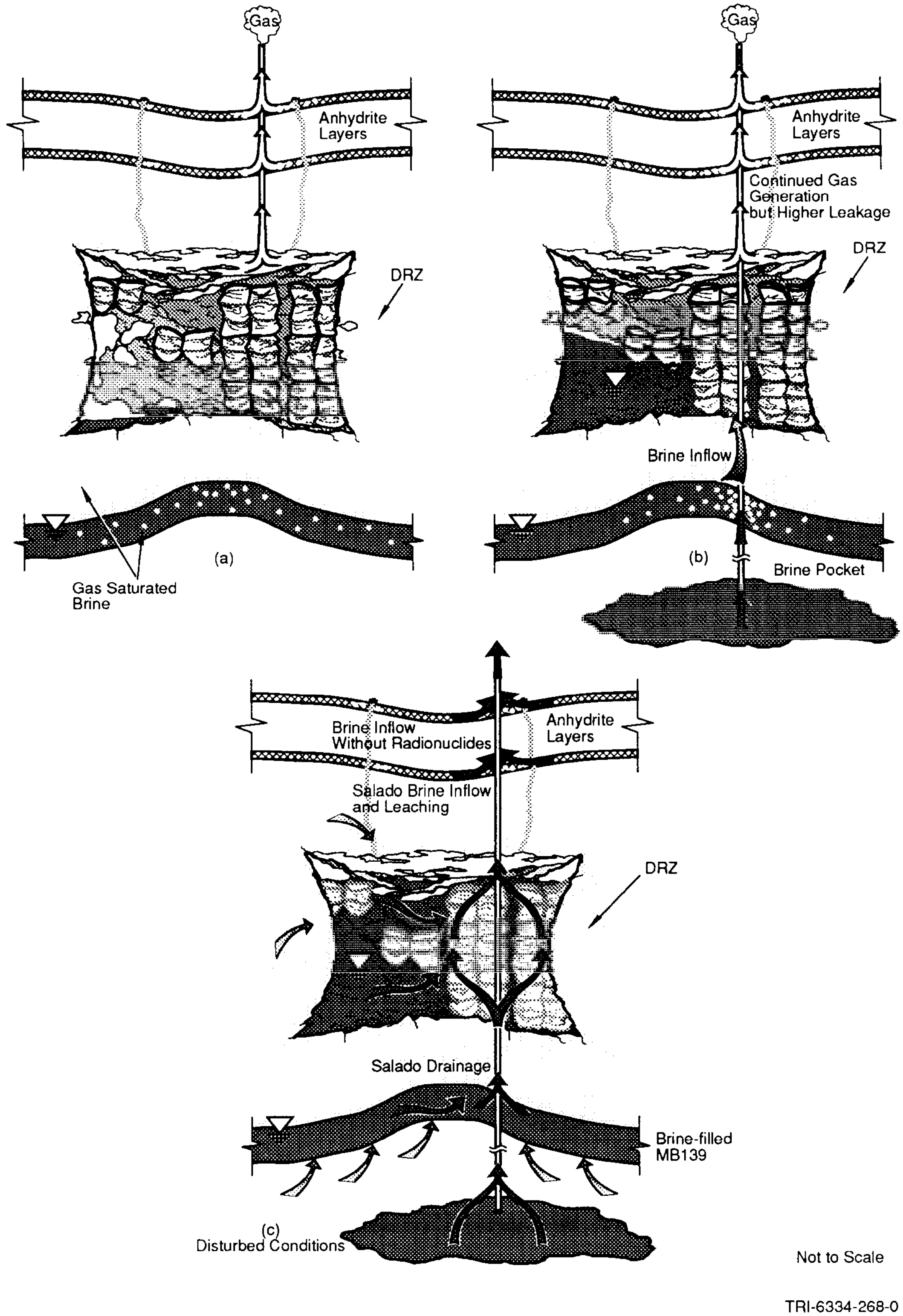

Figure II-11. Hypothesized Episodes in Disposal Area after Human Intrusion. This drawing shows (a) initial room gas depressurization when penetrated by exploratory borehole, (b) final gas and brine depressurization as borehole seals degrade, and (c) brine flow through borehole to Culebra Dolomite.

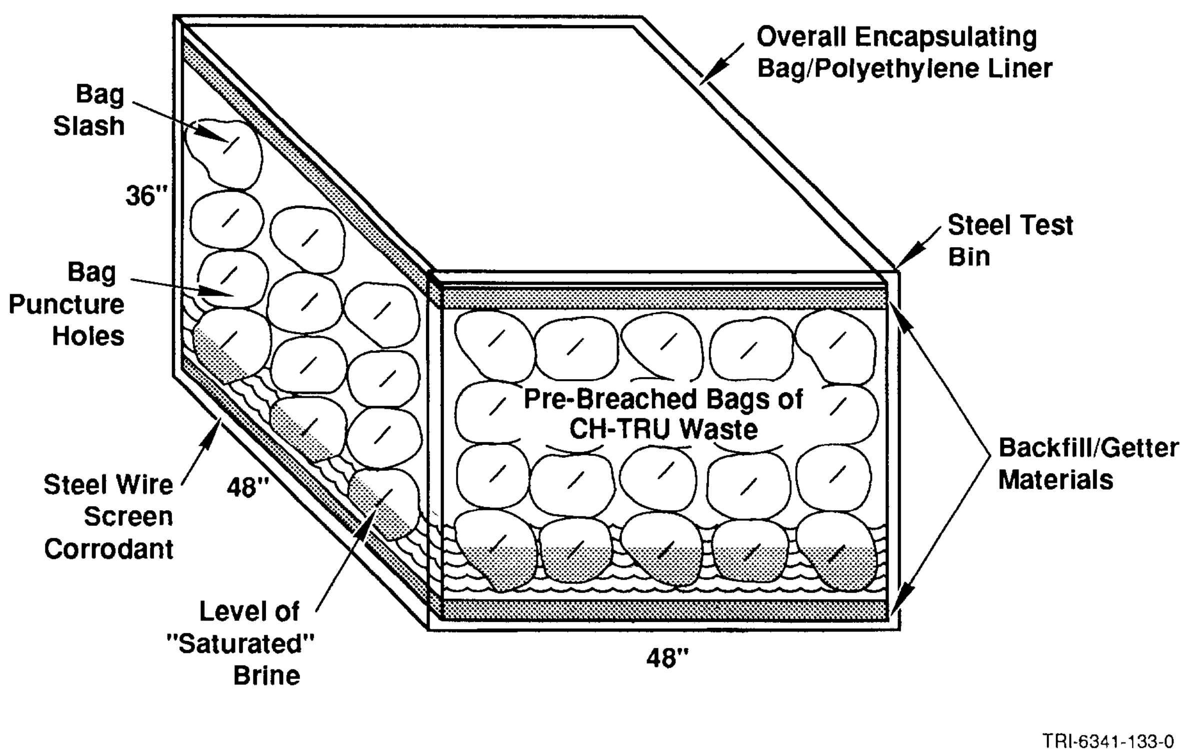

Figure II-12. Bin Tests of Gas Generation by CH-TRU Waste (48" = 122 cm).

will provide a large enough volume of waste to be representative of the repository inventory, the effects of waste heterogeneity will be included. Because the rooms will not be perfectly sealed, inert tracer gases will be used to help determine the volume of gases generated by the waste and lost by leakage (Figure II-13).

Room-closure rates are being investigated in a number of experiments designed to determine the effects of room scale, interbeds in the halite, and the disturbed zone around the openings (Figure II-14). Creep laws used a decade ago underestimated closure rates of the excavations by about a factor of 3. Analysis of experimental work at the WIPP during the past 10 years has improved the predictive capability until current model predictions differ from measurements of closure by only about 2 percent for vertical closure and 18 percent for horizontal closure. Laboratory experiments have studied the effects of moisture on creep rate. The structural response of a seven-room panel is being measured. A large, heated, circular pillar has been studied for several years to refine understanding of creep in salt; the pillar is circular so that two-dimensional axisymmetric models of the process can be used. As a result of these experiments and modeling studies, very close agreement between predicted and measured creep rates is being obtained.

Seals will be emplaced in the panel entrances (Figure II-15), in the shaft at several levels (Figure II-16), and in all boreholes. Reconsolidated or quarried salt blocks and tamped salt, the primary long-term seal, will become nearly indistinguishable from the host rock. Short-term sealing and support for the salt components during reconsolidation will be provided by the concrete components. The underlying anhydrite layer (MB139) will be grouted at the seal locations to prevent preferential flow of brine beneath panel seals. The underground workings will be sealed at the entrances to the panels, at the north end of the waste-storage area, and between the northern four and southern four panels (see Figure II-2). Each panel will be sealed following waste emplacement and backfilling. Shaft seals will be emplaced at three levels (Figure II-17): the bottom of the shaft (not shown); just above the level of expected 100-year salt reconsolidation (right); and at the top of the Salado Formation (left). The reconsolidated salt between the lowermost seal and the middle seal also will be a major barrier to migration of water or radionuclides through the shaft. The principal function of the uppermost seal is to prevent water from the Rustler Formation from entering the shaft and interfering with salt reconsolidation. Concrete components of the seal will provide short-term sealing to protect the salt components while they reconsolidate fully. Boreholes will likely be sealed with cement-based grouts throughout. An active program is under way to develop and test various concretes, such as anhydrite-bonding concretes, that are not readily available from industry or whose long-term properties are not known. Techniques for preparing partially reconsolidated salt blocks for emplacement in the seals

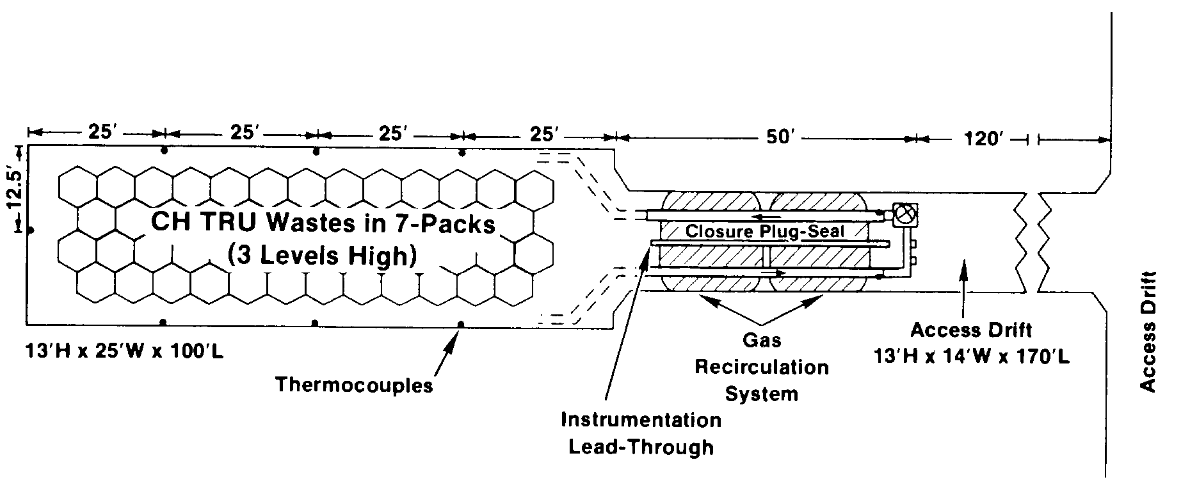

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Figure II-13. Tests of Gas Generation by CH-TRU Waste. Plan view of a test alcove (50' = 15.24 m).

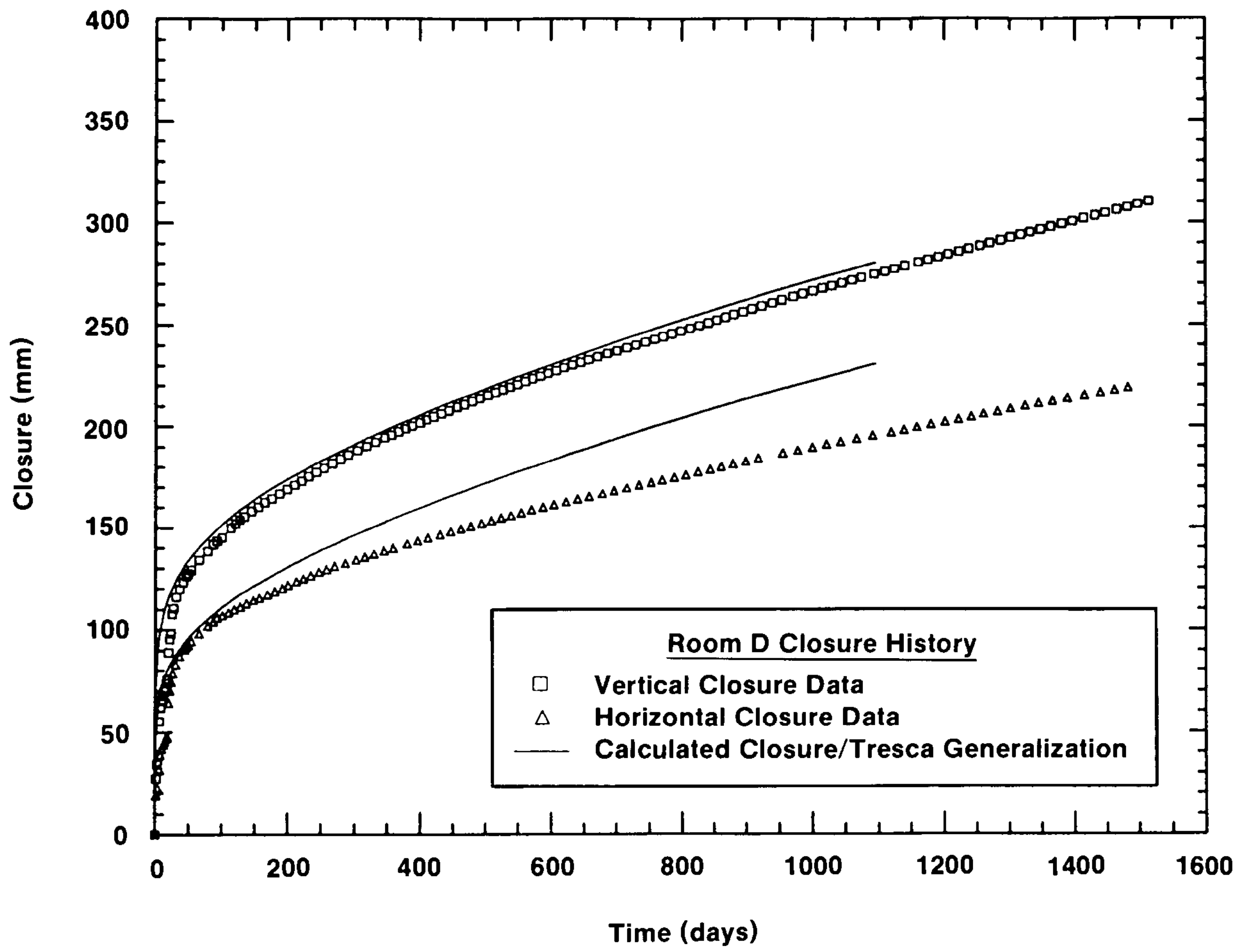

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Figure II-14. Comparison of Measured and Calculated Room-Closure Rates (Munson et al., 1989).

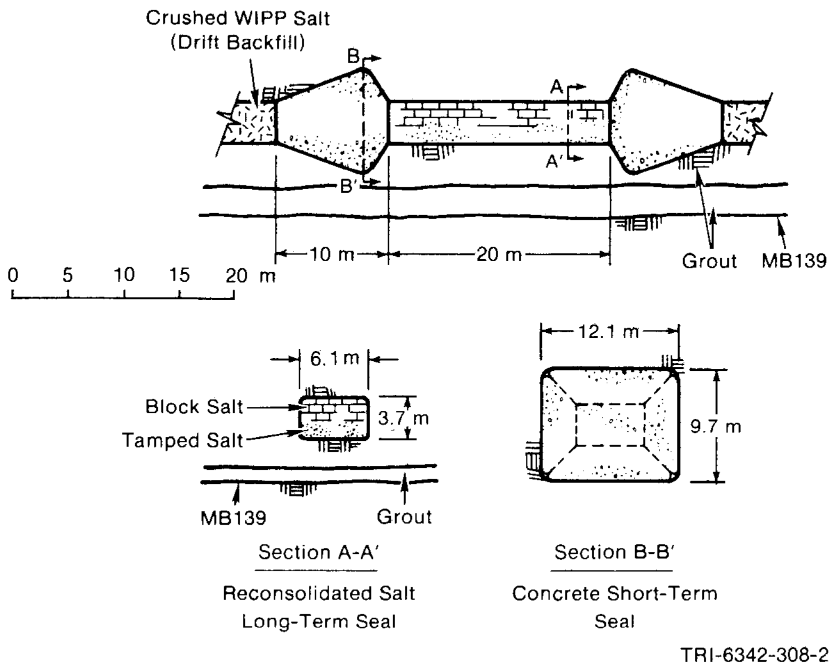

Figure II-15. Preliminary Design of a Panel or Drift Seal (Rechard et al., 1990).

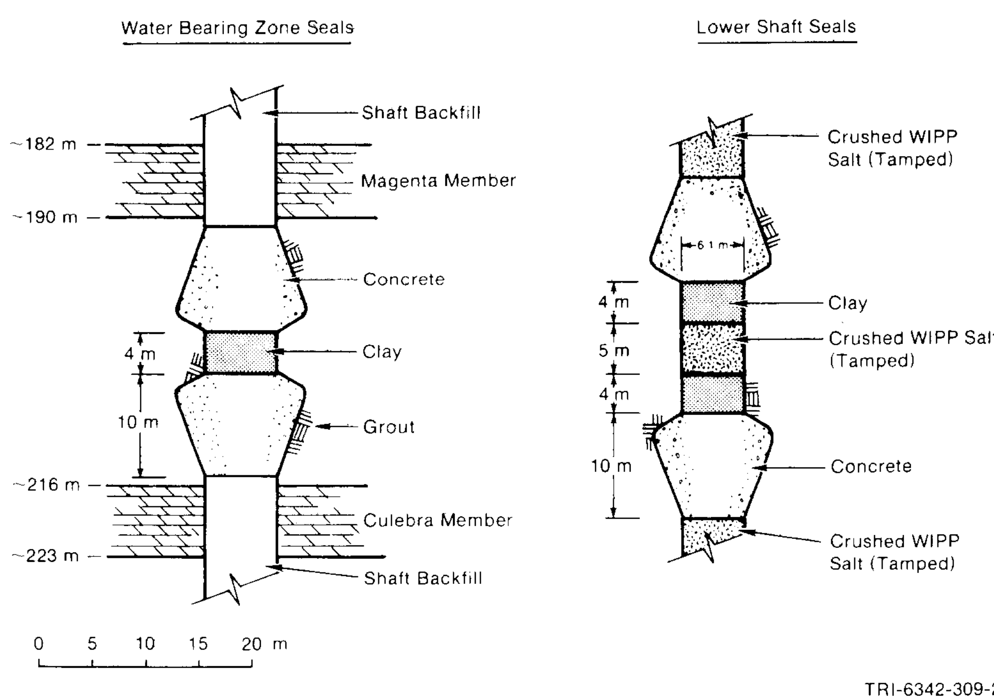

Figure II-16. Preliminary Design of a Shaft Seal (Rechard et al., 1990).

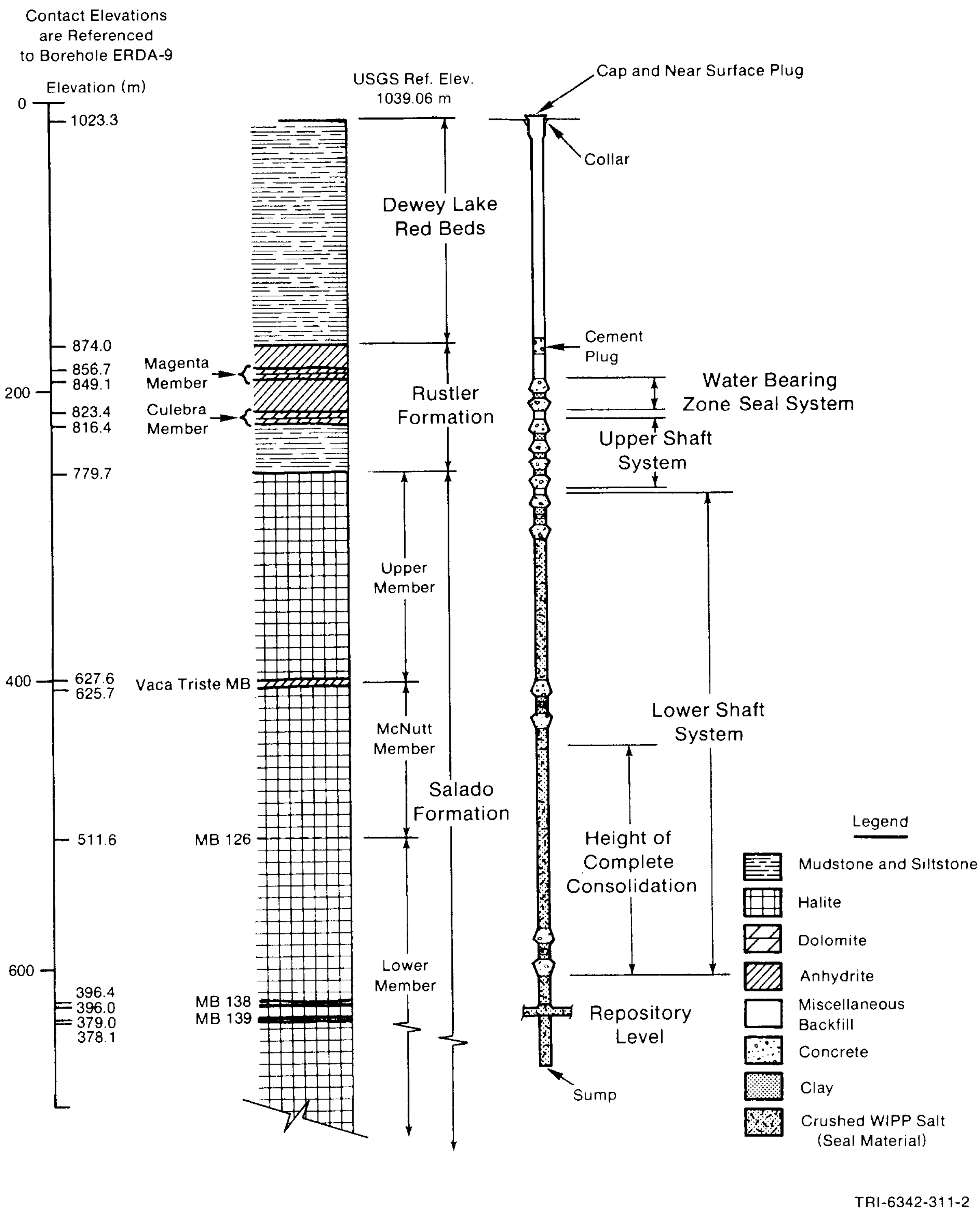

Figure II-17. Typical Backfilled and Sealed Access Shaft (after Nowak et al., 1990).

are being tested. Small-scale seal tests have been emplaced and instrumented, and a large-scale test is planned.

The geology and hydrology of the WIPP and vicinity have been investigated for many years. Programs continue to investigate fracture flow in the Culebra Dolomite, sorption of radionuclides along potential travel paths from the repository to the accessible environment, and the response of the Rustler Formation to the construction of the air-intake shaft, to name a few examples.

Finally, an active program is developing, refining, and validating computer models of most of the processes named above. These computer models will be used to predict the long-term performance of the WIPP, so that the projected performance can be evaluated against the appropriate environmental standards. The combined repository response to both natural events and the effects of human intrusion is the principal performance issue yet to be resolved.

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III. APPLICATION OF 40 CFR PART 191, SUBPART B TO THE WASTE ISOLATION PILOT PLANT

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PREFACE: Synopsis of Considerations for Inadvertent Human Intrusion

The Waste Isolation Pilot Plant (WIPP) must satisfy the requirements of the Environmental Protection Agency's (EPA's) "Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes," 40 CFR Part 191, known as the Standard (U.S. EPA, 1985). Subpart B of the Standard was vacated and remanded to the EPA by the United States Court of Appeals for the First Circuit in July 1987; however, the Second Modification to the Consultation and Cooperation Agreement between the U.S. Department of Energy (DOE) and the State of New Mexico commits the WIPP Project to proceed with the evaluation of compliance with the Standard as first promulgated until the Standard is revised. The determination of compliance with Subpart B depends on estimated releases and doses, assurance strategies that will be implemented, and qualitative judgment of the DOE and its analysts.

Appendix B of the Standard is nonbinding guidance for implementing Subpart B. The WIPP Project will follow the guidance to the extent possible by considering all natural and engineered barriers in the performance assessment; establishing a reasonable scope for the performance assessment that considers processes and events with probabilities above a suggested threshold and those with non-negligible consequences; using best-estimate predictions for uncertainties in undisturbed performance; and using appropriate assumptions about the effectiveness of institutional controls and the frequency and severity of inadvertent human intrusion.

The WIPP disposal system is the combination of the underground repository, shafts, and engineered barriers, and the natural barriers of the controlled area. Engineered barriers are backfill in rooms; seals in drifts and panel entries; backfill and seals in shafts; and plugs in boreholes. Natural barriers are the subsurface geology and hydrology within the controlled area. The boundary of the maximum-allowable controlled area does not coincide with the proposed boundary for the WIPP land withdrawal. The extent of the WIPP controlled area will be defined during the performance assessment but will not be less than the withdrawn area. As defined by the Standard, the surface, but not the subsurface within the controlled area, is part of the accessible environment. Any radionuclides that reached the surface would be subject to the limits set in the Standard, as would any that reached the lithosphere outside the subsurface portion of the controlled area.

The "disposal site" is to be designated by passive institutional controls to indicate the dangers of the wastes and their location. These controls include permanent markers placed at the disposal site, records, government ownership identification, and other methods of preserving knowledge about the disposal system. For the purposes of the WIPP strategy for compliance with Subpart B, the "disposal site" and the controlled area coincide.

The Containment Requirements (§ 191.13) specify the primary objective of Subpart B--to isolate waste from the accessible environment by limiting long-term releases. Performance assessments need not provide complete assurance that the requirements of 191.13(a) will be met. What is required is a reasonable expectation, on the basis of practically obtainable information and analysis, that compliance with 191.13(a) will be achieved. Unequivocal proof of compliance is neither expected nor required because of the substantial uncertainties inherent in such long-term projections.

The EPA intended to discourage overly restrictive or inappropriate implementation of the requirements. The guidance indicates that compliance should be based upon the projections that the DOE believes are more realistic. The quantitative calculations needed may have to be supplemented by reasonable qualitative judgments in order to appropriately determine compliance with the disposal standards. Determining compliance with § 191.13 will entail predicting the likelihood of events and processes that may disturb the disposal system. It will be appropriate for the DOE to use rather complex computational models, analytical theories, and prevalent expert judgment relevant to the numerical predictions. The DOE may choose to supplement such predictions with qualitative judgments.

Qualitative requirements were included in the Standard to ensure that cautious steps are taken to reduce the problems caused by uncertainties in predicting the future. The qualitative Assurance Requirements (§ 191.14) are an essential complement to the quantitative Containment Requirements. Each Assurance Requirement applies to some aspect of uncertainty about the future relative to long-term containment. The Assurance Requirements limit consideration of active institutional controls to reduce reliance on future generations to maintain surveillance, relying instead on markers and records to reduce the chance of systematic and inadvertent intrusion. In the Second Modification to the Consultation and Cooperation Agreement, the DOE agreed to prohibit subsurface mining, drilling, slant drilling under the withdrawn area, or resource exploration unrelated to the WIPP Project on the sixteen square miles to be withdrawn and remain under DOE control. The Standard clearly limits future institutional control in that "performance assessments...shall not consider any contributions from active institutional controls for more than 100 years after disposal."

The most significant event that could affect the disposal system will probably be human intrusion. Analysis of the probability of human intrusion into the repository must include the effectiveness of passive institutional controls over a 9,900-year period. Such controls could substantially reduce the probability of intrusion and improve predicted repository performance. The EPA believes that only realistic possibilities for human intrusion that can be mitigated by design, site selection, and passive institutional controls need be considered.

As long as passive institutional controls "endure and are understood," they can be assumed to deter systematic or persistent exploitation of the "disposal site" and reduce the likelihood of inadvertent, intermittent human intrusion to a degree to be determined by the DOE. Passive institutional controls can never be assumed to eliminate the chance of inadvertent, intermittent human intrusion.

Exploratory drilling, according to the EPA guidance, is the most severe intrusion that should be considered. The EPA suggests that intruders will soon detect or be warned of the incompatibility of their activities with the disposal site by their own exploratory procedures or by passive institutional controls. The number of exploratory boreholes assumed to be drilled inside the controlled area is to be based on site-specific information and need not exceed 30 boreholes/km^2 per 10,000 years.

Appendix B of the Standard indicates that individual events and processes, and by implication their combined form as scenarios, do not have to be considered in performance assessment if their probability of occurrence is less than 1 chance in 10,000 in 10,000 years, or their omission is not expected to significantly change the probability distribution of cumulative releases.

Given the approach chosen by the EPA for the disposal standards, repository performance must be predicted probabilistically to evaluate compliance. Determining the probability of intrusion poses questions that cannot be answered by numerical modeling or experimentation. Projecting future drilling activity requires knowledge about complex variables such as economic demand for natural resources, institutional control over the site, public awareness of radiation hazards, and changes in exploration technology. The value of extrapolating <u>present</u> trends 10,000 years into the future is questionable.

40 CFR Part 191, The Standard (1985)

Before disposing of radioactive waste at the Waste Isolation Pilot Plant (WIPP), the Department of Energy (DOE) must comply with the United States Environmental Protection Agency's (EPA's) "Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes" (40 CFR Part 191; U.S. EPA, 1985), referred to herein as the Standard.

The Standard promulgated in 1985 by the EPA is divided into two subparts (Figure III-1). Subpart A applies to a disposal facility prior to decommissioning and limits annual radiation doses from waste management and storage operations to members of the public outside the site. Subpart B applies after decommissioning and limits cumulative releases of radioactive materials to the accessible environment for 10,000 years. Subpart B also limits both radiation doses to members of the public in the accessible environment and radioactive contamination of certain sources of ground water within or near the controlled area for 1,000 years after disposal. Appendix A of the Standard specifies how to determine release limits, and Appendix B of the Standard provides nonmandatory guidance for implementing Subpart B. Application of the Standard to the WIPP is described in the ***Compliance Strategy*** (U.S. DOE, 1989a), which discusses the Project's initial interpretations of various terms and definitions contained in the 1985 Standard (Bertram-Howery et al., 1989).

The concept of "sites" is integral to limits established by Subparts A and B for releases of waste from the repository, both during operation and after decommissioning. "Site" is used differently in the two subparts; the meaning of "site" at the WIPP for each subpart is discussed and defined below in the appropriate section. The definitions of "controlled area" and "accessible environment," which are also important in assessing compliance with the Standard, depend on the definition of "site." "Site" has also been used generically for many years by the waste-management community (e.g., in the phrases "site characterization" or "site specific"); few uses of the word correspond to either of the EPA's usages (Bertram-Howery and Hunter, 1989).

SUBPART A

Subpart A limits the radiation doses that may be received by members of the public in the general environment as a result of management and storage of transuranic (TRU) wastes at DOE disposal facilities not regulated by the Nuclear Regulatory Commission (NRC). Subpart A requires that "the combined annual dose equivalent to any member of the public in the general environment resulting from discharges of radioactive material and direct radiation from such management and storage shall not exceed 25 millirems to the whole body or

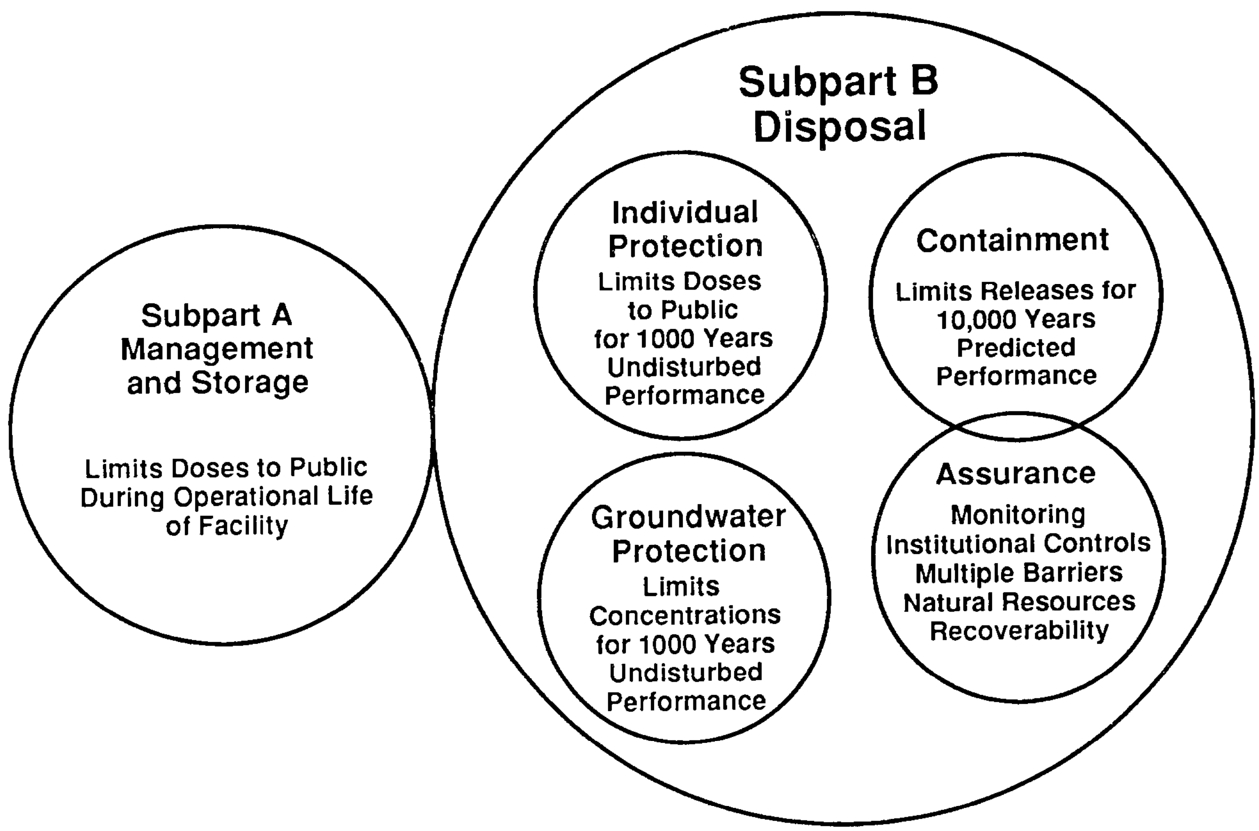

Figure III-1. 40 CFR Part 191 Environmental Standards for Management and Disposal (U.S. DOE, 1989a).

75 millirems to any critical organ" (§ 191.03[b]). The general environment is the "total terrestrial, atmospheric, and aquatic environments outside sites within which any activity, operation, or process associated with the management and storage of...radioactive waste is conducted" (§ 191.02[o]).

"Site" for the purposes of Subpart A is the secured-area boundary shown in Figure III-2. This area will be under the effective control of the security force at the WIPP, and only authorized persons will be allowed within the boundary (U.S. DOE, 1989a). In addition, the DOE will gain control over the sixteen-section area within the land-withdrawal boundary; this boundary is referred to in the agreement with New Mexico and in the WIPP ***Final Safety Analysis Report*** (FSAR)(U.S. DOE, 1989b) as the "WIPP site boundary." This control will prohibit habitation within the boundary. Consequently, for the purposes of operational dose assessment of nearby residents, the assumption can be made that no one lives closer than the latter boundary (Bertram-Howery and Hunter, 1989).

A description of the Subpart A compliance approach is contained in the WIPP ***Compliance Strategy*** (U.S. DOE, 1989a; cf. Bertram-Howery and Hunter, 1989 and U.S. DOE 1989b). Compliance with Subpart B is the topic of this paper; therefore, Subpart A will not be discussed further.

SUBPART B

In evaluating compliance with Subpart B, the WIPP Project intends to follow to the extent possible the guidance found in Appendix B of the Standard (U.S. DOE, 1989a). The Containment Requirements (§ 191.13) and Individual Protection Requirements (§ 191.15) necessitate predicting releases for 10,000 years and doses for 1,000 years. The Assurance Requirements (§ 191.14) qualitatively complement the Containment Requirements. The Ground Water Protection Requirements (§ 191.16) limit radionuclide concentrations. Subpart B of the Standard applies at the WIPP to cumulative releases of radioactive materials into the accessible environment (§ 191.13) and to annual radiation doses received by members of the public in the accessible environment (§ 191.15) as a result of TRU waste disposal. It requires actions and procedures (§ 191.14) to increase confidence that the release limits will be met at the WIPP. It would have applied to radioactive contamination of certain sources of ground water (§ 191.16) in the vicinity of the WIPP disposal system from such TRU wastes had any of these sources of ground water been found to be present (Bertram-Howery et al., 1989).

Appendix B to the Standard is EPA's guidance to the implementing agency (in this case, the DOE). In the preamble to the Standard (U.S. EPA, 1985, p. 38069), the EPA stated that it intends the guidance to be followed.

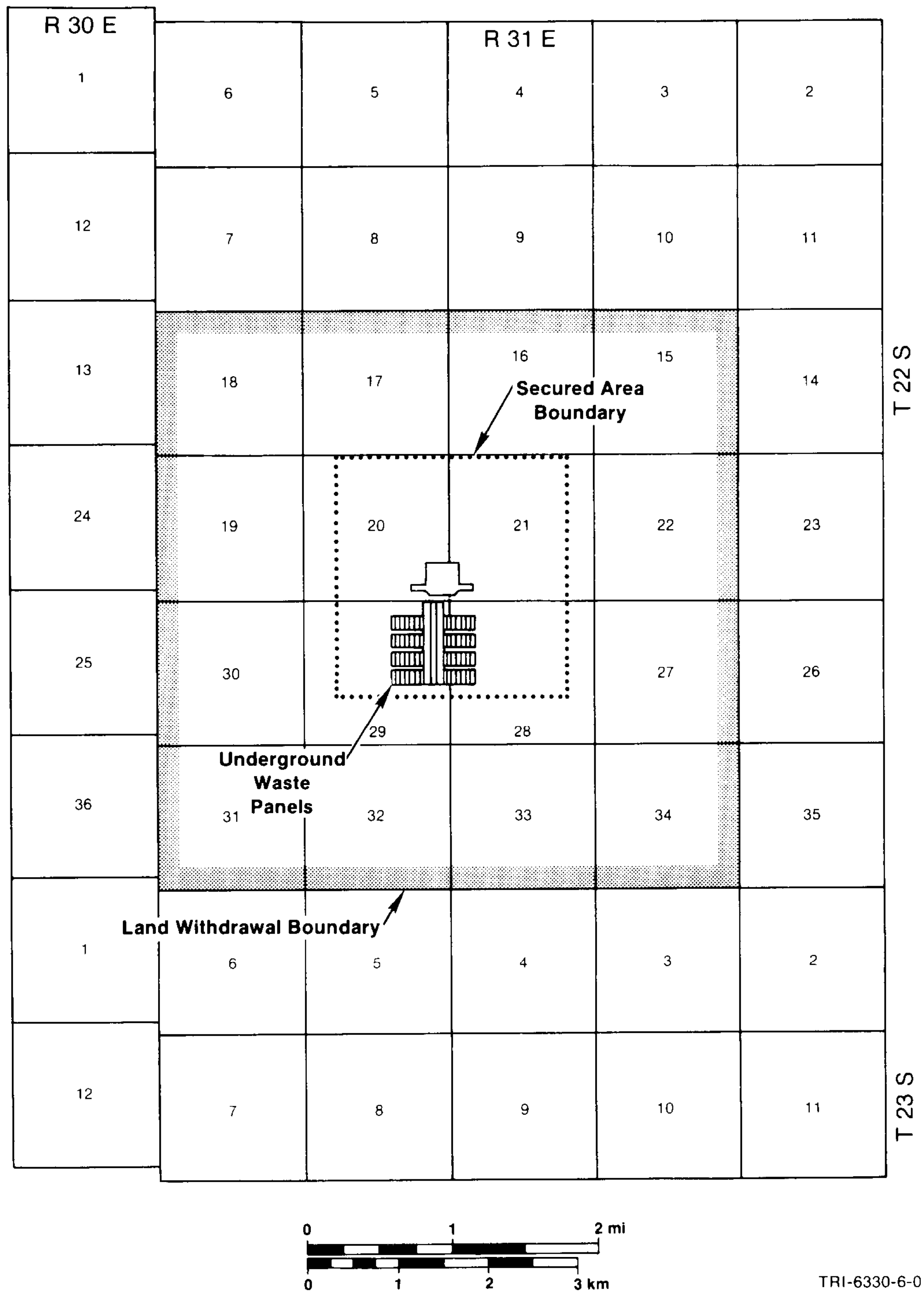

Figure III-2. Map Showing Selected Features Around the WIPP (U.S. DOE, 1989b).

> ...Appendix B...describes certain analytical approaches and assumptions through which the [EPA] intends the various long-term numerical standard of Subpart B to be applied. This guidance is particularly important because there are no precendents for the implementation of such long-term environmental standards, which will require consideration of extensive analytical projections of disposal system performance.

The EPA based Appendix B on analytical assumptions it used in developing the technical basis for the numerical disposal standards. Thus, the EPA "believes it is important that the assumptions used by the [DOE] are compatible with those used by the EPA in developing this rule. Otherwise, implementation of the disposal standards may have effects quite different than those anticipated by EPA" (U.S. EPA, 1985, p. 38074). Appendix B is nonbinding guidance for implementing Subpart B. This guidance includes considering all natural and engineered barriers in the performance assessment; establishing a reasonable scope for the performance assessment by considering processes and events with probabilities above a suggested threshold; using best-estimate predictions for uncertainties in undisturbed performance; and using appropriate assumptions about the effectiveness of institutional controls and the frequency and severity of inadvertent human intrusion (U.S. DOE, 1989a). This paper discusses the assumptions and interpretations of the Standard used in the WIPP compliance assessment.

Controlled Area

The term "disposal site" is used frequently in Subpart B and in Appendix B of the Standard. The "site" for the purposes of Subpart A and the "disposal site" for the purposes of Subpart B are not the same (U.S. DOE, 1989a). The Standard defines "disposal system" to mean any combination of engineered and natural barriers that isolate the radioactive waste after disposal. For the WIPP, the disposal system is the combination of the repository/shaft system and the geologic and hydrologic systems of the controlled area (Figure III-3). The repository/shaft system, as defined, includes the WIPP underground workings and all emplaced materials and the altered zones within the Salado Formation and overlying units resulting from construction of the underground workings. The controlled area defined by the EPA is limited to the lithosphere and the surface within 5 km (3 mi) of the outer boundary of the WIPP waste-emplacement panels. The boundary of this maximum-allowable controlled area does not coincide with the proposed boundary for the WIPP land withdrawal.

The extent of the WIPP controlled area will be defined during performance assessment but will not be less than the withdrawal area (Bertram-Howery and Hunter, 1989). This area will be under U.S. Government administrative control. The surface location is part of the accessible environment. The

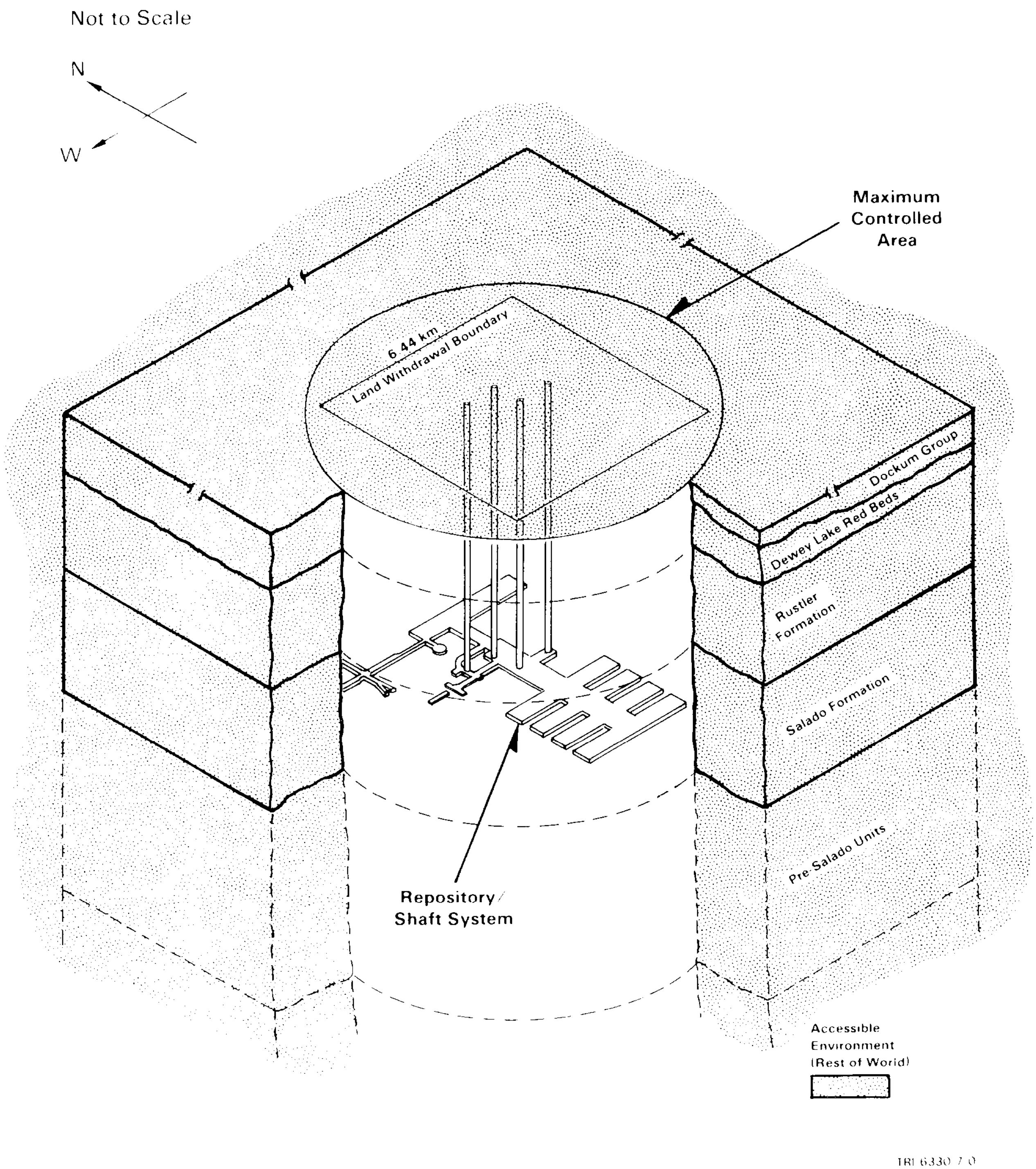

Figure III-3. Artist's Concept Showing the Two Components of the WIPP Disposal System: Controlled Area and Repository/Shaft System. The repository/shaft system scale is exaggerated. The proposed land-withdrawal boundary is shown at the same scale as the maximum extent of the controlled area (Bertram-Howery and Hunter, 1989).

underlying subsurface is not part of the accessible environment. Any radionuclides that reached the surface would be subject to the limits, as would any that reached the lithosphere outside the subsurface portion of the controlled area.

The surface of the controlled area is to be identified by passive institutional controls, which are permanent markers placed at a disposal site, along with records, government ownership, and other methods of preserving knowledge about the disposal system. The disposal site is to be designated by permanent markers and other passive institutional controls to indicate the dangers of the wastes and their location. For the purposes of the WIPP strategy for compliance with Subpart B, the disposal site and the controlled area are assumed to be the same (Bertram-Howery et al., 1989).

Reasonable Expectation

Both the Containment Requirements and the Individual Protection Requirements require a "reasonable expectation" that their various quantitative tests can be met. This test of judgment is meant by the EPA to "acknowledge the unique considerations likely to be encountered upon implementation of these disposal standards" (U.S. EPA, 1985, p. 38071). The Standard "clearly indicates that comprehensive performance assessments, including estimates of the probabilities of various potential releases whenever meaningful estimates are practicable, are needed to determine compliance with the containment requirements" (U.S. EPA, 1985, p. 38076). These requirements "emphasize that unequivocal proof of compliance is neither expected nor required because of the substantial uncertainties inherent in such long-term projections. Instead, the appropriate test is a reasonable expectation of compliance based upon practically obtainable information and analysis" (ibid.). The EPA states that the Standard requires "very stringent isolation while allowing the [DOE] adequate flexibility to handle specific uncertainties that may be encountered" (ibid.).

The EPA's assumptions regarding performance assessments and uncertainties are incorporated in Appendix B of the Standard. The EPA intended these assumptions to "discourage overly restrictive or inappropriate implementation" of the requirements (U.S. EPA, 1985, p. 38077). The guidance in Appendix B to the Standard indicates that "compliance should be based upon the projections that the [DOE] believes are more realistic....Furthermore,...the quantitative calculations needed may have to be supplemented by reasonable qualitative judgments in order to appropriately determine compliance with the disposal standards" (U.S. EPA, 1985, p. 38076). In particular, Appendix B states:

> The [EPA] believes that the [DOE] must determine compliance with §§ 191.13, 191.15, and 191.16 of Subpart B by evaluating long-term predictions of disposal system performance. Determining compliance with § 191.13 will also involve predicting the likelihood of events and processes that may disturb the disposal system. In making these various predictions, it will be appropriate for the [DOE] to make use of rather complex computational models, analytical theories, and prevalent expert judgment relevant to the numerical predictions. Substantial uncertainties are likely to be encountered in making these predictions. In fact, sole reliance on these numerical predictions to determine compliance may not be appropriate; the [DOE] may choose to supplement such predictions with qualitative judgments as well.

The Containment Requirements in § 191.13(b) state:

> Performance assessments need not provide complete assurance that the requirements of 191.13(a) will be met. Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter time frames. Instead, what is required is a reasonable expectation, on the basis of the record before the [DOE], that compliance with 191.13(a) will be achieved.

The EPA recognized that too many uncertainties exist in projecting the behavior of natural and engineered components for 10,000 years, and there are too many opportunities for errors in calculations or judgments for the numerical requirements to be sufficient for determining the acceptability of a disposal system. Qualitative requirements were included in the Standard to ensure that "cautious steps are taken to reduce the problems caused by these uncertainties" (U.S. EPA, 1985, p. 38079). These qualitative Assurance Requirements are an essential complement to the quantitative Containment Requirements. Each qualitative requirement was chosen to compensate for some aspect of the inherent uncertainty in projecting the future performance of a disposal system. The Assurance Requirements begin by declaring that compliance with their provisions will "provide the confidence needed for long-term compliance with the requirements of 191.13" (Bertram-Howery et al., 1989).

The determination of compliance with Subpart B depends on the estimated releases and doses; however, it also depends on the strength of the assurance strategies that will be implemented and on the qualitative judgment of the DOE and its analysts. The preceding discussion clearly demonstrates the EPA's recognition of the difficulties involved in predicting the future and in quantifying the outcomes of future events. It also shows that the EPA expects the DOE to understand the uncertainties in the disposal system's behavior only to the extent practical (Bertram-Howery et al., 1989).

STATUS OF THE STANDARD

Subpart B of the Standard was vacated and remanded to the EPA by the United States Court of Appeals for the First Circuit in July 1987. The Court found that the EPA had neither reconciled the Individual Protection Requirements with Part C of the Safe Drinking Water Act nor explained the divergence between the two sets of criteria; furthermore, the EPA had not explained the basis for the 1,000-year design criterion in the Individual Protection Requirements. The Court also found that the Ground Water Protection Requirements were promulgated without proper notice and comment. The Second Modification to the Consultation and Cooperation Agreement (U.S. DOE and State of New Mexico, 1981, as modified) commits the WIPP Project to proceed with the evaluation of compliance with the Standard as first promulgated until such time as a revised Standard becomes available. Therefore, this paper discusses the Standard as first promulgated. Compliance plans for the WIPP will be revised as necessary in response to any changes in the Standard resulting from the court's decision (Bertram-Howery et al., 1989).

Containment Requirements

The primary objective of Subpart B is isolating waste from the accessible environment by limiting long-term releases. This objective is reflected in § 191.13, the Containment Requirements.

PERFORMANCE ASSESSMENT

Evaluation of compliance is based on a performance assessment, which has specific meaning within the Standard:

> "Performance assessment" means an analysis that: (1) identifies the processes and events that might affect the disposal system; (2) examines the effects of these processes and events on the performance of the disposal system; and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events. These estimates shall be incorporated into an overall probability distribution of cumulative release to the extent practicable. (§ 191.12[q])

The assessment as defined must provide reasonable expectations that all releases resulting from significant processes and events that may affect the disposal system for 10,000 years after disposal have (1) a likelihood of less than 1 chance in 10 of exceeding quantities specified in Appendix A of the rule; and (2) a likelihood of less than 1 chance in 1,000 of exceeding 10 times the specified quantities. The term "performance assessment" has come to be used to refer to the prediction of all long-term performance, because the performance assessment methodology, with minor modifications, can also be used to assess compliance with 1,000-year performance. Henceforth, this paper will refer to the assessment of compliance with both the Containment Requirements and the Individual Protection Requirements as "performance assessment" (Bertram-Howery et al., 1989).

For the WIPP performance assessment, the disposal system consists of the underground repository, shafts and engineered barriers, and the natural barriers of the disposal site. The engineered barriers are backfill in rooms; seals in drifts and panel entries; backfill and seals in shafts; and plugs in boreholes. Natural barriers are the subsurface geology and hydrology within the controlled area. Barriers are not limited to the examples given in the Standard's definition, nor are those examples mandatory for the WIPP. As recommended by the EPA in Appendix B, "...reasonable projections for the protection expected from all of the engineered and natural barriers...will be considered: and no portion will be disregarded, unless that portion of the system makes negligible contribution to the overall isolation provided by the WIPP" (U.S. DOE, 1989a).

In the Second Modification to the Consultation and Cooperation Agreement (U.S. DOE and State of New Mexico, 1981, as modified), the DOE agreed to prohibit subsurface mining, drilling, slant drilling under the withdrawn area, or resource exploration unrelated to the WIPP Project on the sixteen square miles to be withdrawn under DOE control (Bertram-Howery et al., 1989). The Standard clearly limits future institutional control in that "performance assessments...shall not consider any contributions from active institutional controls for more than 100 years after disposal" (191.14[a]). The Standard further requires that "disposal sites shall be designated by the most permanent markers, records, and other passive institutional controls practicable to indicate the dangers of the wastes and their location" (§ 191.14[c]). Analysis of the probability of human intrusion into the repository must include the effectiveness of passive institutional controls over a 9,900-year period. Such controls could substantially reduce the probability of intrusion and improve predicted repository performance (Bertram-Howery and Swift, 1990).

The Containment Requirements consider a broad range of potential unplanned releases; however, the most significant event that may affect a disposal system within a salt formation will probably be human intrusion. Salt formations are easy to mine and are often associated with economic resources. Typical examples of human intrusion include but are not limited to exploratory drilling for any reason, mining, or construction of other facilities for reasons unrelated to the repository. Determining compliance with the Standard, therefore, involves performance assessments that include the probabilities and consequences of disruptive events, including potential human intrusion. The possibility of inadvertent human intrusion into repositories in salt formations because of resource evaluation must be considered, and the use of passive institutional controls to deter such intrusion should be accounted for in performance assessments.

The EPA gives specific guidance in Appendix B of the Standard for consideration of human intrusion. The EPA believes that only realistic possibilities for human intrusion that may be mitigated by design, site selection, and passive institutional controls need be considered. Additionally, the EPA assumes that passive institutional controls should "...reduce the chance of inadvertent intrusion compared to the likelihood if no markers and records were in place" (U.S. EPA, 1985, p. 38080). Exploring for subsurface resources requires extensive and organized effort. Because of these efforts, information from passive institutional controls is likely to reach resource explorers and deter intrusion into the disposal system. In particular, as long as passive institutional controls "endure and are understood," they can be assumed to deter systematic or persistent exploitation of the disposal site, and furthermore, can reduce the likelihood of inadvertent, intermittent human intrusion to a degree to be determined by the DOE. However, passive institutional controls can never be assumed to eliminate the chance of inadvertent, intermittent human intrusion. The EPA (1985) suggests that exploratory drilling for resources is the most severe intrusion that must be considered (Bertram-Howery et al., 1989). Mining for resources need not be considered within the controlled area (Hunter, 1989).

Effects of the site, design, and passive institutional controls can be used in judging the likelihood and consequences of inadvertent drilling intrusion. The EPA suggests in Appendix B of the Standard that intruders will soon detect or be warned of the incompatibility of their activities with the disposal site by their own exploratory procedures or by passive institutional controls (U.S. EPA, 1985).

Four conclusions may be drawn for the WIPP performance assessment relative to human intrusion (Bertram-Howery et al., 1989):

> No human intrusion of the repository will occur during the period of active institutional controls. Credit for active institutional controls can be taken only for 100 years after decommissioning.
>
> While passive institutional controls endure, no deliberate resource exploration or exploitation will occur inside the controlled area, but reasonable, site-specific exploitation outside the controlled area may occur and should be considered in the performance assessment.

Intrusion of the repository leads to its detection. No mechanism for detection need be advanced. The EPA's use of the word "incompatibility" allows the conclusion that intruders will plug and abandon their boreholes to avoid effects of the repository.

The number of exploratory boreholes assumed to be drilled inside the controlled area is to be based on site-specific information and need not exceed 30 boreholes/km^2 (0.4 mi^2) per 10,000 years. No more severe scenarios for human intrusion inside the controlled area need be considered. While passive institutional controls endure, the drilling rate may be significantly reduced, although the likelihood cannot be eliminated.

PERFORMANCE-ASSESSMENT METHODOLOGY

Performance assessment for the Containment Requirements will include scenario development and screening, consequence assessment, sensitivity and uncertainty analysis, and comparison with the EPA requirements (U.S. DOE, 1989a). A performance assessment methodology consists of the following parts: (1) procedures for scenario development; (2) models for predicting releases to the accessible environment (Cranwell et al., 1990; Hunter et al., 1986); and (3) a procedure to assess compliance with the regulatory requirements (Marietta et al., 1989).

Scenario Development

Scenarios are sets of naturally occurring, human-induced, or waste-induced conditions that represent realistic potential future states of the repository, the geologic systems, and the ground-water flow systems that could affect the migration and transport of radionuclides from the repository to the accessible environment (Cranwell et al., 1990). Whereas the Standard does not mention "scenarios" as such, the need for their development is implied in § 191.13 (Bertram-Howery et al., 1989).

Scenario development provides a means for analysis of uncertainty in future states of the disposal system. Uncertainty in the events and processes that make up a scenario is represented by assigning a probability of occurrence to each event or process. The probability of occurrence of the scenario is derived from the constituent events and processes. These constituent probabilities are estimated where possible and determined by expert judgment when data are insufficient to support probability estimates. The goal is to develop a comprehensive set of mutually exclusive scenarios that could result in the release of radionuclides to the accessible environment (Bertram-Howery et al., 1989).

Appendix B of the Standard indicates that individual events and processes, and by implication their combined form as scenarios, do not have to be considered in performance assessment if their probability of occurrence is less than 1 chance in 10,000 in 10,000 years, or their omission is not expected to significantly change the probability distribution of cumulative releases. The term "scenario" is used once in Appendix B but is not defined. An appropriate procedure for developing scenarios should result in a set of scenarios that includes all combinations of the processes and events.

Both the wording of the Standard and the suggestion that a complementary cumulative distribution function (CCDF) be used to display the results of the performance assessment require that the scenario-development procedure produces a final set of scenarios that have certain characteristics. The definition of performance assessment requires that cumulative releases be determined for all significant processes and events, and by implication, for all scenarios. Because of this requirement, the procedure for developing scenarios must produce a comprehensive set, so that no important scenarios are omitted. In addition, the scenarios must be mutually exclusive, so that the cumulative releases and the probabilities of occurrence can be combined in a CCDF. If the scenarios are not mutually exclusive, the cumulative releases for all scenarios would not be accurate because of duplication of some releases by more than one scenario. Another reason for requiring mutually exclusive scenarios is that the sum of the probability of occurrence of all the scenarios must be equal to 1. If the scenarios are not mutually exclusive, the sum of the probabilities will be more than 1, which is impossible (Guzowski, 1990).

One of the products of the scenario-development technique chosen (Cranwell et al., 1990) is a base-case scenario. This scenario consists of the repository/shaft system, the geologic system, and the ground-water flow system as defined by the conditions at the time of decommissioning, and those changes that are expected to occur to these systems within 10,000 years after decommissioning. The parameters that define the systems have ranges of values resulting from a variety of uncertainties. For any other scenario being analyzed, the common parameter values of the base-case scenario are replaced by the corresponding values in the disruptive scenario. Parameters unaffected by the disruptive scenario retain their base-case values. Neither "unlikely natural events," nor by implication, "likely natural events," are defined in the Standard. If the events and the processes used to develop disruptive scenarios for the containment analyses are by some criteria considered to be "unlikely natural events" (and processes) or are limited to human-intrusion events, the base-case scenario can be used to determine undisturbed performance for the Individual Protection Requirements. If some of these natural events and processes are determined to be "likely," these events and processes would necessarily be added to the base-case scenario in order to analyze undisturbed performance (Guzowski, 1990).

The scenario methodology relies on "logic diagrams," with branch points controlled by external events (Guzowski, 1990), and parameter variability is incorporated directly into the data base. This permits a comprehensive and fully probabilistic analysis of the disposal system using a set of scenarios defined to include all realistic future processes and events potentially affecting repository performance. The preliminary set of scenarios in current use for the WIPP has been narrowed to an undisturbed "base case" and 15 disruptions of base-case conditions (Guzowski, 1990). The base case (undisturbed scenario) incorporates all naturally occurring events and processes including phenomena such as long-term climatic change. The 15 additional scenarios describe the consequences of human activities in the region, specifically exploration and exploitation of natural resources. These scenarios may be modified and others may be added as needed. Probabilities for the scenarios will be determined by expert judgment (Bertram-Howery and Swift, 1990).

Although undisturbed performance is not mentioned in the Containment Requirements (§ 191.13), undisturbed performance is not precluded from the containment calculations. Undisturbed performance is the base case of the scenario-development methodology (Cranwell et al., 1990; Bertram-Howery et al., 1989; Marietta et al., 1989). Human-intrusion events define the scenarios for the Containment Requirements. The events are (1) potash mining outside the WIPP boundary, (2) exploratory drilling that intersects a waste-filled room or drift and a pressurized brine reservoir in the underlying Castile Formation, (3) exploratory drilling that intersects a waste-filled room or drift and does not hit a brine reservoir, and (4) the emplacement of withdrawal wells downgradient from the waste panels. Nuclear criticality was retained for separate evaluation. At this stage of the scenario development, the results of the analyses of undisturbed conditions (Marietta et al., 1989) were assumed to be applicable to the base-case scenario. With no radionuclides reaching significant water-producing units in 10,000 years, three scenarios that could affect the transport of radionuclides under base-case conditions were eliminated from further consideration. The result of this screening is a set of six scenarios consisting of combinations of the drilling events and a set of these same six combinations with potash mining added (Guzowski, 1990).

Prediction of Releases

Appendix A to the Standard establishes release limits for all regulated radionuclides. Table 1 in that appendix gives the limit for cumulative releases to the accessible environment for 10,000 years after disposal for each radionuclide per unit of waste. Note 1(e) to Table 1 defines the unit of waste as an amount of TRU wastes containing one million curies of alpha-emitting transuranic radionuclides with half-lives greater than 20 years. Note 2(b) describes how to develop release limits for a TRU waste disposal system: the release limits are the quantities in Table 1 multiplied by the units of waste. Note 6 describes the manner in which the release limits are to be used to determine compliance with § 191.13: for each radionuclide released, the ratio of the cumulative release to the total release limit for that radionuclide must be determined; ratios for all radionuclides released are then summed for comparison to requirements of § 191.13. Thus the quantity of a radionuclide that may be safely released depends on the quantities of all other nuclides projected to be released, but cannot exceed its own release limit. The summed normalized release cannot exceed 1 for probabilities greater than 0.1 and cannot exceed 10 for probabilities greater than 0.001. Potential releases estimated to have probabilities less than 0.001 are not limited (Bertram-Howery et al., 1989).

For example, Table 1 in Appendix A to the Standard lists the release limits for plutonium-239 and americium-241 as 100 curies each per waste unit; for a repository with a waste unit of one and a release that contained only those two nuclides, the sum of the two must not be greater than 100 curies unless the probability of release is less than 0.1 and must not be greater than 1,000 curies unless the probability is less than 0.001. The smallest release limit in the table is 10 curies per waste unit for thorium-230 or -232; the largest release limit is 1,000 curies per waste unit for technitium-99. For the WIPP, the maximum possible waste unit for the stated capacity is about 15; however, all radioactivity in the waste cannot be included in the waste unit because it is not all from "alpha-emitting transuranic radionuclides with half-lives greater than 20 years." The waste unit for the WIPP will likely be about six. Regardless of the waste unit, all regulated radionuclides must be included in release calculations (Bertram-Howery et al., 1989).

Uncertainties

The EPA recognized that Subpart B must be implemented in the design phase because active surveillance cannot be relied upon over the very long time frames of interest. The EPA also recognized that the Standard "must accommodate large uncertainties, including uncertainties in our current knowledge about disposal system behavior and the inherent uncertainties regarding the distant future" (U.S. EPA, 1985, p. 38070).

Performance assessment requires consideration of numerous uncertainties in projected performance of the disposal system. The WIPP Project will use the interpretation of the EPA requirement for uncertainty analysis developed in previous work at Sandia National Laboratories (SNL) for high-level waste disposal (Cranwell et al., 1990; Pepping et al., 1983; Hunter et al., 1986; Cranwell et al., 1987; Campbell and Cranwell, 1988; Rechard, 1989). The EPA has explicitly recognized that performance assessments will contain uncertainties and that many of these uncertainties cannot be eliminated (Bertram-Howery et al., 1989). For the WIPP, uncertainties will be parameter uncertainties (i.e., uncertainties about the numerical values in or resulting from data) and uncertainties in the conceptual model and its mathematical representation. One type of uncertainty that cannot be completely resolved is the validity of various models for predicting disposal-system behavior 10,000 years into the future. Although models will be validated to the extent possible, expert judgment must be relied upon where validation is not possible. In the case of competing conceptual models, if a single conceptual model cannot be demonstrated to be the most consistent with available data, multiple conceptual models will be developed, and performance-assessment calculations will incorporate each model as appropriate (Bertram-Howery et al., 1989). The consideration of the uncertainties arising from the numerical solutions of the mathematical model is a function of the verification of the computational codes and is not included in the uncertainties of the predicted behavior. Uncertainties in scenario development or screening are also excluded, as these are most appropriately addressed through peer review and probability assignment (U.S. DOE, 1989a).

The WIPP Project will reduce uncertainty to the extent practicable using a variety of techniques (Table III-1). The necessity of considering uncertainty in predicted behavior, projected performance, and estimates of cumulative releases is recognized in the Standard in § 191.12(p), § 191.12(q)(3), § 191.13(b), and paragraphs 1 and 2 in Appendix B (U.S. EPA, 1985). Parameter uncertainty is mentioned only in paragraph 3 of that appendix, although parameter uncertainty is a major contributor to the other areas of uncertainty.

Although uncertainties must be addressed, no guidance is provided in the Standard as to how this is to be accomplished. The amount of variability in model results that can be attributed to the uncertainty or natural variability of the input data can be determined by a parameter-uncertainty analysis.

Several techniques that can be used to quantify parameter uncertainty are differential-analysis techniques, statistical methods, and stochastic modeling (Cranwell and Bonano, 1987). A study that compared several uncertainty and sensitivity analysis techniques concluded that Latin hypercube sampling with regression analysis provides the best overall results (Iman and Helton, 1985; Marietta et al., 1989). In WIPP performance assessment, data uncertainties are handled by first selecting ranges and distributions for each parameter and

TABLE III-1. TECHNIQUES FOR ASSESSING AND REDUCING UNCERTAINTY IN THE WIPP PERFORMANCE ASSESSMENT (after Bertram-Howery and Hunter, 1989)

Type of Uncertainty	Technique for Assessing or Reducing Uncertainty
Scenarios (Completeness, Logic, and Probabilities)	Expert Judgment and Peer Review; Quality Assurance
Conceptual Models	Expert Judgment and Peer Review; Sensitivity Analysis; Quality Assurance
Computer Models	Expert Judgment and Peer Review; Verification and Validation*; Sensitivity Analysis; Quality Assurance
Parameter Values and Variability	Expert Judgment and Peer Review; Data-Collection Programs; Sampling Techniques; Sensitivity Analysis; Uncertainty Analysis; Quality Assurance

*to the extent possible

then repeatedly using Latin hypercube sampling to select parameter values for deterministically simulating repository performance (Bertram-Howery et al., 1989).

Compliance-Assessment Procedure

Given the approach chosen by the EPA for defining the disposal standards, repository performance must be predicted probabilistically to evaluate compliance. Determining the probability of intrusion poses questions that cannot be answered by numerical modeling or experimentation. Projecting future drilling activity requires knowledge about complex variables such as economic demand for natural resources, institutional control over the site, public awareness of radiation hazards, and changes in exploration technology. Extrapolating present trends 10,000 years into the future is questionable. All approaches to assessing drilling probability presently being considered by SNL must include expert judgment (Bertram-Howery and Swift, 1990).

The Standard requires that results of the performance assessment be incorporated into an overall probability distribution of cumulative release to the extent practicable. In Appendix B, the EPA suggests that results be assembled into a single CCDF that indicates the probability of exceeding various levels of cumulative release (Figure III-4). The EPA suggests that this single curve will incorporate all parameter uncertainty, and if this single distribution function meets the requirement of § 191.13, then a disposal system can be considered to be in compliance with the Containment Requirements (Bertram-Howery and Hunter, 1989). Thus, the EPA states that satisfying the numeric requirements is sufficient to demonstrate compliance with § 191.13 but does not say it is absolutely necessary for demonstrating compliance (Bertram-Howery et al., 1989). The Containment Requirements state that, based upon performance assessment, releases shall have probabilities not exceeding specified limits. This would mean noncompliance if the CCDF exceeded the limits; however, § 191.13 also states that performance assessments need not provide complete assurance that the requirement will be met and that the determination should be "on the basis of the record before the [DOE]." Given the discussions on use of qualitative judgment in Appendix B, this means the entire record, including qualitative judgments. The likelihood that excess releases will occur must be considered before a qualitative decision can be made about a "reasonable expectation" of compliance (Bertram-Howery and Swift, 1990).

MODIFYING THE REQUIREMENTS

The EPA acknowledged that implementation of the Containment Requirements might require modifying those requirements in the future. This implementation

> will require collection of a great deal of data during site characterization, resolution of inevitable uncertainties in such information, and adaptation of this information into probabilistic risk assessments. Although [EPA] is currently confident that this will be successfully accomplished, such projections over thousands of years to determine compliance with an environmental regulation are unprecedented. If--after substantial experience with these analyses is acquired--disposal systems that clearly provide good isolation cannot reasonably be shown to comply with the containment requirements, the [EPA] would consider whether modifications to Subpart B were appropriate.
>
> Another situation that might lead to suggested revisions would be if additional information were developed regarding the disposal of certain wastes that appeared to make it inappropriate to retain generally applicable standards addressing all of the wastes covered by this rule. (U.S. EPA, 1985, p. 38074)

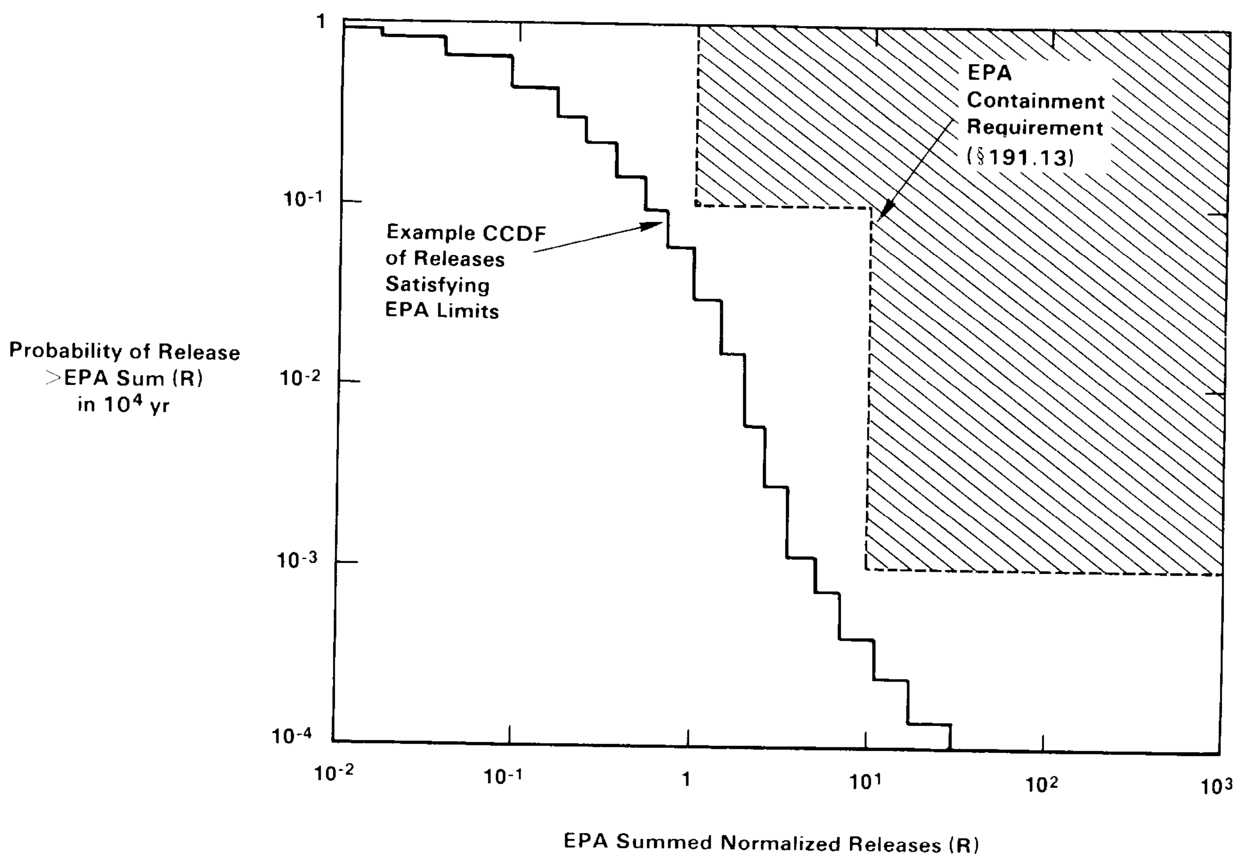

Figure III-4. Sample CCDF Compared with the Containment Requirements (after Hunter, et al., 1986). The CCDF illustrates compliance with § 191.13.

In discussing the regulatory impacts of the Standard (U.S. EPA, 1985, p. 38083), the EPA acknowledged that no impact analysis was performed for TRU wastes. Although the costs of the various engineering controls potentially needed for commercial repositories to meet different levels of protection for the Containment Requirements were evaluated and the EPA concluded additional precautions beyond those already planned were found to be unnecessary, no such analysis was performed for defense waste repositories.

Assurance Requirements

The EPA has included Assurance Requirements (§ 191.14) in the Standard to provide the confidence needed for long-term compliance with the Containment Requirements for those facilities not regulated by the NRC. These requirements are designed to complement the Containment Requirements because of the uncertainties involved in predicting long-term performance of disposal systems (U.S. EPA, 1985, p. 38072).

The Assurance Requirements include six provisions: active institutional controls; post-decommissioning monitoring for performance deviations; passive institutional controls; different types of barriers encompassing both engineered and natural barriers; avoidance of sites where a reasonable expectation of future resource exploration exists, unless favorable disposal characteristics compensate; and the possibility of removal of wastes for a reasonable period of time. Each Assurance Requirement applies to some aspect of uncertainty about the future relative to long-term containment. Limiting reliance on active institutional controls to 100 years reduces reliance on future generations to maintain surveillance. Carefully planned monitoring will mitigate against unexpectedly poor system performance going undetected. Markers and records will reduce the chance of systematic and inadvertent intrusion. The inclusion of multiple barriers, both engineered and natural, will reduce the risk should one type of barrier not perform as expected. The consideration of future resource potential and a finding that the favorable characteristics of the disposal site compensate for the likelihood of disturbance will add to the confidence that the Containment Requirements can be met. A system design that permits possible future recovery of the wastes for a reasonable period of time after disposal allows future generations the option of relocating the wastes should new developments warrant such recovery (U.S. DOE, 1989a).

The WIPP Project has prepared a plan for implementing the Assurance Requirements (U.S. DOE, 1987). In accordance with the Project's interpretation of the EPA's intention, the Project will select assurance measures based on the uncertainties in the final performance assessment. The current plan includes definitions and clarifications of the Standard as it applies to the WIPP, the implementation objective for each requirement, an outline of the implementation steps for each requirement, and a schedule of activities leading to final compliance (Bertram-Howery et al., 1989).

Individual Protection Requirements

The Individual Protection Requirements (§ 191.15) necessitate predicting potential doses to man resulting from releases to the accessible environment during the first 1,000 years after decommissioning of the repository, in the event that performance assessments predict such releases. Although challenges to this requirement contributed to the remand of Subpart B to the EPA, the WIPP Project cannot assume that the requirement will change when the Standard is repromulgated.

The methodology developed for assessing compliance with the Containment Requirements can be used to predict releases for estimating doses as specified by the Individual Protection Requirements. In the undisturbed-performance analysis of the disposal system, variations from the design-basis behavior will be considered using uncertainties in the numerical values of the design parameters and in the available data. The undisturbed performance of the repository is not necessarily its design-basis behavior. Undisturbed performance for the WIPP is understood to mean that such repository features as engineered barriers (backfill, seals, and plugs) must be specifically included in the analysis of the predicted behavior (U.S. DOE, 1989a).

However, the EPA suggests in Appendix B of the Standard that compliance with § 191.15 can be determined based upon "best estimate" predictions rather than a CCDF. Thus, when uncertainties are considered, only the mean or median of the appropriate distributions, whichever is greater, need fall below the limits.

The Individual Protection Requirements limit the annual dose equivalent from the disposal system to any member of the public in the accessible environment to 25 millirems to the whole body or 75 millirems to any critical organ. These requirements apply to undisturbed performance of the disposal system, considering all potential release and dose pathways for 1,000 years after disposal. One of the requirements is that modeled individuals be assumed to consume 2 ℓ (0.5 gal)/day of drinking water from a significant source of ground water, which is specifically defined in the Standard.

> "Undisturbed performance" means predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events. (§ 191.12[p])

> "Significant source of ground water"...means: (1) An aquifer that: (i) Is saturated with water having less than 10,000 milligrams per liter of total dissolved solids; (ii) is within 2,500 ft of the land surface; (iii) has a transmissivity greater than 200 gal per day per foot...; and (iv) is capable of continuously yielding at least 10,000 gallons per day to a pumped or flowing well for a period of at least a year; or (2) an aquifer that provides the primary source of water for a community water system as of [November 18, 1985].
> (§ 191.12[n])

Human intrusion means any human activity other than those directly related to repository characterization, construction, operation, or monitoring. The effects of intrusion are specifically excluded for undisturbed performance analysis (U.S. DOE, 1989a).

Unlikely natural events at the WIPP will be those events and processes that have not occurred in the past at a sufficient rate to affect the Salado Formation at the repository horizon within the controlled area in such a way as to have caused release of radionuclides, had they been present. Only the presence of ground water has affected the Salado Formation in the vicinity of the WIPP at the repository horizon for the past several million years. Therefore, the WIPP Project will model only ground-water flow and effects of the repository as the undisturbed performance (U.S. DOE, 1989a). Because of the relative stability of the natural systems within the region of the WIPP disposal system, all naturally occurring events and processes that are expected to occur are part of the base-case scenario and are assumed to represent undisturbed performance (Marietta et al., 1989).

No water-bearing unit at the WIPP meets the first definition of significant source of ground water everywhere because the level of dissolved solids is high and the transmissivity is low in most places (Mercer, 1983); however, the WIPP Project will assume that any *portion* of an aquifer that meets the first definition is a significant source of ground water. Communication between nonqualifying and qualifying portions will be evaluated. No community water system is being supplied by any aquifer near the WIPP; therefore, no aquifer meets the second definition of significant source of ground water (U.S. DOE, 1989a).

The Dewey Lake Red Beds (Figure III-5) are saturated only in some areas. Neither the Magenta Member nor the Culebra Member of the Rustler Formation appears to be a significant source of ground water. Aquifers below the Salado are more than 762 m (2,500 ft) below the land surface at the WIPP. The nearest aquifer that meets the first definition of a significant source of ground water over its entire extent is the alluvial and valley-fill aquifer along the Pecos River. Communication between this aquifer and any other aquifers in the vicinity of the WIPP will be evaluated (U.S. DOE, 1989a).

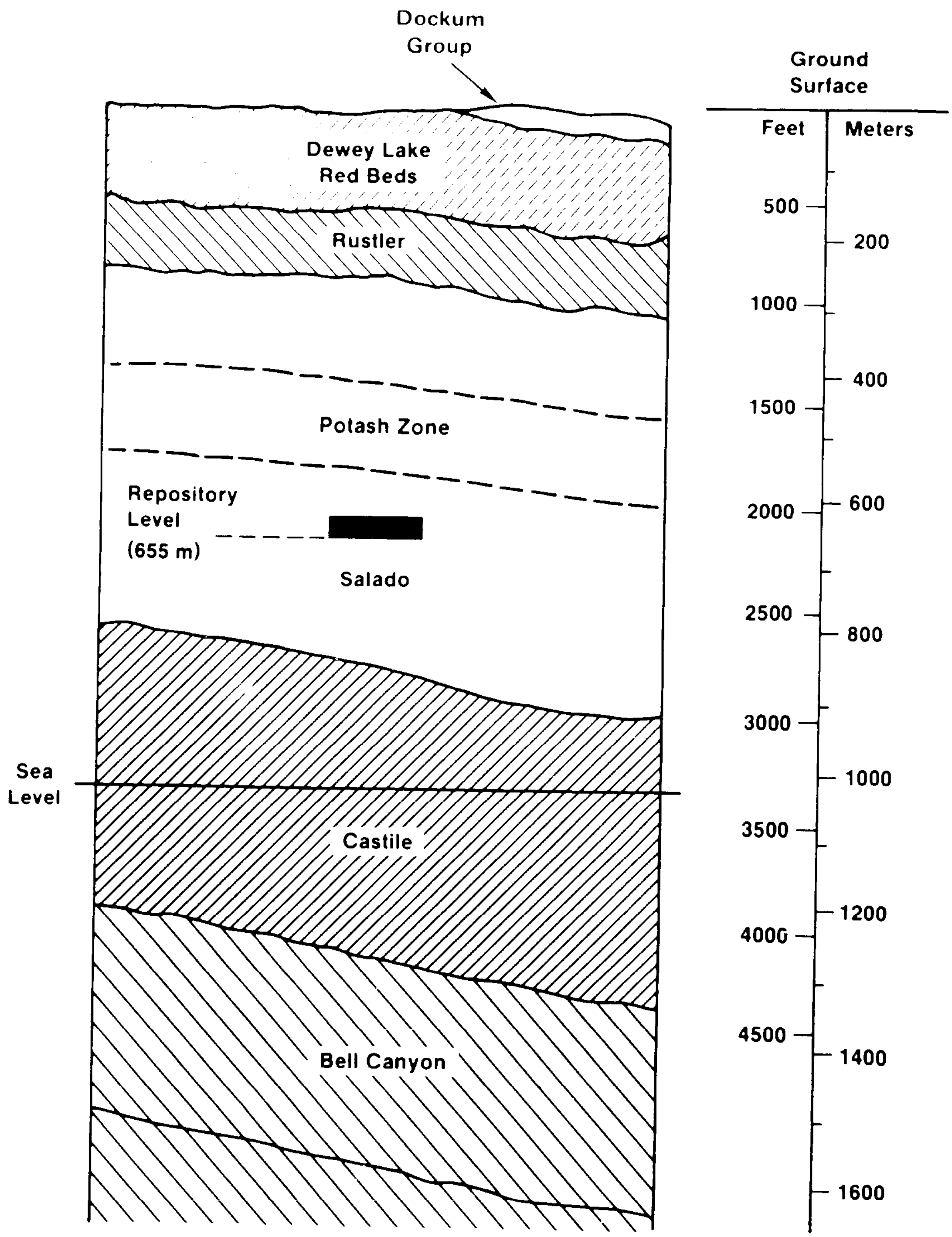

Figure III-5. WIPP Stratigraphy (after Waste Management Technology Dept., 1987).

No releases from the repository/shaft system are expected to occur within 1,000 years (Lappin et al., 1989; Marietta et al., 1989); therefore, dose predictions for undisturbed performance may be unnecessary. Although analysis of undisturbed conditions indicates successful long-term isolation of the waste, analysis of human-intrusion scenarios results in a nonzero probability of exceeding EPA limits. Clearly, demonstrating compliance with EPA regulations must focus on human-intrusion events (Marietta et al., 1989).

Ground Water Protection Requirements

Special sources of ground water are protected from contamination at levels greater than certain limits by the Ground Water Protection Requirements (§ 191.16).

SPECIAL SOURCES OF GROUND WATER

Special sources of ground water are defined as

> ...those Class I ground waters identified in accordance with the [EPA's] Ground-Water Protection Strategy published in August 1984 that: (1) Are within the controlled area encompassing a disposal system or are less than five kilometers beyond the controlled area; (2) are supplying drinking water for thousands of persons as of the date the [DOE] chooses a location within that area for detailed characterization as a potential site for a disposal system...; and (3) are irreplaceable in that no reasonable alternative source of drinking water is available to that population. (§ 191.12[o])

REQUIREMENT NOT RELEVANT TO THE WIPP

The definition of special source of ground water excludes any ground water or any portion of an aquifer that is more than five kilometers (3.1 mi) from the controlled area.

When the DOE chose the WIPP location (and indeed at present), no source of water within five km (3.1 mi) of the maximum allowable extent of the controlled area (Figure III-6) was supplying drinking water for thousands (or even tens) of persons. Therefore, no special sources of ground water will be affected by the WIPP Project, and the requirement to analyze radionuclide concentrations in such ground water is not relevant (Bertram-Howery et al., 1989).

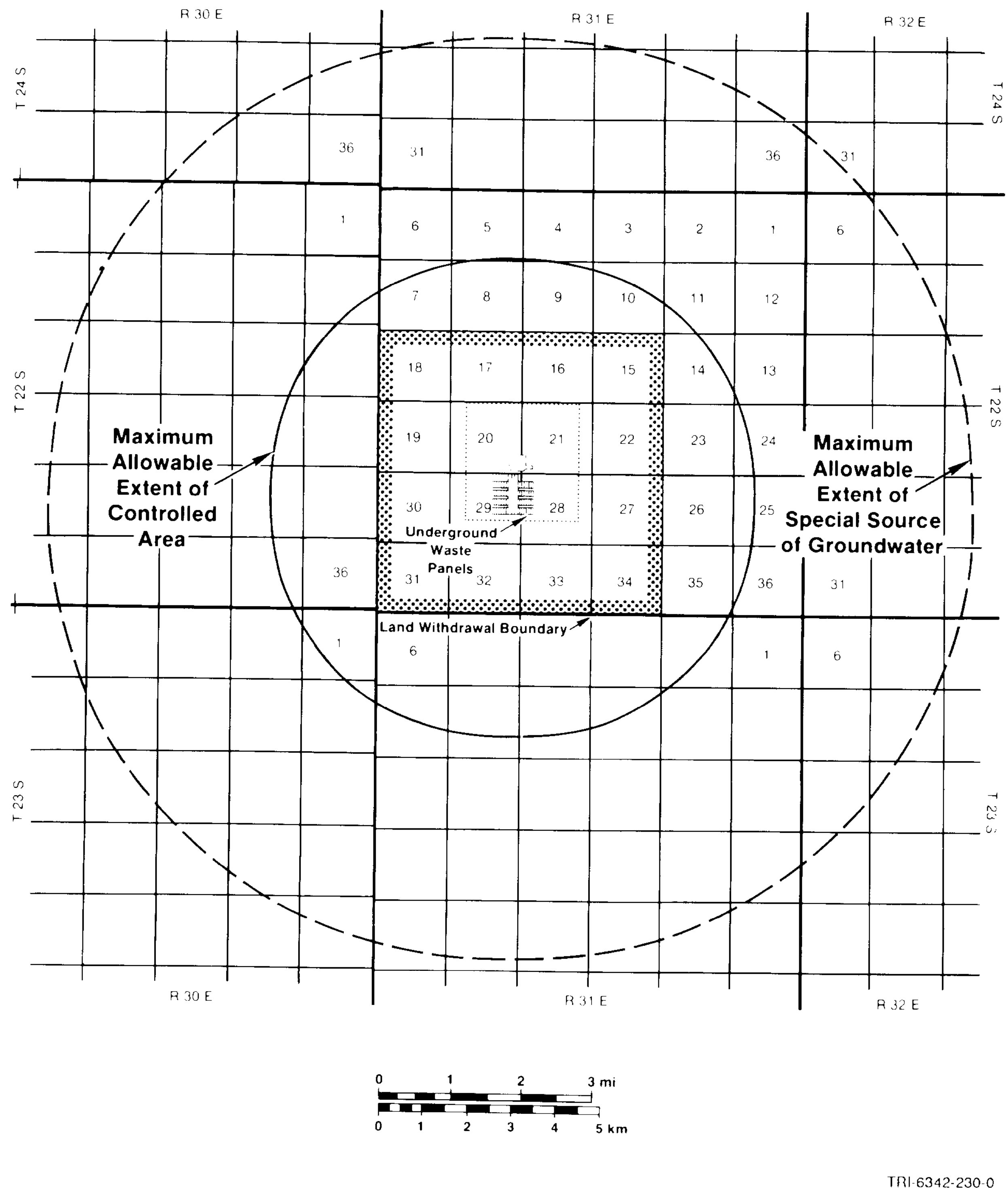

Figure III-6. Illustration of Certain Definitions (from U.S. DOE, 1989b). The dashed line, drawn 5 km from the maximum allowable extent of the controlled area (§ 191.12[g]) shows the maximum area in which the occurrence of a special source of ground water (§191.12[o]) is of regulatory interest. The performance assessment will determine the extent of the WIPP controlled area.

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IV. SCENARIO DEVELOPMENT AND MODELING FOR PERFORMANCE ASSESSMENT

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The U.S. Department of Energy has agreed that the Waste Isolation Pilot Plant must meet the environmental standards for radioactive waste disposal established by the U.S. Environmental Protection Agency. These standards require performance assessments, which in turn require the identification of potentially disruptive scenarios. By application of an established scenario-selection procedure to the WIPP, 16 scenarios were identified. Preliminary calculations indicate that 4 of these scenarios do not result in radionuclide releases to the accessible environment.

Introduction

The Waste Isolation Pilot Plant (WIPP) is designed for the disposal of transuranic waste generated by the Department of Energy (DOE) defense programs. An agreement between the U.S. DOE and the State of New Mexico (1981, as modified) requires that the WIPP meet the Environmental Protection Agency's (EPA's) "Environmental Radiation Protection Standards for Management And Disposal of Spent Nuclear Fuel, High-Level and Transuranic Wastes" (40 CFR Part 191, referred to in this report as the Standard) (U.S. EPA, 1985). Subpart B of the Standard contains the environmental standards that apply to the disposal system after decommissioning.

Regulatory Basis for Scenarios

One set of standards with which the WIPP must comply is described in the Containment Requirements (40 CFR 191.13). Part (a) of these requirements states that disposal systems must be designed to provide reasonable expectation, based on performance assessments, that cumulative releases to the accessible environment for 10,000 years will meet certain criteria for all significant processes and events that may affect the disposal system. The definition of performance assessment (40 CFR 191.12[q]) refers to an analysis identifying all significant processes and events that might affect the disposal system.

Whereas the Standard uses the term scenario only once and does not provide a definition, the expression "all significant processes and events" used in the Containment Requirements and the definition of performance assessment imply that all combinations of processes and events also must be examined. Any analysis that examined only individual processes and events would be incomplete, because the occurrence of a process or event does not preclude the occurrence of another process or event during the 10,000 years of regulatory concern. These combinations of processes and events are referred to as scenarios.

Requirement of a Scenario-Selection Procedure

Whereas Appendix B of Subpart B of the Standard does not bind the implementing agency to procedures, the statement is made that "[t]he Agency assumes that, wherever practicable, the implementing agency will assemble all of the results of the performance assessments to determine compliance with § 191.13 into a 'complementary cumulative distribution function' [CCDF] that indicates the probability of exceeding various levels of cumulative release" (U.S. EPA, 1985, p. 38088). In order to construct a CCDF, the scenario-selection procedure must provide a comprehensive set of mutually exclusive scenarios, cumulative radionuclide releases to the accessible environment for each scenario, and a probability of occurrence for each scenario such that the probabilities of all scenarios sum to 1.

Scenario-Selection Procedure

The procedure adopted to identify scenarios for the WIPP performance assessment was developed by Cranwell and others (1990). In 1987, the Nuclear Energy Agency formed a Working Group on the Identification and Selection of Scenarios for Performance Assessment of Nuclear Waste Disposal. This working group identified the desirable characteristics that a scenario-development procedure should contain. While not endorsing the Cranwell-and-others (1990) procedure, the working group concluded that this procedure came closest to meeting the identified characteristics. As designed, the procedure develops a set of scenarios that overestimates the detrimental effects of events and processes on the disposal system. This conservative approach was intentional, but the procedure can be readily modified if needed.

In Cranwell and others (1990), scenarios are defined as sets of naturally occurring and human-induced events and processes that represent realistic future changes to the repository, geologic, and hydrologic systems that may affect the escape and transport of radionuclides. The sequence of events and processes does not define a scenario, and the time of occurrence of each event and process is not an integral part of defining a scenario. Time of occurrence is an input parameter that can be sampled during modeling.

This procedure consists of five basic steps. The first step consists of the compilation or adoption of a comprehensive list of events and processes that could affect the long-term isolation of radioactive waste in a disposal system. These events and processes should be generic for disposal systems in any geologic setting. The list developed for Cranwell and others (1990) is presented in Table IV-1.

Step 2 classifies the events and processes using any of several possible classification schemes. The purpose of this step is to address arguments on completeness and to provide guidance in modeling the scenarios.

Step 3 screens the events and processes based on well-defined criteria. These criteria are physical reasonableness, probability of occurrence, and consequence. From a practical standpoint, the occurrence of certain events and processes at a particular location may be physically impossible. Appendix B of the Standard states that the performance assessment does not need to consider events and processes with probability of occurrence less than 1 chance in 10,000 in 10,000 years. Consequence at this stage of the procedure means affecting the ground-water flow system. Events and processes that do not affect flow are eliminated.

Step 4 develops scenarios by combining the remaining events and processes through the use of a logic diagram (Figure IV-1). At each junction in the diagram, a yes/no decision is made as to whether the event or process being considered is added to the scenario. The base-case scenario results when no disruptive events and processes occur. This scenario corresponds to the undisturbed performance defined in the Standard. All possible combinations of the remaining events and processes are developed with this diagram, and each combination is unique.

Step 5 screens the scenarios based on probability of occurrence and consequence. Scenario probabilities are determined by combining the probabilities of occurrence of the events and processes occurring in the scenario and the probabilities of the events and processes not occurring in the scenario (Figure IV-2). From a practical approach, scenarios with probabilities lower than the limit set by the Standard for events and processes will have virtually no impact on the position of the CCDF no matter what cumulative releases occur, so consequence analyses are not necessary. Scenarios resulting in no or extremely low cumulative releases to the accessible environment also will have minimal impact on the position of the CCDF no matter what the probability of occurrence. Physical reasonableness of the combination of events and processes can be virtually eliminated as a

TABLE IV-1. POTENTIALLY DISRUPTIVE EVENTS AND PROCESSES BY CATEGORY (after Cranwell and others, 1990)

Natural Events and Processes

Celestial Bodies

Meteorite Impact

Surficial Events and Processes

Erosion/Sedimentation
Glaciation
Pluvial Periods
Sea-Level Variations
Hurricanes
Seiches
Tsunamis
Regional Subsidence or Uplift (also applies to subsurface)
Mass Wasting
Flooding

Subsurface Events and Processes

Diapirism
Seismic Activity
Volcanic Activity
Magmatic Activity
Formation of Dissolution Cavities
Formation of Interconnected Fracture Systems
Faulting

Human-Induced Events and Processes

Inadvertent Intrusions

Explosions
Drilling
Mining
Injection Wells
Withdrawal Wells

Hydrologic Stresses

Irrigation
Damming of Streams or Rivers

Waste- and Repository-Induced Events and Processes

Subsidence and Caving
Shaft and Borehole Seal Degradation
Thermally Induced Stress/Fracturing in Host Rock
Excavation-Induced Stress/Fracturing in Host Rock

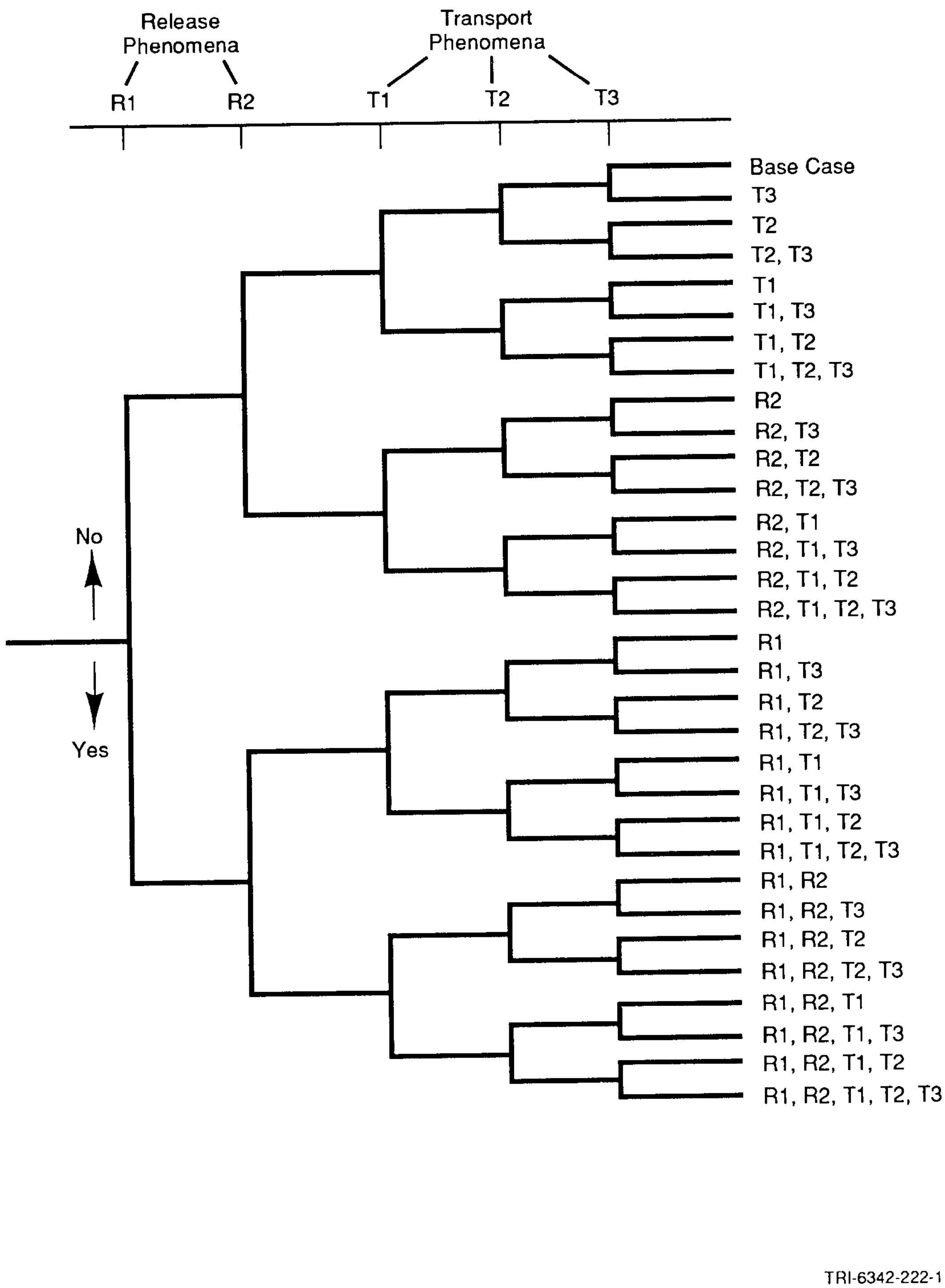


Figure IV-1. Demonstration Logic Diagram for the Construction of Scenarios for Hypothetical Events and Processes (after Cranwell and others, 1990).

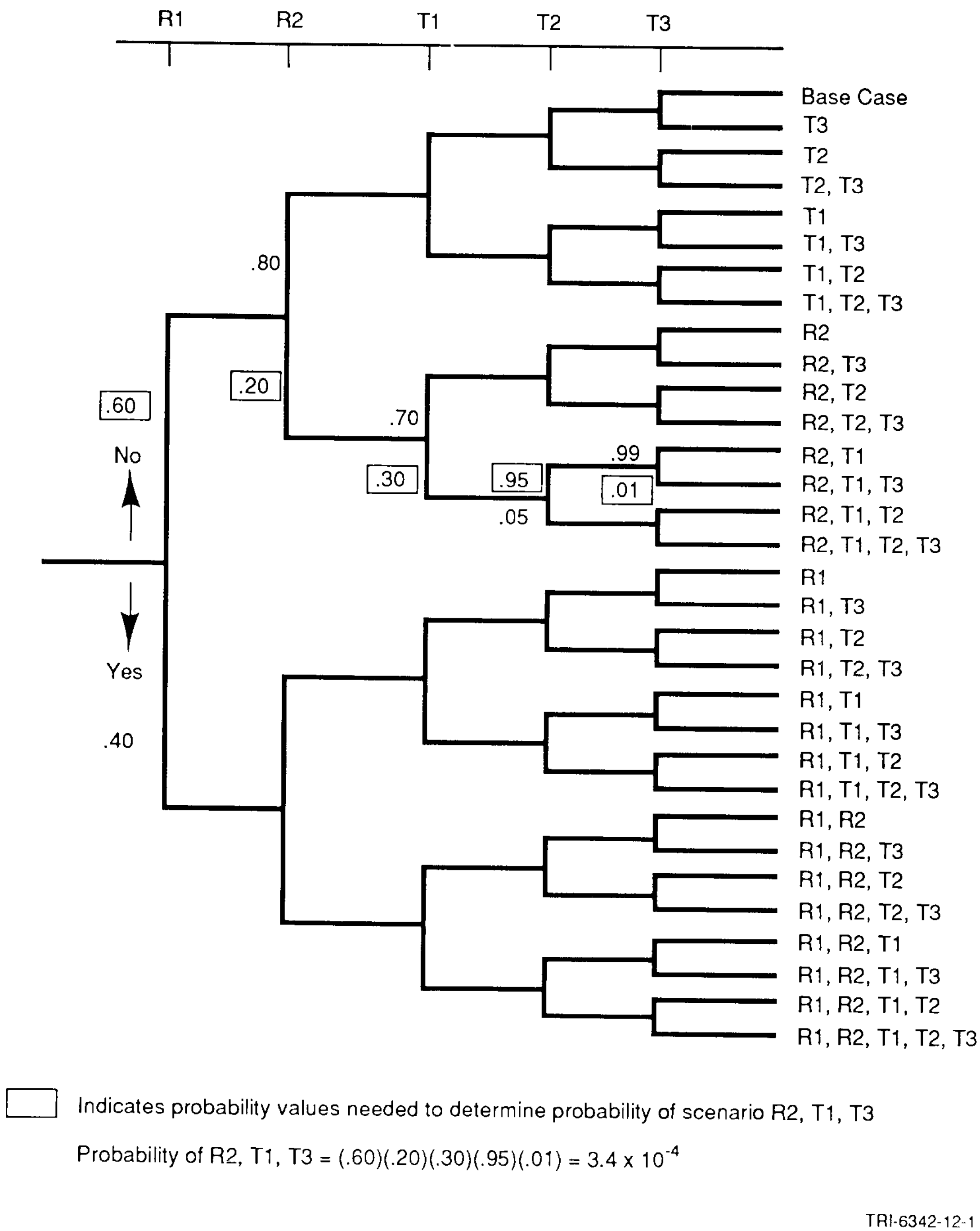


Figure IV-2. Example of the Calculation of the Probability of Occurrence of a Scenario (Guzowski, 1990).

screening criterion if parameter values and specific locations are not used to define events and processes.

Application of the Scenario-Development Procedure to the WIPP

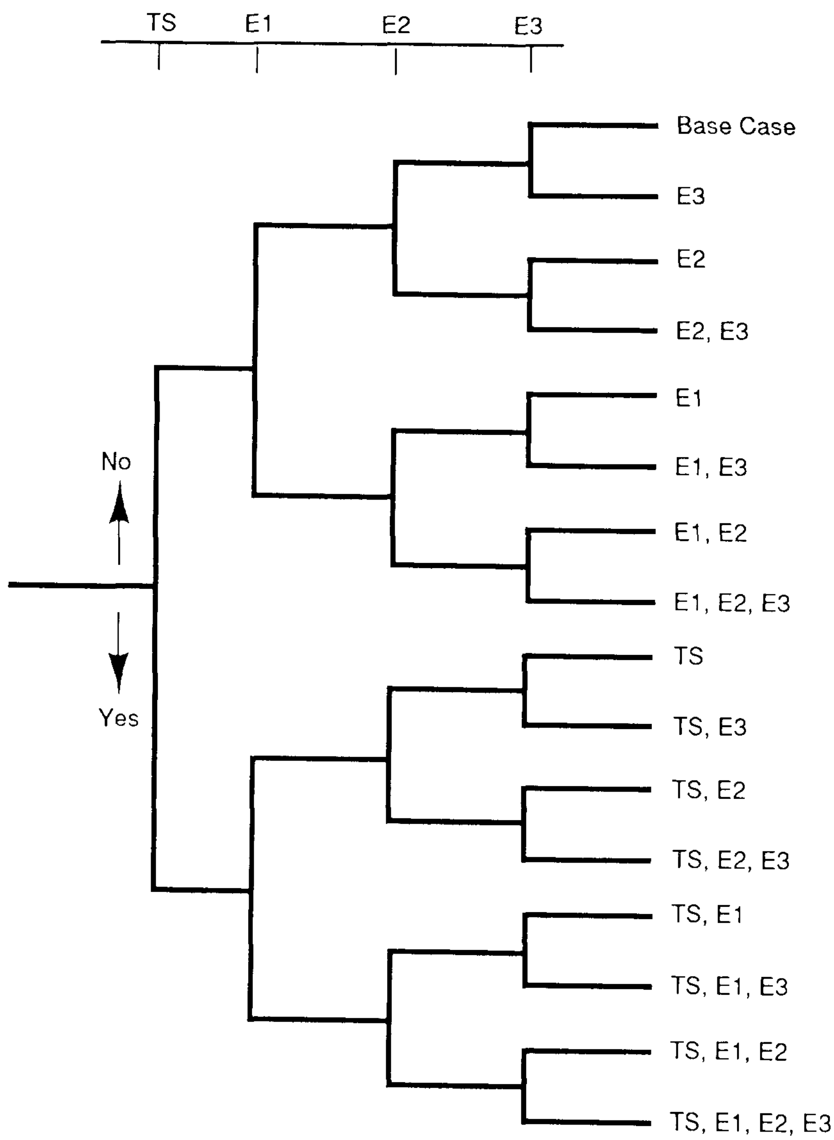
The identification and screening of events and processes that may adversely affect the WIPP disposal system were completed by Hunter (1989). Although the approach used did not directly follow the Cranwell and others (1990) procedure, this approach roughly corresponded to the application of Steps 1 and 3. The events and processes were not classified in any way, but Step 2 of the Cranwell and others (1990) procedure is not critical to the successful development of scenarios.

Preliminary scenarios for use in the development of the WIPP performance-assessment methodology were constructed (Step 4) by Guzowski (1990). Four events were used in scenario development: (1) exploratory drilling through a waste-filled room or drift and into a brine reservoir in the underlying Castile Formation (E1); (2) exploratory drilling into or through a waste-filled room or drift (E2); (3) drilling withdrawal wells downgradient from the waste-panel area (E3); and (4) potash mining outside of the land-withdrawal area. Sixteen scenarios were constructed by the implementation of Step 4 (Figure IV-3). Because these scenarios are intended for use in development of the performance-assessment methodology and not for the actual performance assessment, screening of the scenarios (Step 5) has not been performed.

Preliminary Modeling of Scenarios and the Use of Panels' Judgment

The purposes of modeling are to determine the cumulative releases of radionuclides to the accessible environment as part of the performance assessment of the WIPP and to determine releases of radionuclides to the surface for dose calculations in a safety analysis. Preliminary modeling of Scenario El (Figure IV-4) indicates that the performance of the disposal system is sensitive to the values of certain parameters (Figures IV-5 and IV-6). Because of the decay of the radioactive inventory (Figure IV-7), the time of human intrusion can have a significant influence on the source term used in modeling disposal-system performance.

The futures and markers panels may identify additional human-intrusion events that need to be included in either or both the performance-assessment or safety analyses. Some of these additional events may require the development of new modeling systems. The panels also will identify the frequency or time of intrusion events.



TS - Potash Mining Outside the WIPP Boundary
E1 - Drilling Through Room or Drift and Into Brine Reservoir
E2 - Drilling into a Room or Drift
E3 - Emplacement of Withdrawal Well Downgradient From Repository

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Figure IV-3. Preliminary Scenarios Developed with a Logic Diagram for the WIPP Disposal System (Guzowski, 1990).

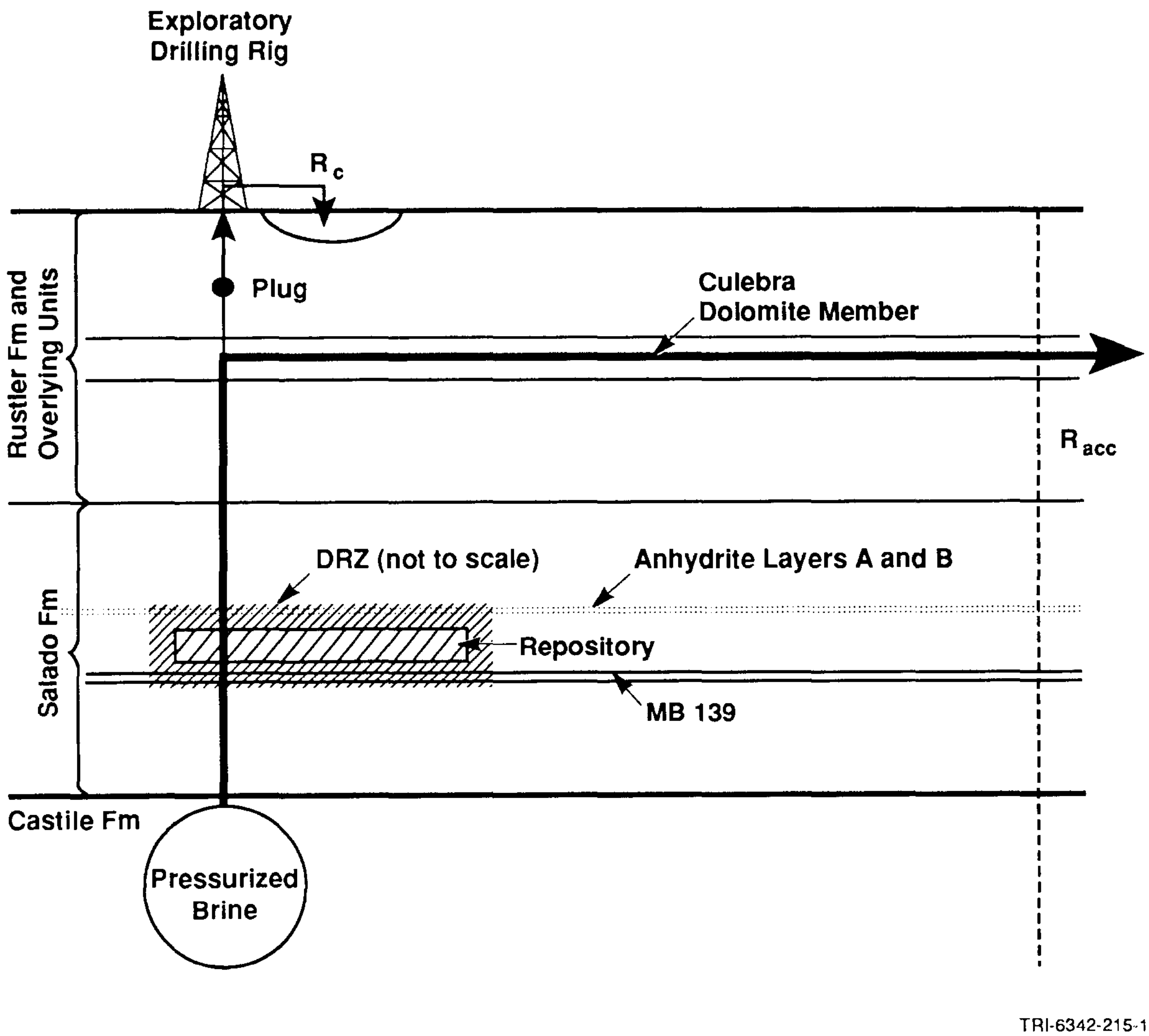

Figure IV-4. Conceptual Model for Scenario E1 (Marietta and others, 1989).

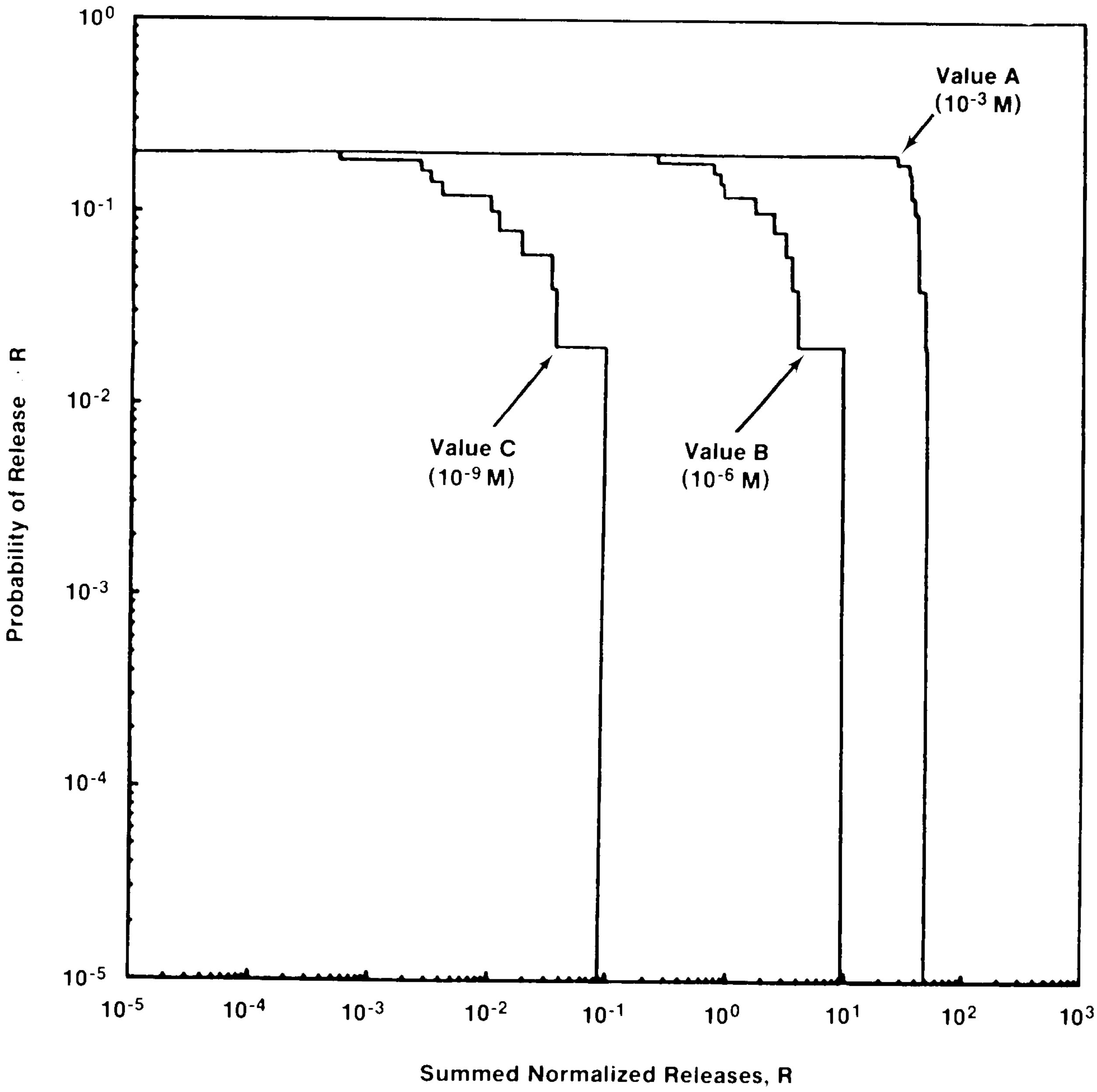

Figure IV-5. Conditional CCDF Curves Showing Sensitivity to Variations in Radionuclide Solubility (after Anderson and others, 1990).

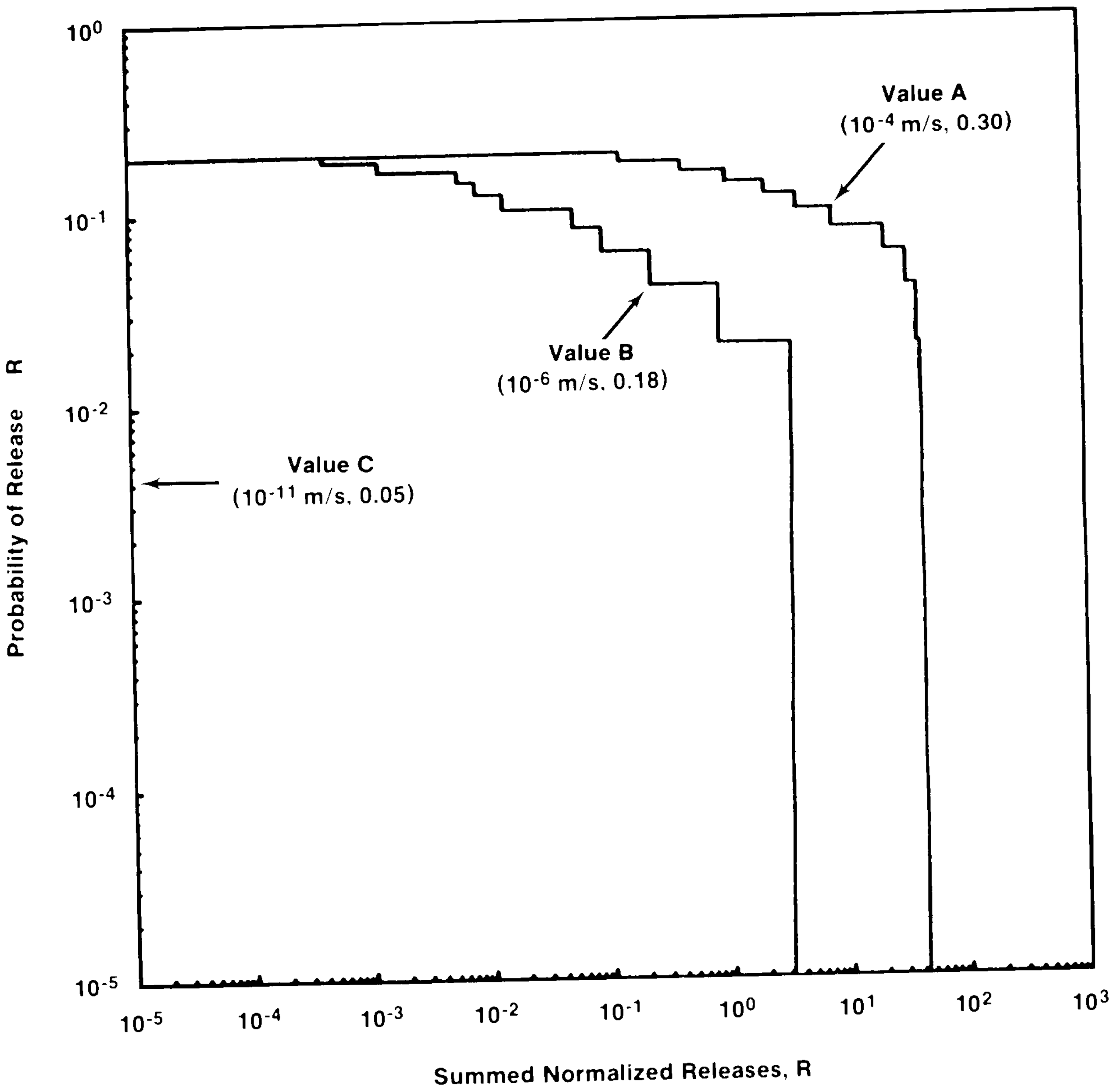

Figure IV-6. Conditional CCDF Curves Showing Sensitivity to Variations in Room Porosity and Hydraulic Conductivity (after Anderson and others, 1990).

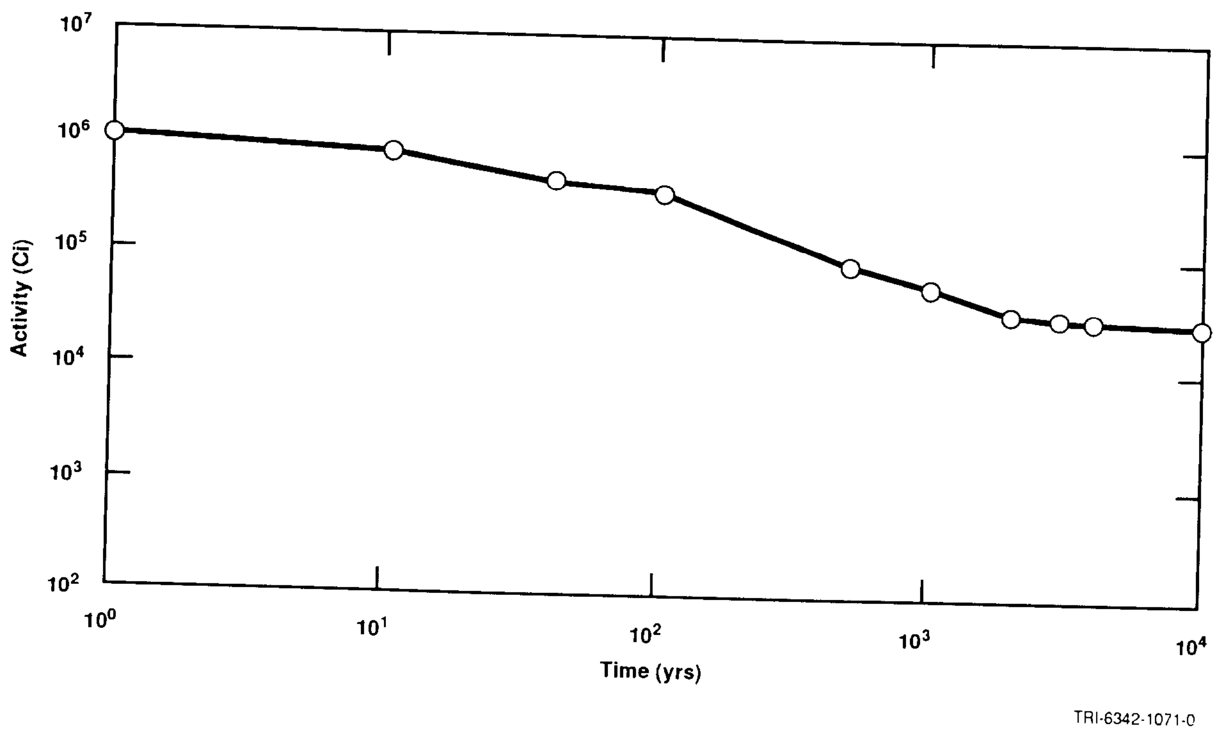

Figure IV-7. Preliminary Estimates of Change in Source-Term Activity as a Function of Time. WIPP repository inventory, CH-TRU derivation--1 million curies.

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V. A SUMMARY OF THE HYDROGEOLOGY AND GEOMORPHOLOGY OF THE NORTHERN DELAWARE BASIN NEAR THE WASTE ISOLATION PILOT PLANT

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Introduction

The disposal of transuranic waste is being planned by the U.S. Department of Energy (DOE) for a deep geologic repository in the Los Medaños region near Carlsbad, New Mexico. The purpose of the Waste Isolation Pilot Plant (WIPP) is to demonstrate that a safe facility for handling, storing, and disposing of unclassified transuranic (TRU) waste generated by the nation's defense plants is feasible.

The DOE, the implementing agency for the WIPP, must comply with the U.S. Environmental Protection Agency's (EPA's) "Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes," 40 CFR Part 191 (U.S. EPA, 1985). These standards specify that the controlled area for the WIPP is limited to the lithosphere and the surface within 5 km (3 mi) of the outer boundary of the waste-emplacement panels. The boundary of this maximum-allowable controlled area does not coincide with the proposed boundary for the WIPP land withdrawal, which is 16 mi^2 (about 41 km^2) surrounding the WIPP.

The Los Medaños Study Area (the Study Area) is located in the north-central part of the Delaware Basin in the southern Pecos Valley section of the Great Plains Physiographic Province (Figure V-1). This area lies between the high plains of West Texas and the Guadalupe Mountains in southeastern New Mexico. The Study Area covers approximately 1600 km^2 and extends from the Pecos River in southern Eddy County eastward into Lea County and southward from just inside the Delaware Basin edge to about 20 km north of the New Mexico-Texas state line (Figure V-2).

The evaporite deposits in southeastern New Mexico were chosen as a potential repository for TRU wastes because the bedded salt has several characteristics that make it a suitable geologic medium for storage of radioactive waste.

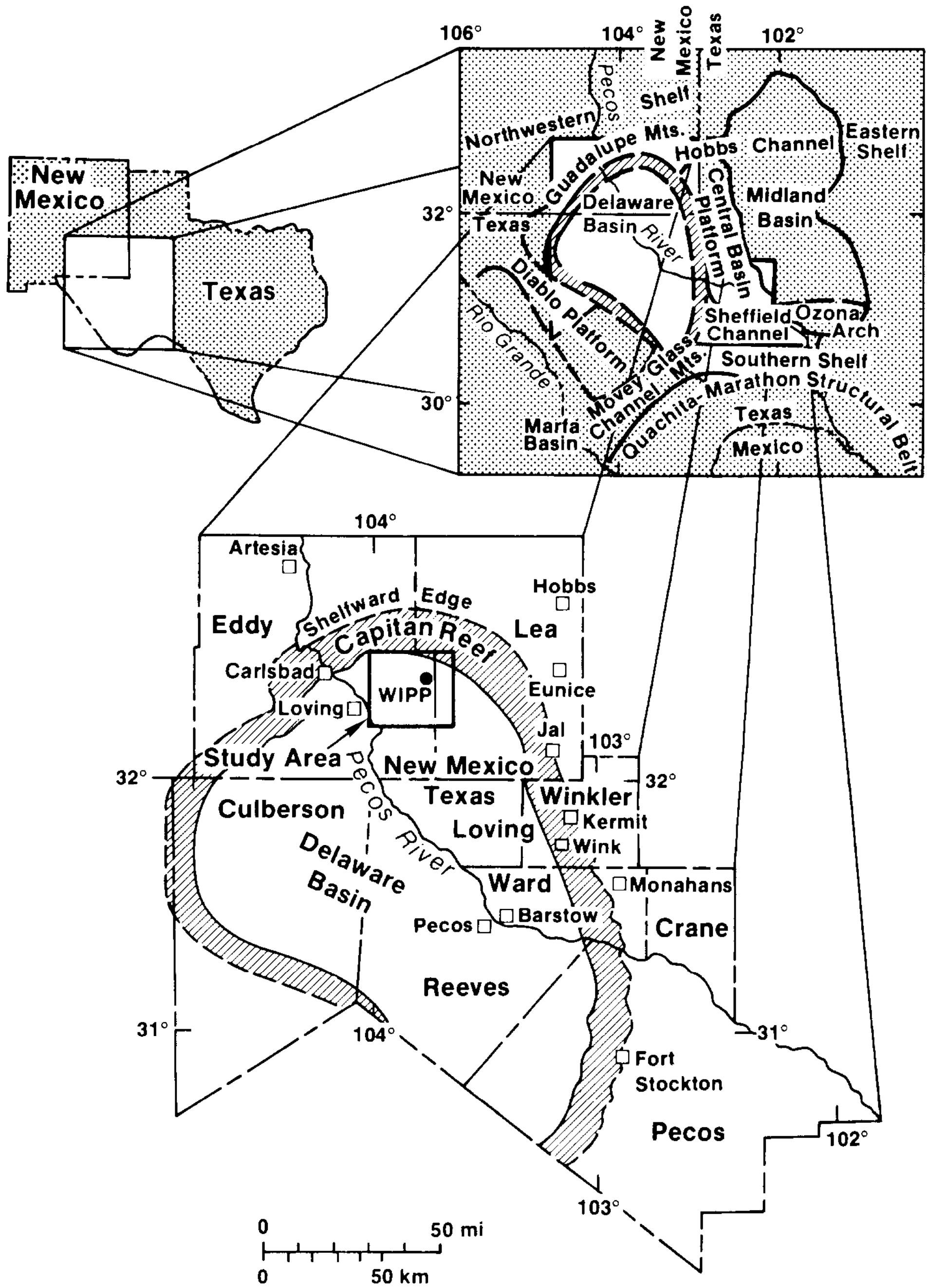

Figure V-1. Location of the WIPP in Southeastern New Mexico (modified from Richey and others, 1985).

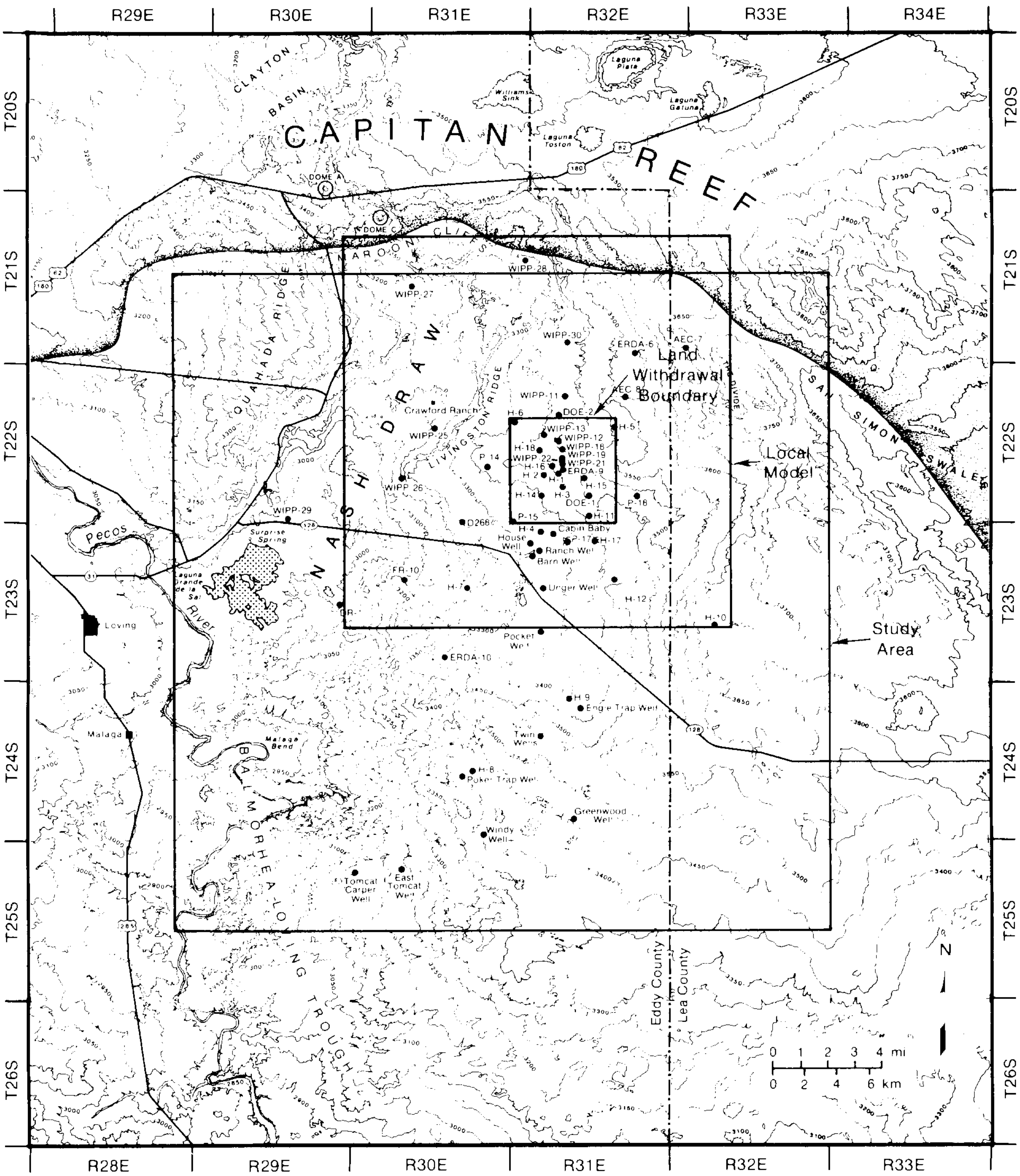

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Figure V-2. Map of the Los Medaños Study Area Showing the Boundaries of the Los Medaños Model (Brinster, 1991), the Local Model (LaVenue and others, 1988), the Proposed Land Withdrawal, and the Observation Well Network (Haug and others, 1987).

The Salado Formation fulfills the basic criteria for a repository as listed below (from Powers and others, 1978):

> Geologic Criteria: The geology (topography, lithology, thickness, and structure) shall provide suitable assurances that the repository shall not be breached by natural phenomena as long as the waste is hazardous to man.
>
> Hydrologic Criteria: The hydrology of the site shall not allow a possible breach of the repository by dissolution of the evaporites, thereby releasing waste that poses a threat to man.
>
> Tectonic Criteria: The site shall be suitably stable, and no geologic activity shall occur to breach the repository as long as the stored waste is hazardous to man.
>
> Physico-chemical Criteria: The geologic medium must not react with the waste material and must not pose a threat to man.

An understanding of the geomorphology and hydrogeology of the WIPP area (the Study Area) is fundamental to performance assessment. Evaluation of radionuclide travel time, possible flow paths, and radionuclide retardation depends on the regional geology, hydrology, and geomorphology. The stratigraphy, hydrostratigraphic units, and landforms important to modeling regional ground-water flow in the northern Delaware Basin are summarized in this paper.

The Study Area includes two prominent surface features, Nash Draw and The Dunes (Los Medaños) (Figure V-3).

Nash Draw, in the western part of the Study Area, is a broad, shallow topographic depression with no external surface drainage. Nash Draw extends almost 35 km from the Pecos River east of Malaga, New Mexico, almost due north to the Maroon Cliffs area (Figure V-3) and is bounded on the east by Livingston Ridge and on the west by Quahada Ridge.

The Dunes is a region of gently rolling hills that slopes upward to the northeast from Livingston Ridge on the eastern boundary of Nash Draw to a low ridge called "The Divide." The elevation of the Study Area ranges from 900 m at Malaga Bend to 1,100 m near the Eddy-Lea county line. The WIPP is located in The Dunes.

Regional Geology

A dominant regional geologic feature in southeastern New Mexico and western Texas is the Permian Basin, which is comprised of a sequence of rocks that have a classic limestone to sandstone facies relationship, that is, a gradual change is represented in the rocks. The following is a brief description of

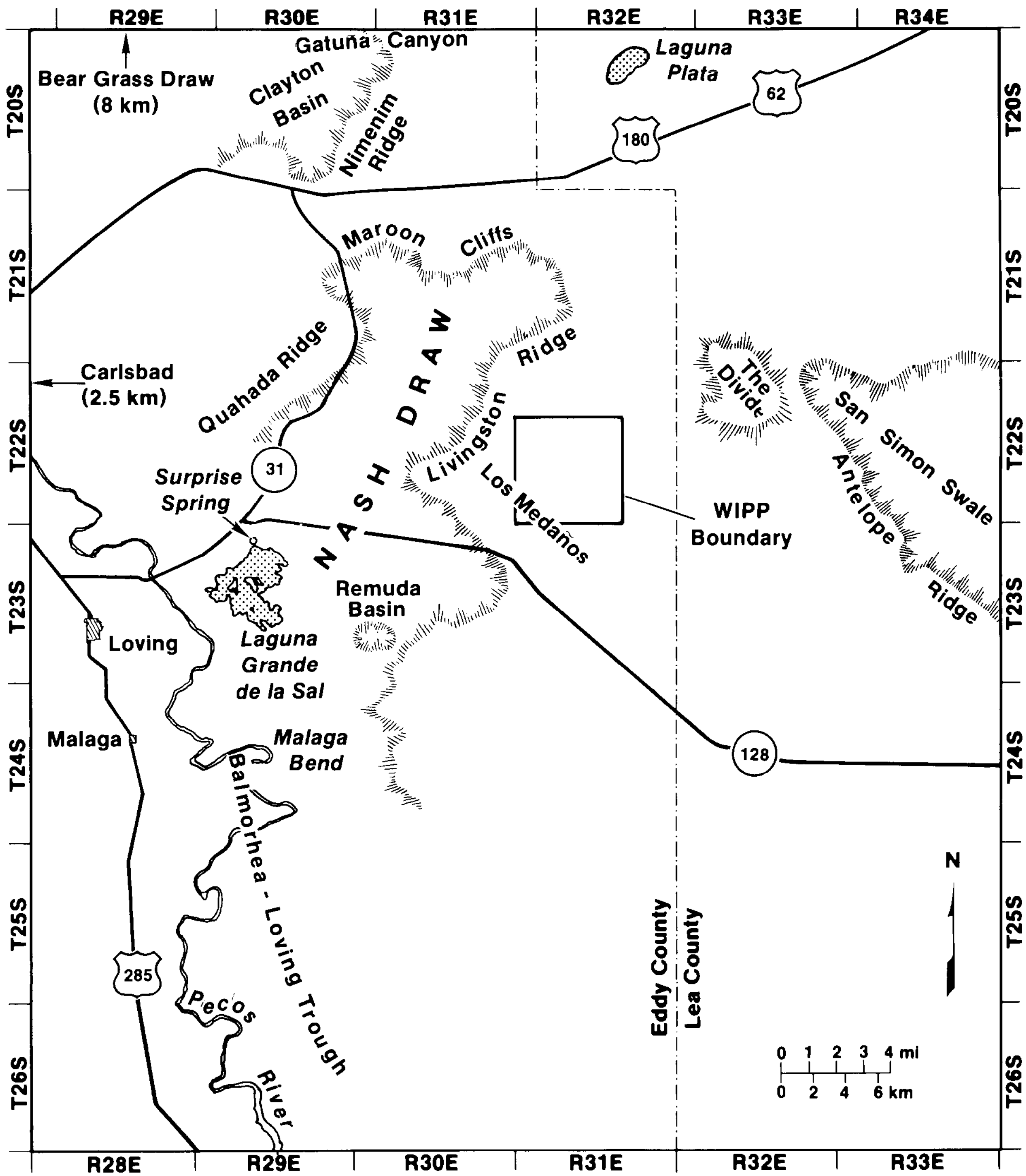

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Figure V-3. Physiographic Features of the WIPP Area.

the formation of the Permian Basin and, subsequently, the Midland and Delaware Basins.

GEOLOGIC HISTORY OF THE DELAWARE BASIN

The Delaware Basin extends from just north of Carlsbad, New Mexico, into Texas west of Fort Stockton (Figure V-1). The elongated basin, one-fourth of which is in New Mexico (Figure IV-4), covers an area of over 33,000 km^2 and is filled to depths as great as 7,300 m with Phanerozoic rocks (Hills, 1984).

The precursor of the Permian Basin, the Tobasa Basin, began forming as a broad, low depression in Ordovician time when transgressing seas began accumulating clastic and carbonate sediments. After a long period of subsidence and sediment accumulation, the basin began separating into the Delaware and Midland Basins when the area now called the Central Platform uplifted during Pennsylvanian time.

During the Early Permian, the subsiding basin, which was delineated by a reef complex, began subsiding at a faster rate, and clastics to the south and reef deposits to the north formed the Wolfcampian rocks (Cheeseman, 1978) (Table V-1). Leonardian-time rock units consisting of thick shelf and marginal dolomites (San Andreas Dolomite and Victorio Peak Dolomite, respectively) and a thick basinal limestone (Bone Spring Limestone) comprise the basal units for the shelfward Artesia group. The marginal reef units and the clastic basinal Delaware Mountain Group of Guadalupian time form the Capitan Reef and Delaware Basin.

Ochoan time is represented by the Castile Formation, which is confined within the basin by the reef; the Salado Formation, which extends over the reef margin and shelf rocks; the Rustler Formation; and the Dewey Lake Red Beds (Table V-1). A period of erosion and deposition, now apparent in the present-day Study Area, occurred at the end of Ochoan time, which also corresponds to the end of Permian time. The only Triassic rocks present are of the Dockum Group. The Jurassic is not represented in this area, and the Cretaceous is almost completely missing. The Tertiary is represented only by the Ogallala Formation. The Quaternary is represented by the Gatuña Formation, the informally named Mescalero caliche, and dune sands.

RESOURCES

Figures V-5, V-6, and V-7, geologic columns at the WIPP, illustrate the lithology and resources of the formations with descriptions, relative ages, minerals found, and exploitability.

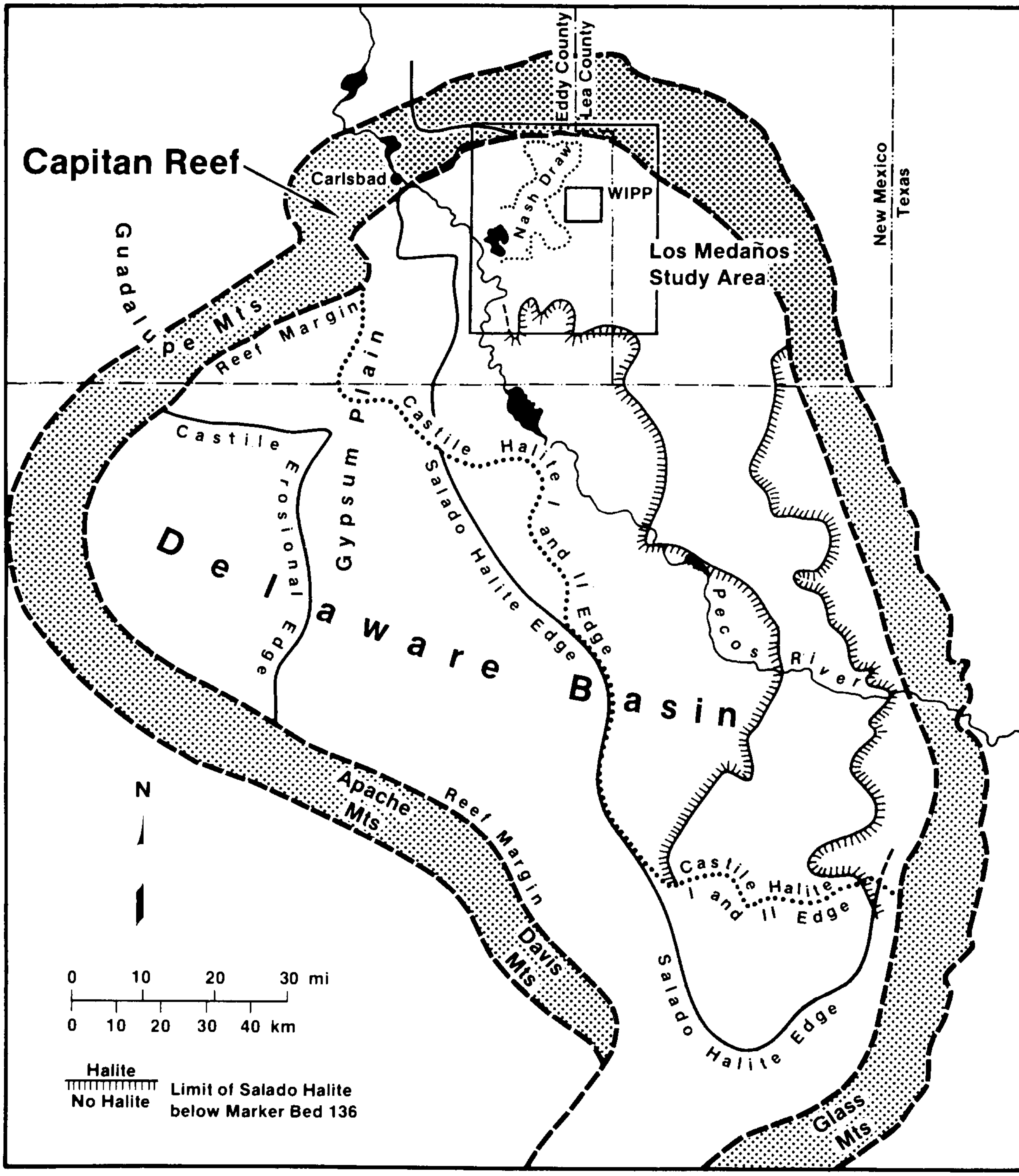

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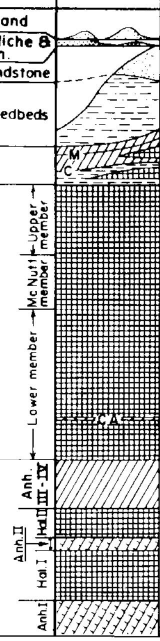
Figure V-4. Generalized Distribution of the Castile and Salado Formations in the Delaware Basin, with Emphasis on Distribution of Halite (Lappin, 1988).

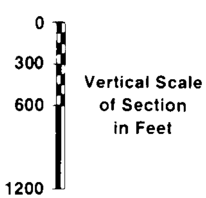
TABLE V-1. MAJOR STRATIGRAPHIC AND TIME DIVISIONS, SOUTHEASTERN NEW MEXICO

Era	System	Series	Formation	Age Estimate (yr)
Cenozoic	Quaternary	Holocene	Windblown sand	
		Pleistocene	Mescalero Caliche	~500,000
			Gatuña Formation	~600,000+
	Tertiary	Pliocene		
			Ogallala Formation	5 million
		Miocene		
				25 million
		Oligocene	Absent Southeastern New Mexico	
		Eocene		
		Paleocene		
				65 million
Mesozoic	Cretaceous	Upper (Late)	Absent Southeastern New Mexico	
		Lower (Early)	Detritus preserved	
				144 million
	Jurassic		Absent Southeastern New Mexico	
				208 million
	Triassic	Upper (Late)	Dockum Group	
		Lower	Absent Southeastern New Mexico	
				245 million
Paleozoic	Permian	Ochoan	Dewey Lake Red Beds	
			Rustler Formation	
			Salado Formation	
			Castile Formation	
		Guadalupian	Capitan Limestone and Bell Canyon Formation	
		Leonardian	Bone Springs	
		Wolfcampian	Wolfcamp	
				275 million

Source: Modified from Bachman, 1987



Era	System	Series	Formation	Approx. Depth to Contact at Site	Principal Lithology	Approx. Thickness (feet)	General Character	Resource	Evaluation
CENOZOIC	RECENT		Surficial sand	10	BLANKET SAND AND DUNE SAND; SOME ALLUVIUM INCLUDED	0-100	- Dune sand	None	No resource
CENOZOIC	QUATERNARY	PLEISTOCENE (Kansan?)	Mescalero caliche & Gatuna Fm.	40	PALE REDDISH BROWN, FINE-GRAINED FRIABLE SANDSTONE. CAPPED BY 5 10 FT. HARD, WHITE CRYSTALLINE CALICHE (LIMESTONE) CRUST	0-35	- Caliche & gravels	Road mettle	Abundant everywhere
MESOZOIC	TRIASSIC	UPPER TRIAS.	Santa Rosa Sandstone	50	PALE RED TO GRAY, CROSS-BEDDED, NON-MARINE, MEDIUM TO COARSE GRAINED FRIABLE SANDSTONE, PINCHES OUT ACROSS SITE	0-250	- Sandstone	Uranium	Oxidizing conditions, none over site
		OCHOAN	Dewey Lake Redbeds	540	UNIFORM DARK RED BROWN MARINE MUDSTONE AND SILTSTONE WITH INTERBEDDED VERY FINE GRAINED SANDSTONE; THINS WESTWARD	100-550	- Siltstone, sandstone	Uranium	Minor amounts outside WIPP area
		OCHOAN	Rustler	850	GRAY, GYPSIFEROUS ANHYDRITE WITH SILTSTONE INTERBEDS IN UPPER PART. REDDISH BROWN SILTSTONE OR VERY FINE SILTY SANDSTONE IN LOWER PART, HALITIC NEAR BASE. CONTAINS 2 DOLOMITE MARKER BEDS MAGENTA (M) IN UPPER PART AND CULEBRA (C) IN LOWER PART. THICKENS EASTWARD DUE TO INCREASING CONTENT OF UNDISSOLVED ROCK SALT.	275-425	- Anhydrite, halite dolomite	Gypsum & sand	Abundant but more accessible elsewhere
		OCHOAN	Salado	CH ZONE RH-ZONE 2825	MAINLY ROCK SALT (85–90%) WITH MINOR INTERBEDDED ANHYDRITE, POLYHALITE AND CLAYEY TO SILTY CLASTICS. TRACE OF POTASH MINERALS IN MC NUTT ZONE. THE MINOR INTERBEDS ARE THIN AND OCCUR IN COMPLEXLY ALTERNATING SEQUENCES. THICKEST NON HALITE BED IS THE COWDEN ANHYDRITE (CA), 17 FT THICK. MULTIPLE ANHYDRITE INTERBEDS ARE MOST COMMON IMMEDIATELY BELOW THE COWDEN AND IMMEDIATELY ABOVE BASE OF SALADO	1750-2000	- Rock salt, anhydrite, polyhalite, potassium ore, magnesite	Potassium salt, salt, gypsum	Commerical quantities of langbeinite & sylvite
		OCHOAN	Castile	4075±	THICK MASSIVE UNITS OF FINELY INTERLAMINATED ("VARVED") ANHYDRITE CALCITE ALTERNATING WITH THICK HALITE (ROCK SALT) UNITS CONTAINING THINLY INTERBEDDED ANHYDRITE. TOP ANHYDRITE UNIT LACKS CALCITE INTERLAMINATIONS	1250±	- Anhydrite, halite, some limestone reservoirs	Sulfur-salt lithium brine	Salt abundant, lithium subeconomic, sulfur not known to exist at site



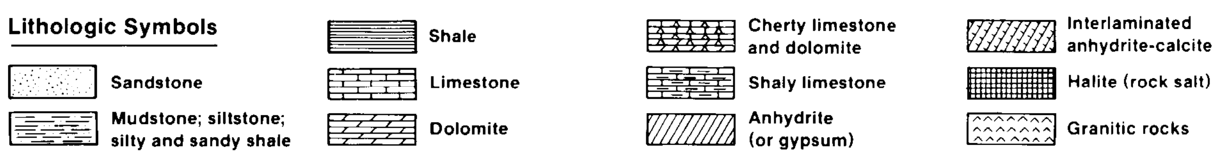


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Figure V-5. Stratigraphic Column of the Ochoan and Younger Rocks in the Delaware Basin (modified from Powers and others, 1978).

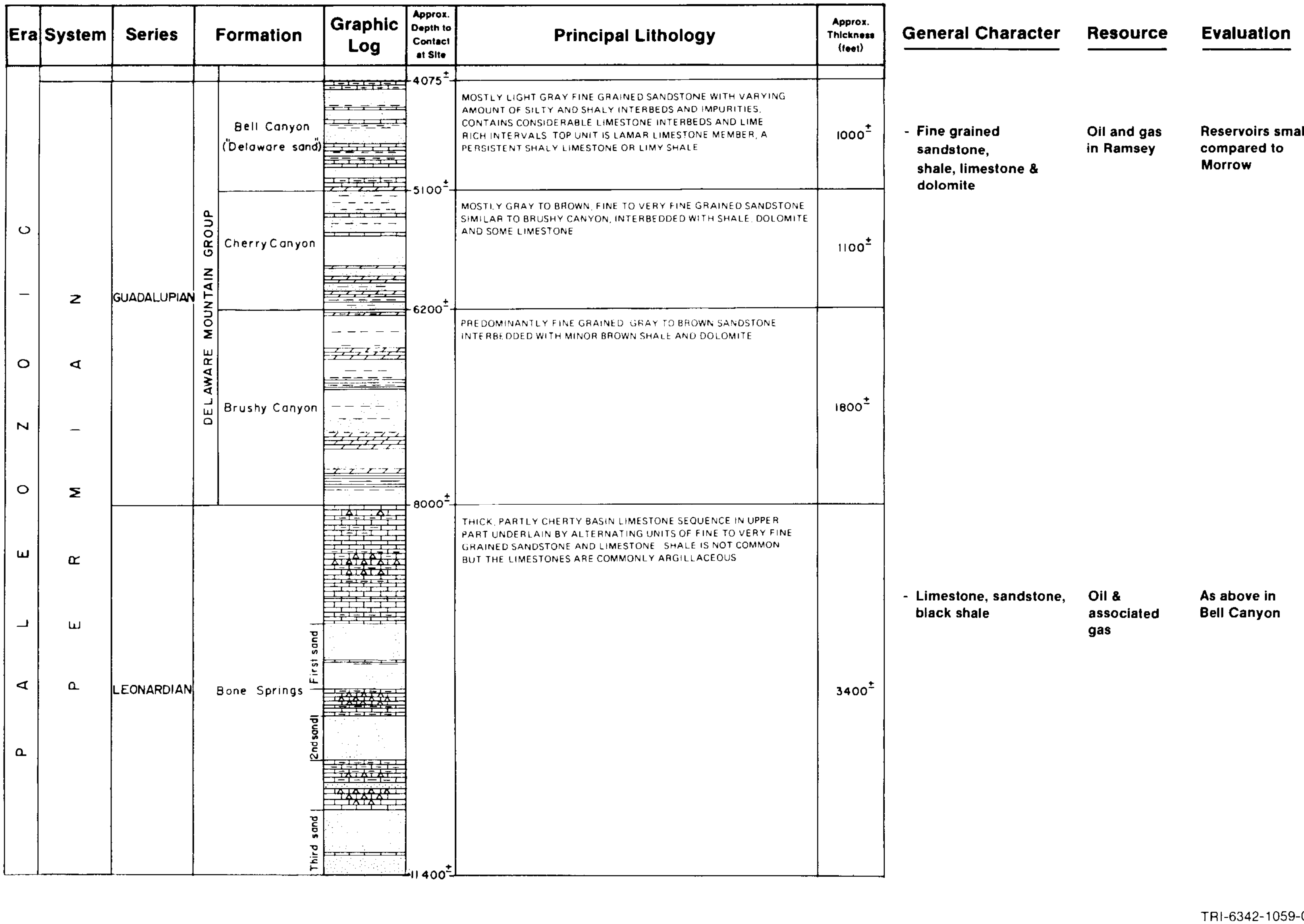


Figure V-6. Stratigraphic Column of the Guadalupian and Leonardian Rocks in the Delaware Basin (modified from Powers and others, 1978).

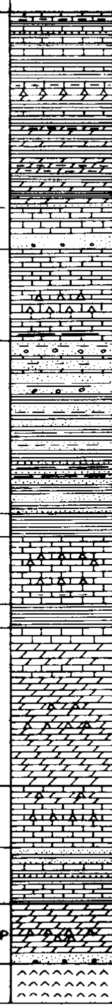
Era	System	Series	Formation	Graphic Log	Approx. Depth to Contact at Site	Principal Lithology	Approx. Thickness (feet)	General Character	Resource	Evaluation
PALEOZOIC	PERMIAN	WOLFCAMPIAN	"Wolfcamp"		11400±	DARK COLORED BASIN LIMESTONE AND DOLOMITE WITH INTERBEDDED SHALE. SANDSTONE IS SCARCE. SHALE AND CARBONATE CONTENT ROUGHLY EQUAL. MAY CONTAIN A FEW HUNDRED FEET OF LITHOLOGICALLY SIMILAR UPPER PENNSYLVANIAN STRATA (CISCO AND CANYON EQUIVALENTS)	1400±	- Limestone, black & green shale, sandstone conglomerate	Oil & gas	As above in Bell Canyon
	PENNSYLVANIAN	DESMOINESIAN ? DERRYAN ?	Strawn		12800±	DOMINANTLY LIMESTONE WITH SOME CHERT AND INTERBEDDED SHALE IN UPPER PART. DOMINANTLY LIGHT GRAY, MEDIUM TO CONGLOMERATIC SAND IN LOWER PART	300±	- Limestone, shales	Oil & gas	As above in Bell Canyon
		MORROWAN ?	Atoka		13100±	PRINCIPALLY LIMESTONE, CHERTY IN MIDDLE PART, ALTERNATING WITH DARK SHALE	650±	- Limestone, shales	Natural gas	Commerical quantities
			Morrow		13800±	MOSTLY FINE TO COARSE OR CONGLOMERATIC SANDSTONE WITH DARK GRAY SHALE. SOMEWHAT LIMY SEQUENCE NEAR TOP INTERBEDDED WITH SANDSTONE IS REFERRED TO AS "MORROW LIME".	1250	- Limestone, shales & sandstone	Natural gas	Commerical quantities
	MISSISSIPPIAN	UPPER MISS.	Barnett Shale		15000±	(UNCONFORMITY) LIGHT YELLOWISH BROWN, LOCALLY CHERTY LIMESTONE OVERLAIN BY DARK BROWN SHALE (BARNETT).	650±	- Black shale, shaly limestone	None	None likely
		LOWER MISS.								
	DEVONIAN	UPPER DEV.	Woodford Shale		15600±	BLACK, ORGANIC SHALE; PYRITIC.	175	- Shale	None	None likely
	SILURIAN				15800±	(UNCONFORMITY) LIGHT COLORED, CHERTY DOLOMITE; CONTAINS TWO LIMESTONE INTERVALS IN UPPER HALF OF SECTION.	1150	- Limestone, dolomite, shales	Oil & gas	Present in folded rocks
	ORDOVICIAN		MONTOYA GROUP		16900±	CHERTY LIMESTONE AND DOLOMITE.	1300±			
			SIMPSON GROUP			ALTERNATING BEDS OF LIMESTONE AND GRAY OR GREEN SHALE, WITH MINOR SANDSTONE UNITS.				
			ELLENBURGER GROUP			CHERTY DOLOMITE, INCLUDES BASAL SANDSTONE MEMBER.		- Acidic volcanics, meta sediments	Sulfide deposits	Too deep to exploit
PRECAMBRIAN					18200±	(UNCONFORMITY) IGNEOUS INTRUSIVE TERRANE (AGE 1.2–1.4 BILLION YEARS).				

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Figure V-7. Stratigraphic Column of the Wolfcampian and Older Rocks in the Delaware Basin (modified from Powers and others, 1978).

The oldest rocks in the Delaware Basin are Precambrian rocks at a depth greater than 5,500 m. The units consist of acidic volcanics and metamorphosed sedimentary rocks; they also may contain sulfide ores but are too deep to exploit.

The oldest rocks with exploitable resources are Silurian limestones, dolomites, and shales where oil and gas are present. Mississippian and Devonian rocks at 4,600 m have no recognized exploitable resources. The units that are found from 4,600 to 1,200 m deep are, at present, being exploited for oil and gas. The only minerals mined in the area come from the Salado Formation at around 400 m. No commercial resources are in the units above the Salado Formation.

Regional Geomorphology

In the Study Area, regional karst topography is of particular geomorphological significance. The term karst is usually applied to regions where dissolution of dolomite and/or limestone has resulted in collapse of the surface, forming a unique topography. In the Study Area, however, the term is applied to features formed by dissolution of evaporites such as halite and anhydrite as well as carbonates. The formation of the karst topography in Eddy and Lea Counties is thoroughly discussed by Bachman (1973, 1974, 1980, 1981, 1984, 1985, and 1987). Locally, no karst features are near the WIPP because of the depth of the evaporites in the Rustler Formation and the protection afforded by the thick overburden (Mercer, 1983).

Nash Draw (Figure V-3) is the largest surface expression of evaporite dissolution in southeast New Mexico. It is a large, open feature of coalesced solution cavities formed by dissolution of evaporites in the shallow subsurface. As the surface subsides, the walls of the dissolution cavities cave in, forming a debris-filled "valley." The process is known as solution and fill. Nash Draw is described as follows (Vine, 1963):

> Topography and surface structure conform in some areas with the configuration of the underlying solution surface at the top of the massive salt in the Salado formation; however, locally there is an inverse correspondence. Many circular karst features 1/10 to 1/2 mile in diameter are in the area. Some of these features are structural domes, but they contain a core of tilted or brecciated rock.

A much larger but not as obvious feature is south of Nash Draw just beyond the Study Area (Figure V-3). This feature is a relic consisting of a series of coalesced, lens-shaped solution troughs formed by an ancestral Pecos River (Bachman, 1984). Up to 550 m of debris from sedimentary rocks, ranging in age from Triassic to Holocene, fill the trough (Hiss, 1975). The series of troughs extending from Balmorhea, Texas, northward to just south of Loving, New Mexico, has been collectively termed the Balmorhea-Pecos-Loving Trough by Hiss (1975) but was later shortened to Balmorhea-Loving Trough (Bachman, 1984). A second trough extends from Belding, Texas, northward to San Simon Swale and is parallel with and coincidental to the Capitan Reef.

Regional Hydrology

Study of the regional hydrology of the WIPP area includes the roles of both surface water and ground water in providing possible flow paths for radionuclides to reach the accessible environment.

SURFACE WATER

A discussion of the hydrology of the Study Area requires understanding the interrelationships of the complex surface- /ground-water system as it exists in an arid environment. Constructing a water budget of the Study Area does this best. Basic data requirements of this phase of the Los Medaños model development are the following (Brinster, 1991):

Inflow and outflow rates of the Pecos River, its tributaries, and the lakes in the model area;

Precipitation and evapotranspiration rates;

Withdrawal rates (consumption) from both the surface and ground waters;

Surface and subsurface storage; and

Inflow rates from higher ground-water basins and outflow rates to lower ground-water basins.

Precipitation

The average annual rainfall over the Study Area is about 0.3 m (12-in contour in Figure V-8). In the Study Area, most of the precipitation becomes runoff or evaporates. In southeastern New Mexico, the evaporation from a class A pan is 2.8 m/yr (Powers and others, 1978), with 1.85 m/yr from May to October. Of the small amount of precipitation that does infiltrate, about 90 percent undergoes evapotranspiration. Any water going through the topsoil must then percolate through a tight Mescalero caliche layer that is ubiquitous throughout the Study Area except in Nash Draw. Recharge to the regional system from rainfall is considered negligible in this study but warrants attention for performance-assessment purposes. Recharge ranges from 8 to 23 mm/yr (Geohydrology Associates, Inc., 1978a,b).

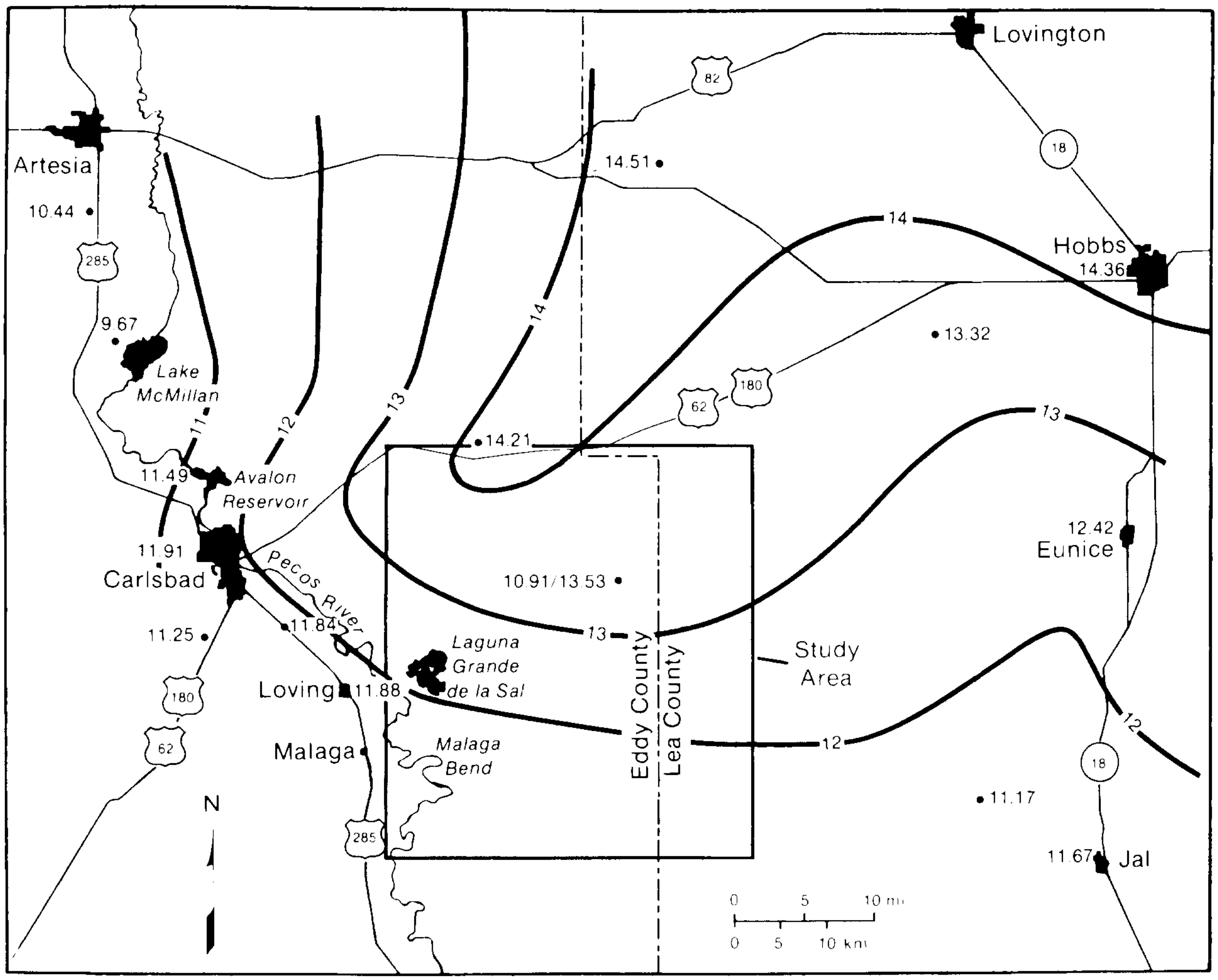

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Figure V-8. Precipitation Contours (in inches) in and near the Study Area (Hunter, 1985).

Rivers, Lakes, and Springs

The Pecos River drainage system is the primary surface-water feature in southeastern New Mexico. The river flows southeastward in New Mexico, approximately parallel to the axis of the Delaware Basin in Eddy County, and drains into the Rio Grande in West Texas. In the vicinity of the WIPP, the drainage system consists of small ephemeral streams and draws in addition to the Pecos River and drains an area of about 50,000 km^2. The Pecos River, which is about 20 km from the southwestern boundary of the WIPP, flows diagonally across the southwest corner of the Study Area at the lowest elevation within the Study Area.

The principal sources of surface water in the northern Delaware Basin are the Pecos River, salt lakes, and springs. To be considered as a surface-water source, water must meet three primary criteria: accessibility, quality, and quantity. The first criterion, accessibility, is determined by how far the water must be transported from its origin to the point of usage. Water quality is determined by the amount of dissolved solids the water contains. Water with less than 3,000 ppm is considered acceptable for human consumption. Water with less than 10,000 ppm is adequate for livestock. Water for industrial usage has greater latitude.

The third limiting factor is quantity. The Pecos River is used mainly for irrigation in southeastern New Mexico. The water is stored in reservoirs north of Carlsbad at Lake McMillan and Avalon Reservoir. The water has about 2,300 ppm of dissolved salts at Carlsbad, which increases to about 13,000 ppm in Texas. The salt lakes in the region have water with a high salinity (>100,000 ppm) and are not considered good sources.

GROUND WATER

The primary sources of ground water in the northern Delaware Basin are the Bell Canyon Formation, Capitan aquifer, Rustler Formation, Triassic rocks (Dockum Group and Santa Rosa Formation), and Cenozoic alluvium.

The Bell Canyon Formation is a source of saline water (>100,000 ppm). Although water is present in large quantities in sandstone stringers, it is very deep for a source of water and not easily accessible.

The Capitan aquifer, which forms an east-west arc north of the WIPP, supplies the city of Carlsbad, New Mexico, from wells that are 100 to 300 m deep. The average total dissolved solids in the water in the reef is about 8000 ppm, but near Carlsbad, the water contains >2000 ppm. In addition to domestic use by Carlsbad and White's City, the water from the reef is used for irrigation and enhanced oil recovery. The water levels in the aquifer have been dropping for the last 50 years, but the Capitan aquifer is still considered an excellent source of water.

The Rustler hydrostratigraphic units range from 60 to 150 m deep beneath the WIPP and are present everywhere in the Study Area. The salinity averages about 16,000 ppm and ranges from less than 10,000 ppm south of the WIPP in the Culebra Dolomite to over 100,000 ppm in the contact residuum at the base of the Rustler. Where possible, the water is used for livestock and irrigation if its salinity is low, and for enhanced oil recovery if the salinity is high. The Rustler Formation wells in New Mexico have a low yield and must be specially developed to obtain water in usable quantities.

Water from Triassic rocks has a low salinity (<1000 ppm) and is shallow (<100 m), but saturation of the unit is sporadic. When available, the water is used for domestic purposes and livestock.

Ground water from the Cenozoic alluvium is shallow (<100 m) and only slightly saline (~2,400 ppm). The alluvium is located along the Pecos River in New Mexico in thin layers, which results in a limited yield. The water is used for public water supply (in Texas), irrigation, livestock, and rural domestic use.

Conclusions

Southeastern New Mexico is an area with a limited water supply because of high salinity and lack of availability in large quantities. Potable ground water is obtained from the Cenozoic alluvium along the Pecos River and is used for domestic purposes and livestock in New Mexico. The Rustler ground water is usually too saline for domestic use, but locally, some wells supply enough low-salinity water for irrigation and watering livestock. The Santa Rosa Formation is a source of water at some ranches but is usually not available in large enough quantities to supply large operations. The cities of Carlsbad and White's City (about 27 km (17 mi) southwest of Carlsbad) get their water from the Capitan aquifer.

Large quantities of nonpotable water are available from the Capitan aquifer east of the WIPP, associated shelfward units, and units from deep below the WIPP.

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VI. AN OVERVIEW OF THE NATURAL RESOURCES AT THE WASTE ISOLATION PILOT PLANT

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Based on the geologic setting of the Waste Isolation Pilot Plant, certain natural resources are likely to be present. Evaluations of the site-specific resource potential identified potash and natural gas as potentially present in economic quantities. Trends in domestic consumption of hydrocarbons suggest that the hydrocarbon industry based on conventional deposits has a relatively short life expectancy. The applicability of these trends to potash or other natural resources is not clear, although continued long-term exploitation of potash probably would require large price increases or technological advancements in recovery or processing.

Introduction

One way to breach a disposal system at depth is to drill into it. Several reasons exist as to why such drilling could occur. Some of the more obvious reasons are the exploration for or evaluation, development, or extraction of natural resources. Other reasons include emplacing injection wells for waste disposal, and the gathering of information for either a specific or a general purpose. With exploration for or exploitation of natural resources as primary reasons for drilling, the potential for natural resources at the Waste Isolation Pilot Plant (WIPP) needs to be considered.

The WIPP is located in the northern part of the Delaware Basin in southeastern New Mexico (Figure VI-1). At this location, approximately 18,000 feet of sedimentary rock unconformably overlies a much older basement complex primarily composed of granitic rock (Powers and others, 1978a). This geologic setting suggests that certain natural resources should be present, although not necessarily in economic quantities. Resource exploration and exploitation in the region around the WIPP indicate that the presence of natural resources in economic quantities is also a possibility at this location. Several studies have examined the resource potential of the WIPP area, and the purpose of this report is to summarize the results. In addition, trends in resource exploitation and availability on a national scale are examined. These trends also may apply to the long-term resource potential of the WIPP area.

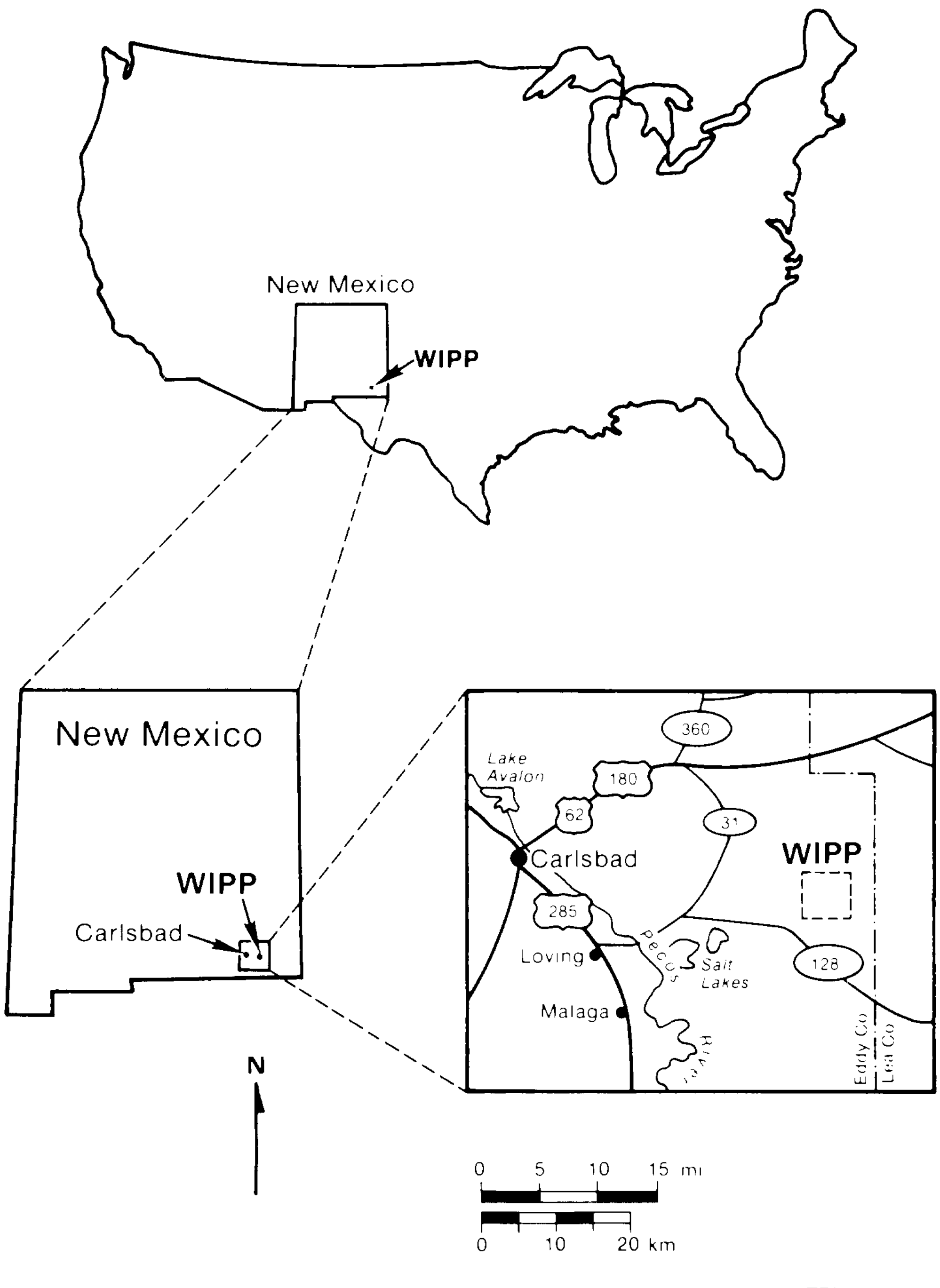


Figure VI-1. Location of the WIPP (Bertram-Howery and Hunter, 1989).

Definition of Terms

No universally accepted set of terms exists for the classification of energy and mineral resources. The two terms generally used and whose definitions generally are accepted are resource and reserve. Resources are "[r]eserves plus all other mineral [or fuel] deposits that may eventually become available--either known deposits that are not economically or technologically recoverable at present, or unknown deposits, rich or lean, that may be inferred to exist but have not been discovered" (Bates and Jackson, 1980, p. 532). Reserves are "[i]dentified resources of mineral- or fuel-bearing rock from which the mineral or fuel can be extracted profitably with existing technology and under present economic conditions" (Bates and Jackson, 1980, p. 531). In this report, reserves will refer to those resources that are currently recoverable under present economic conditions and using currently available technology, and resources will be used to refer to mineral or fuel deposits that are not currently economical or have not been discovered.

The current WIPP location was originally divided into four control zones (Figure VI-2), with the distinction between zones based on the location of surface and subsurface facilities and the amount of control on resource exploration and exploitation activities. Control Zone I was the original location of the surface facility, and Control Zone II was designated for the underground waste-storage facility. Control Zones III and IV were buffers surrounding the waste-disposal area. Mining and drilling activities were prohibited from Control Zones I, II, and III, and the Department of Energy (DOE) could control mining and drilling activities in Control Zone IV. Although this zone designation is no longer in effect, the resource surveys of the WIPP were completed at a time when the designations were used. The current classification of land use defines a land-withdrawal area consisting of 16 sections that includes an area slightly larger than Control Zones I, II, and III (Figures VI-2 and VI-3). All drilling and mining activities are prohibited from within this land-withdrawal boundary for as long as active institutional controls on the WIPP are in effect.

Summary of WIPP-Specific Natural-Resource Evaluations

One of the tasks in the geological characterization of the WIPP location was an evaluation of the natural resources that might be present (Powers and others, 1978b). The potential resources examined were caliche, gypsum, salt, uranium, sulfur, lithium, potash, and hydrocarbons (crude oil and natural gas). Uranium was not found to be present in even marginally economical concentrations in the most favorable geologic settings for uranium deposition. Sulfur was considered because of the existence of a sulfur deposit being mined 50 miles to the south of the WIPP location. An analogous geologic setting to

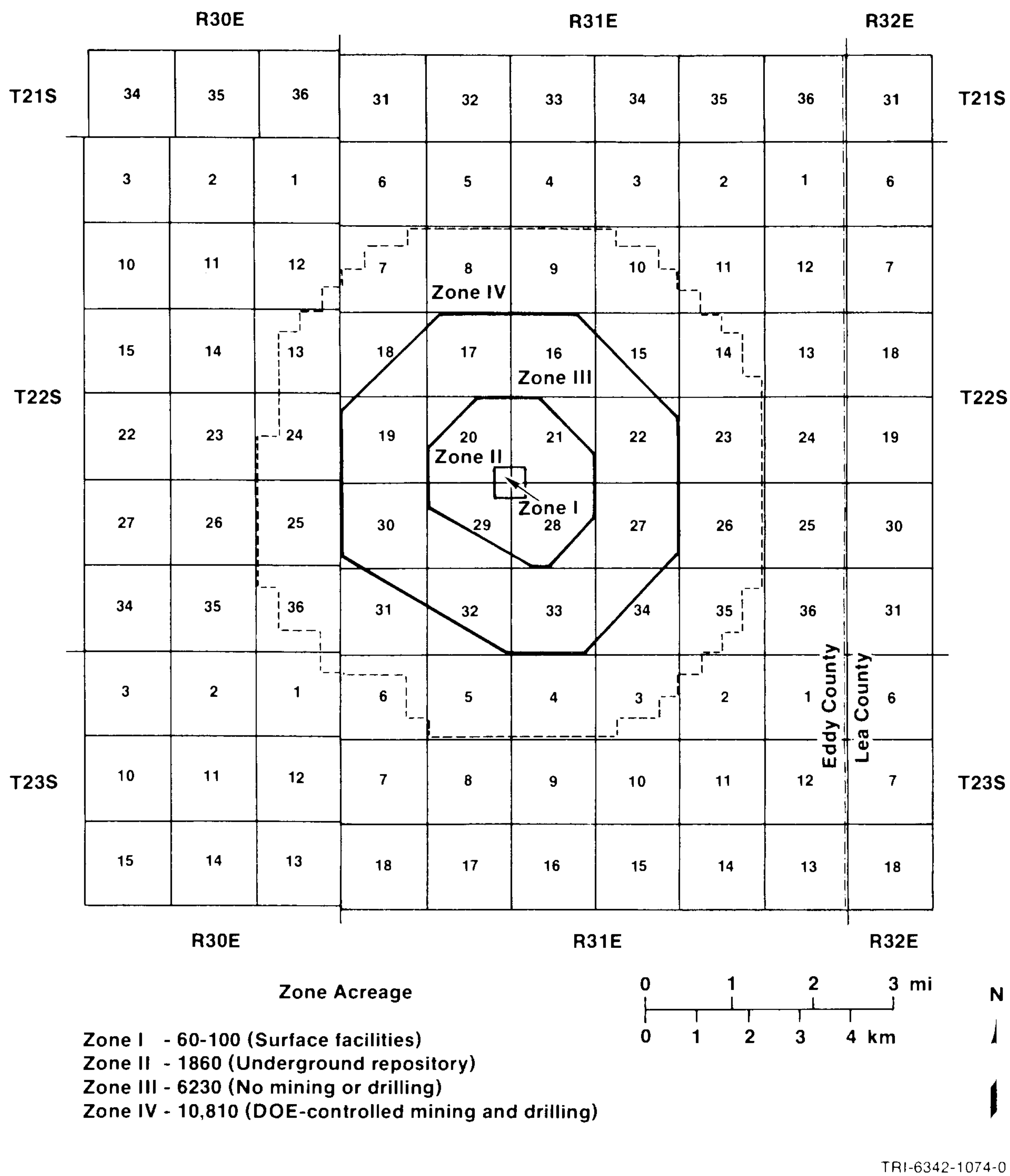


Figure VI-2. Control Zones at the WIPP (Powers and others, 1978a).

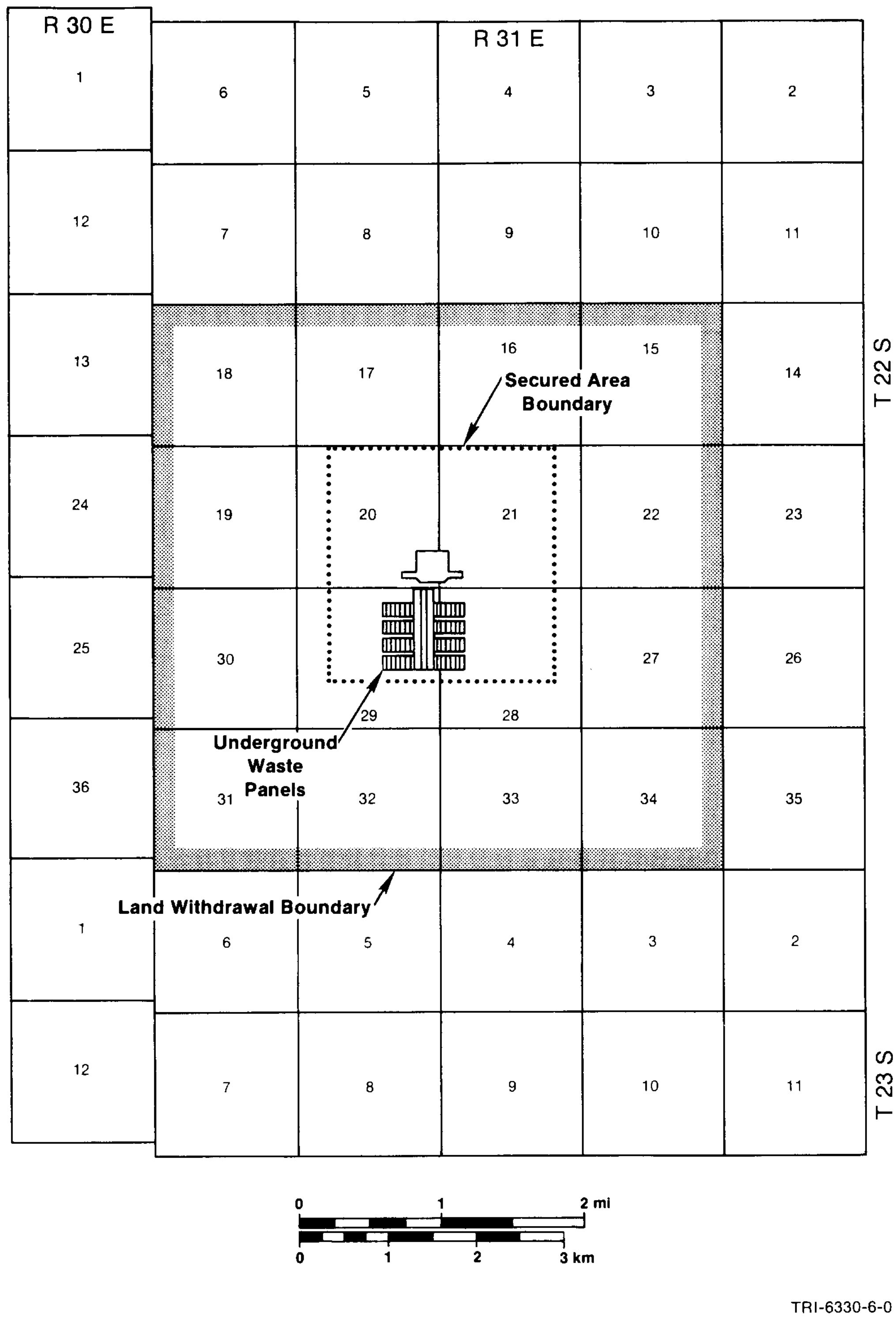


Figure VI-3. Land-Withdrawal Boundary at the WIPP (DOE, 1989).

this sulfur deposit does not exist in the northern Delaware Basin. Lithium was found in anomalous amounts (140 ppm) in samples from a brine reservoir encountered during drilling (ERDA 6) to the northeast of the controlled zones. At the time of the study, the lithium was marginally economical if the brine could be recovered in sufficiently large quantities, which were not proven to exist. Caliche, gypsum, and salt were not considered to be economical because of widespread occurrence and/or more easily accessible deposits elsewhere in the region. Of the hydrocarbons, crude oil was not considered to be available in sufficient quantity to qualify as a potentially economical resource. Based on detailed predictions of the amounts of potash and natural gas available, Powers and others (1978b) concluded that these resources are the only ones with the potential to occur as significant exploitable deposits.

An additional natural resources study was completed by Brausch and others (1982). This study considered caliche, gypsum, salt, potash (as both sylvite and langbeinite ores), and hydrocarbons (crude oil, natural gas, and distillate). The total amount of each resource for all four control zones is indicated in Table VI-1. As in Powers and others (1978b), caliche, gypsum, salt, and crude oil were not considered to qualify as reserves under the economic conditions at the time of the study. Both potash minerals, natural gas, and distillate were considered to qualify as reserves. The distribution of resources and reserves within the controlled zones was considered (Table VI-2). Control Zone IV contains most of both potash resources, all of the sylvite-ore reserves, and nearly three-quarters of the langbeinite-ore reserves. For hydrocarbons, Control Zone IV contains slightly more than half of the crude-oil, natural-gas, and distillate resources and the natural-gas reserves; and three-quarters of the distillate reserves. By area, Control Zone IV contains 57 percent of the total area of all four control zones.

In the northern Delaware Basin, potash classified as resources are restricted to the MuNutt Potash Member of the Salado Formation (Figure VI-4). This member is located approximately 400 feet above the planned waste panels (Nowak and others, 1990). In a slight variation in resource classification, potash resources generally are subdivided based on the thickness of the mineralized zone and equivalent K_2O content of the rock for a particular potash mineral (U.S. DOE, 1980). Based on this classification, economic langbeinite ore and high-standard potash resources exist in the northern and northeastern portions of the land-withdrawal area, and a portion of two waste panels are partially overlain by low-standard potash resources (Figure VI-5). Depending on the economic situation at a particular time and the location of the potash deposit, high-standard and occasionally lease-standard resources can be economically viable (Powers and others, 1978b).

With regard to potash resources, Brausch and others (1982) concluded that: (1) "[n]early 75 percent of all attractive potash deposits underlie this outer

TABLE VI-1. TOTAL MINERAL AND ENERGY RESOURCES WITHIN CONTROL ZONES (after Brausch and others, 1982)

Resource*			
Caliche	185 MT	at surface	Not a reserve
Gypsum	1.3 BT	300-1,500 ft	Not a reserve
Salt	198 BT	500-4,000 ft	Not a reserve
Potash			
Sylvite	133.2 MT	1,600 ft	27.43 MT reserves
Langbeinite	351.0 MT	1,800 ft	48.46 MT reserves
Hydrocarbons			
Crude Oil	37.50 MB	4,000-20,000 ft	Not a reserve
Natural Gas	490 BCF	4,000-20,000 ft	44.62 BCF at 14K ft
Distillate	5.72 MB	4,000-20,000 ft	0.12 MB at 14K ft

*Estimates are for all four control zones

TABLE VI-2. DISTRIBUTION OF RESOURCES WITHIN CONTROL ZONES (after Brausch and others, 1982)

Resource	I, II, III	IV	% in IV
Potash			
Sylvite Ore	39.1 MT	94.1 MT	71
Langbeinite Ore	121.9 MT	229.1 MT	65
Hydrocarbons			
Crude Oil	16.12 MB	21.38 MB	57
Natural Gas	211 BCF	279 BCF	57
Distillate	2.46 MB	3.26 MB	57
Reserves			
Potash			
Sylvite Ore	none	27.43 MT	100
Langbeinite Ore	13.30 MT	35.16 MT	73
Hydrocarbons			
Natural Gas	21.05 BCF	23.57 BCF	53
Distillate	0.03 MB	0.09 MB	75

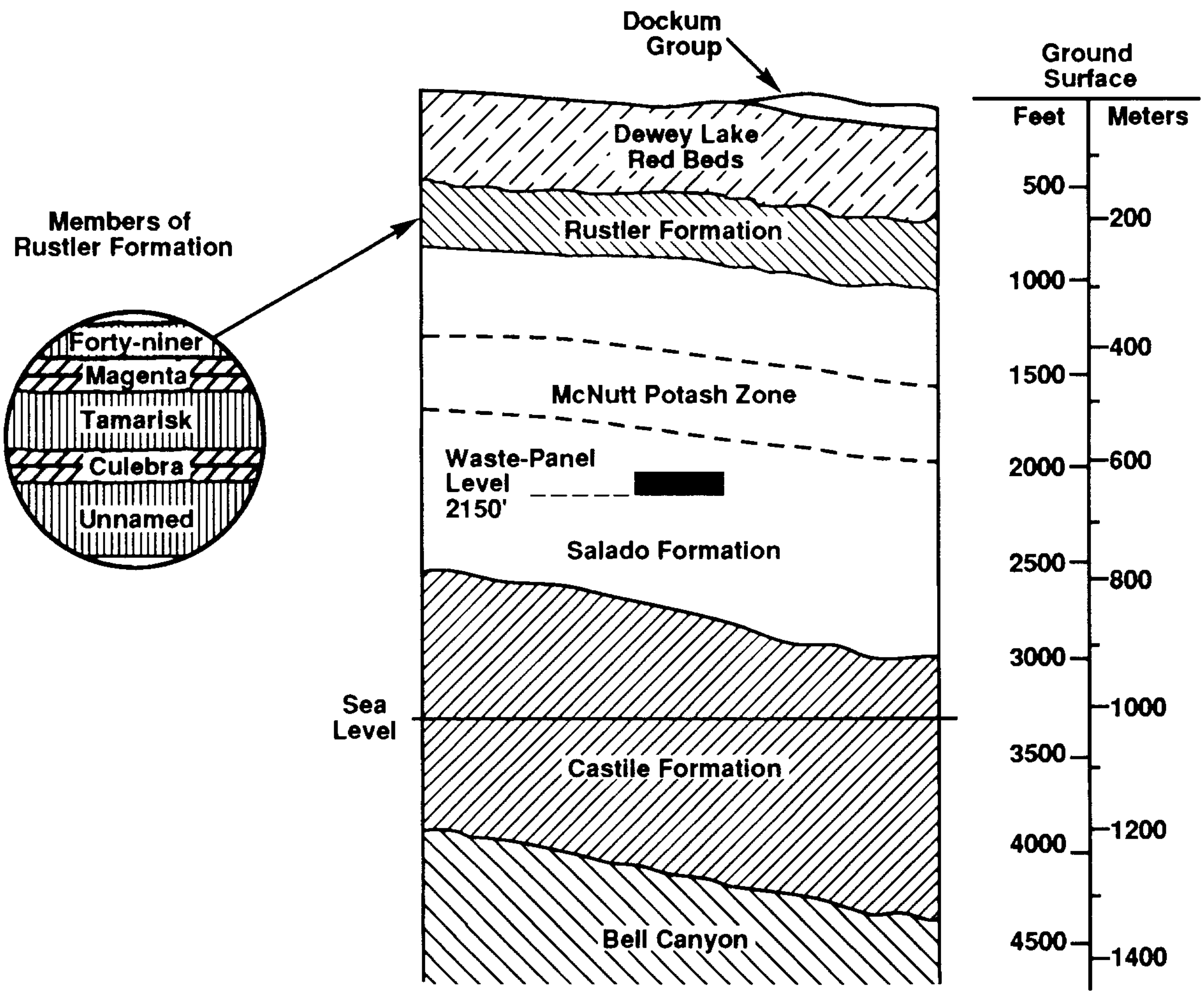


Figure VI-4. Position of McNutt Potash Member Relative to Waste Panels (after Rechard, 1989; based on DOE, 1980).

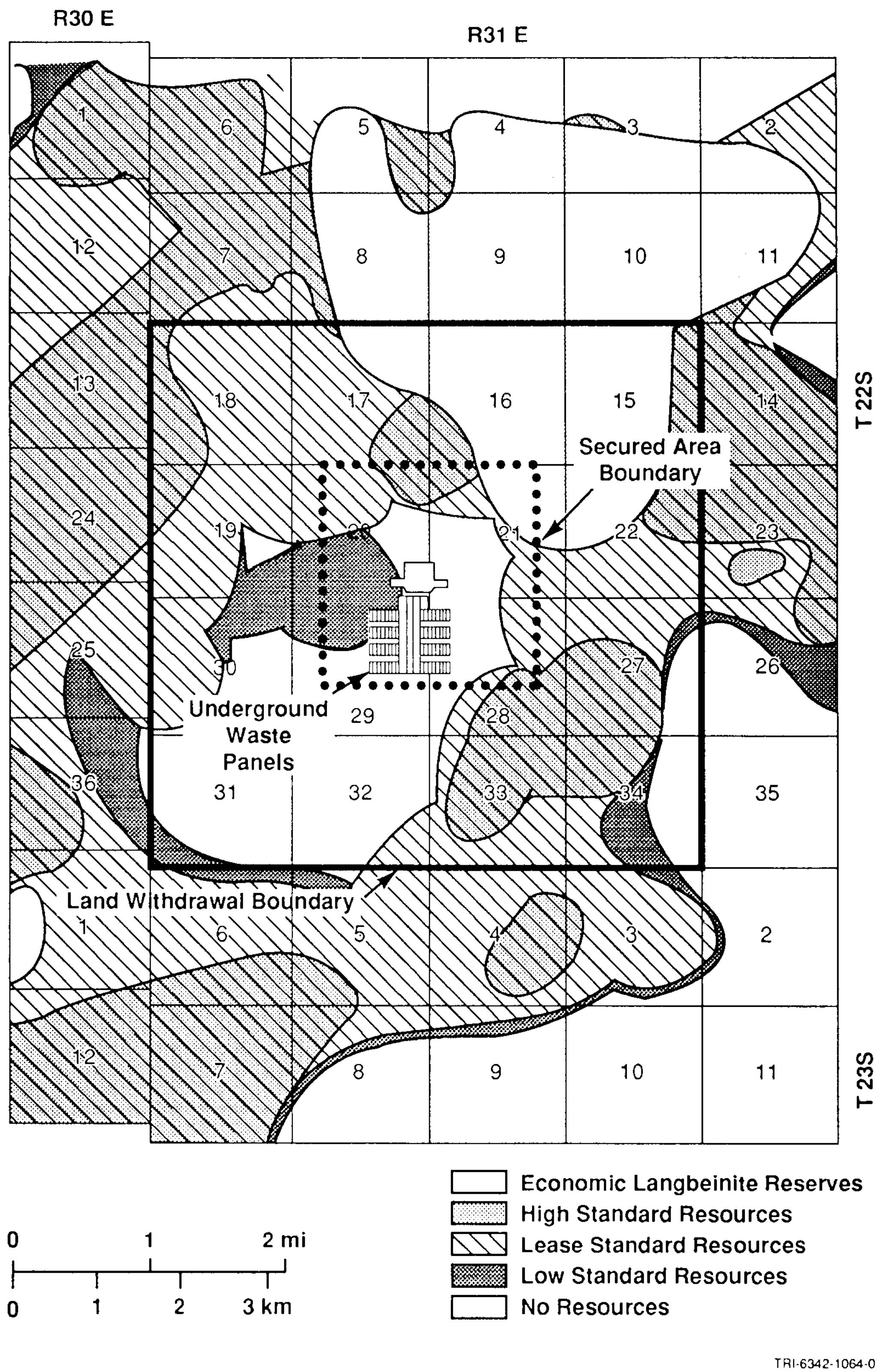


Figure VI-5. Generalized Distribution of Potash Resources in the Vicinity of the WIPP (Guzowski, 1990; potash distribution based on Brausch and others, 1982).

buffer zone [Control Zone IV]..." (p. 14); (2) langbeinite is less soluble than the surrounding host rock, so solution mining cannot be used to extract the mineral; (3) solution mining has not been successful for sylvite in the Delaware Basin because of the low grade of the ore, the thinness of the ore beds, problems with pumping and heating the injection water, and the lack of adequate supplies of fresh water; and (4) underground mining is the only currently available technology for mining potash in this region. These conclusions are consistent with the results reported in Powers and others (1978b).

In the northern part of the Delaware Basin, numerous stratigraphic zones (Figure VI-6) have produced hydrocarbons in economic quantities. The presence of these zones beneath the WIPP indicates the possible presence of these resources. A fundamental assumption in the resource analysis by Brausch and others (1982) was that the WIPP area has the same potential for containing hydrocarbons as the larger area considered in the resource study. Based on analyses by Keesey (1976, 1979, 1980, cited in Brausch and others, 1982), the Morrow Formation at a depth of 14,000 feet (Figure VI-6) was concluded to be the only zone likely to produce enough natural gas to warrant the risk of exploratory drilling, although the overlying Atoka Formation could provide an auxillary supply to production from the Morrow. An additional conclusion was that "...<u>all of the natural gas and distillate reserves can be accessed by existing drilling techniques (either vertical or directional) from within Control Zone IV</u>" (Brausch and others, 1982, p. 14, original emphasis). A complicating factor to this conclusion of resource accessibility is that an agreement between the DOE and the State of New Mexico (U.S. DOE and State of New Mexico, 1981, as modified) prohibits directional (slant) drilling beneath the land-withdrawal area for as long as active institutional controls are maintained.

Summary of Estimates of Undiscovered Hydrocarbon Resources

In 1989, the Department of the Interior published a special report (Mast and others, 1989) updating 1981 estimates of total U.S. undiscovered crude-oil and natural-gas deposits, and 1985 estimates for the federal outer continental shelf. These updated estimates are for 78 onshore and state-water and 35 federal offshore provinces. Results are reported for crude oil, natural gas, and natural-gas liquids (distillate); recoverable (without regard to economics) and economically recoverable quantities; and quantities at the 95- and 5-percent confidence levels and the mean value. Assumptions used in these estimates included minimum field size that could be operated at a profit and conditions that would determine future prices of resources. The conditions considered were base price of oil and gas, rate of inflation, rate of change in resource prices, relationship between oil and gas prices (price/BTU), prevailing rates of return after taxes, field development cost, cost of infrastructure, and timing of field development.

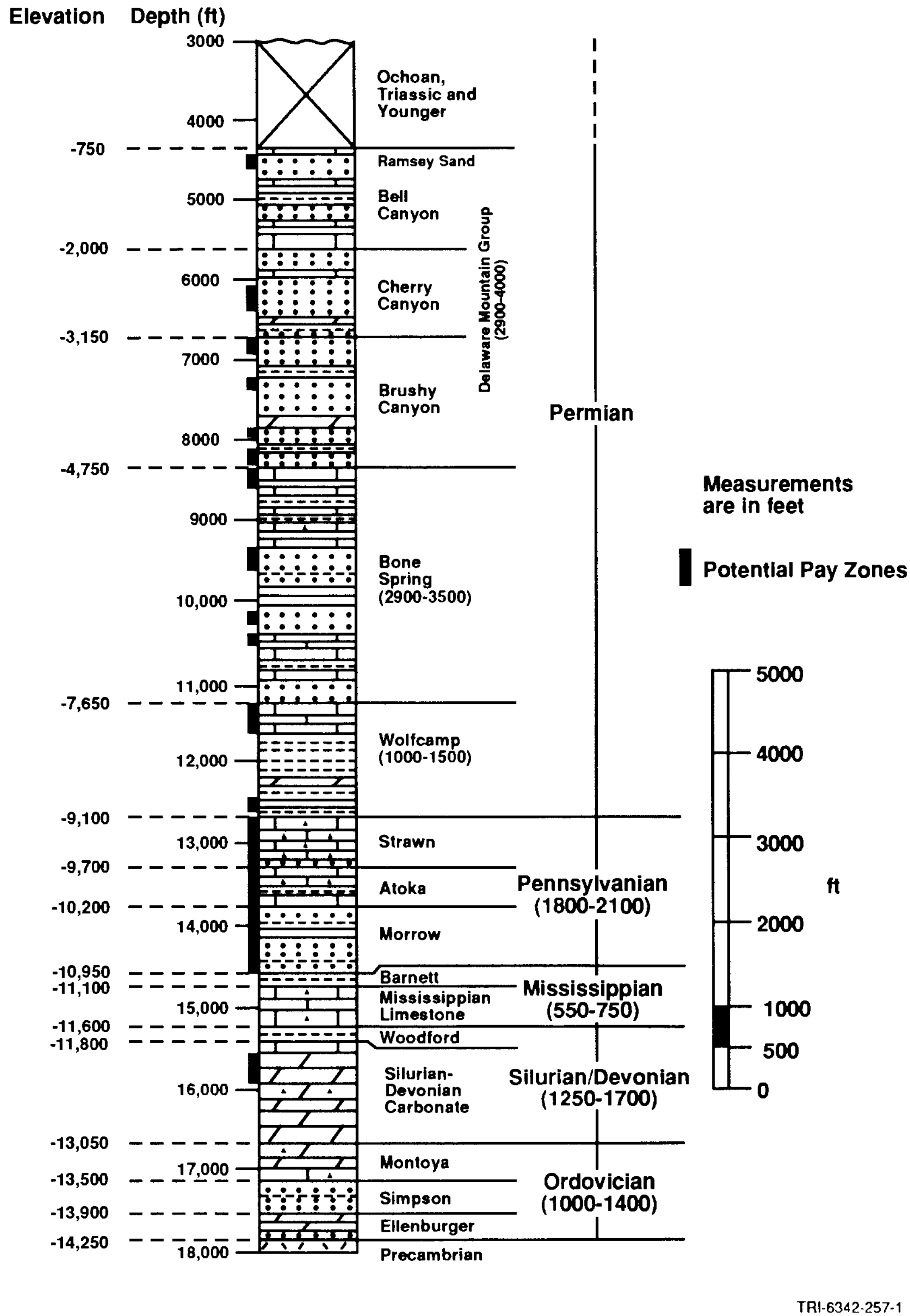


Figure VI-6. Stratigraphic Location of Potential Hydrocarbon Reservoirs for the Delaware Basin (Powers and others, 1978b; after Foster, 1974).

One of the provinces considered (Province 92, Figure VI-7) includes most of the southern half of New Mexico, and this area includes the WIPP. Because the area covers much more than just the northern Delaware Basin or the WIPP, the resource estimates of Mast and others (1989) (Table VI-3) are not directly comparable to those of Brausch and others (1982) (Table VI-1).

Distribution of Oil and Gas in the Northern Delaware Basin

Most oil and gas fields in southeastern New Mexico are concentrated along certain trends. In Figure VI-8, a trend of primarily oil, but including some gas fields, extends from the southeastern corner of the map area to the central part and then toward the southwestern corner. This arc roughly corresponds to the location of the Capitan Reef. Figure VI-9 is an enlargement of the southern half of Figure VI-8 and shows more detail of the distribution of oil and gas fields relative to the location of the WIPP. In the WIPP region, few oil and gas fields exist, and the sizes of the fields are substantially smaller than those fields associated with the Capitan Reef. Resource-exploration efforts tend to be concentrated in those areas where resources are most likely to be encountered. The distribution of wildcat (exploratory) wells for the 25 townships including and surrounding the WIPP is illustrated in Figure VI-10. An absence of a uniform distribution to the wells is pronounced. Some areas contain a concentration of wells, some areas have a few scattered wells, and some areas are devoid of wells. The reasons for a lack of drilling in some areas can range from the land not being available for exploration, to the lease holders not being able to afford to explore, to the resource potential being too low to justify exploratory drilling. This lack of a uniform distribution for wildcat wells is reinforced by also considering the location of production wells in addition to the wildcats (Figure VI-11). Certain areas have a high density of wells, and other areas have few to none. Whether these patterns are maintained into the future will depend on resource economics in the future and the geologic potential of an area to produce the resources.

Conclusions about the Resource Potential of the WIPP

Based on the currently recognized resource potential of the WIPP, several conclusions can be reached. Crude oil will not be a target for exploration unless the price of oil rises to levels substantially higher than the price during past energy crises. Natural gas in the Morrow Formation will remain the main and perhaps only hydrocarbon of potential economic importance in the area. All currently recognized potash resources are confined to a zone several hundred feet above the proposed waste-filled rooms and drifts, and only the lowest grade of potash resources overlies part of the waste-panel area. Other resources that

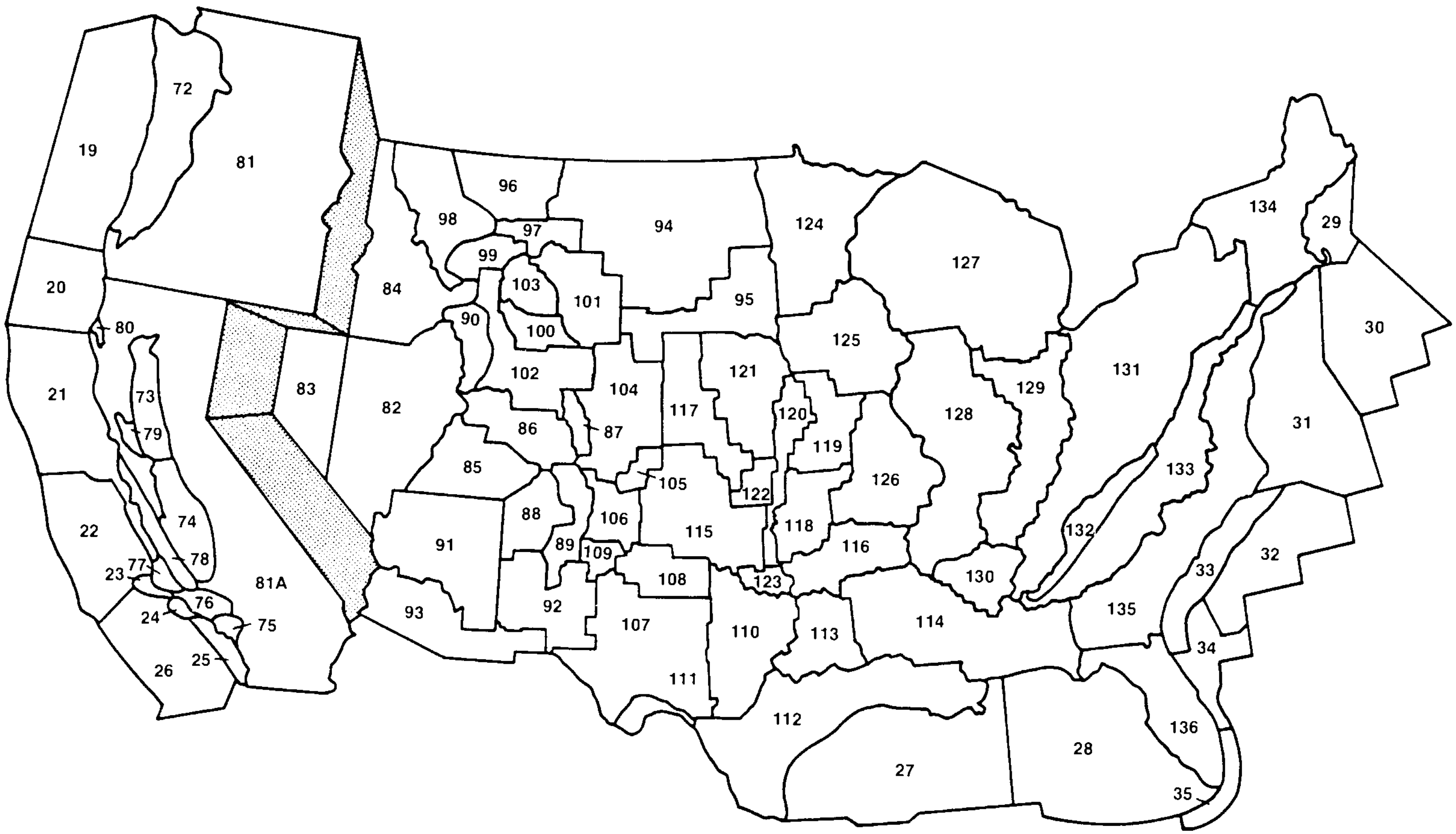
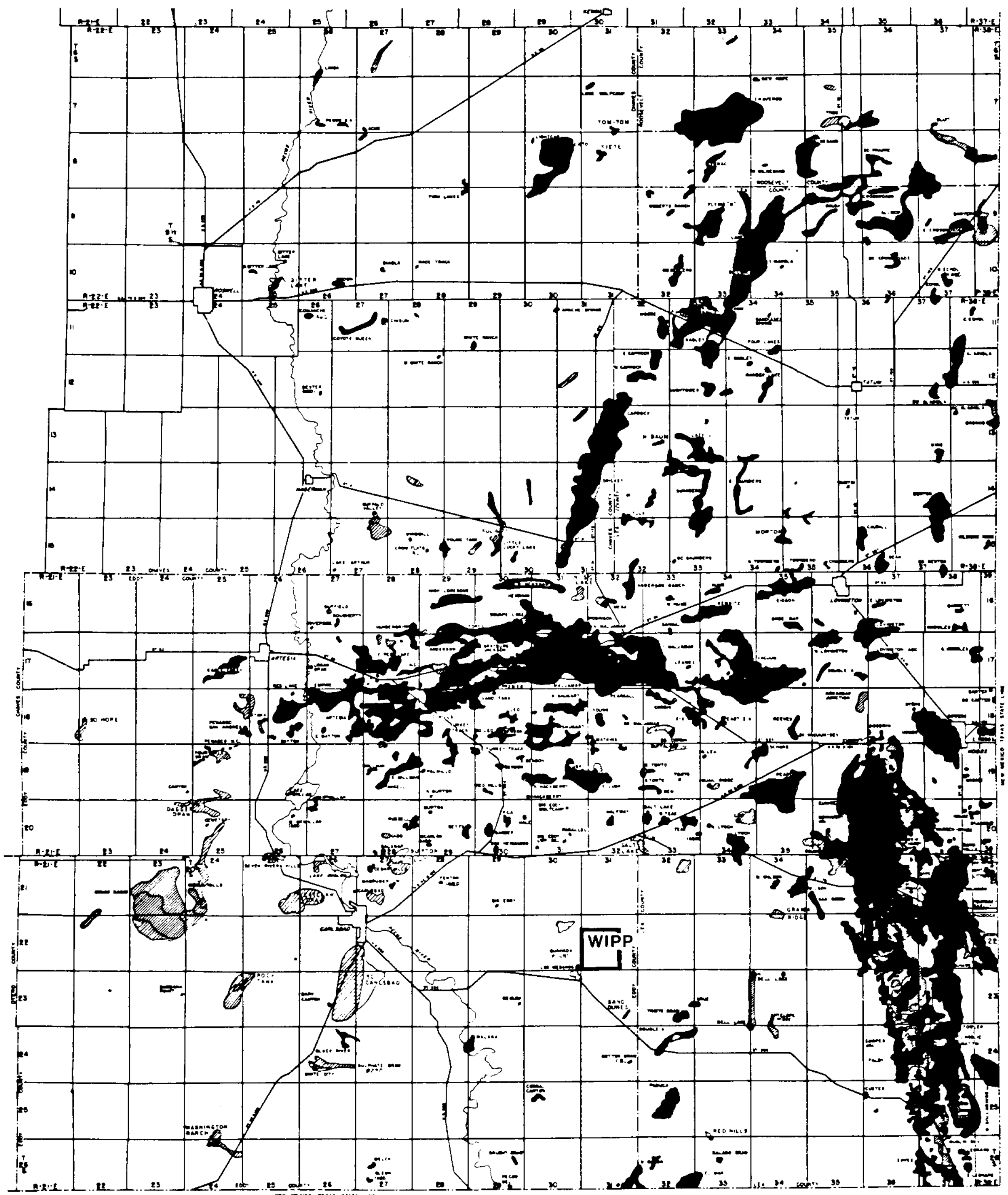


Figure VI-7. Location of Province 92 (Mast and others, 1989).

TABLE VI-3. ESTIMATES OF UNDISCOVERED HYDROCARBON RESOURCES--PROVINCE 92 (after Mast and others, 1989)

Resource	Mean	F95	F5
Crude Oil			
Recoverable	0.02 BB	Negl.	0.05 BB
Economically recoverable	0.02 BB	Negl.	0.05 BB
Natural Gas			
Recoverable	0.24 TCF	0.05 TCF	0.67 TCF
Economically recoverable	0.24 TCF	0.05 TCF	0.67 TCF
Natural-Gas Liquids			
Recoverable	0.00	0.00	0.00
Economically Recoverable	0.00	0.00	0.00



Explanation

- Oil Field
- Gas Field

0 2 4 6 mi

0 2 4 6 8 km

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Figure VI-8. Oil and Gas Fields in Southeastern New Mexico (Roswell Geological Society, 1977).

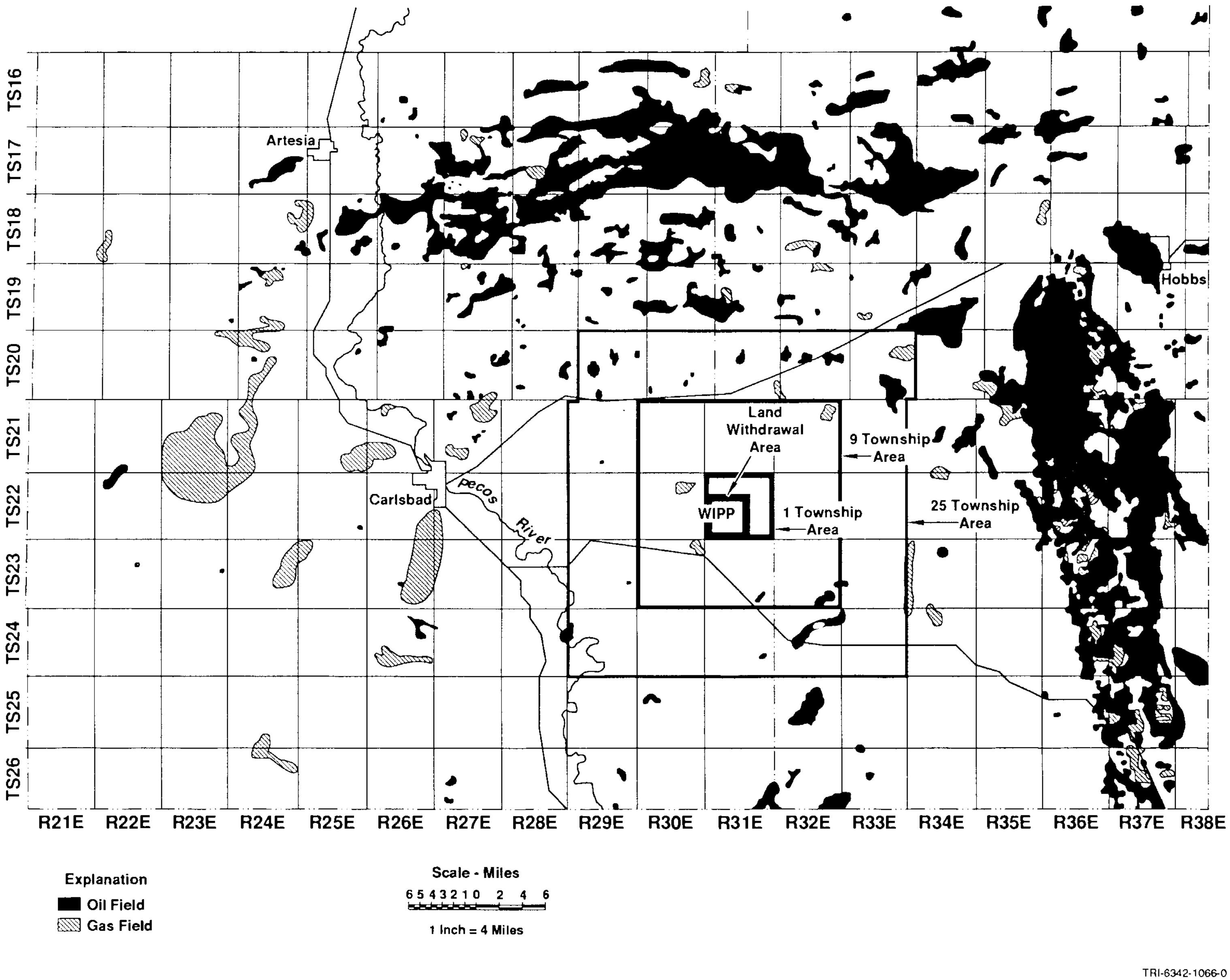

Figure VI-9. Oil and Gas Fields in Northern Delaware Basin (Roswell Geological Society, 1977).

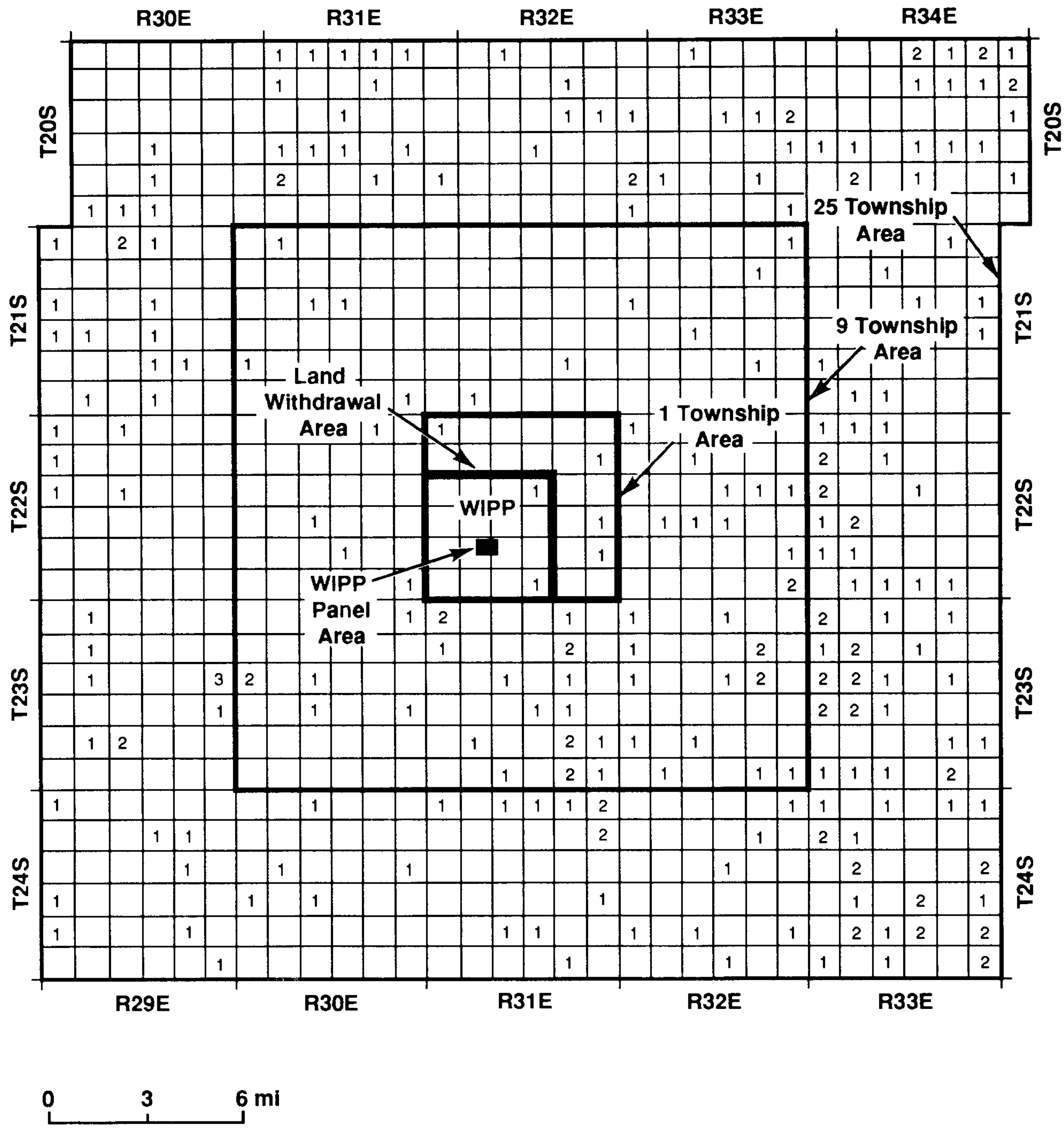

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Figure VI-10. Number of Wildcat Oil and Gas Wells per Section in the WIPP Region (data from Midland Map Company, 1987a,b).

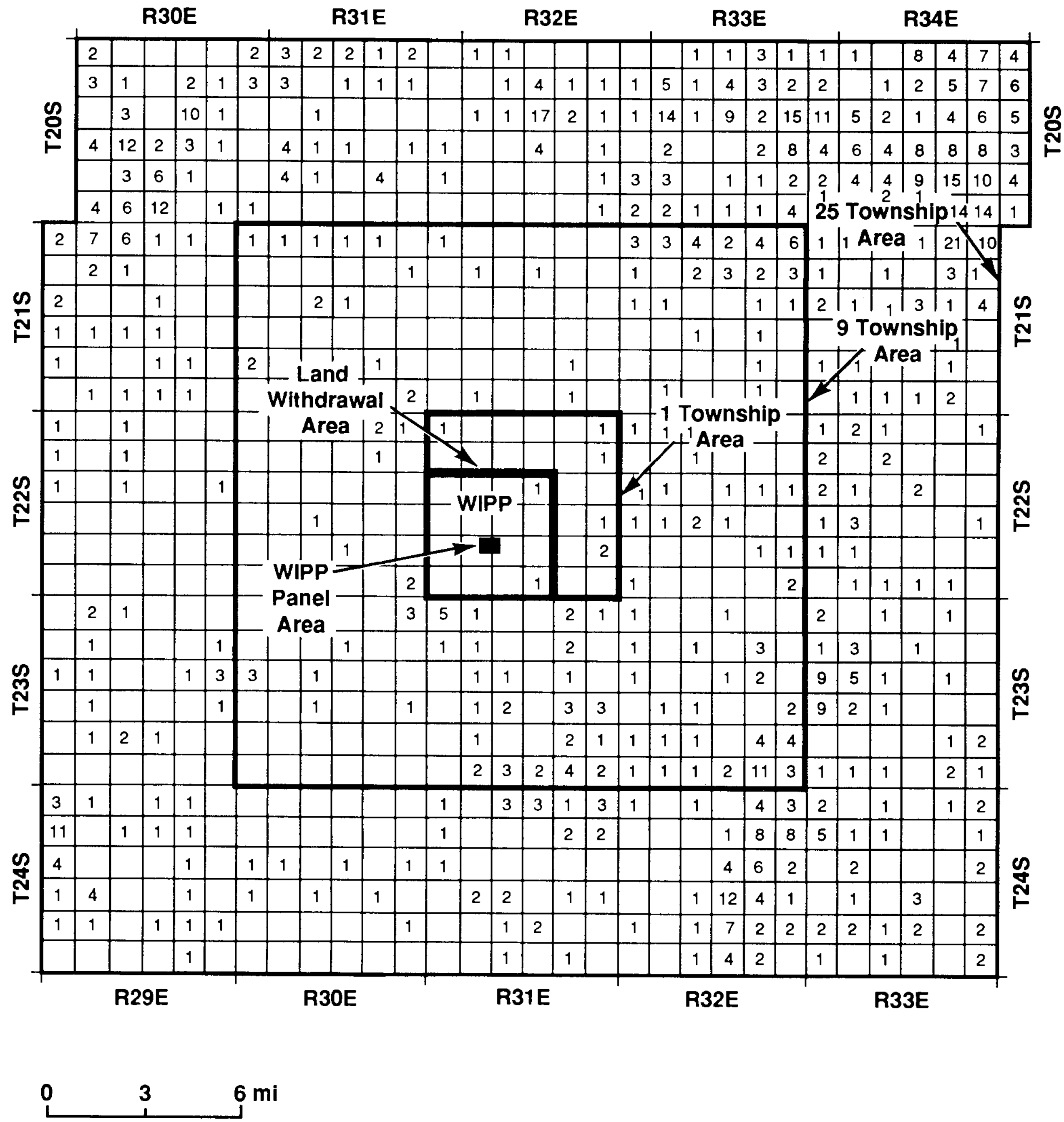

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Figure VI-11. Total Number of Oil and Gas Wells per Section in the WIPP Region (includes wildcat and developmental) (data from Midland Map Company, 1987a,b).

are present at the WIPP are not of economic importance because of the abundance and/or greater accessibility of these resources elsewhere.

Trends in Resources

Exploitation of a resource results in certain trends involving such factors as the size and/or grade of the deposits of the resource and the amount of the resource produced. These trends can be altered by changes in the price of the resource and changes in the technology used to exploit the resource. Rather than discuss these trends in abstract terms, an example is used. The following discussion considers trends in crude oil and natural gas.

CHANGES IN FIELD SIZE WITH TIME

Crude-oil and natural-gas fields in a particular sedimentary basin tend to have a logarithmic size distribution (dashed line in Figure VI-12). Relatively few large deposits and progressively more smaller deposits exist. In addition to representing observed fields, the shaded area in Figure VI-12 also represents those fields that are economically viable. The largest fields are economical at all locations and geologic settings in a basin. As size decreases, fields of a particular size will be economical at some locations and depths and uneconomical at others. The area between the shaded area and the dashed line in Figure VI-12 can be considered to represent uneconomical oil fields because of location or setting. As prices increase or recovery technology improves, the size of economically viable deposits will decrease.

Figures VI-13 and VI-14 demonstrate the decrease in undiscovered field size as a result of continuing resource exploitation in two geographic areas.
Figure VI-13 represents the percentage of discovered oil fields in the northern Central Kansas uplift containing more than 256,000 barrels. Whereas no trend existed in this percentage from the 1920s through the mid-1940s, the percentage has been in almost continuous decline since the mid-1940s. Figure VI-14 represents the change in the size of natural-gas fields in the Permian Basin of Texas and New Mexico. This area does not include the WIPP region. For the three time intervals considered, the discovered resource volume, the largest field size, and the mean field size have all decreased as exploration and exploitation of the natural-gas fields have progressed.

CHANGES IN PRODUCTION

As indicated in Figure VI-14, the resource volume discovered during the time periods considered decreased from older to more recent periods. A similar trend has occurred for crude oil since 1986 (Table VI-4) with successively less yearly production. Decreasing yearly production during this time interval reversed an

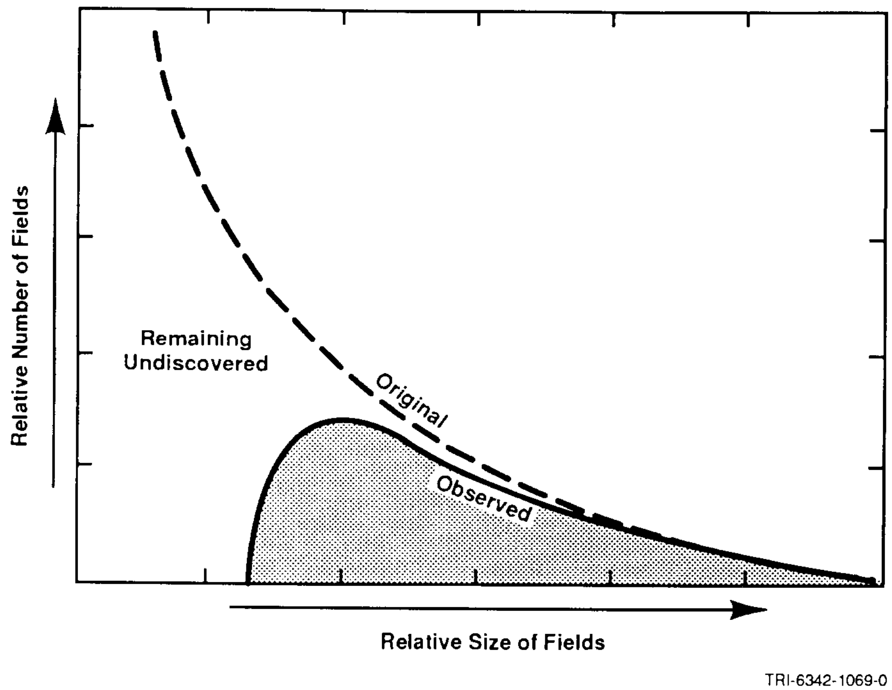


Figure VI-12. Relationship between Size Distribution of Fields Originally in Basin, Observed, and Undiscovered Fields (Davis and Chang, 1989).

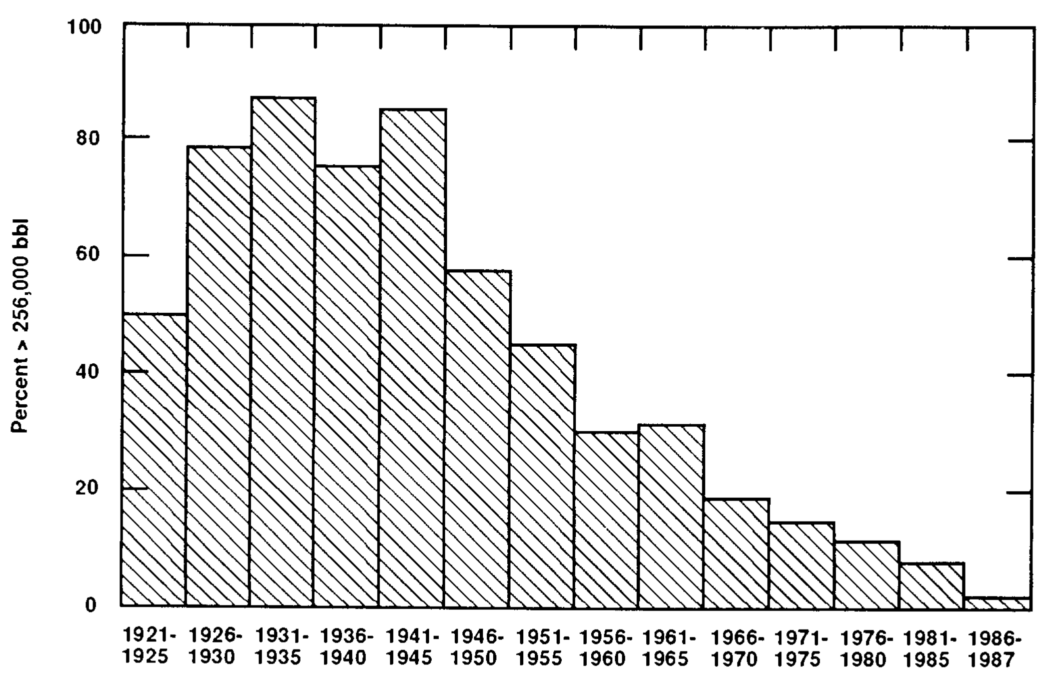


Figure VI-13. Percentage of Discovered Oil Fields Larger than 256,000 Barrels, Northern Central Kansas Uplift (Davis and Chang, 1989).

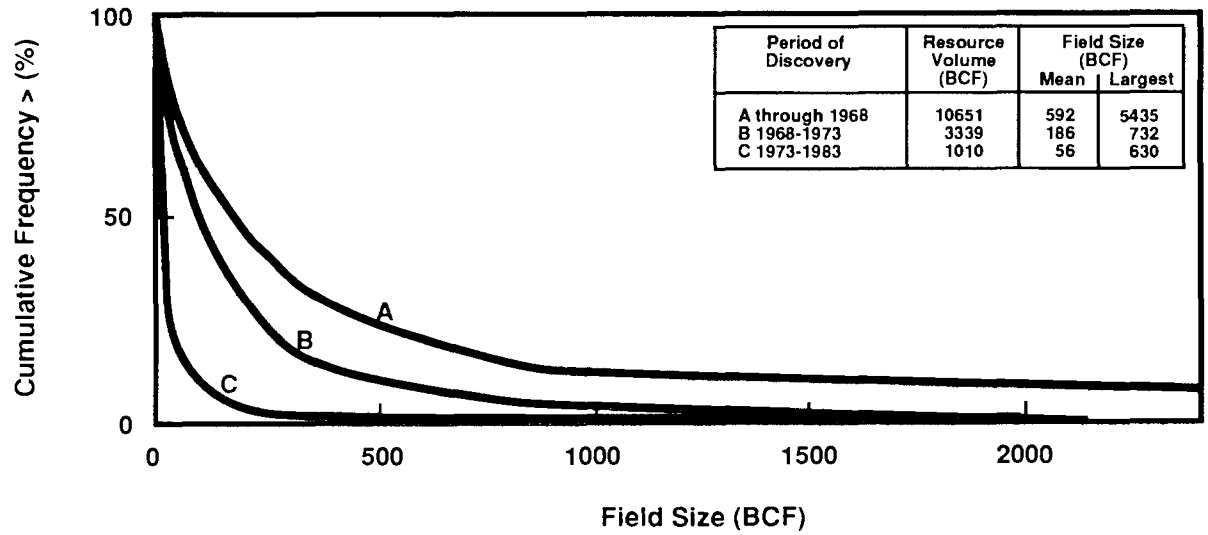


Figure VI-14. Change in Size of Fields Discovered through Time, Permian Basin, Texas and New Mexico (Mast and others, 1989).

TABLE VI-4. DOMESTIC HYDROCARBON PRODUCTION (data from International Energy Agency, 1989).

	Year	Production	Change From Previous Year
Crude Oil	1978	428447	-
(000 MT)	1980	424153	-1.0%
	1982	425548	+0.1%
	1983	427474	+0.5%
	1984	439148	+2.7%
	1985	442507	+0.8%
	1986	428142	-3.2%
	1987	411808	-3.8%
	1988	402032	-2.4%
NGL	1978	53462	-
(000 MT)	1980	53523	+0.1%
	1982	51921	-3.0%
	1983	51564	-0.7%
	1984	51476	-0.2%
	1985	50816	-1.3%
	1986	48859	-3.9%
	1987	50262	+2.9%
	1988	51204	+1.9%

earlier trend of increased yearly production. Production in 1988 was at the lowest level in at least 10 years, and imports, both as a percentage of domestic production (66 percent) and refinery intake (40 percent), were at the highest levels since 1980. The decline in production is not necessarily the sole result of an inability of the nation to produce more oil. Other contributing factors to this decrease in production are a large decline in the price of oil, which decreases the incentives to produce or to find replacements for consumed reserves, and readily available imports.

Yearly production of natural gas tends to be inversely related to oil production (Table VI-4). With imports of natural gas ranging from 13 to 17 percent of domestic production over the past decade, domestic production seems to be at steady-state condition.

PREDICTED QUANTITIES OF REMAINING RESOURCES AND LIFE EXPECTANCY

The known recoverable amounts of crude oil and natural gas as of January 1, 1987, were 51.2 billion barrels (BB) and 305.4 trillion cubic feet (TCF), respectively (Mast and others, 1989). Estimates of both recoverable and economically recoverable undiscovered resources and the total possible remaining resources of oil and gas at confidence limits of 95, 50 (mean), and 5 percent are listed in Table VI-5. The recent rates of consumption of oil and gas were approximately 5.4 BB/year and 16.3 TCF/year, respectively (Kerr, 1989). Based on these rates of consumption, oil would last 19 years (range 16 to 22 years) if undiscovered recoverable resources are considered and 16 years (range 13 to 19 years) if undiscovered economically recoverable resources are considered. For natural gas, the life expectancy would be 43 years (range 38 to 50 years) for recoverable resources and 35 years (range 32 to 39 years) for economically recoverable resources.

Some estimates of undiscovered oil and gas resources in the early 1970s tended to be highly optimistic when compared to later estimates. The estimates of undiscovered resources by Mast and others (1989) are reasonably consistent with most other estimates (Figures VI-15 and VI-16). Whereas the amounts of hydrocarbons consumed yearly will change in the future, the amount of change, either with additional or less consumption, is not likely to be substantial, and the life expectancy of the resources will not be substantially changed. For example, the mean life expectancy for oil using known reserves and economically recoverable resources is 16 years. A 10-percent decrease in the rate of consumption would add less than 2 years to the life expectancy, and a 20-percent decrease would add less than 4 years. Because the estimates of undiscovered resources by Mast and others (1989) are reasonably consistent with other estimates and moderate decreases in the rate of consumption will not

TABLE VI-5. PREDICTION OF REMAINING RESOURCES

ESTIMATES [undiscovered: mean (95%-5% confidence)]

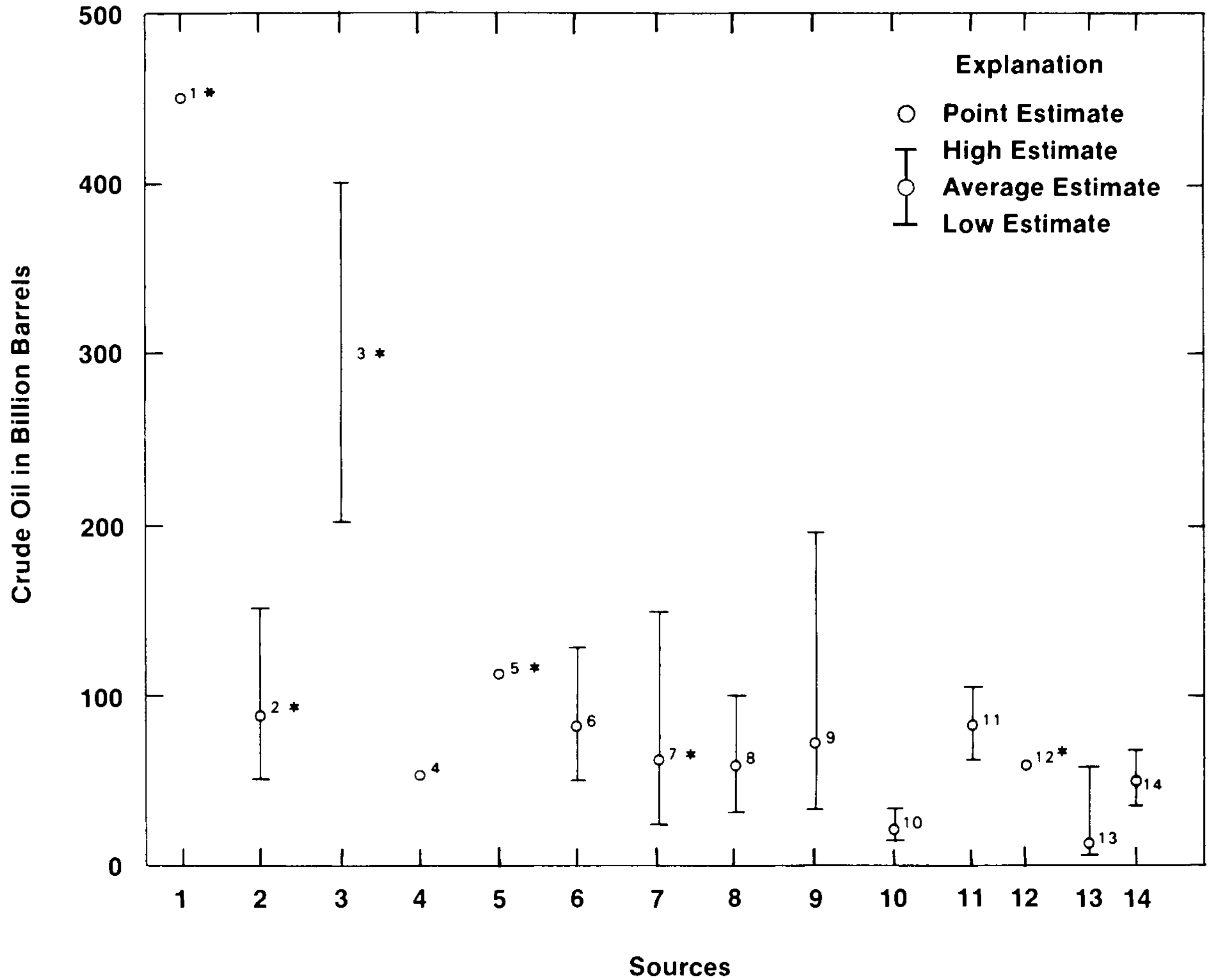
Crude Oil
Known recoverable 51.2 billion barrels (BB)
Undiscovered recoverable [49.4 BB (33.2-69.9)]
Undiscovered economically recoverable [34.8 BB (20.7-53.8)]

Natural Gas
Known recoverable 305.4 trillion cubic feet (TCF)
Undiscovered recoverable [399.1 TCF (306.8-507.2)]
Undiscovered economically recoverable [262.7 TCF (208.2-325.5)]

TOTALS (known + undiscovered recoverable)
Crude Oil [100.6 BB (84.4-121.1)]
Natural Gas [704.5 TCF (612.2-812.6)]

TOTALS (known + undiscovered economically recoverable)
Crude Oil [85.8 BB (71.7-104.8)]
Natural Gas [568.7 TCF (514.2-631.5)]

Source: Mast and others, 1989



Explanation of Sources

1. Theobald and others, 1972
2. Moody, 1974
3. USGS, 1974
4. Hubbert, 1974
5. NRC, 1975
6. Miller and others, 1975
7. Exxon Company, USA, 1976
8. Oil and Gas Journal, 1978
9. Halbonty and Moody, 1980
10. Nehring and van Driest, 1981
11. Dolton and others, 1981
12. Rozendal, 1986
13. Lewis, 1986
14. Mast and others, 1989

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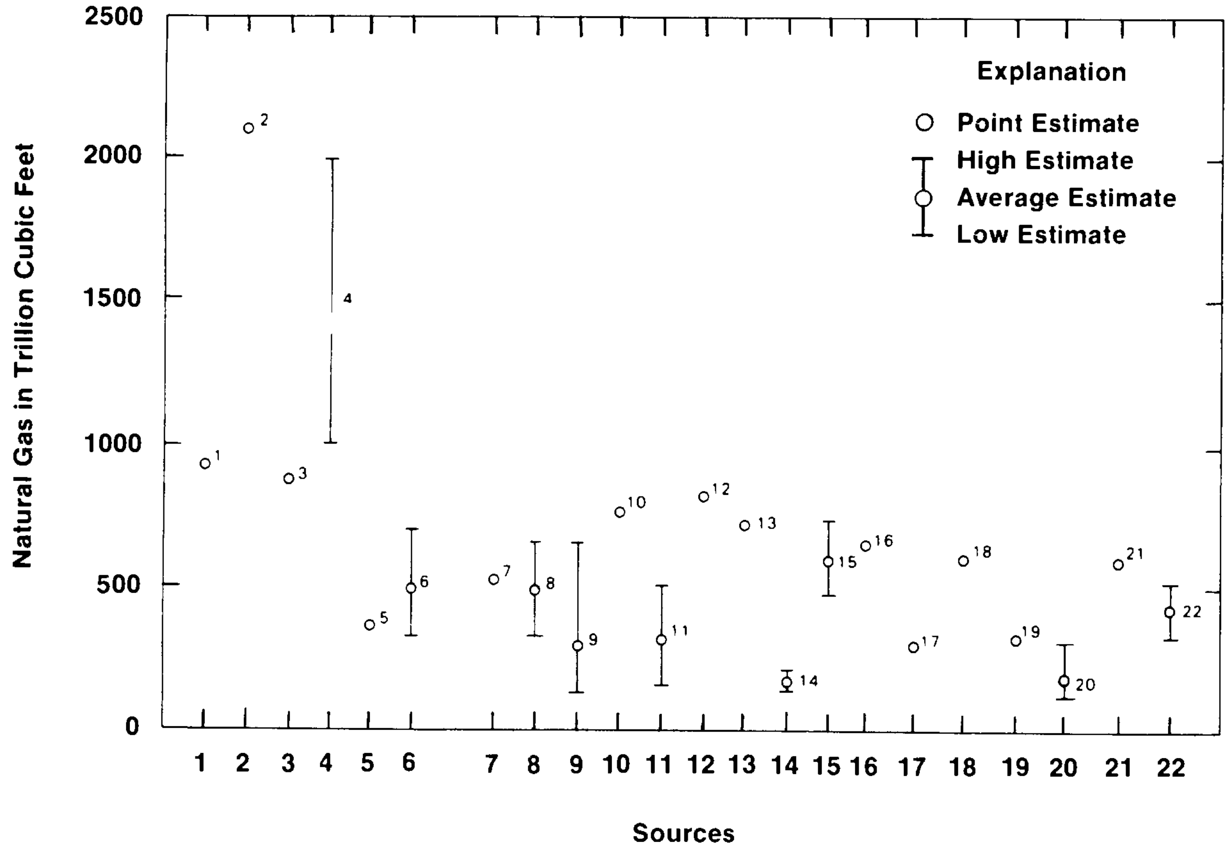
Figure VI-15. Selected Estimates of Undiscovered, Recoverable Conventional Oil in U.S. Estimates may be for different areas and commodities. Asterisk includes NGL. (Mast and others, 1989).



Explanation of Sources

1. Potential Gas Committee, 1971
2. Theobald and others, 1972
3. Potential Gas Committee, 1973
4. USGS, 1974
5. Hubbert, 1974
6. Moody, 1974
7. NRC, 1975
8. Miller and others, 1975
9. Exxon Company, USA, 1976
10. Potential Gas Committee, 1977
11. Oil and Gas Journal, 1978
12. Potential Gas Committee, 1979
13. Potential Gas Committee, 1981
14. Nehring and van Driest, 1981
15. Dolton and others, 1981
16. Potential Gas Committee, 1983
17. Platt's Oilgram News, 1984
18. Potential Gas Committee, 1985
19. Rozendal, 1986
20. Lewis, 1986
21. Potential Gas Committee, 1987
22. Mast and others, 1989

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Figure VI-16. Selected Estimates of Undiscovered, Recoverable Conventional Natural Gas for the U.S. Estimates may be for different areas and commodities. (Mast and others, 1989).

substantially increase the life expectancy of the resources, the life-expectancy estimates presented above are reasonable. This life expectancy can be extended by imports, but as pointed out by Hirsch (1990), imports of oil could rise to 60 to 70 percent of consumption by the year 2000 at a cost of $100 billion/year. Extending the life of the resource could devastate the nation's economy.

Applicability of Oil and Gas Trends to Other Resources

The applicability of the trends in the oil and gas industry to other resources depends on the particular resource, future prices, future demand, technological developments for exploiting lower-grade or less accessible deposits, the availability of alternate sources of the resource, and the availability of cost-effective alternate materials to replace the resource. An additional factor possibly affecting certain resources is the availability of imports. Whereas imports supplement the U.S. production of oil and gas, imports have nearly displaced the domestic production of potash. Domestic production could be temporarily suppressed by imports followed by a renewal of the domestic industry after the sources of the imports are exhausted, or the domestic production could be permanently suppressed.

Factors to Consider About Resource Exploration and Exploitation

Tables VI-6 and VI-7 list currently available and possible future sources of resources and energy, respectively. Certain factors need to be considered when predicting future activities associated with resource exploration and exploitation at the WIPP. The first factor deals with what resources will be needed by future societies, which of these resources are present at the WIPP, and how long these resources will be economically exploitable. A second factor is based on economics. If a hiatus occurs in resource exploitation of the area that results in the deterioration or elimination of the industrial infrastructure, will the value of the resources justify rebuilding the infrastructure? For example, if natural-gas production in the northern Delaware Basin ceases long enough for the pipeline system to decay, are there sufficient resources to justify rebuilding the pipelines? A third factor is target potential. The WIPP consists of an area of approximately 41 km^2, and the waste-panel area is approximately 0.5 km^2. If resource exploration and exploitation continues in the northern Delaware Basin, what resources could be at these locations after the loss of administrative control that would attract exploration activity, and will the size of either area be sufficiently large to have the resource potential to attract this activity?

TABLE VI-6. SOURCES OF RESOURCES

Continental Sources
- Currently recognized deposits
- Alternate sources (e.g., lower grade, alternate host rock, alternate geologic setting)

Oceanic Sources
- Subseabed (e.g., oil, gas, coal, potash, etc.)
- Sea Floor (e.g., manganese nodules, deposits at thermal vents)
- Sea Water (dissolved elements)
- Near Shore (heavy minerals in placer deposits)

Extraterrestrial Sources
- Moon and Planets (e.g., lunar helium-3)
- Asteroids

Other Sources
- Byproducts of geothermal energy (K, Li, Ca, B, etc.)
- Landfills

TABLE VI-7. FUTURE SOURCES OF ENERGY

Conventional Hydrocarbon Sources
- Coal
- Petroleum
- Natural Gas
- Heavy-Oil and Tar Sands

Conventional Nonhydrocarbon Sources
- Geothermal
- Solar
- Wind
- Waste Heat (cogeneration)
- Tides
- Nuclear (fission reactors)

Alternate Future Sources
- Oil shale
- Nuclear (fusion and breeder reactors)
- Warm ocean currents
- Biomass

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VII. LONG-TERM CLIMATE VARIABILITY AT THE WASTE ISOLATION PILOT PLANT

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ABSTRACT

Changes in climate during the next 10,000 years (10 ka), particularly long-term increases in precipitation, may affect performance of the Waste Isolation Pilot Plant (WIPP). Data from deep-sea sediments indicate that fluctuations in global climate corresponding to glaciation and deglaciation of the northern hemisphere have been regular in both frequency and amplitude for at least 780 ka. Field data from the American Southwest and global climate models indicate that the coolest and wettest conditions in the past at the WIPP have occurred during glacial maxima, when the North American ice sheet reached its southern limit roughly 1200 km north of the WIPP and deflected the jet stream southward. Field data indicate that average precipitation in the Southwest during the last glacial maximum 22 to 18 ka BP (before present) was approximately twice that of the present. Mean annual temperatures were probably no lower than 5°C below present. Driest conditions (precipitation approximately 90 percent of present) occurred 6.5 to 4.5 ka BP, after the ice sheet had retreated to its present location. Wet periods of unknown duration have occurred since the retreat of the ice sheet, but none have exceeded glacial limits. Modeling of glacial periodicity suggests that, barring anthropogenic controls, the next glacial maximum may occur in approximately 60 ka. Global climate models suggest that anthropogenic effects (e.g., warming caused by an increased greenhouse effect) will not result in a significant increase in precipitation at the WIPP. The climate of the last glacial maximum is therefore suitable for use as a cooler and wetter limit for variability during the next 10 ka.

Introduction

Changes in the climate of southeastern New Mexico during the next 10,000 years (10 ka) may affect the performance of the Waste Isolation Pilot Plant (WIPP). In particular, changes in the average level of precipitation could affect recharge to the Rustler Formation and the currently unsaturated overlying units. Hydrologic models indicate that an increase in recharge may increase flow through the Culebra Dolomite Member of the Rustler Formation, reduce ground-water travel time from the vicinity of the repository to the accessible environment, and, in the event of an intrusion, increase the cumulative radionuclide release to the accessible environment (Brinster, 1991). Climatic changes may also affect agricultural uses of the area. Data about the nature of expected climatic changes are essential for assessments of repository performance.

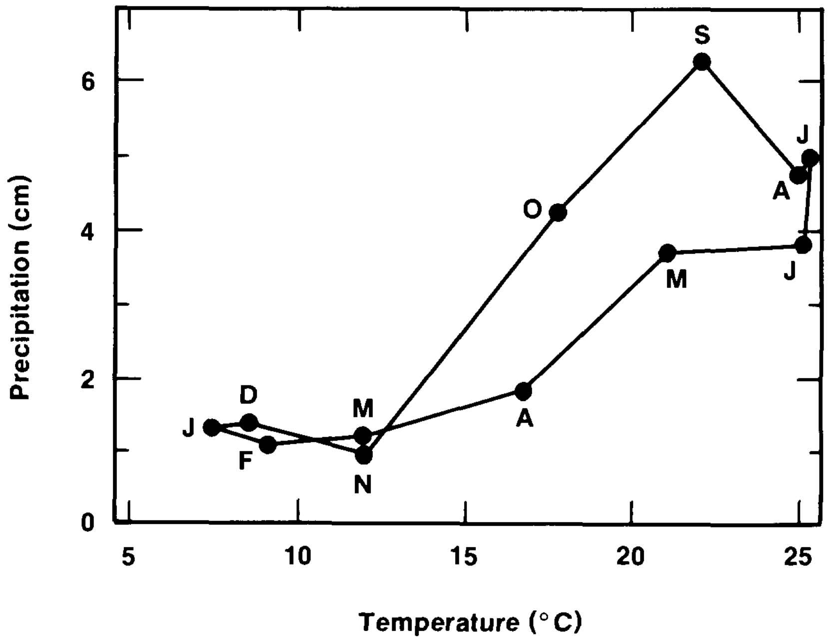
MODERN CLIMATE

At present, the climate at the WIPP is arid to semi-arid. Mean annual precipitation at the WIPP has been estimated to be between 28 and 34 cm/yr (Hunter, 1985). At Carlsbad, 38 km west of the WIPP and 100 m lower, 53-year (1931-1983) annual means for precipitation and temperature are 32 cm/yr and 17.1°C (University of New Mexico, 1989). Short-term variation about the annual means can be considerable, and historic weather data cannot be used to predict long-term climatic shifts. For example, the 105-year (1878 to 1982) precipitation record from Roswell, 135 km northwest of the WIPP and 60 m higher, shows an annual mean of 27 cm/yr with a high of 84 cm/yr and a low of 11 cm/yr (Hunter, 1985).

The climate of southeastern New Mexico is monsoonal: most of the precipitation falls in late summer, when solar warming of the continent creates an atmospheric pressure gradient that draws moist air inland from the Gulf of Mexico (Cole, 1975). The coincidence of precipitation and temperature maxima is typical of a monsoonal climate (Figure VII-1). Much of the rain falls during localized and often intense summer thunderstorms, and winters are cool and generally dry. Both temperature and precipitation are dependent on elevation, and climates vary according to local topography. At lower elevations throughout the region, including the vicinity of the WIPP, potential evaporation greatly exceeds precipitation. Freshwater pan evaporation in the region is estimated to exceed 274 cm/yr (Hunter, 1985). Effective moisture, defined by Neilson (1986) as precipitation minus potential losses to evaporation and transpiration by plants, is extremely limited most of the year. Surface runoff and infiltration of rainwater into the subsurface are also limited. Hunter (1985) concluded from a literature review that within the vicinity of the WIPP, on the average, 96 percent of precipitation is lost to evapotranspiration. Evapotranspiration values may be significantly higher or lower locally.

CLIMATIC CHANGE

Because currently available long-term climate models are incapable of resolution on the scales required (e.g., Hansen et al., 1988; Mitchell, 1989), it is not possible to predict the climate of southeastern New Mexico for the



(from Harris, 1987) TRI-6342-530-1

Figure VII-1. Climatograph Showing Thirty-Year (1931-1960) Monthly Precipitation and Temperature Means for Carlsbad Caverns (Harris, 1987). Carlsbad Caverns are approximately 65 km southwest of the WIPP and 300 m higher.

next 10 ka. Instead, this report reviews evidence of past climatic changes in the region, and establishes limits on future precipitation based on known and modeled past extremes. Much of the available paleoclimatic data only record long-term average levels of precipitation, and these limits do not reflect the high variability apparent in the modern short-term data. The precipitation record presented here primarily reflects gradual shifts in long-term mean values, as is appropriate for recharge modeling.

A fundamental assumption, analogous to that made by Spaulding (1985) in his study of climatic variability at the Nevada Test Site, is that the climatic extremes of the next 10 ka will not exceed those associated with the glaciations and deglaciations that have recurred repeatedly in the northern hemisphere since the late Pliocene approximately 2.5 million years ago (2.5 Ma BP). The assumption is based on strong evidence, reviewed briefly in this report, which shows that past glacial cycles have been consistent in both intensity and frequency. The possibility that human-induced changes in the composition of the earth's atmosphere may influence future climates complicates projections of this cyclic pattern into the future, but, as presently modeled, fluctuations during the next 10 ka will remain within past limits.

None of the currently available models of the greenhouse effect predict long-term global climatic changes larger than those during the last 2.5 Ma (e.g., Mitchell, 1989). Furthermore, a short-term increase in the greenhouse effect appears unlikely to degrade predicted repository performance. The highest past precipitation levels in the American Southwest, up to twice those of the present, occurred during full-glacial conditions associated with global cooling (e.g., Van Devender et al., 1987; other sources cited below). Greenhouse models, however, predict average equilibrium global warming of 1.8 to 5.2°C with carbon dioxide concentrations twice present levels (Mitchell, 1989), a condition which could delay the start of renewed glaciation. Model predictions of future precipitation trends accompanying greenhouse warming are less consistent and less reliable than temperature predictions, but none suggest significantly higher levels of precipitation in southern New Mexico than those of the present (Washington and Meehl, 1984; Wilson and Mitchell, 1987; Schlesinger and Mitchell, 1987). Because long-term increases in recharge are improbable without increases in precipitation, the highest risk climatic change that will be considered here is, therefore, a return to the glacial extremes of the past.

Data that can be used to interpret paleoclimates in the American Southwest come from a variety of sources and indicate an alternation of arid and sub-arid to subhumid climates throughout the Pleistocene.[1] Prior to 18 ka BP, radiometric dates are relatively scarce, and the record is incomplete. From 18 ka BP to the present, however, the climatic record is relatively complete and well constrained by radiocarbon dates. This report cites extensive floral, faunal, and lacustrine data from the Southwest that permit reconstructions of precipitation and temperature during the late Pleistocene and Holocene. These data span the transition from the last full-glacial maximum to the present interglacial period, and, given the global consistency of glacial fluctuations as described below, they can be taken to be broadly representative of extremes for the entire Pleistocene.

Variability in Global Climate over the Last 2.5 Million Years

Core samples of datable marine sediments provide a continuous record that reveals as many as 50 glaciation/deglaciation events in the last 2.5 Ma. Specifically, correlations have been made between major glacial events and three independent variables: oceanic ratios of $^{18}O/^{16}O$ as measured in the

1 The Pleistocene Epoch began approximately 1.6 Ma BP (Geological Society of America, 1984). Following the usage of Van Devender et al. (1987), I have selected 11 ka BP as the end of the Pleistocene Epoch and the beginning of the present Holocene Epoch. Some authors prefer 10 ka BP for the Pleistocene/Holocene boundary.

remains of calcareous foraminifera, the record of past sea-surface temperatures as determined from planktonic assemblages, and the total percent calcium carbonate ($CaCO_3$) in individual layers of oceanic sediment (Ruddiman and Wright, 1987).

Oxygen isotope ratios provide the most direct evidence because they reflect past volumes of glacial ice (Imbrie et al., 1984). Evaporation fractionates ^{18}O and ^{16}O populations in water, producing a vapor-derived meteoric facies relatively enriched in ^{16}O and an oceanic facies relatively enriched in ^{18}O. Glacial ice sheets store large volumes of meteoric water, preventing the remixing of the isotope fractions and significantly altering $\delta^{18}O$ values in the world's oceans.[2] Foraminifera preserve samples of past $\delta^{18}O$ values when they extract oxygen from sea water and incorporate it into calcareous body parts, and abundant fossil remains permit the construction of detailed records such as that shown in Figure VII-2a, covering the last 780 ka. High positive values of $\delta^{18}O$ reflect glacial maxima, and negative values reflect warm interglacial periods. Because the largest volumes of ice were in the North American sheet, $\delta^{18}O$ fluctuations can be interpreted directly as a first order record of North American glaciation and deglaciation (Mix, 1987; Ruddiman and Wright, 1987). Because the correlation is quantitative, the isotopic record indicates that most glacial events, including the most recent one, have been of roughly equivalent intensity. It also indicates that the present value is at or near that of a glacial minimum.

Sea-surface temperature records, although not as closely tied to glacial events, show the same alternating pattern. Temperatures at the surface of northern hemisphere oceans, as determined from the fossil assemblages of planktonic foraminiferal species, were measurably colder during glaciation and warmer during interglacial periods (Ruddiman, 1987). Plots of total $CaCO_3$ content of deep marine sediments confirm the pattern. Major glacial peaks, as distinguished from the pelagic calcareous background by the high silicic signal from ice-rafted continental debris, coincide with those determined from isotope and temperature data (Ruddiman and Wright, 1987).

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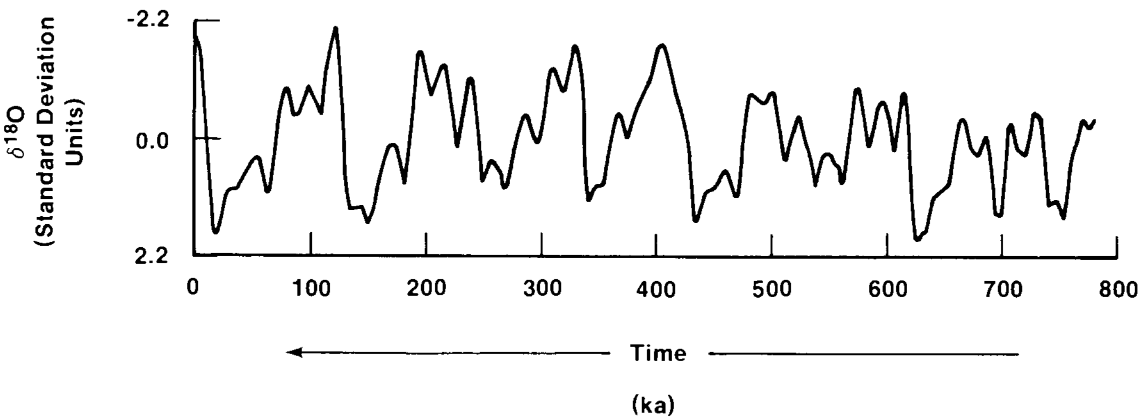
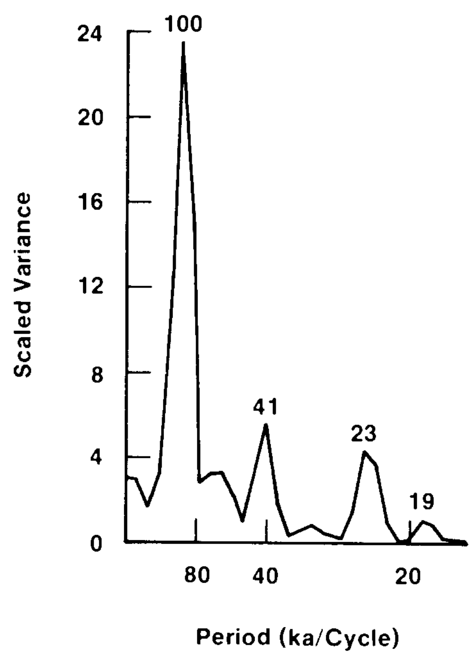
2 By convention, $^{18}O/^{16}O$ ratios are reported as:

$$\delta\,^{18}O \equiv 1000 \times \frac{(^{18}O/^{16}O_{sample} - {}^{18}O/^{16}O_{reference})}{^{18}O/^{16}O_{reference}}$$



a. $\delta^{18}O$ variations from five deep-sea core samples. Data have been normalized, stacked, and smoothed with a 9-point Gaussian filter (Imbrie et al., 1984).



b. Spectral analysis of $\delta^{18}O$ record in Figure a, showing periodicity of glaciation and deglaciation (after Imbrie, 1985).

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Figure VII-2. Foraminiferal $\delta^{18}O$ Record of the Last 780,000 Years.

Complete causes for glaciation and deglaciation are complex and not fully understood (Ruddiman and Wright, 1987), but the strong periodicity of the $\delta^{18}O$ record indicates that climatic alternations have been consistent in the past. Spectral analysis of the $\delta^{18}O$ curve for the last 780 ka shows that within that time the primary control on the periodicity of glacial events has been variation in global insolation (the amount of energy received from the sun) caused by irregularities in the earth's orbit (Figure VII-2b). Glacial intervals of 19, 23, 41, and 100 ka correspond to calculated intervals between northern hemisphere summer insolation minima of 19 and 23 ka related to the precession of the earth's axis, 41 ka related to the tilt of earth's axis, and 94, 125, and 413 ka related to eccentricity of the earth's orbit (Milankovitch, 1941; Hays et al., 1976; Imbrie et al., 1984; Imbrie, 1985). Calculations based on astronomical observations indicate that orbital parameters have not changed significantly in the last 5 Ma (Berger, 1984), and geological evidence suggests they may have been stable for at least 300 Ma (Anderson, 1984; Heckel, 1986).

Longer term global climatic changes, such as the beginning of the present pattern of glaciation and deglaciation 2.5 Ma BP, are in part controlled by changes in the configuration of the earth's continents, which in turn controls both global circulation patterns and the potential distribution of ice sheets (e.g., Crowell and Frakes, 1970; Caputo and Crowell, 1985). Continental masses move at plate-tectonic rates of centimeters per year, several orders of magnitude too low to affect glacial processes within the next 10 ka. Vertical uplift or subsidence of large continental regions may also affect global climate by changing circulation patterns (e.g., Boulton, 1989; Ruddiman and Kutzbach, 1989), but maximum uplift rates are at least an order of magnitude too low to change present circulation patterns within the next 10 ka.

This long-term stability of the cycles of glaciation and deglaciation provides the basis for concluding that climatic extremes of the next 10 ka will remain within past limits. The relative amplitudinal consistency (Figure VII-2a) implies that future glaciations will be comparable in severity to past ones. The periodicity of the pattern indicates that, although glacial minima such as that of the present are relatively brief, glacial advances are slow, and the next maximum will not occur for many tens of thousands of years. Predictions about the precise timing of future glacial events are complicated by uncertainties about feedback processes involved in the growth of ice sheets, but extrapolation of the isotopic curve using a relatively simple model for nonlinear climate response to insolation change suggests that, in the absence of anthropogenic effects, the next glacial maximum will occur in approximately 60 ka (Imbrie and Imbrie, 1980). Combined with the climatic data discussed below, these observations justify the choice of the late-Pleistocene, full-glacial climate as a conservative upper limit for precipitation during the next 10 ka.

Pleistocene and Holocene Climates of the Southwestern United States

Climatic data for the early and middle Pleistocene are incomplete and permit neither continuous reconstructions of paleoclimates nor direct correlations between climate and glaciation prior to the last glacial maximum 22 to 18 ka BP. Stratigraphic and pedologic data from several locations (Figure VII-3), however, indicate that cyclical alternation of wetter and drier climates in the Southwest had begun by the early Pleistocene. Fluvial gravels in the Gatuña Formation exposed in the Pecos River Valley of eastern New Mexico indicate wetter conditions 1.4 Ma BP and again 600 ka BP (Bachman, 1987). The Mescalero caliche, exposed locally over much of southeastern New Mexico, suggests drier conditions 510 ka BP, and loosely dated spring deposits in Nash Draw west of the WIPP imply wetter conditions again later in the Pleistocene (Bachman, 1981, 1987). The Blackwater Draw Formation of the southern High Plains of eastern New Mexico and western Texas, time correlative to both the Gatuña Formation and the Mescalero caliche, contains alternating soil and eolian sand horizons that show at least six climatic cycles beginning more than 1.4 Ma BP and continuing to the present (Holliday, 1989a). The duration, frequency, and total number of Pleistocene climatic cycles in the Southwest have not been established.

Data used to construct the more detailed climatic record for the latest Pleistocene and Holocene come from six independent lines of evidence dated using carbon-14 techniques: plant communities preserved in packrat middens throughout the Southwest, including sites in Eddy and Otero Counties, New Mexico (Van Devender, 1980; Van Devender et al., 1984, 1987); pollen assemblages from lacustrine deposits in western New Mexico and other locations in the Southwest (Markgraf et al., 1984; Van Devender et al., 1987); gastropod assemblages from western Texas (Pierce, 1987); ostracode assemblages from western New Mexico (Markgraf et al., 1984); paleo-lake levels throughout the Southwest (Markgraf et al., 1983, 1984; Benson and Thompson, 1987; Holliday and Allen, 1987; Bachhuber, 1989; Waters, 1989; Enzel et al., 1989); and faunal remains from caves in southern New Mexico (Harris, 1987, 1988). Figure VII-3 shows the locations of key sites discussed here and in the references cited.

Because decreases in temperature and increases in precipitation produce similar environmental changes, not all data cited uniquely requires the paleocli-

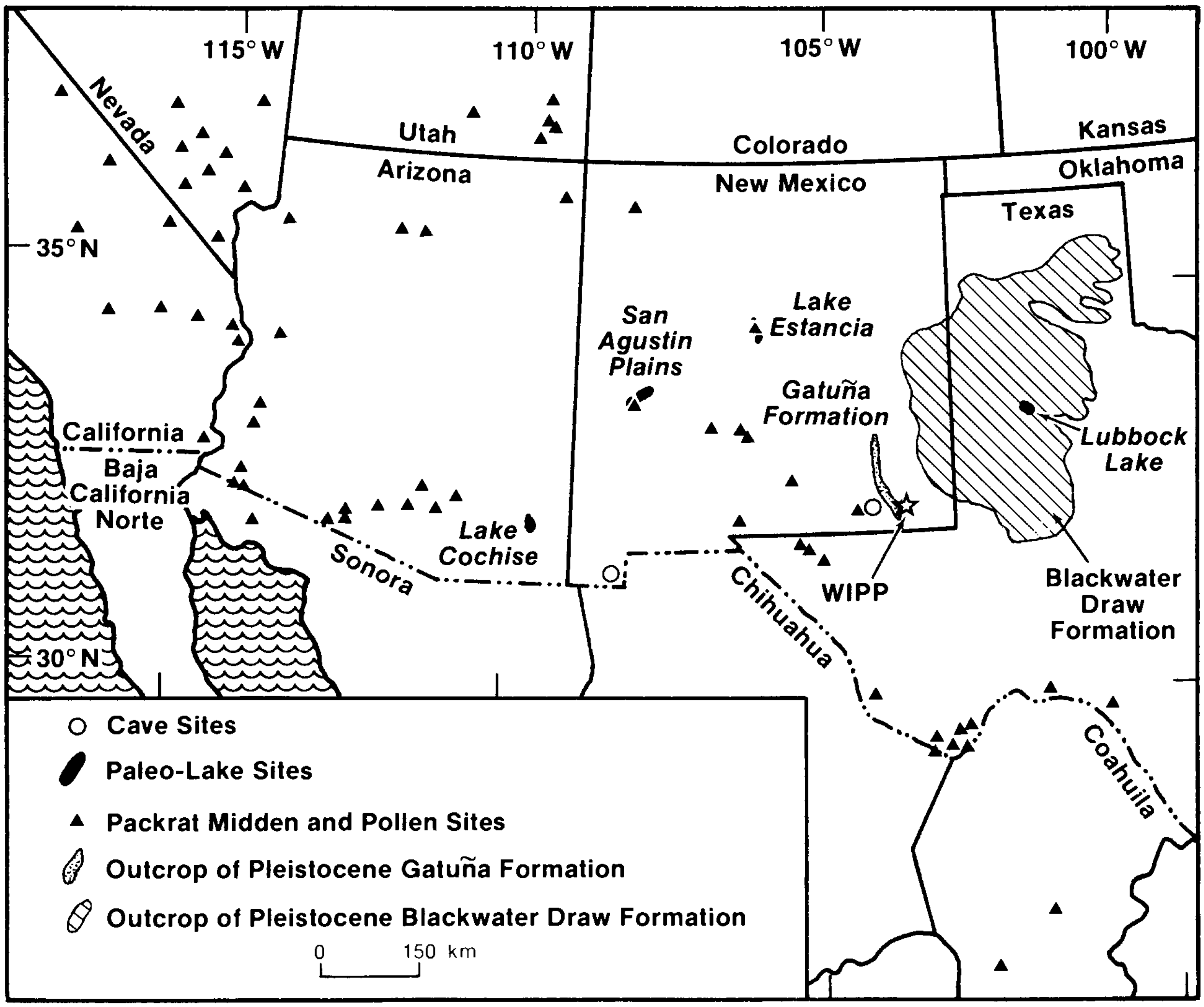

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Figure VII-3. Location Map for Paleoclimate Data. Data from Bachman, 1981; Markgraf et al., 1983; Harris, 1987; Pierce, 1987; Van Devender et al., 1987; Waters, 1989; Bachhuber, 1989; Holliday, 1989a.

matic interpretation presented in this report (Figure VII-4). For example, lake-level increases can, in theory, result solely from decreased evaporation at lower temperatures. Interpretations drawn individually from each of the data sets are consistent with the overall trends, however, and the pattern of change is confirmed by global climate models (Spaulding and Graumlich, 1986; Kutzbach and Guetter, 1986; COHMAP Members, 1988). Furthermore, specific floral and faunal assemblages are sufficiently sensitive to precipitation and temperature effects to distinguish between the two (e.g., Van Devender et al., 1987; Pierce, 1987). The paleoclimates described here are those that best explain data from all sources.

Prior to the last glacial maximum 22 to 18 ka BP, evidence from mid-Wisconsin faunal assemblages in caves in southern New Mexico, including the presence of extralimital species such as the desert tortoise, which are now restricted to warmer climates, suggests hot summers and mild, dry winters (Harris, 1987, 1988). Lacustrine evidence confirms the interpretation of a relatively dry climate prior to and during the glacial advance. Permanent water did not appear in what was later to be a major lake in the Estancia Valley in central New Mexico until sometime before 24 ka BP (Bachhuber, 1989), and water depths in lakes at higher elevations in the San Agustin Plains in western New Mexico did not reach a maximum until between 22 and 19 ka BP (Forester, 1987).

Ample floral and lacustrine evidence documents cooler and wetter conditions in the Southwest during the glacial peak (e.g., Benson and Thompson, 1987; Van Devender et al., 1987; Pierce, 1987; Bachhuber, 1989). These changes were not caused by the immediate proximity of glacial ice. None of the Pleistocene glaciations advanced farther southwest than northeastern Kansas, and the most recent, late-Wisconsin ice sheet reached its limit in South Dakota, roughly 1200 km from the WIPP (Andrews, 1987). Discontinuous alpine glaciers formed at the highest elevations throughout the Rocky Mountains, but these isolated ice masses were symptoms, rather than causes, of cooler and wetter conditions, and had little influence on regional climate at lower elevations. The closest such glacier to the WIPP was on the northeast face of Sierra Blanca Peak in the Sacramento Mountains, 220 km to the northwest (Richmond, 1962).

Global climate models indicate that the dominant glacial effect in the Southwest was the disruption and southward displacement of the westerly jet stream by the physical mass of the ice sheet to the north (Figure VII-5) (Manabe and Broccoli, 1985; Kutzbach and Guetter, 1986; COHMAP members, 1988). At the glacial peak, major Pacific storm systems followed the jet stream across New Mexico and the southern Rocky Mountains, and winters were wetter and longer than either at the present or during the previous interglacial period.

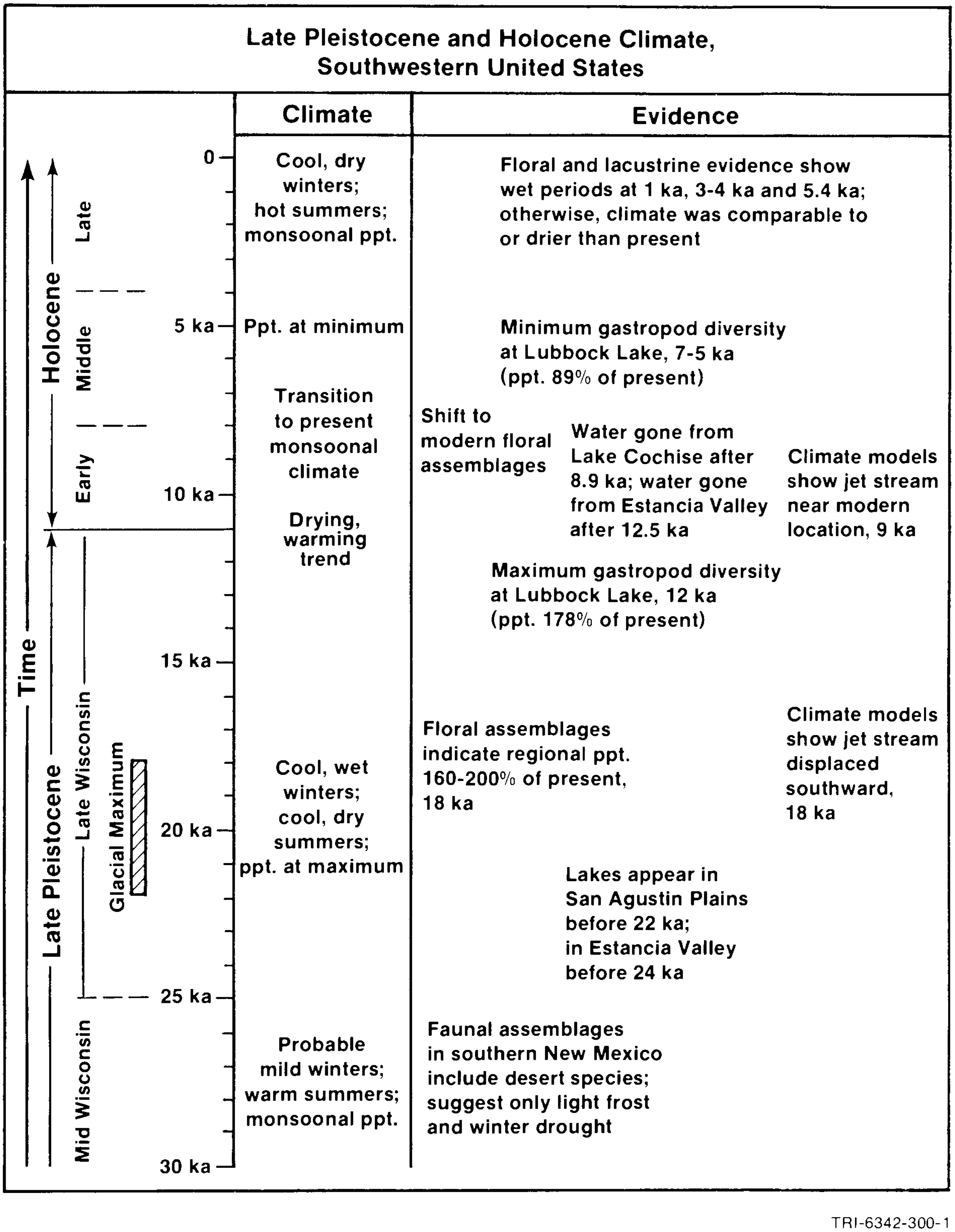

Figure VII-4. Late Pleistocene and Holocene Climate, Southwestern United States. Time scale after Van Devender et al., 1987. Climate references cited in text.

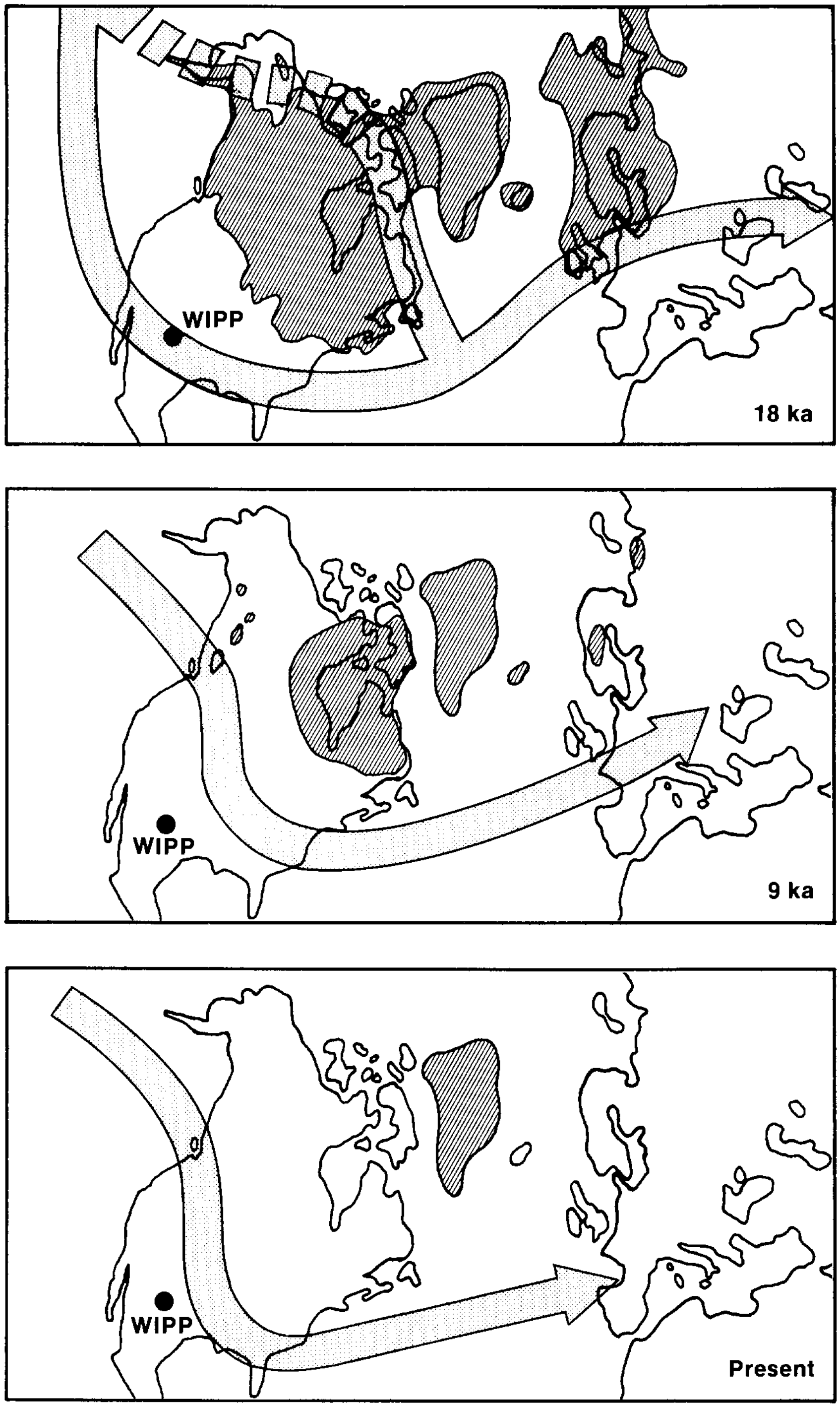

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Figure VII-5. Distribution of Northern Hemisphere Ice Sheets and Modeled Average Position of Jet Stream at 18 ka BP, 9 ka BP, and Present (from COHMAP Members, 1988). Ice shown with dark pattern, jet stream shown with arrow (broken where disrupted or weak).

Field evidence does not support the suggestion (Galloway, 1970, 1983; Brakenridge, 1978) that higher lake levels and changed faunal and floral assemblages at the glacial maximum could have resulted solely from lowered temperatures. Plant communities indicate the decrease in mean annual temperatures below present values was significantly less than the 7 to 12°C required by cold and dry climate models (Van Devender et al., 1987). Gastropod assemblages at Lubbock Lake in western Texas suggest mean annual temperatures 5°C below present values (Pierce, 1987). Both floral and faunal evidence indicate annual precipitation throughout the region was 60 to 100 percent more than today (Spaulding and Graumlich, 1986; Pierce, 1987; Van Devender et al., 1987). Floral evidence also suggests winters may have continued to be relatively mild, perhaps because the glacial mass blocked the southward movement of arctic air. Summers at the glacial maximum were cooler and drier than at present, without a strongly developed monsoon. Piñons, oaks, and junipers grew at lower elevations throughout southern New Mexico (Van Devender et al., 1987), probably including the vicinity of the WIPP.

The jet stream shifted northward following the gradual retreat of the ice sheet after 18 ka BP (Figure VII-5), and the climate responded accordingly. By the Pleistocene/Holocene boundary approximately 11 ka BP, conditions were significantly warmer and drier than previously, although still dominated by winter storms and still wetter than today (Van Devender et al., 1987). Major decreases in total precipitation and the shift toward the modern monsoonal climate did not occur until the ice sheet had retreated into northeastern Canada in the early Holocene.

Evidence for an early Holocene drying trend comes from several sources. Permanent water disappeared from late-Pleistocene lakes in the Estancia Valley after 12.5 ka BP (Bachhuber, 1989), and from Lake Cochise (the modern Willcox Playa) in southeastern Arizona after 8.9 ka BP (Waters, 1989). Water remained in lakes in the higher elevation San Agustin Plains until 5 ka BP, but ostracode assemblages suggest an increase in salinity by 8 ka BP, and the pollen record shows a gradual shift at that location from a spruce-pine forest 18 to 15 ka BP to a juniper-pine forest by 10 ka BP (Markgraf et al., 1984). Packrat middens in Eddy County, New Mexico, indicate that desert-grassland and desert-scrub communities predominated at lower elevations between 10.5 and 10 ka BP (Van Devender, 1980). Soil studies indicate drier conditions at Lubbock Lake after 10 ka BP, although marshes and small lakes persisted at the site until the construction of a dam and reservoir in 1936 (Holliday and Allen, 1987). Based on a decrease in diversity of both terrestrial and aquatic gastropod species, Pierce (1987) estimated a drop in annual precipitation at Lubbock Lake from a high of 80 cm/yr (nearly twice the modern level at that location of 45 cm/yr) at 12 ka BP to 40 cm/yr by 7 ka BP. Coincident with this decrease in precipitation, evidence from vole remains recovered from caves in southern New Mexico (Harris, 1988) and from plant communities throughout the Southwest (Van Devender et al., 1987) indicates a rise in summer temperatures.

By mid-Holocene time, the climate was similar to that of the present, with hot, monsoon-dominated summers and cold, dry winters. The pattern has persisted to the present, but not without significant local variations. Soil studies show the southern High Plains were drier from 6.5 to 4.5 ka BP (Holliday, 1989b) than before or since. Gastropod data from Lubbock Lake indicate the driest conditions from 7 to 5 ka BP (precipitation 89 percent of present, mean annual temperature 2.5°C higher than present), with a cooler and wetter period at 1 ka BP (precipitation 145 percent of present, mean annual temperature 2.5°C lower than present) (Pierce, 1987). Plant assemblages from southwestern Arizona suggest steadily decreasing precipitation from the middle Holocene to the present, except for a brief wet period around 990 years ago (Van Devender et al., 1987). Stratigraphic work at Lake Cochise shows two mid-Holocene lake stands, one near or before 5.4 ka BP and one between or before 3 to 4 ka BP, but both were relatively short-lived, and neither reached the maximum depths of the late-Pleistocene high stand that existed before 14 ka BP (Waters, 1989).

Precipitation maxima during these Holocene wet periods were less in both magnitude and duration than those of the late Pleistocene. Enzel et al. (1989) observed comparable Holocene wet periods recorded in playa deposits in the Mojave Desert 3620 ± 70 and 390 ± 90 years ago, and related them to short-term changes in global circulation patterns that resulted in increased winter storm activity in the region. Historical records over the last several hundred years indicate numerous lower intensity climatic fluctuations, some too short in duration to affect floral and faunal assemblages, which may also be the result of temporary changes in global circulation (Neilson, 1986). Sunspot cycles and the related changes in the amount of energy emitted by the sun have been linked to historical climatic changes elsewhere in the world (e.g., Lamb, 1972), but the validity of the correlation is uncertain (Robock, 1979). Correlations have also been proposed between volcanic activity and climatic change (Robock, 1979; Bryson, 1989). In general, however, causes for past short-term changes are unknown, and it is difficult at present to accurately predict frequency or amplitude of recurrence. Despite this uncertainty, the past record does support the conclusion that future short-term fluctuations in the Southwest will not be as severe as the long-term climatic changes created by major ice sheets in the northern hemisphere. Full-glacial conditions remain a conservative upper limit for precipitation at the WIPP during the next 10 ka.

Climatic Implications of Data from WIPP Ground-Water Samples

Isotopic data from ground-water samples collected from the Rustler and Dewey Lake Formations in the vicinity of the WIPP are generally consistent with the climatic changes described above. Lambert (1986) and Lambert and Harvey (1987) concluded that although deuterium/hydrogen and $^{18}O/^{16}O$ ratios indicate a meteoric origin for water in the confined aquifers, they are sufficiently distinct from modern surface-water values to suggest that the contribution of modern recharge to the system is slight. Chapman (1986) disagreed with this interpretation, noting similar ratios in the presumably young waters of the Roswell Artesian Basin immediately to the north, and she concluded that stable-isotope data from the WIPP area do not permit interpretations about the age of the ground water. Tritium data are less ambiguous. Low tritium levels in all WIPP-area samples indicate minimal contributions from the atmosphere since 1950 (Lambert, 1987; Lambert and Harvey, 1987). The four internally consistent radiocarbon analyses currently available for water samples from the Rustler and Dewey Lake Formations support this interpretation. Modeled minimum ages in each case are between 12 and 16 ka, suggesting that both units have had little recharge since the period immediately following the late-Pleistocene glacial maximum (Lambert and Harvey, 1987). Lambert and Carter (1987) presented uranium isotope data that also support this interpretation: observed high $^{234}U/^{238}U$ activity ratios require a conservative minimum residence time in the Culebra Dolomite of several thousands of years, and more probably reflect minimum ages of 10 to 30 ka. Chapman (1988) questioned the validity of equating isotope residence times with ground-water age, but agreed that high $^{234}U/^{238}U$ activity ratios occur in regions of low transmissivity, where flow is presumably slower and residence times are longer. Lappin et al. (1989) used ground-water isotope data, along with supporting evidence from $^{87}Sr/^{86}Sr$ ratios in vein fillings, to argue that the Rustler Formation has been essentially a closed hydrologic system for the last 12 ka. In their interpretation, significant recharge last occurred during the late Pleistocene, and the present flow in the Culebra Dolomite reflects the slow draining of the aquifer. If this interpretation is correct, recharge may not occur again until precipitation levels are substantially higher than at present.

Other data suggest that, isotopic evidence notwithstanding, some recharge may be occurring at the present. Anomalous increases in water levels have been observed at 7 WIPP-area wells since hydraulic tests at the H-11 multipad in 1988 (Beauheim, 1989). Vertical recharge from the surface cannot be ruled out as a cause for these rises, although no specific link to precipitation events has been demonstrated. Other possible causes include decreases in discharge from the Culebra Dolomite, changes in reservoir volume related to incomplete recovery from the transient pressure changes associated with the pumping test itself, changes in reservoir volume related to external changes in the regional stress field, or undetected recharge from other aquifers through existing boreholes (Beauheim, 1989). Numerical modeling of ground-water flow in the WIPP area indicates that, although it is hydraulically possible for present flow to reflect late-Pleistocene recharge (Davies, 1989), some component of modern vertical recharge is also compatible with observed conditions (Haug et al., 1987; Davies, 1989). Major ion chemical analyses of Culebra Dolomite water samples support the interpretation of vertical recharge south of the WIPP, where low salinities may be the result of mixing with fresh surface water (Chapman, 1988). Lappin et al. (1989) suggested instead that water chemistry is a function of host rock composition, noting that ground-water salinity correlates well with the distribution of halite in the Rustler Formation.

Questions about vertical recharge to the Culebra Dolomite and the true age of WIPP-area ground water remain unanswered. In the absence of definitive data, this report makes no assumptions about ground-water age, and conservatively allows the possibility of recharge under present climatic conditions.

Summary of Climate Variability

Speculation about future climate variability must be based on observed past fluctuations. The largest global climatic changes in the last 2.5 Ma have been those associated with glaciation and deglaciation in the northern hemisphere. The high degree of consistency in both frequency and intensity displayed in the glacial record indicates that an accurate interpretation of past climatic cycles does provide a useful guide for estimating future changes.

Geologic data from the American Southwest show repeated alternations of wetter and drier climates throughout the Pleistocene. Floral, faunal, and lacustrine data permit detailed and quantitative reconstructions of precipitation that can be linked directly to glacial events of the late Pleistocene and Holocene. Figure VII-6 shows estimated mean annual precipitation for the WIPP for the last 30 ka, interpolated from the composite regional data cited above and based on present average precipitation at the site of 30 cm/yr (Brinster, 1991). This plot should be interpreted with caution because its resolution and accuracy are limited by the nature of the data used to construct it. Floral and faunal assemblages change gradually, and show only a limited response to climatic fluctuations that occur at frequencies higher than the typical life span of the organisms in question. For long-lived species such as trees, resolution may be limited to hundreds or even thousands of years (Neilson, 1986). Sedimentation in lakes and playas has

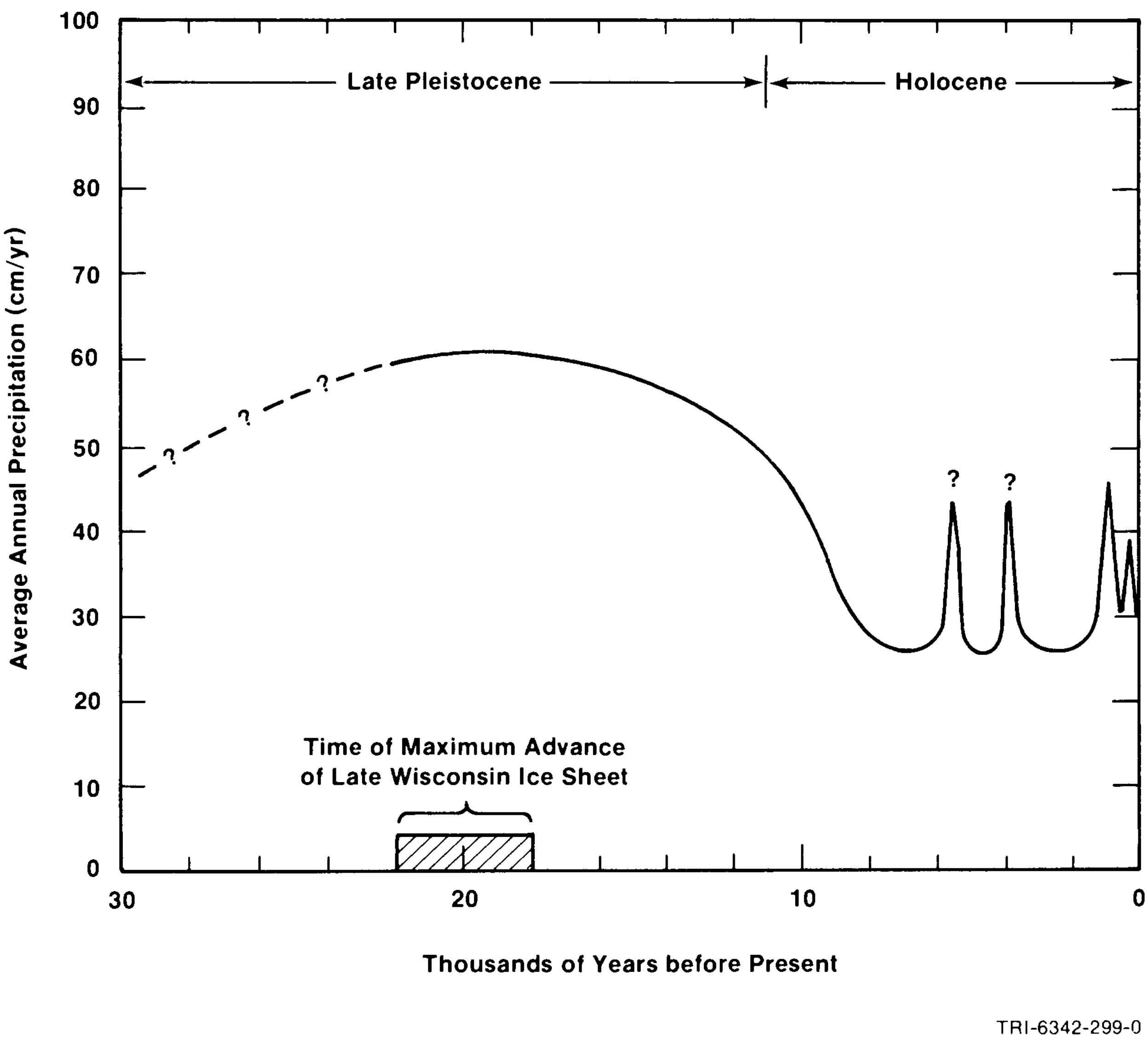

Figure VII-6. Estimated Mean Annual Precipitation at the WIPP during the Late Pleistocene and Holocene. Data from Van Devender et al., 1987; Pierce, 1987; Waters, 1989; and other sources cited in text.

the potential to record higher frequency fluctuations, including single-storm events, but only under a limited range of circumstances. Once water levels reach a spill point, for example, lakes show only a limited response to further increases in precipitation. Dry playas generally show little response to decreases in precipitation. A more complete record of precipitation would almost certainly show far more variability than that implied by the plot presented here. Specifically, Figure VII-6 may fail to record abnormal precipitation lows during the Holocene, and it may also underestimate the number of high-precipitation peaks during the same period. It is also possible that precipitation variability during the Pleistocene was comparable to that of the Holocene, with fluctuations occurring above and below the higher average level indicated in Figure VII-6.

With these observations in mind, three significant conclusions can be drawn from the climatic record of the American Southwest. First, maximum precipitation in the past coincided with the maximum advance of the North American ice sheet. Minimum precipitation occurred after the ice sheet had retreated to its present limits. Second, past maximum long-term average precipitation levels were roughly twice present levels. Minimum levels may have been 90 percent of present levels. Third, short-term fluctuations in precipitation have occurred during the present, relatively dry, interglacial period, but they have not exceeded the upper limits of the glacial maximum.

It would be unrealistic to attempt a direct extrapolation of the precipitation curve of Figure VII-6 into the future. Too little is known about the relatively short-term behavior of global circulation patterns, and it is at present difficult to accurately predict the probability of a recurrence of a wetter climate such as that of approximately 1000 years ago. The long-term stability of patterns of glaciation and deglaciation, however, do permit the conclusion that future climatic extremes are unlikely to exceed those of the late Pleistocene. Furthermore, the periodicity of glacial events suggests that a return to full-glacial conditions is highly unlikely within the next 10,000 years.

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VIII. AGRICULTURE AND CLIMATIC CHANGE AT THE WASTE ISOLATION PILOT PLANT

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ABSTRACT

Grazing of native rangeland is the only agricultural use of more than 90 percent of land in southeastern New Mexico, including the immediate vicinity of the Waste Isolation Pilot Plant (WIPP). Irrigated crops and pasturage are grown west of the WIPP along the Pecos and Black Rivers and east of the WIPP on the southern High Plains. The nearest nonirrigated crops are approximately 70 km northeast, in northeastern Lea County, New Mexico.

If climatic changes in the next 10,000 years result in an increase in average annual precipitation to twice present levels, the productivity of native rangeland will be greatly increased, dryland farming of a wide range of crops will be possible throughout the region where soil quality permits, and more water will be available for irrigation. Because of relatively poorer soils and abundant sand at the WIPP, it is possible that, even with increased precipitation, grazing will remain the primary agricultural use of the site.

Introduction

This report provides a brief review of current agricultural practices in southeastern New Mexico. The report is intended only to be an informative outline of the subject and other sources should be consulted for detailed information. Observations made here about future agricultural potential of the region are purely speculative. Detailed research has not been done concerning soil fertility and the specific requirements of various crops. Economic and cultural controls on agricultural activity are not considered. Interpretations of future potential are based on the premise that climate will change, and that increases in precipitation will result in a potential increase in agricultural uses of the land. In keeping with available climatic data (Swift, 1991), the upper limit for long-term average precipitation during the next 10,000 years is assumed to be twice the present level. Actual increases in precipitation are likely to be less, and it is also possible that there will be extended periods in which precipitation is somewhat less than at present.

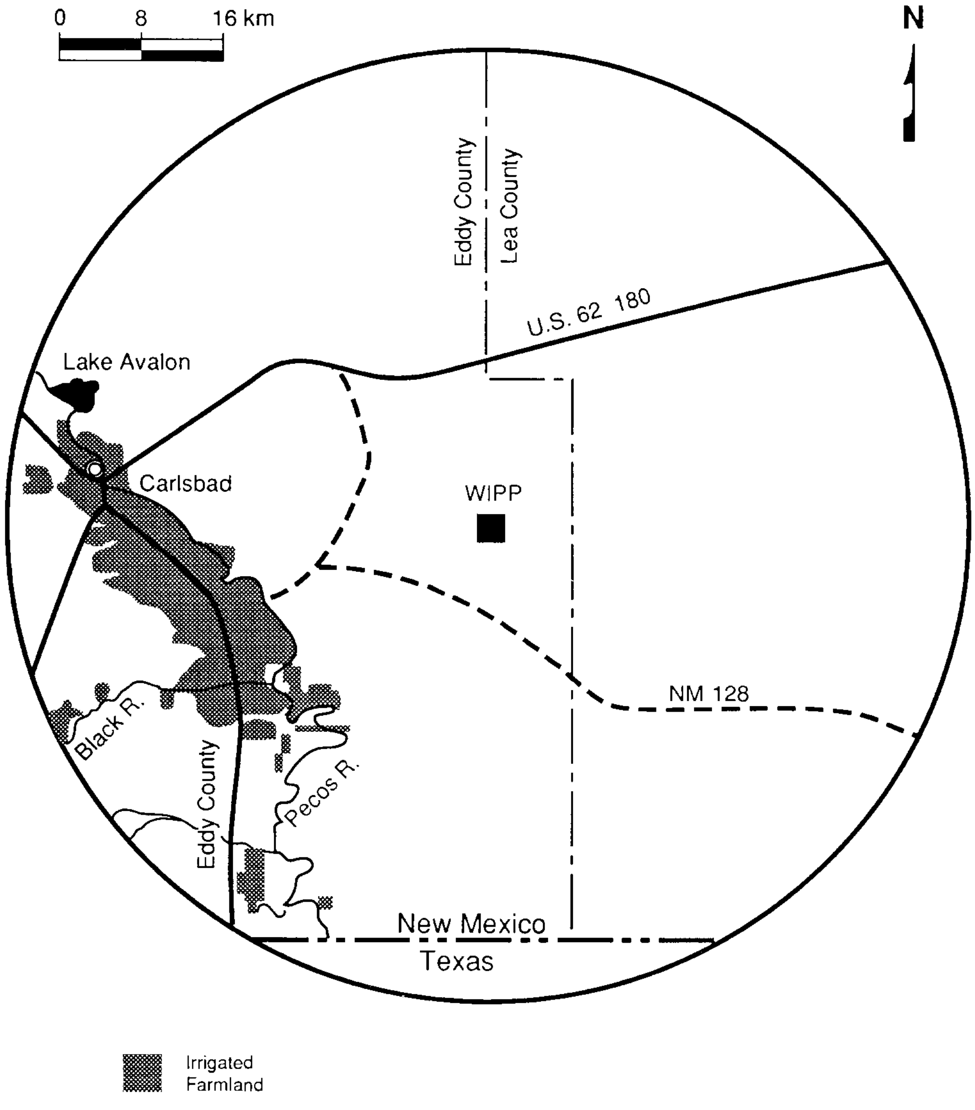
Present Agriculture in the Vicinity of the WIPP

Most of southeastern New Mexico, including the Waste Isolation Pilot Plant (WIPP) and vicinity, is covered by native vegetation used only for grazing cattle. Rangeland covers approximately 97 percent of Eddy County (Chugg, et al., 1971) and 90 percent of Lea County (Turner et al., 1974). The quality of the rangeland and the number of cattle it can support vary with soil type, precipitation, elevation, topography, and the availability of surface water. In the vicinity of the WIPP, rangeland currently supports between six and nine head of cattle per square mile (U.S. DOE, 1980). Where soils near the WIPP are not buried by unconsolidated dune sand, they can be productive of grasses and native vegetation, given adequate rainfall and protection from overgrazing (Chugg et al., 1971). Potential productivity of crops is unknown because water for irrigation is unavailable, but it is believed to be low because of the coarse texture and low fertility of the soil. In addition to irrigation and fertilization, the growing of crops in the immediate vicinity of the WIPP would require stabilization of the soil to prevent wind erosion and burial by blowing sand (Chugg et al., 1971).

Irrigated cropland in Eddy County is restricted almost entirely to the immediate vicinity of the Pecos and Black Rivers, where soils are relatively more fertile and water is available for irrigation (Figure VIII-1). Crops include cotton, alfalfa, sorghum, and grains (Chugg et al., 1971; Hunter, 1985). From Avalon Dam upstream of Carlsbad south to the Texas border, about 80 percent of irrigation is with surface water taken from the Pecos and Black Rivers. Shallow wells in alluvial aquifers near the rivers provide most of the remaining irrigation water (Hunter, 1985).

Irrigated cropland in Lea County is located in the eastern and northern portion of the county, on the southern High Plains. Crops include cotton, grain, sorghum, alfalfa, and some vegetables. There are no perennial streams in Lea County, and all water for irrigation is pumped from the Ogallala Formation, a shallow aquifer not present in the vicinity of the WIPP (Turner et al., 1974). Withdrawal rates greatly exceed recharge, and irrigated agriculture cannot be sustained indefinitely in Lea County at its present level without additional, and as yet unidentified, sources of water. As of 1974, Turner et al. (1974, p. 85) noted that "under present controls, a minimum of 40 years of development appears assured."

There are essentially no crops grown without irrigation in Eddy County (Chugg et al., 1971). Dryland farming is practiced in a limited portion of northeastern Lea County, on the southern High Plains 70 km or more northeast of the WIPP. Crops successfully grown without irrigation include grains and



From: U.S. DOE, 1980.

Source: Bureau of Reclamation Land Use Map, 1968; New Mexico Bureau of Mines and Mineral Resources, New Mexico Energy Resources Map, 1974; Adcock and Associates, field surveys, 1978.

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Figure VIII-1. Irrigated Farmland within 48 km (30 mi) of the WIPP.

cotton (Turner, et al., 1974). The relative success of dryland farming is dependent in large part on adequate rainfall. Average annual precipitation at the WIPP has been estimated to be between 28 and 34 cm/yr (Hunter, 1985). Lovington, in central Lea County 62 km northeast of the WIPP, receives approximately 39 cm/yr, and precipitation levels increase eastward and northward, reaching 45 cm/yr at Lubbock, Texas, 125 km northeast of the WIPP (Turner et al., 1974; Pierce, 1987). A minimum of approximately 40 cm/yr of precipitation appears to be required for dryland farming under present conditions. Soil quality, temperature, and variability and seasonality of precipitation are also factors influencing the success or failure of nonirrigated crops.

Possible Future Agriculture in the Vicinity of the WIPP

Agriculture in the future will be constrained by the same major factors that control present land use: the availability of water, the length of the growing season, and the fertility of the soil. Climatic changes will significantly affect the availability of water. As discussed elsewhere (Swift, 1991), for some time periods within the next 10,000 years, southeastern New Mexico may receive substantially more average annual precipitation than at present, with maximum levels probably not exceeding twice present. The seasonal distribution of precipitation may also change, possibly resulting in a more uniform availability of moisture throughout the year. Climatic changes may also alter the length of the growing season, but probably not sufficiently to affect agricultural activities. Soil characteristics will change in response to climate changes, but changes may occur too slowly to be of significance during the next 10,000 years. For example, the Berino soil, which underlies dune sand at the WIPP, has been estimated to be 350,000 years old (Bachman, 1987). The discussion presented here tacitly assumes that, in the absence of major human efforts to improve soil quality, soils in the vicinity of the WIPP will remain comparable to those of the present. The assumption warrants further examination because soils can develop under favorable conditions in time periods considerably shorter than 10,000 years (Birkeland, 1984).

A doubling of average annual precipitation will increase the amount of both surface water and ground water available for irrigation. It will make dryland farming of a wide variety of crops feasible throughout the region wherever soil quality and topography permit. It will greatly increase the productivity of native rangeland, allowing more cattle to be grazed on the same acreage. Doubling precipitation will not, however, transform the landscape into lush farmland. Vegetation in southeastern New Mexico during the wet climate of the last glacial maximum was still dominated by plants of the semi-arid West: piñons, junipers, and oaks. Precipitation levels approximately twice those estimated for the WIPP are found today in the United States in a north-south belt through the Great Plains roughly between 98° and 100° W longitude (Espenshade and Morrison, 1980). Examples include portions of west-central Oklahoma, the Sand Hills of Nebraska, and the Edwards Plateau of central Texas (e.g., Mobley and Brinlee, 1967; Allison et al., 1975; Moffatt and Conradi, 1979; Indra et al., 1988). Not all land within these regions is suitable for farming, and large areas of poorer soils are used exclusively for grazing. It is possible, and perhaps likely, that the poorer, sandier soils of southeastern New Mexico, including those in the immediate vicinity of the WIPP, will continue to be used for grazing rather than for crops, regardless of climate change.

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IX. A HISTORICAL PERSPECTIVE OF CULTURAL DEVELOPMENT IN SOUTHEASTERN NEW MEXICO

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The archaeological and historical record of the Waste Isolation Pilot Plant (WIPP) area in Eddy County, New Mexico, is largely incomplete. Anthropologists and archaeologists are not in agreement as to the cultural sequence of prehistoric southeastern New Mexico, and a historical survey of this region of the state has yet to be written. Descriptions of prehistoric and historic cultures, therefore, must be gleaned from a variety of sources. Moreover, because cultural boundaries and historical events are not usually confined to well-delineated geographical or geological sections, any consideration of the history of the WIPP area must be made within the broader context of the cultural events and sequences of the southern Great Plains and the Pecos River Basin. This report summarizes existing knowledge about these larger regions with special attention, where possible, to developments specific to the WIPP area. For the prehistoric period, the focus is on the broader area of the Great Plains physiographic province. For the historical period, the focus is on the political division of Eddy County (Figures IX-1, IX-2, and IX-3). The text and references are intended to introduce the reader to the cultural history of southeastern New Mexico and suggest further avenues of research. Because of time constraints, no effort has been made to conduct extensive research in primary documents. Rather, this report is a survey based on a review of secondary-source material.

Prehistoric Peoples

Any discussion of prehistoric peoples in southeastern New Mexico must be pieced together from a variety of sources, as the archaeological record for this portion of the state is especially incomplete. The accepted chronology for New Mexico's prehistory, moreover, does not easily apply to the southeastern quadrant, where the cultural patterns and nature of cultural development were in many ways distinct from the rest of the state. Because of the lack of both factual information and a basic research methodology, accurate chronometric data for the southeastern quadrant is still nonexistent (Mariah Associates, 1987; Collins, 1971).

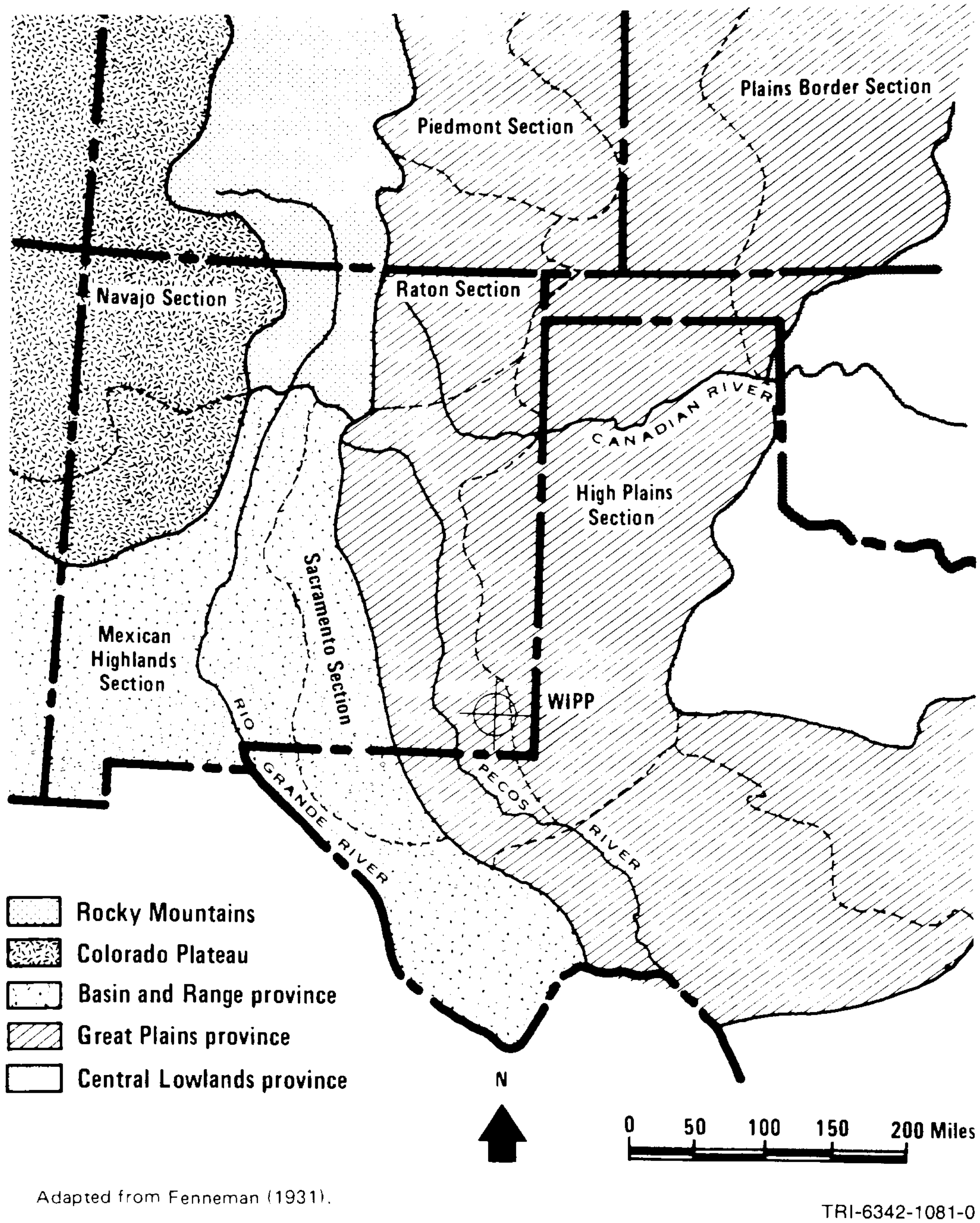

Figure IX-1. Physiographic Provinces and Sections of New Mexico (after U.S. DOE, 1980).

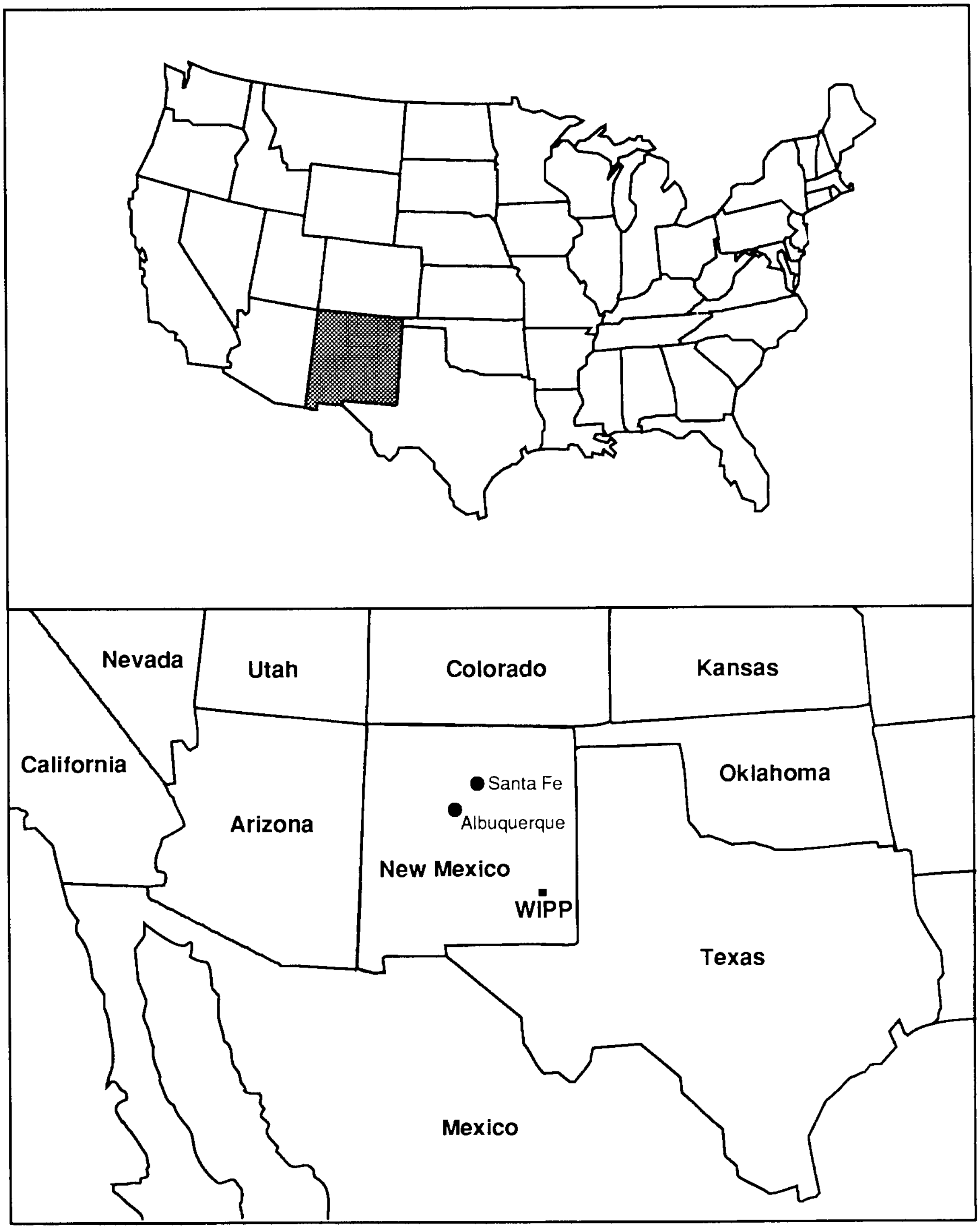

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Figure IX-2. Location of the WIPP in Southeastern New Mexico (after Williams, 1986).

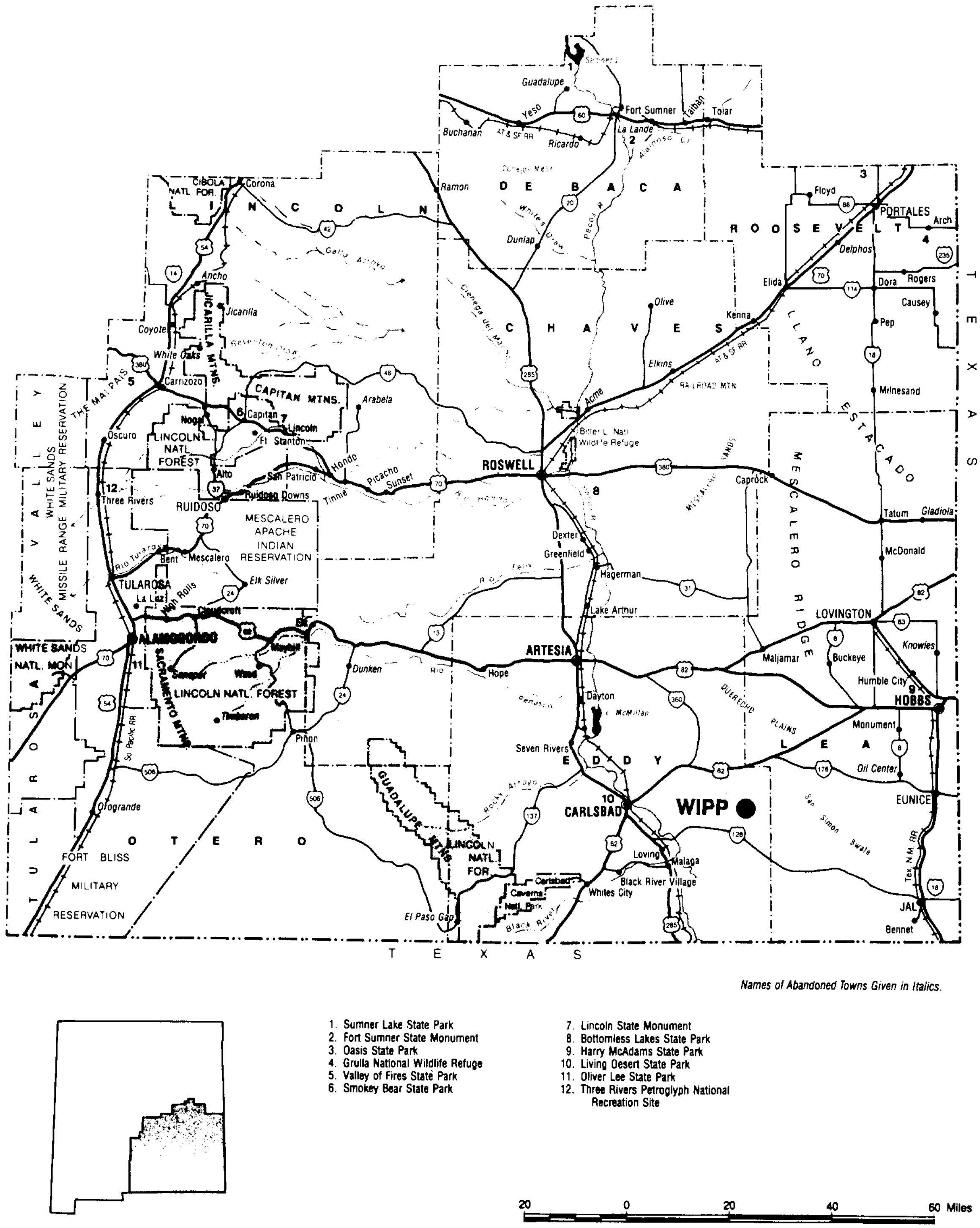

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Figure IX-3. Southeastern New Mexico (after Williams, 1986).

PALEO-INDIANS

There is evidence of human life in New Mexico as early as 10,000 B.C. The first residents, Paleo-Indians, were scavengers and hunters of mammoth and other big game. Archaeologists have identified several phases of the Paleo-Indian period in New Mexico, each distinguished by the characteristics of the projectile points used for hunting. These periods are the Clovis Period (approximately 9500-9000 B.C.), the Folsom-Midland Period (9000-8000 B.C), the Post-Folsom Period (dates uncertain), and the Cody Period (6800-6000 B.C.). All Paleo-Indian periods were characterized by bison hunting and gradual climatic drying and warming (Williams, 1986).

Paleo-Indians probably appeared on the plains of southeastern New Mexico beginning in 10,000 B.C. Projectile points, as well as several campsites, occupied intermittently by Paleo-Indian hunters beginning in 10,000 B.C., have been identified (Southeastern New Mexico Historical Society, 1982) (Figure IX-4).

In most of present-day New Mexico, the Paleo-Indian period ended by approximately 6000 B.C. In response to a drier climate, the big game animals and paleohunters retreated to the north and east, and the Archaic Period began. Archaic culture in New Mexico was influenced by the higher civilizations of Mexico. With the introduction of maize from Mexico, the Archaic hunter-gatherers made a slow transition to agriculture and sedentary life. By about 3000-2000 B.C., there is evidence of an agricultural revolution and the beginnings of village life. In the northern and western sections of the state, the Anasazi culture arose as the most important group of Archaic peoples. Between about 1 A.D. and 700 A.D. the Anasazi were in the Basket-Maker phase as a semi-agricultural people living in the San Juan drainage area (Figure IX-5).

This transition to Archaic culture was largely limited to the northwestern portion of the state. In southeastern New Mexico the Paleo-Indian phase persisted beyond 6000 B.C., and paleocultures were still present as late as 1000 A.D. Even after that date, the transition to the Archaic Period was incomplete (Mariah Associates, 1987). Little is known about the Paleo-Indians of southeastern New Mexico.

PUEBLO INDIANS

Archaeologists date New Mexico's pre- or proto-historic phase from approximately 900 A.D. In the northern and western parts of the state, this phase includes the beginning of the Pueblo cultural phase (about 700 A.D. to

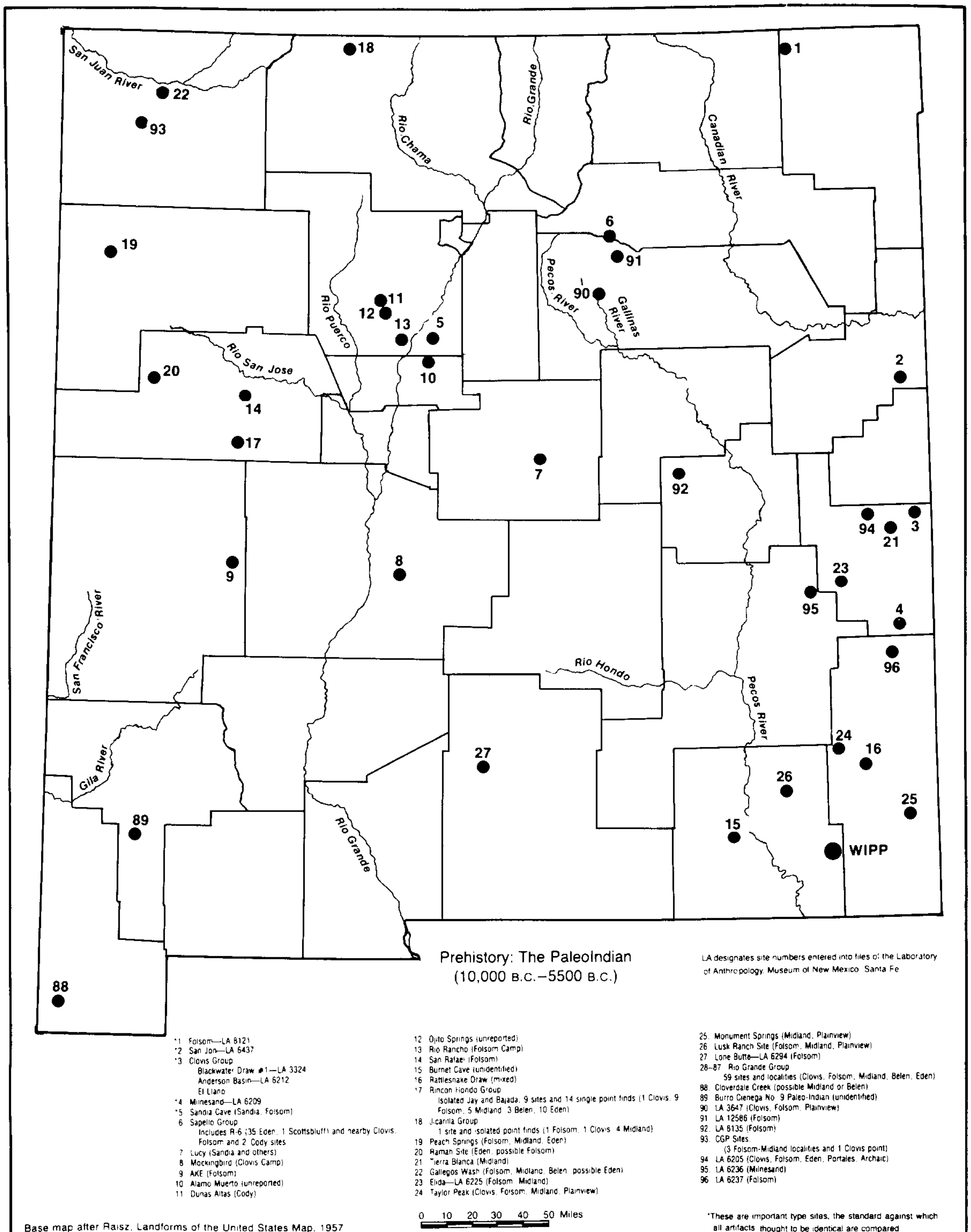

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Figure IX-4. Paleo-Indian Sites (after Williams, 1986).

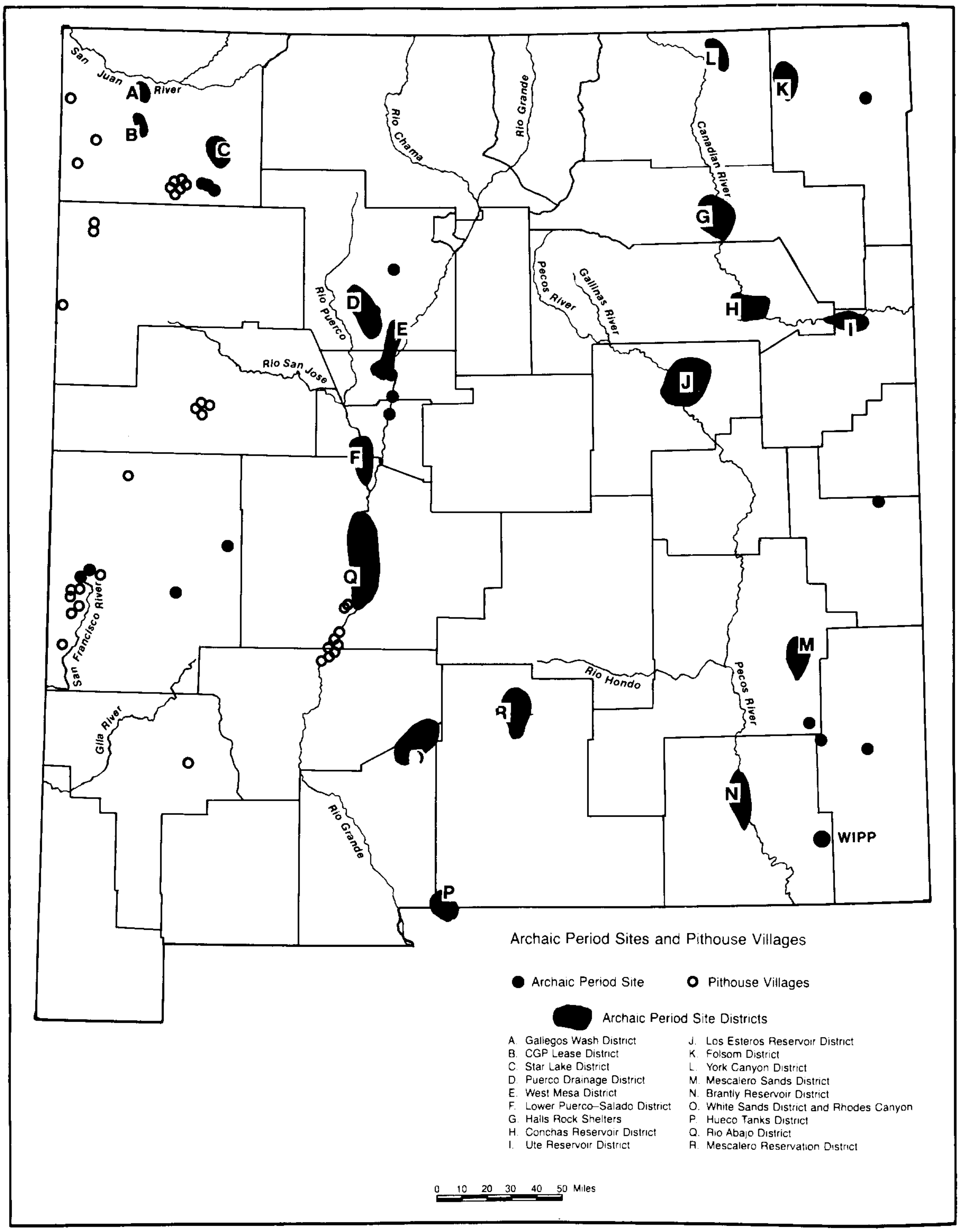

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Figure IX-5. Archaic Sites (after Williams, 1986).

the present). It was during this period that the Anasazi culture reached its height, with the complete transition to agriculture and sedentary life and the replacement of baskets with pottery. Anasazi culture culminated in the Great Pueblo Period (1000-1300 A.D.) with the development of the Chaco cultural system: a vast trade network extended over an area of 30,000 square miles (78,000 km^2) in the San Juan Basin.

Southeastern New Mexico probably did not experience the Pueblo cultural phase as did most other parts of the state. Instead, the proto-historic period was characterized by the late and incomplete transition from the Paleo hunter-gatherer culture to agriculture, village life, and the use of ceramics. Indeed, the subsistence pattern of hunting and gathering persisted beyond European contact in the sixteenth century. Native peoples hunted on the Plains east of the Pecos River, and gathered plant foods, particularly mescal (an agave plant with fleshy leaves and trunk which the Plains Indians baked and used as a staple food), west of the Pecos (Southeastern New Mexico Historical Society, 1982). Although the inhabitants of southeastern New Mexico did not have contact with the Anasazi culture to the north, archaeological evidence indicates that by 1000 A.D. they were interacting with another branch of the Pueblo farming cultures of the Southwest that began to appear during the Archaic Period in southern New Mexico--the Jornada Mogollon (Mariah Associates, 1987; Williams, 1986; Southeastern New Mexico Historical Society, 1982).

Although it is unclear whether the Jornada Mogollon penetrated into the study area, some scholars suggest that this culture extended onto the eastern plains of New Mexico and into the Llano Estacado region of Texas (Mariah Associates, 1987; Collins 1971; Williams, 1986). The extent to which the hunter-gatherer peoples of southeastern New Mexico were influenced by the more sedentary, agricultural Pueblo Indians is unclear. One indication that Plains cultures had significant contact with Pueblo peoples is the presence of southwestern ceramics in the archaeological record of the Llano Estacado. Collins (1971) suggests that the presence of ceramics can be explained in several ways: relatively permanent (and possibly Pueblo Indian) hunting and gathering communities may have existed in the area, agricultural Pueblo Indian communities may have existed in the area, or Plains peoples may have received Pueblo ceramics through trade.

While there was certainly some contact between the Plains inhabitants of southeastern New Mexico and the Pueblo Indian cultures, significant change in the subsistence strategy of the former group probably did not occur. The southeastern section remained on the fringes of the Mogollon area and only partially experienced the cultural flourishing (based on village life and dry farming) known as the Classic Mimbres phase that began about 1100 (Williams, 1986). It is possible, however, that native cultures of the southeastern

Plains practiced primitive agriculture in addition to hunting and gathering (Southeastern New Mexico Historical Society, 1982).

The flourishing of the Anasazi-Chaco culture and the Mogollon-Mimbres culture corresponds to what archaeologists call the Classic Period (approximately 900-1150 A.D.) (Figure IX-6). By 1150, the dry farming upon which these two cultures depended was in decline. Widespread drought caused these peoples to retreat to the mountains, ushering in the Upland Period of New Mexico's prehistory (approximately 1100-1300 A.D.). The Upland site nearest to the study area is the Bonnell site, north of present-day Eddy County (Figure IX-6) (Williams, 1986).

Beginning about 1300, renewed drought conditions upset the upland villages and forced movement to permanent streams and rivers. Most native peoples settled along the Rio Grande, and a series of droughts and floods forced them to move up and down the river as they shifted for survival. This period is known as the Riverine Period and lasted until about 1500 (Williams, 1986).

PREHISTORY: THE ARCHAEOLOGICAL RECORD

Archaeological investigation in New Mexico has traditionally emphasized the northern and western sections of the state. Scholars have only recently turned to extensive study of the southeastern quadrant. Archaeologists who have focused on the WIPP area have identified sites representative of all pre-historic and proto-historic cultures, including Paleo-Indian, Archaic, and Jornada Mogollon (U.S. DOE, 1980; Lord and Reynolds et al, 1985; Mariah Associates, 1987) (Figure IX-7). The most recent site-specific study (Mariah Associates, 1987) indicates that many archaeological sites are definitely or potentially eligible for nomination to the National Register of Historic Places, and recommends extensive data collection before the area is developed.

NOMADIC INDIANS: THE MESCALERO APACHE

Shortly before European contact in the sixteenth century, a nomadic group appeared in southeastern New Mexico. Part of the Athapaskan (or Athabaskan) linguistic grouping, the Apaches arrived in New Mexico about 1400 A.D. and worked their way onto the eastern Plains. Their origins and exact time of arrival are disputed. During migration to the Southwest, linguistic differentiation began and the Apaches divided into smaller groups. The two Apache groups appearing in the study area were the Mescalero and the Lipan. The Mescaleros, first distinguished as a separate tribe in the seventeenth century, predominated in the study area. They moved south through the Rio Grande Valley in the sixteenth and early seventeenth centuries, roaming east of the Pecos River into Texas (Opler, 1983).

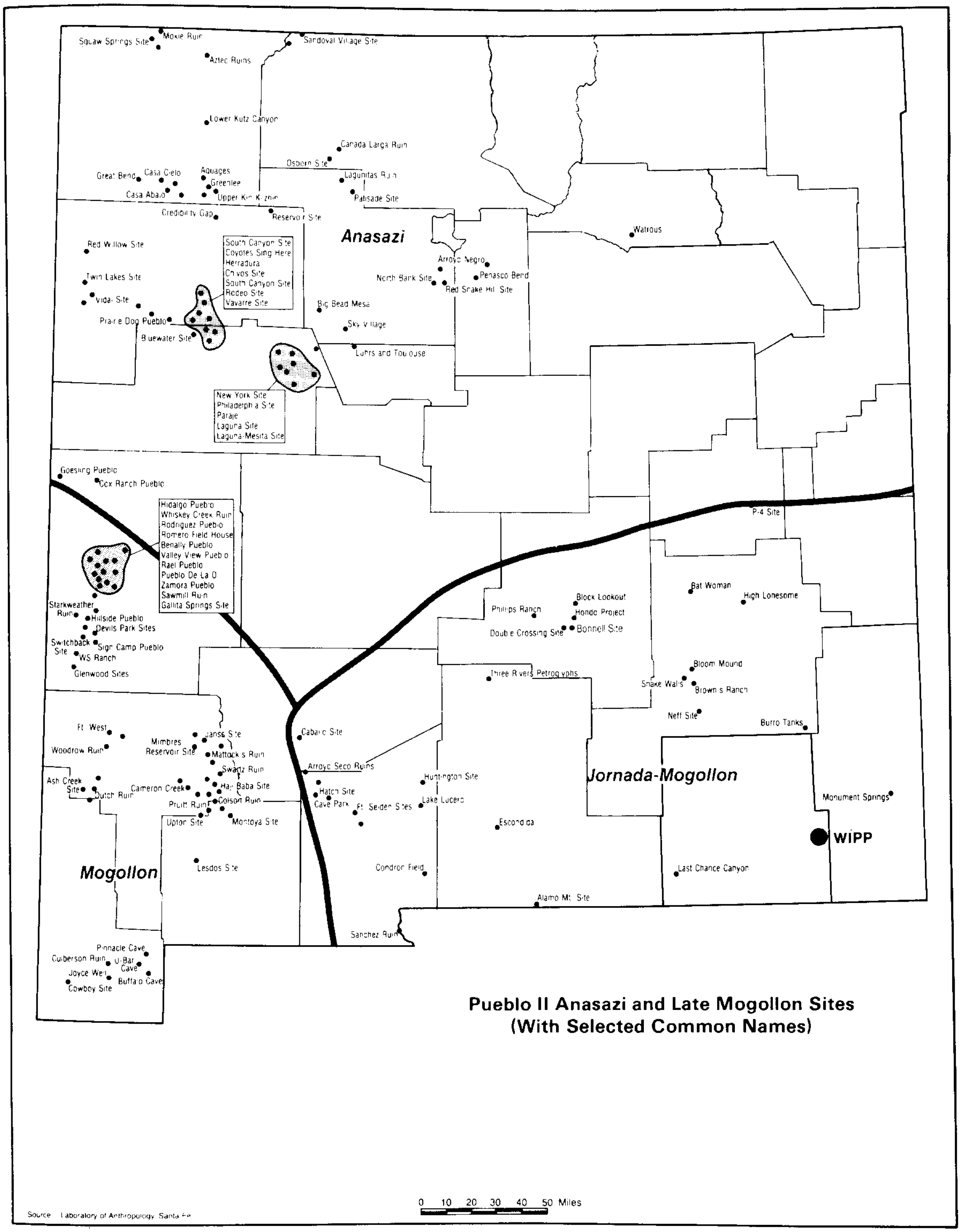

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Figure IX-6. The Basin Classic (after Williams, 1986).

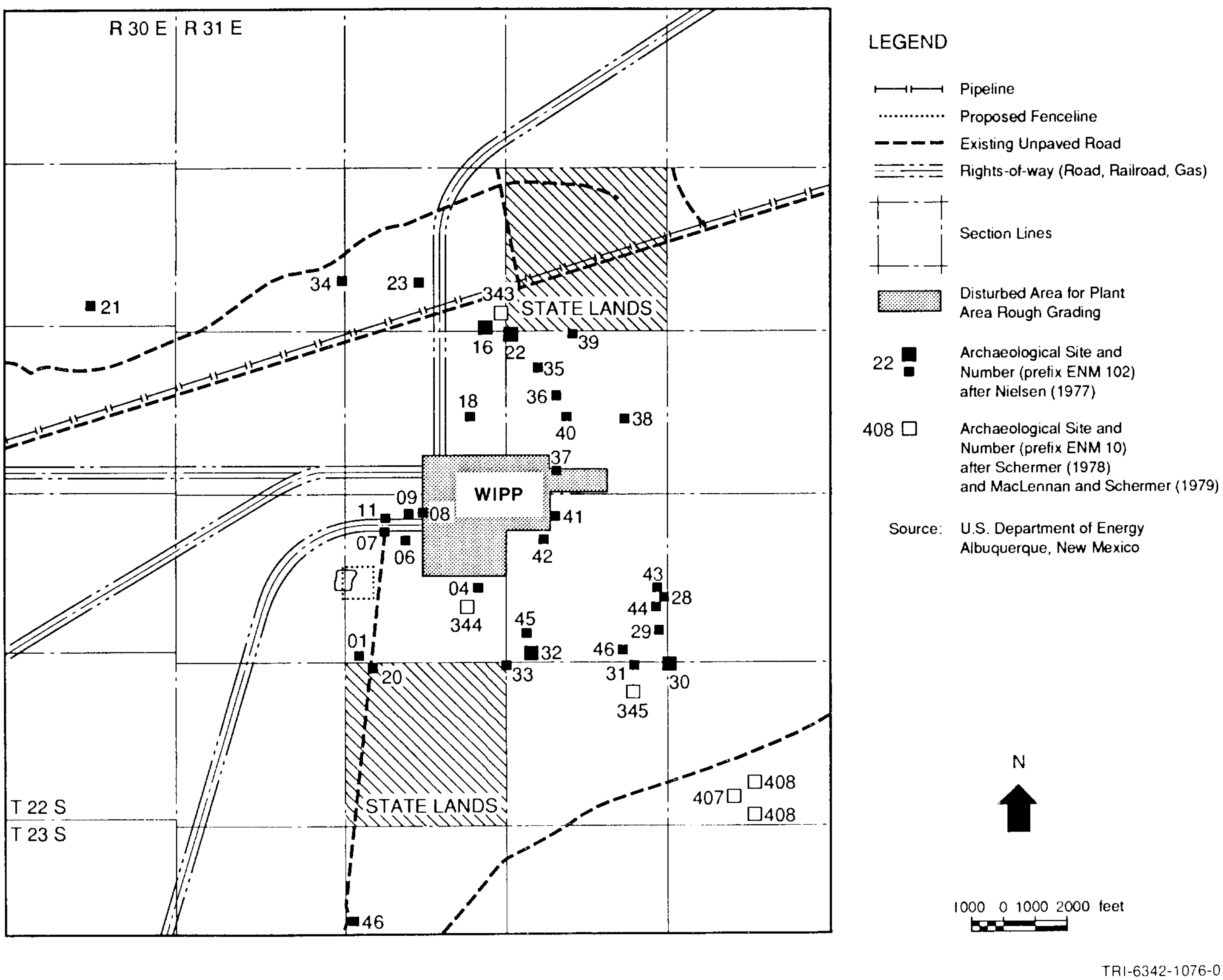

Figure IX-7. Archaeological Sites Identified in 1970s Studies.

From the seventeenth century until they were placed on a reservation in the mid-nineteenth century, the Mescaleros continuously occupied the same territory, from the Rio Grande eastward into Texas and southward into northern Mexico (Figure IX-8). The Mescalero encampments were located west of the Pecos River, but these Apaches journeyed east to hunt buffalo and antelope, find salt and horses, and campaign against enemies (Opler, 1983). They were constantly moving to keep up with the food supply, particularly their staple food, mescal (from which the tribe's name is derived). The Mescalero Apaches inhabited the Sacramento and Guadalupe mountains and overlapped onto the Plains. They were never numerous in the study area, but were in control of present-day Eddy County when Spaniards arrived (Sonnichsen, 1958; Southeastern New Mexico Historical Society, 1982).

Historic Cultures

EARLY SPANISH CONTACT

The first Spanish entries, or entradas, into New Mexico during the sixteenth century did not involve the study area (Figure IX-9). However, several Spaniards, including Francisco Vázquez de Coronado in 1540, encountered and described Plains Indians, including the Apaches and the Jumanos. The Jumano Plains Indians frequented the buffalo plains of Texas and New Mexico and were probably centered on the Rio Colorado in Texas (Kessell, 1987; Bolton, 1911). The first Spanish entrada to traverse the study area was led by Antonio de Espejo in 1582. Espejo's party was returning from northern New Mexico by way of the Pecos River, which Espejo dubbed the "Salt River," or the Rio Salado (Southeastern New Mexico Historical Society, 1982). Espejo apparently encountered no Indians until he reached Texas (Sheridan, 1975). The next expedition to pass through the area was the abortive colonizing expedition of Gaspar Castaño de Sosa in 1589-91. Castaño de Sosa's party encountered both Jumanos and Apaches, the latter group located west of Carlsbad in the Guadalupe Mountains and along the Pecos River. The Spaniards described a few rancherías (clusters of huts) in the Carlsbad area, but there was no real evidence of settlement (Mariah Associates, 1987; Sheridan, 1975).

Although the Espejo and Castaño de Sosa expeditions were the only Spanish entradas to traverse the study area, other Spaniards, such as Don Juan de Oñate, who led the first successful colonizing expedition to New Mexico in 1598, described Indian groups native to southeastern New Mexico. The Spaniards also identified a trading relationship between the Plains Indians (Apache and Jumano) and Pueblos, specifically the Humano Pueblos of Gran Quivira (the Jumano Plains Indians may have derived their name from this

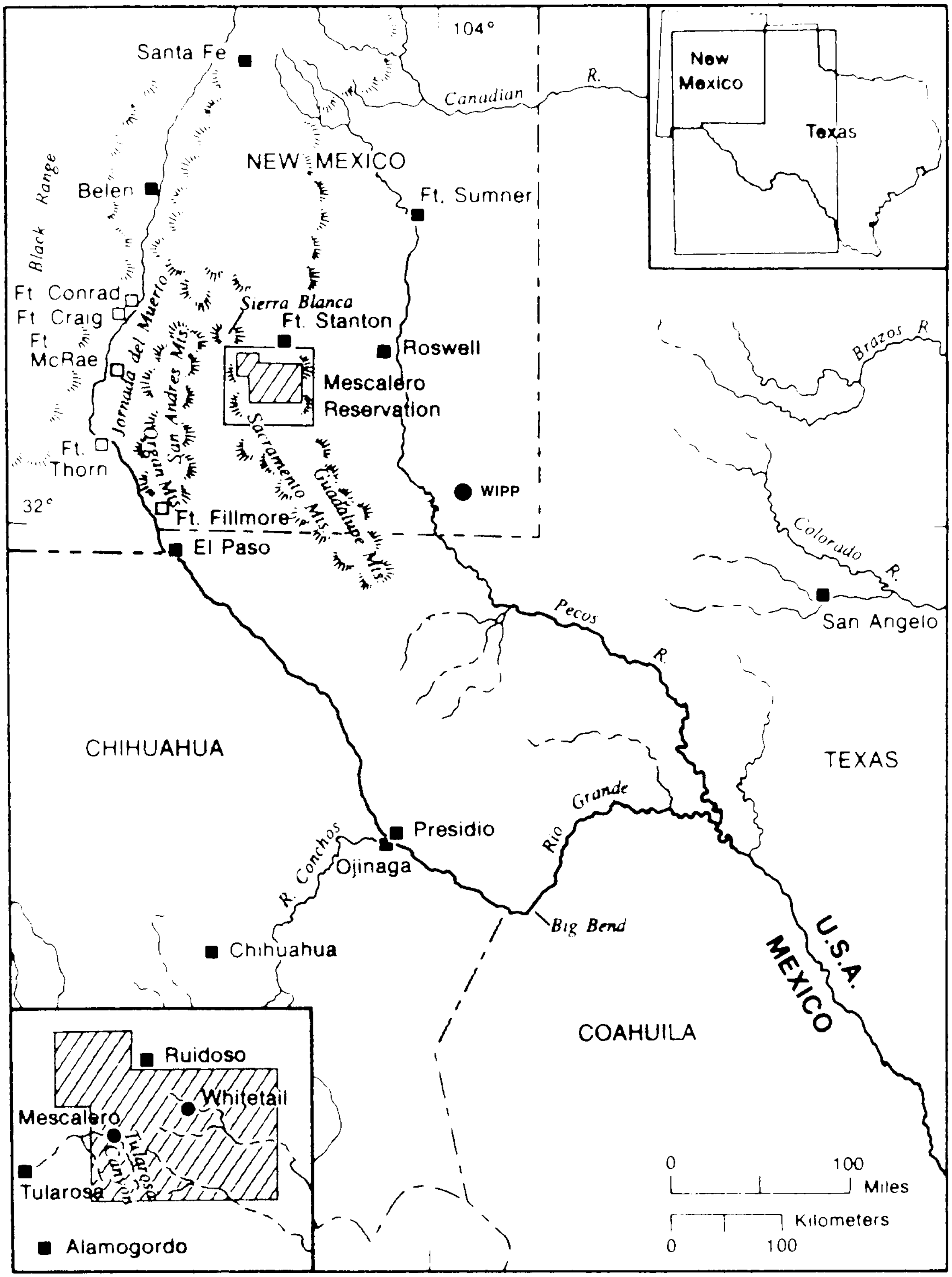

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Figure IX-8. Mescalero Apache Territory (after Opler, 1983).

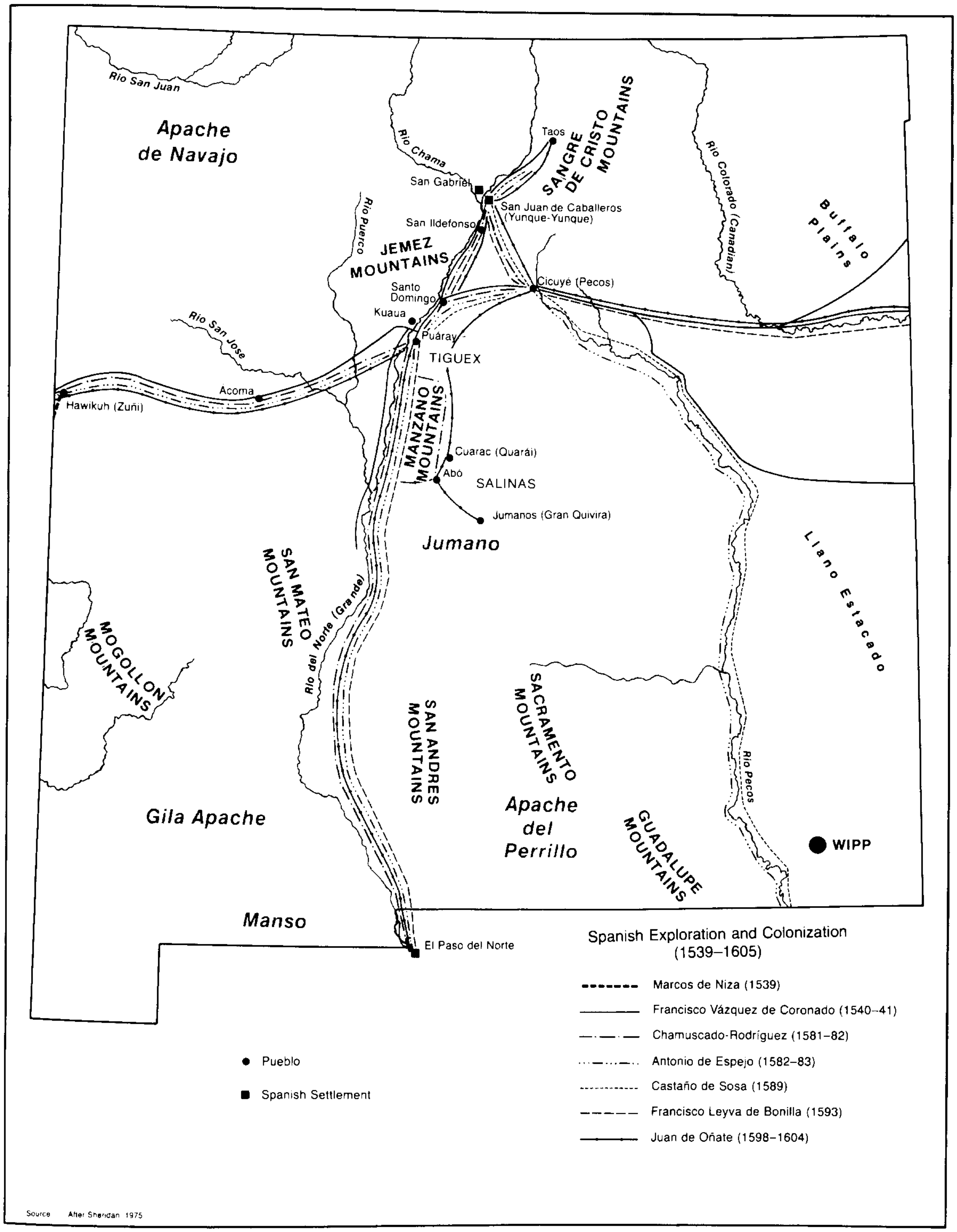

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Figure IX-9. Contact and Exploration, 1539-1605 (after Williams, 1986).

trading relationship with the Humanos, also sometimes spelled with a "J", but the two tribes were distinct).

Documentation from the sixteenth-century entradas is also significant because of descriptions of the physical environment of the study area. These primary sources, however, must be used with caution. In some cases, historians can only estimate the particular location of the Espejo and de Sosa expeditions when specific observations about physical surroundings were made. Nevertheless, accounts from these expeditions, particularly that of de Sosa, do provide some interesting information about the physical environment of the Pecos River Valley in southeastern New Mexico.

The de Sosa expedition travelled through the region in the autumn of 1590, following the east side of the Pecos River. Near the Texas-New Mexico border, the Spaniards noted the presence of "large salines with incredible amounts of very white salt, . . . marshes formed by water from the river, which emptied into them in considerable volume" (Hammond and Rey, 1966), and poor grazing land, which caused the horses to stray. Southeast of Carlsbad, de Sosa observed abundant game, "many tracks of cattle," plentiful fish and mesquite, "rich salt beds," and "an extensive marsh." De Sosa also noted the "fine plains," and river banks "thick with reed grass." In the Artesia-Roswell area to the north, however, the Spaniards noticed that "the vegetation was extremely dry, indicating that it had not rained here for a long time." Despite the dryness of the land, however, when de Sosa reached the Rio Hondo near Roswell (on December 1), he could not cross it because the water was too deep and the current too rapid (Hammond and Rey, 1966, pp. 257-262).

Based on primary accounts from the Espejo and de Sosa expeditions and a 1763 expedition, Mariah Associates (1987) concludes that the Spaniards found in the Pecos River Valley of southeastern New Mexico a region with a high water table and rich animal and plant resources. Mariah Associates argues that "prior to the introduction of irrigation and artesian drilling the entire middle Pecos region had not only a higher water table but more surface water. The Rio Hondo was at that time a deep, permanent stream with a rapid current" (Mariah Associates, 1987, p. 153).

While the southeastern quadrant may have seemed rich to early Spanish explorers, the area was not colonized. The Middle Pecos River Valley was dominated by the Mescalero Apaches, who frequently raided Pueblo and Spanish settlements to the north and west of the valley. Apache raids became more destructive when Apaches acquired horses at the beginning of the seventeenth century (Worcester, 1941). Unlike the Pueblos, the Apaches could not be converted by the Spaniards into a native labor force (a prerequisite for Spanish settlement because Spaniards often refused to work the land). Apache tribal areas, moreover, did not promise the easily obtained mineral wealth that many Spaniards hoped to find.

Animosity between the Mescaleros and Spaniards intensified because of the slaving raids of the conquerors that continued throughout the era of Spanish control of New Mexico. In response to this abuse, the Apaches harried the Spaniards even as they retreated to El Paso during the Pueblo Revolt of 1680 (Opler, 1983). Spaniards did, however, join in trade networks with the Mescaleros and other Plains tribes, travelling up and down the Pecos River and onto the Plains. At the trading posts of Pecos and Gran Quivira, Apaches, Jumanos, Spaniards, and Pueblos met to exchange goods. The Seven River Apaches, the dominant Mescalero group living just north of the study area, traded buffalo meat, tallow, and hides to the Spaniards for horses, metal goods, and manufactured items (Sonnichsen, 1958; Opler, 1983; Mariah Associates 1987).

Throughout the seventeenth century, the study area was peripheral to Spanish settlement and central to the activities of the Plains Indians. As before European contact, the area of present-day Eddy County was used primarily for hunting and gathering. The prominent group in the area was the Seven River Apaches, whose range extended from Seven Rivers north of Carlsbad to the Los Medaños (sand dunes) area (where WIPP is located) and onto the Llano Estacado (Mariah Associates, 1987) (Figure IX-10).

NOMADIC INDIANS: THE COMANCHES

In the early eighteenth century, the Comanches (a tribe of the Shoshonean linguistic group) arrived on the Plains east of the study area. Acquiring the horse by 1720, they became raiders. By 1740 they had surpassed the Apaches as the dominant tribe on the southern Plains. Until the 1780s, the Comanches were a significant deterrent to Spanish settlement.

Despite the presence of Comanche and Apache raiders, the Spaniards continued to trade with these and other Plains tribes. Spaniards passing through the study area in 1763 encountered Lipan and Mescalero Apaches camping in the Los Medaños sand dunes. Although the Spaniards saw at least one ranchería in the area, the Apaches were still primarily hunter-gatherers (Mariah Associates, 1987).

After several decades of warfare, the Spaniards secured an alliance with the Comanches. In 1786 Juan Bautista de Anza negotiated the Comanche Peace, which endured in New Mexico into the American territorial period and ensured Hispanos (New Mexicans of Spanish descent and culture) some degree of protection when venturing onto the eastern Plains. The treaty definitively opened the Plains for buffalo hunting and trade and secured Comanche assistance in suppressing Mescalero raiders.

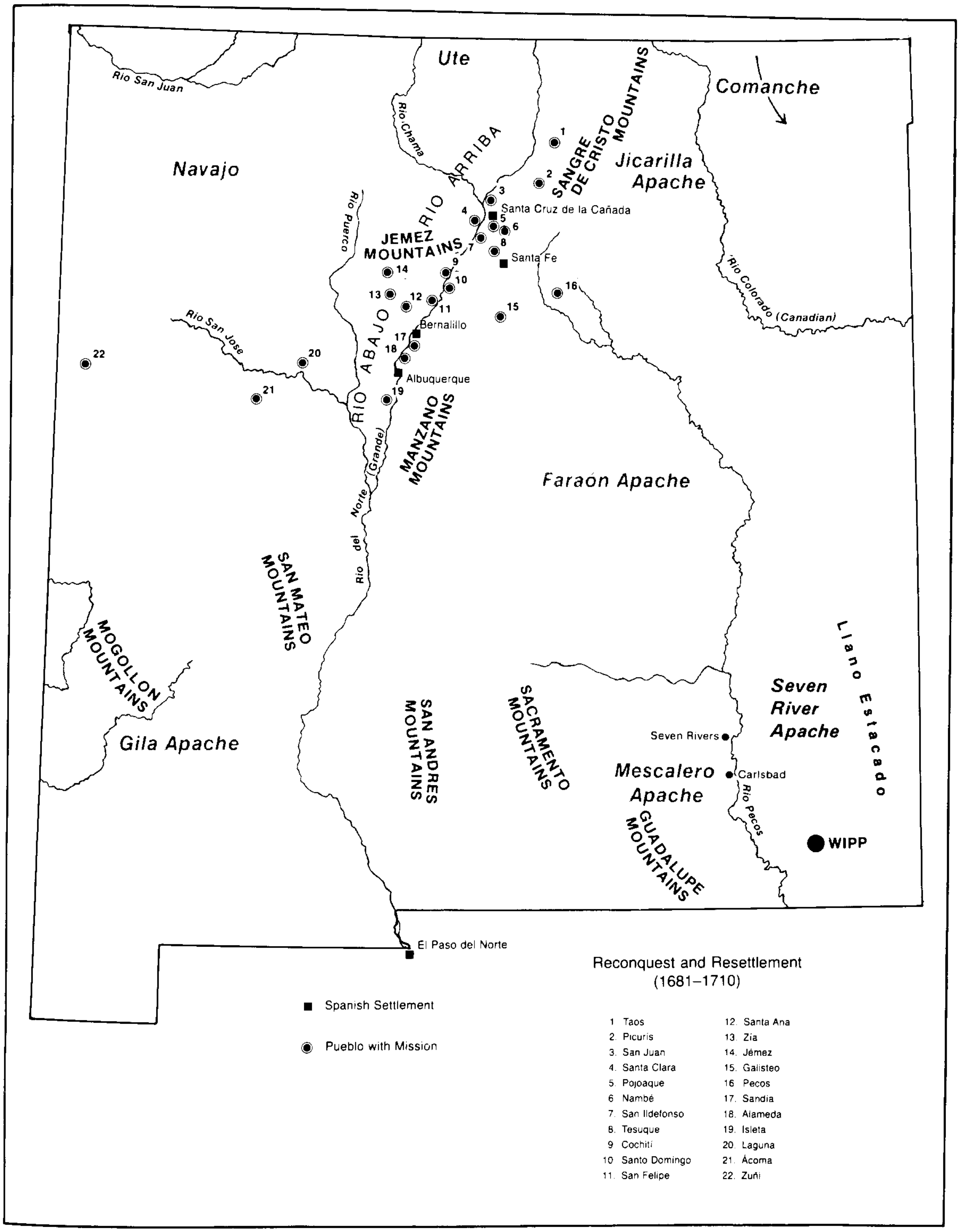

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Figure IX-10. Reconquest and Resettlement, 1681-1710 (after Williams, 1986).

CIBOLEROS AND COMANCHEROS

Spaniards and Pueblo Indians engaged in buffalo hunting in increasing numbers after 1786, and Plains tribes continued this activity, which provided both subsistence and trade goods. Some cíboleros (buffalo hunters) crossed the study area on their way north from Mexico, and there were at least a few cíbolero trails traversing the project area on the east side of the Pecos River. Buffalo hunting continued through the Mexican and American territorial periods until the southern buffalo herd was finally all slaughtered, between 1876 and 1879 (Mariah Associates, 1987).

After 1786, trade in the Plains area also expanded as Hispanos and Pueblos ventured east to trade with the Plains Indians, exchanging foodstuffs for horses, buffalo meat and hides, and sometimes slaves. The comanchero trade, as it was called, continued through the 1860s. Over time comancheros, including Americans, began exchanging guns, ammunition, and whiskey for stolen cattle, mules, and slaves. New Mexico became an outlet for stolen goods, and the trade did not completely end until the 1870s, when the United States Army succeeded in placing the Comanches and Apaches on reservations (Williams, 1986; Mariah Associates, 1987).

The comanchero trade, like the activities of the cíboleros, possibly involved the project area (Mariah Associates, 1987). The increased contact between Pueblo and Plains Indians, moreover, did result in significant cultural as well as economic exchange. Pueblo culture was especially affected by contact with the Plains tribes: the Pueblos learned horsemanship and adopted Plains Indian dances (Kenner, 1969). For the Plains Indians, however, contact with the Spaniards and the sedentary Pueblos did not significantly alter subsistence patterns. Mescalero Apaches and Comanches remained hunter-gatherers, although they increasingly supplemented these activities with trade.

HISPANO EXPANSION

Just as the Comanche Peace stimulated increased economic activities in the plains of southeastern New Mexico and West Texas, so did it usher in what historians call "the century of Hispano expansion," 1790-1880. The extent of Hispano expansion into the southeastern quadrant is not well documented. Nostrand (1987) shows that Hispanos extended only as far south as the area of present-day Alamogordo, with the founding of the town of La Luz in 1863 (see Figure IX-11). Hispanos and perhaps settlers from Mexico also settled in the Hondo Valley northeast of La Luz. Indeed, Mexican cíboleros were apparently some of the earliest settlers of the Hondo Valley in the nineteenth century (Mariah Associates, 1987) (Figure IX-11).

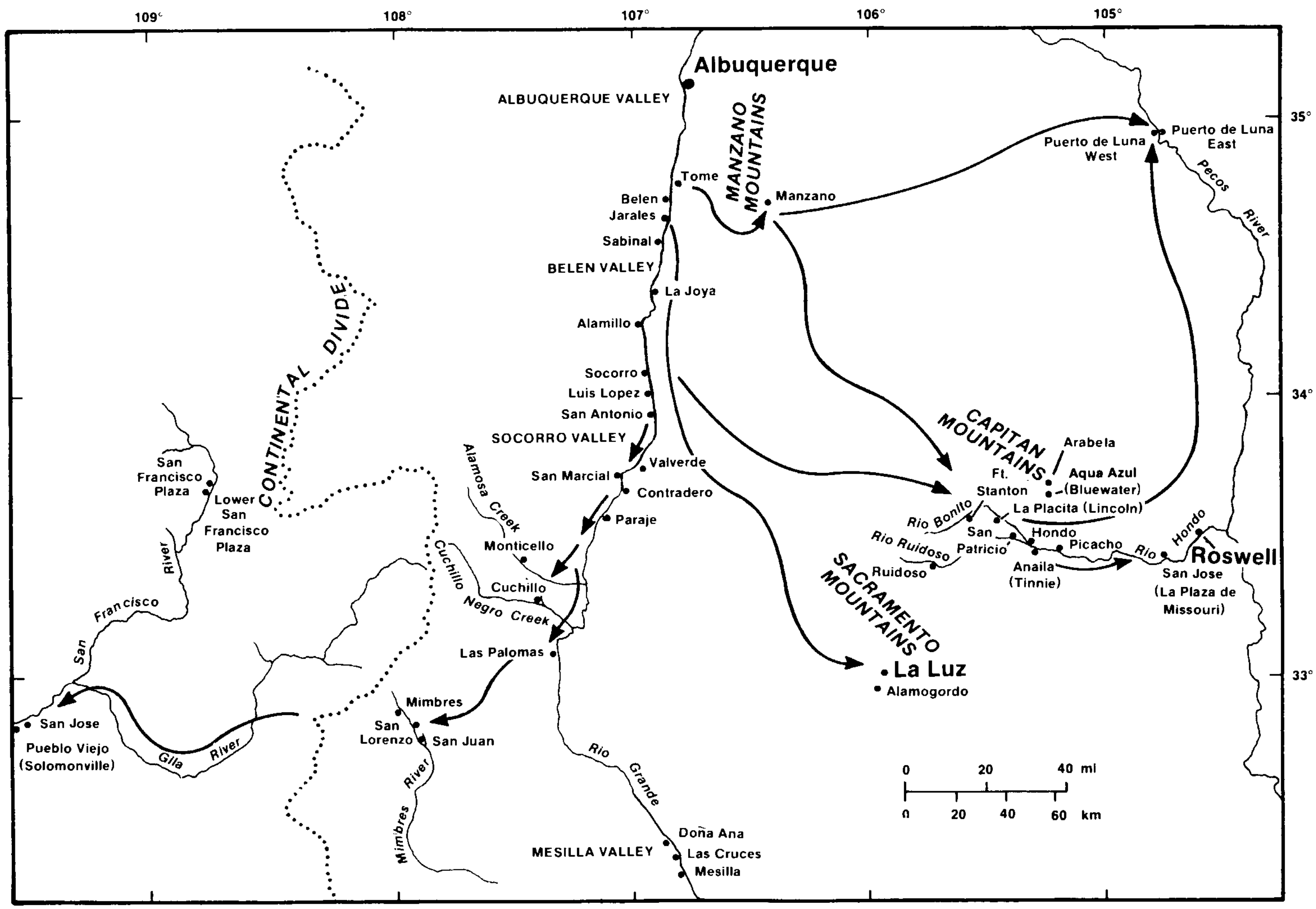

Figure IX-11. The Century of Hispano Expansion, 1790-1880 (after Nostrand, 1987).

Hispano settlements included La Placita (Lincoln), established in 1849 on the Bonito River by New Mexicans from Socorro. In 1867 New Mexicans from Manzano founded La Plaza de San José. Settlement along the eastern edge of the mountains and onto the Pecos plains was encouraged not only by the Comanche Peace, but also by population pressure from the west and the growing sheep industry. Yet, while Hispanos settled as far east as the Hondo Valley and as far south as the Alamagordo area, settlement in the Carlsbad area was halted by Apache raids and the lack of irrigable streams. The influx of American settlers (Anglos) between 1866 and 1873 also deterred Hispano expansion and ensured that southeastern New Mexico would be dominated socially and economically by Anglos. Many Hispano towns such as La Placita were eventually taken over by Anglos as well (Mariah Associates, 1987; Nostrand, 1987).

Mexican and American Territorial Periods

THE APACHES AND THE SEARCH FOR WATER

Two decades after the century of Hispano expansion began, New Mexico came under the political control of Mexico. Mexican independence in 1821, however, brought few changes to New Mexico. Most activity was still centered in the north-central section of the state, especially with the opening of the Santa Fe and Old Spanish trails (Figure IX-12). Depredations by Apaches from the east continued throughout the Mexican period (Jenkins and Schroeder, 1974).

The era of United States dominance in New Mexico was ushered in by Stephen Watts Kearny, whose troops took over Santa Fe in 1846. In 1848 the Treaty of Guadalupe Hidalgo ended the war with Mexico and in 1850 New Mexico became a territory of the United States. During the conflict with Mexico, Captain Randolph B. Marcy led the first U.S. military contingent in an exploration of the Middle Pecos Valley. Marcy was followed by Major John Pope who entered the area just southeast of Carlsbad in 1855. Pope was attempting to find water for the proposed transcontinental railroad. He established a minor military post in the area and drilled three artesian wells. The water resources of the Middle Pecos Valley, however, eluded Pope and the project was abandoned in 1858 (Myers, 1963; Sheridan, 1975).

While the water resources of the study area remained elusive for almost forty years, Anglos could rely on Apache raids. In 1855 Fort Stanton was established east of Roswell, and beginning in 1862 the Mescaleros were forced onto the Bosque Redondo reservation near Fort Sumner, north of Roswell. This experiment in acculturation failed and the Mescaleros fled back to their own territory in 1865. U.S. campaigns against the Apaches continued until the

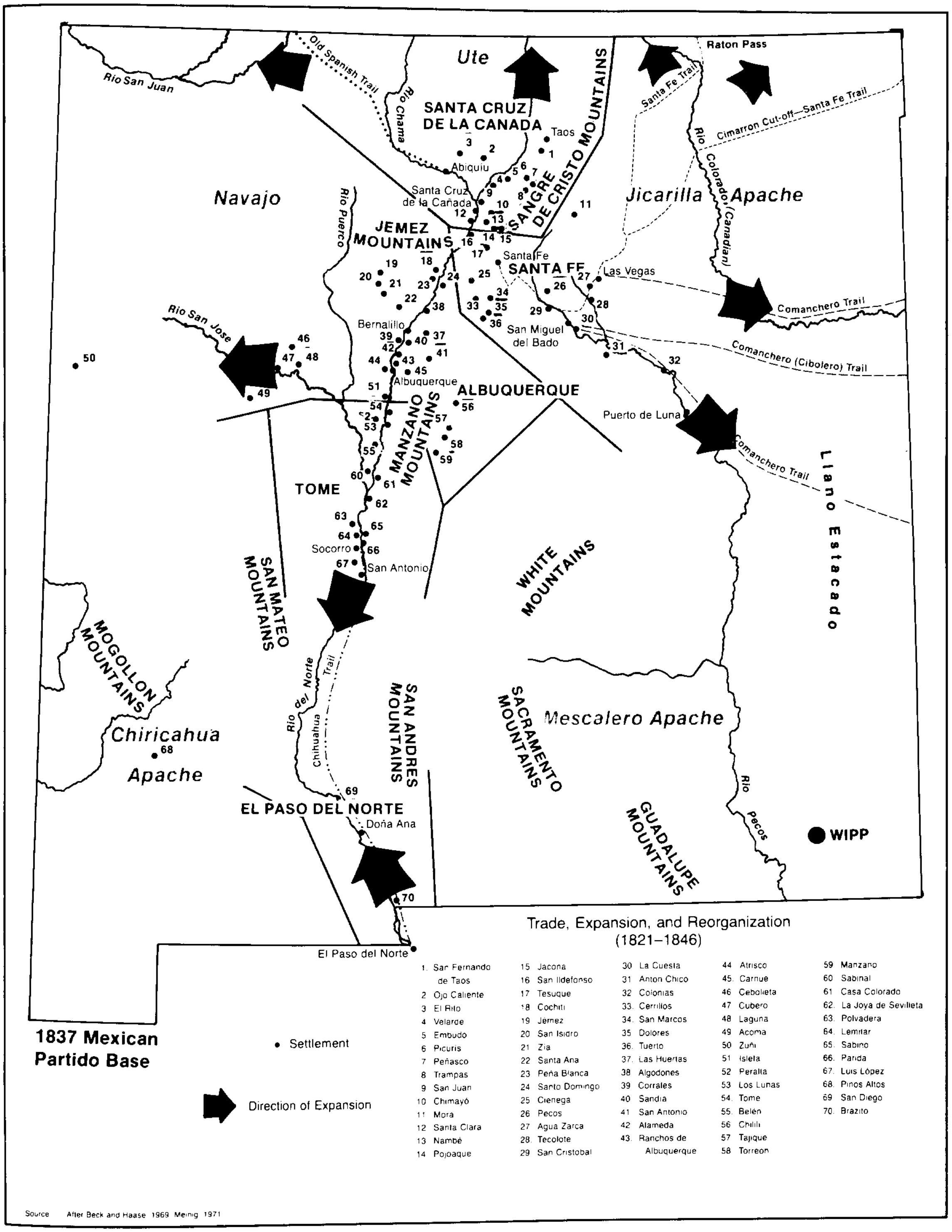

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Figure IX-12. The Mexican Period, 1821-1846 (after Williams, 1986).

early 1870s when the government designated a reservation for the Mescaleros in their old tribal country, along the eastern slopes of the White and Sacramento mountains (Figure IX-12). Removal of the Apaches to a defined area finally opened southeastern New Mexico to settlement and economic development (Sonnichsen 1958; Opler, 1983; Ogle, 1940).

NINETEENTH-CENTURY ECONOMIC DEVELOPMENT

Cattle ranching dominated the southeastern New Mexico economy from 1866 to 1900. The industry developed to supply forts and reservations connected to the Anglo-Apache campaigns. Charles Goodnight and Oliver Loving blazed the first cattle trail on the east bank of the Pecos in 1866. They were followed by John Chisum in 1868 who became the cattle king of southeastern New Mexico. The influx of cattlemen made the Pecos Valley "one huge grazing ground" that eventually extended throughout eastern New Mexico. Several trading posts were established, including Seven Rivers, 16 miles north of Carlsbad (Myers, 1974).

The cattle industry dominated southeastern New Mexico for the next 20 years and cattlemen became the political barons of the region. In addition, outlaws from Texas began to move into southeastern New Mexico after the Civil War, particularly to the Seven Rivers area. Disputes over cattle contracts and the tight political and economic control held by a few cattlemen, coupled with the general lawlessness of the southwestern frontier, eventually led to the Lincoln County War of the 1870s.

Although present-day Eddy County was part of the huge Pecos Valley grazing lands and, beginning in 1878 was included in Lincoln County, the activities of most cattlemen and Lincoln County outlaws such as Billy the Kid were centered in the Roswell area. The first substantial settlement near the study area was Seven Rivers, which began as a series of scattered ranches and became a town in 1884 (Mariah Associates, 1987) (Figure IX-13). The importance of the cattle industry brought southeastern New Mexico into the public domain, so that settlers could acquire land through the Homestead Act, the Timber Culture Act, and the Desert Lands Act (Westphall, 1958). The actual settlement of Eddy County and the Carlsbad area, however, did not begin until the development of irrigation.

IRRIGATION IN THE PECOS RIVER VALLEY

In 1884 Charles Bishop Eddy arrived in the area to raise cattle. By the 1880s, however, overgrazing, drought, and declining cattle prices led to the decline of the cattle industry. Between 1884 and 1886 Eddy County experienced a period of drought and freezing weather which, along with the overstocking of the range, caused the death of 35 percent of all cattle (Southeastern New

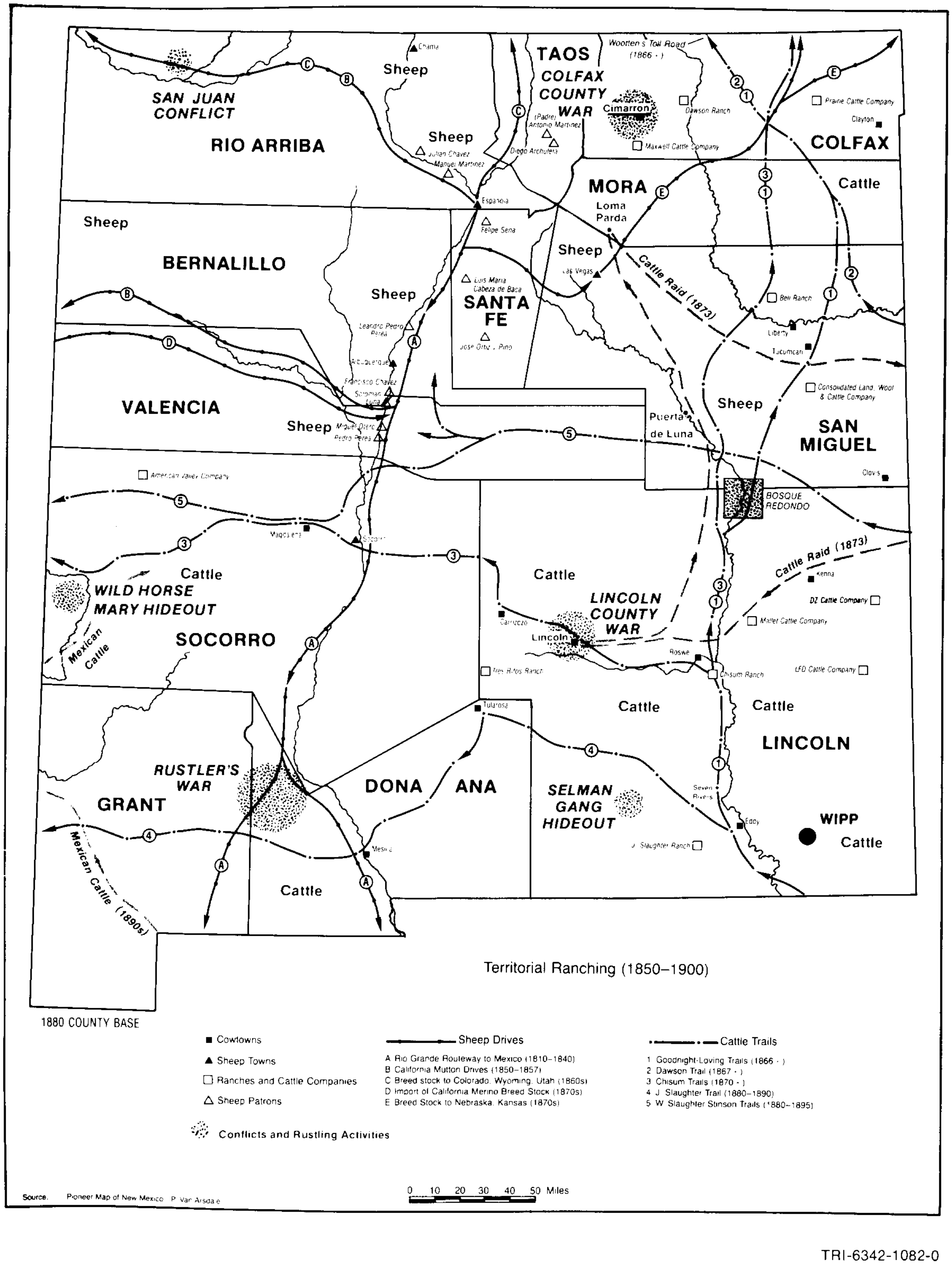

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Figure IX-13. Ranching in New Mexico, 1850-1900 (after Williams, 1986).

Mexico Historical Society, 1982). Eddy resorted to the irrigation of the Pecos River Valley. His efforts began in 1887 with the first diversion ditch. Eddy, joined by Roswell developers, envisioned a huge system of dams, reservoirs, and canals that would irrigate the entire Pecos Valley from Roswell to Carlsbad (Myers, 1974). The system utilized artesian wells and waters from the Pecos River and eventually included Avalon and MacMillan dams, both in Eddy County (Jenkins and Schroeder, 1974).

In 1888 Eddy formed an irrigation company and began to sell lots for what became the town of Eddy in 1893. In 1899 the town's name was changed to Carlsbad after a spring near the town was discovered to be similar in mineral content to the springs at the famous Karlsbad health resort in Austria-Hungary. Developers hoped the name change would encourage the town's growth (Myers, 1974).

Eddy's irrigation company also contributed to the county's development by building railroad lines. In 1891 the first line was completed, linking Eddy to Pecos, Texas. In 1894, another line was extended to Roswell and in 1899 the Pecos Valley Railroad was connected to the Atchison Topeka and Santa Fe Railroad (Myers, 1974; Sheridan, 1975; Southeastern New Mexico Historical Society, 1982). During the twentieth century, lines were extended into potash mining areas east of Carlsbad (Figure IX-14).

The irrigation company, which after 1889 was led by Roswell developer James J. Hagerman, was directly responsible for the prosperity of the Middle Pecos River Basin during the late nineteenth century. In 1889, Lincoln County was divided, and Chaves County with Roswell as the county seat and Eddy County with Eddy/Carlsbad as the county seat were created. Hundreds of workers flocked to Eddy to help dig canals and work on the railroad. The irrigation system, in turn, brought in more settlers (Sheridan, 1975).

MEXICAN-AMERICAN SETTLEMENT

Although southeastern New Mexico has been socially and economically dominated by Anglos, as throughout most of New Mexico's history, cultural influences have easily crossed political boundaries. Chilton and Chilton et al. (1984) argue that the Carlsbad-Hobbs area of southeastern New Mexico is "topographically, culturally, and linguistically linked with west Texas" (p. 569). Perhaps more importantly, Mexican-American settlement has been an important component of Eddy County's development. Mariah Associates (1987) refers to settlers of southeastern New Mexico as Mexican-Americans rather than Hispanos, noting that most came from Texas and Mexico and thus tended to identify themselves as Mexican-Americans rather than Hispanos.

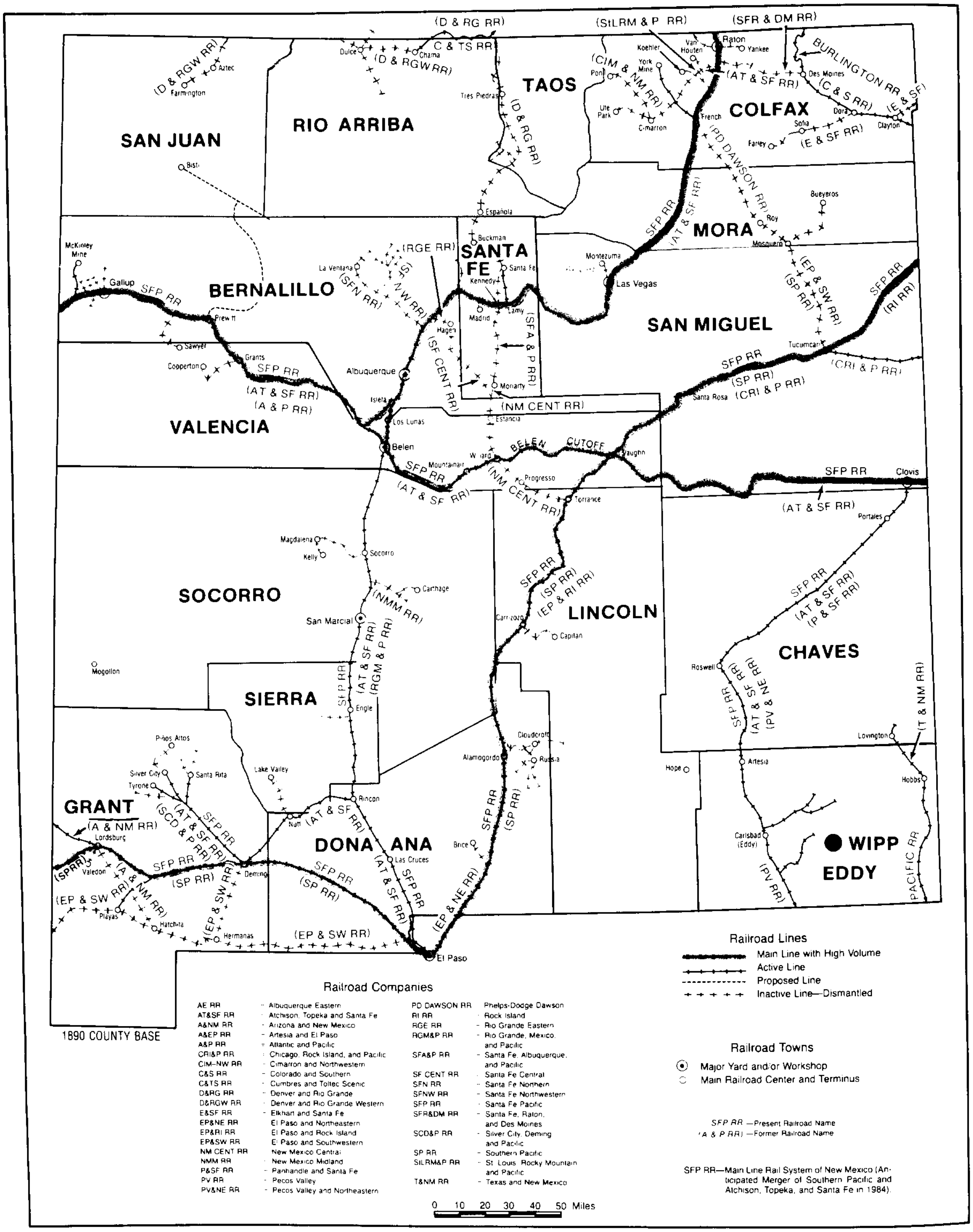

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Figure IX-14. Railroad Development in New Mexico (after Williams, 1986).

Mexican-American settlement in the Lower Pecos Valley including the Carlsbad area occurred after Anglos started settling in the 1870s. The first Mexican-Americans followed the cattle herds from Texas. Others came from Texas and Mexico to build dams and work on the farms. By 1890, Carlsbad had an established Mexican population. Many Mexicans also came from Jalisco during the Mexican Revolution. In 1892, a group crossed the Pecos River from Chihuahua State and established the town of Phoenix, New Mexico, one mile south of Eddy/Carlsbad.

FARMING IN EDDY COUNTY

Farming had become a major economic activity in Eddy County by the 1890s. Early farmers tried a variety of crops, especially fruit, which was well-suited to the limey soil. Alfalfa and other feed crops, which had a ready market, were the most profitable agricultural products (Southeastern New Mexico Historical Society, 1982). Promoters were justifiably optimistic about Eddy County's agricultural potential, but by the turn of the century, the situation changed.

Alfalfa developed root disease as did other crops, which caused them to fail or substantially decline in yield (Sheridan, 1975). Late spring frosts, root-rot disease, the high salt content of the water, seepage water, gypsum soils, and phosphate-poor soils all contributed to the crop failures. Despite the enthusiasm of developers, settlers were unprepared for these Pecos Valley conditions. Agricultural problems in Eddy County were also related to poor irrigation methods, specifically the overuse of water, which resulted in salt flats and poorly drained fields (Southeastern New Mexico Historical Society, 1982).

Structural faults in the irrigation system were also apparent by the turn of the century. In 1893 and again in 1904, the Avalon Dam was destroyed by flooding. In 1905, the Federal Reclamation Service assumed control of the irrigation system and began repairs in both Eddy and Chaves counties. By 1909 the repairs were completed; by 1912, 16,000 acres were under irrigation. Additional programs of reclamation, however, were less successful. In Chaves County, the Hondo River irrigation project failed, and farmers were forced to rely on artesian water for irrigation, just as they do today. In southern Eddy County, in and around the project area, the Carlsbad reclamation program remains the main source of irrigation water. The Carlsbad project continues to be expensive and the Eddy County economy depends on subsidized agriculture. Both the McMillan and Avalon dams are vulnerable to floods, and in the 1930s, the Alamogordo dam was built to provide storage and flood control (Hundertmark, 1972).

The Twentieth Century

ECONOMIC ACTIVITIES

Despite the efforts of the Federal Reclamation Service, which also attempted to instruct farmers in the correct methods of irrigation, some crops continued to fail. By 1923, fruit crops were no longer significant. Cotton, alfalfa, and other feed and grain crops predominated. Since World War II, alfalfa has been Eddy County's primary crop. As of 1981, 25,055 acres (10,000 hectares) were suitable for farming (Southeastern New Mexico Historical Society, 1982).

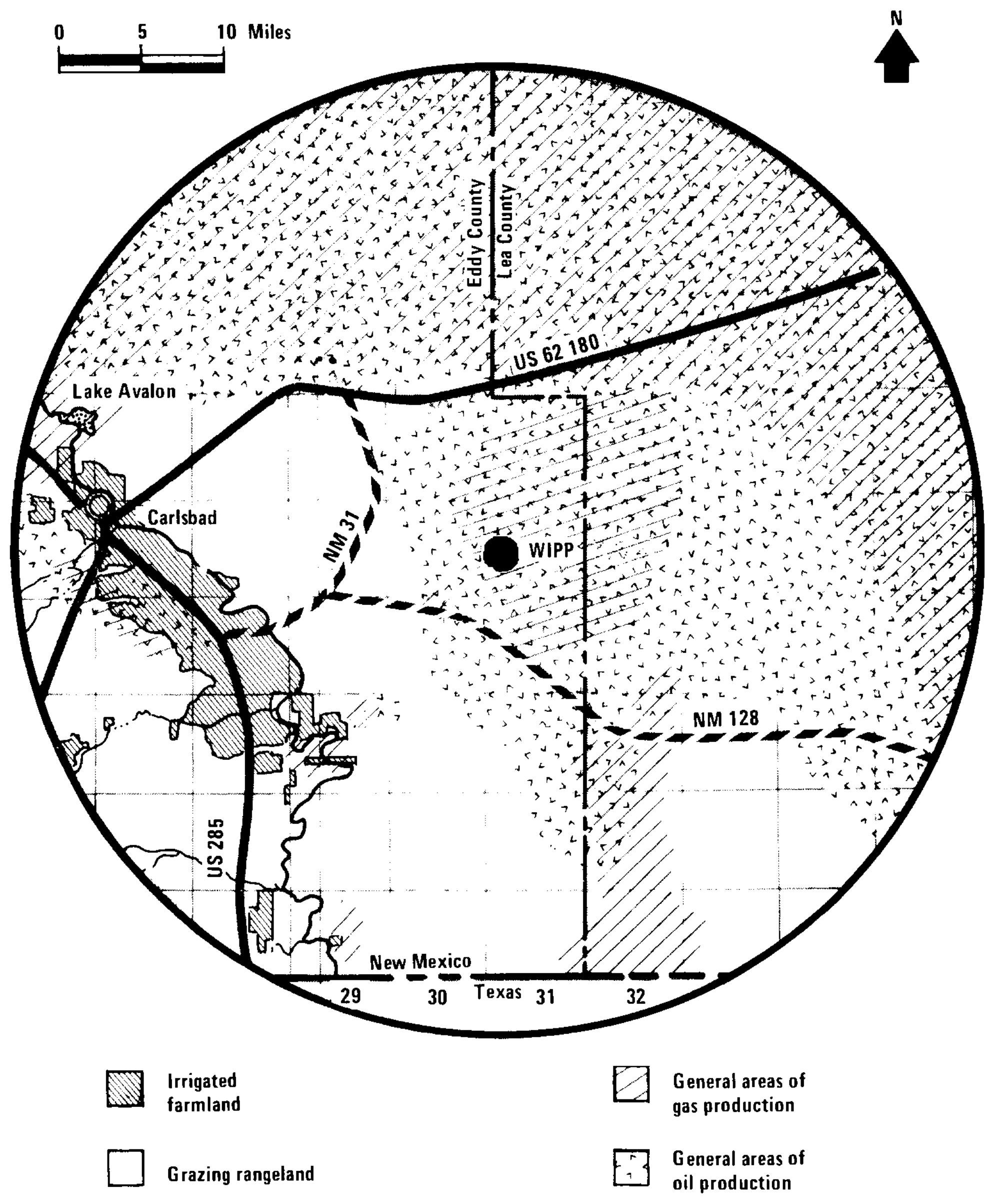
Ranching remained part of the Eddy County economy and, in the early 1900s, both sheep and cattle were raised on irrigated farms in the Carlsbad area (Parish, 1963). During the first two decades of the twentieth century, livestock raising continued to be the most important industry in Chaves and Eddy counties (Sheridan, 1975). By the 1920s, Carlsbad was a settled agricultural community with most residents engaged in ranching, farming, and related services. In 1909, petroleum was first discovered, and in 1925, potash was found east of Carlsbad. After 1925 oil, gas, and potash mining became significant aspects of the local economy (Sheridan, 1975; Southeastern New Mexico Historical Society, 1982).

In the 1960s, Carlsbad suffered an economic depression because of a world oversupply of potash. During the last decade, potash demand again decreased. Despite fluctuations in the potash market, during the 1980s potash mining and tourism were Carlsbad's key industries. Ranching and agriculture continue to contribute to the Eddy County economy, although most of the employed population is involved in nonagricultural activities, including mining (Figures IX-15 and IX-16).

DEMOGRAPHIC STATISTICS

Population statistics for Eddy County during the twentieth century indicate a relatively stable growth pattern that is expected to continue into the next millenium (Figure IX-17 and Table IX-1). As of 1986, Eddy County had a total population of 52,400, and Carlsbad had a total population of 27,850. By 2010, the county population is expected to reach 64,800.

As throughout New Mexico's history, cultural influences continue to cross political boundaries. Mexican immigration to the United States (documented and undocumented, permanent and temporary) has increased during the 1980s. Legal immigration reached a new peak in 1988. Statistics for the last decade indicate that over 1,000 Mexican immigrants are legally admitted to New Mexico each year (U.S. Department of Justice, Immigration and Naturalization Service,



Sources: Bureau of Reclamation Land Use Map, 1968; New Mexico Bureau of Mines and Mineral Resources, New Mexico Energy Resources Map, 1974; Adcock and Associates, field surveys, 1978.

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Figure IX-15. Land Use within 30 Miles of the WIPP (after U.S. DOE, 1980).

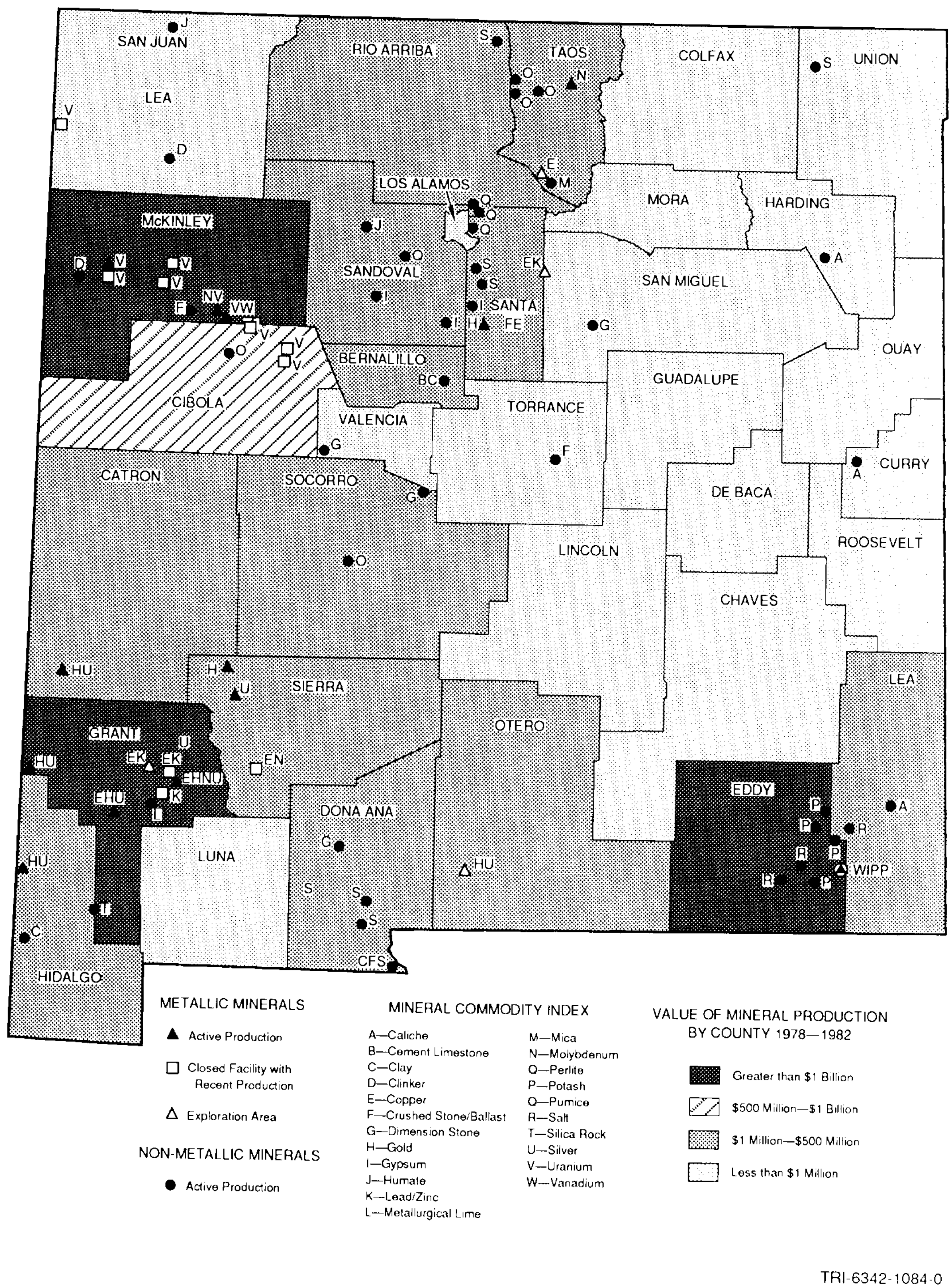

Figure IX-16. Mineral Mining (after Williams, 1986).

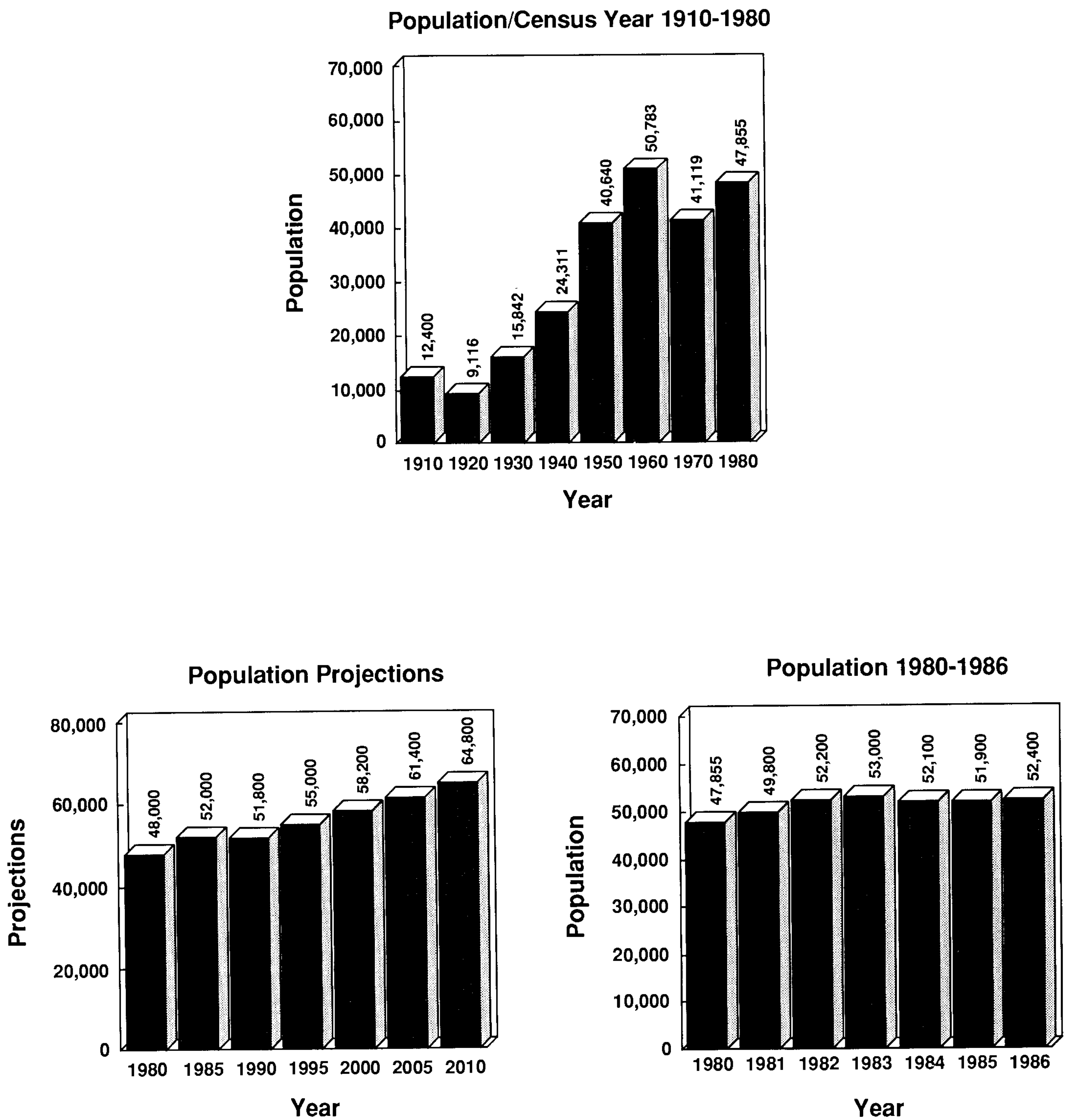

Figure IX-17. Population Statistics for Eddy County (UNM, 1989).

TABLE IX-1. EDDY COUNTY: A CURRENT DEMOGRAPHIC PROFILE

1981-1989). The Eddy County is located near the southeast corner of the state, bordering Texas on the south. The Pecos River crosses the county from north to south and enters Texas at the lowest elevation in New Mexico (2,841 feet). The river has been dammed at several points in the county forming various reservoir lakes. Irrigated land in the Pecos Valley produces hay and cotton, but most of the county is semiarid brush and grassland suitable only for cattle ranching. Mining of potash, oil, and gas provides the principal source of income in the county. However, the potash industry until recently has been suffering from strong foreign competition and a weak agricultural sector, while low oil prices have severely hurt the oil and gas extraction industries. Agreements in 1987 with Canadian producers have now improved the prospects for the New Mexico potash industry. Tourists visiting Carlsbad Caverns National Park and the Lincoln National Forest also contribute to the economic base. Carlsbad, the most populous community and county seat, has commanded national attention as the location of the Waste Isolation Pilot Project (WIPP), a national radioactive waste depository near the city.

COUNTY: Eddy	
COUNTY SEAT: Carlsbad	
CLIMATE (Carlsbad, 1931-1983)	
Elevation (feet)	3,120
Average Temperature (January)	43.1
Average Temperature (July)	81.5
First Freeze Date (1986)	Nov. 3
Annual Precipitation (inches)	12.67
LAND AREA (square miles)	4,184
POPULATION	
County, 1980	47,865
County, 1986	52,400
Density (persons per square mile)	12.5
CITY POPULATION, 1986	
Artesia	11,620
Carlsbad	27,850
Hope	130
Loving	1,520
COMPONENTS OF POPULATION CHANGE	
Change in Population, 1980-85	4,600
Births	6,100
Deaths	2,700
Net Migration	1,200
NUMBER OF PERSONS 65 AND OVER, 1980	5,997
NUMBER OF PERSONS UNDER 18, 1980	15,138
RACE AND ETHNICITY, 1980 (percent)	
White	97.6
Black	1.8
American Indian	0.4
Asian/Pacific Islander	0.2
Other	
Total	100.0
Hispanic (total)	30.7

POPULATION PROJECTIONS	
1990	51,800
1995	55,000
2000	58,200
2005	61,400
2010	64,800
PUBLIC SCHOOL EMPLOYMENT 1985-1986	10,452
MEDIAN SCHOOL YEARS COMPLETED, 1980	12.3
INCOME	
Per Capita, 1986	$10,938
Ranking among New Mexico Counties	10
Median Household, 1979	$14,725
Median for Families Headed by a Female Householder, No Husband Present, 1979	$8,198
POVERTY AND WELFARE	
Percent of Persons Below Poverty, 1979	13.5
Number of Persons Receiving AFDC, Mar. 1985	1,464
Number of Persons Receiving Food Assistance, FY 1986-87	5,485
Number of Persons Receiving Medical Assistance, FY 1986-87	1,788
HOUSING	
Median Contract Rent, 1980	$153
Median House Value, 1980	$32,000
UNEMPLOYMENT RATE, 1986 (percent)	14.2
EMPLOYMENT, 1986	
Total Nonagricultural Wage and Salary	16,149
Manufacturing	777
Miining	2,772
Construction	1,430
Transportation and Public Utilities	1,090
Wholesale and Retail Trade	3,584
Finance, Insurance and Real Estate	713
Services and Miscellaneous	3,141
Government	2,642

TABLE IX-1. EDDY COUNTY: A CURRENT DEMOGRAPHIC PROFILE (continued)

GROSS RECEIPTS BY MAJOR SECTOR, 1986 ($000S)	
Agriculture	$ 1,092.6
Mining	59,641.0
Construction	88,286.4
Manufacturing	76,679.3
Transportation, Communications, Utilities	174,415.4
Wholesale Trade	76,701.4
Retail Trade	238,947.4
Finance, Insurance and Real Estate	6,189.8
Services	95,975.4
Government	2,646.2
Total	$ 820,575.1
CONSTRUCTION, 1986 (Carlsbad and Artesia)	
Value of Nonresidential Permits ($000s)	$2,229.3
Value of Residential Permits ($000s)	$5,184.2
Total Nonresidential Permits	109
Total Residential Units	95
Single Family Units	90
Multi Family Units	5
AGRICULTURE	
Average Farm Size, 1982 (acres)	2,058
Cash Receipts, 1986 ($000s)	
All Farm Commodities	$44,486
Ranking among New Mexico Counties	6
Livestock	$30,790
Crops	$13,696

MINING ($000S)	
Value of Sales, 1986	
Oil	$166,796.1
Gas	$202,305.4
Carbon Dioxide	--
FINANCE, as of Dec. 31, 1986 ($000)	
Bank Assets	$446,471
Savings and Loan Assets	$43,494
Bank Deposits	$397,611
Savings and Loan Deposits	$38,872
NET TAXABLE PROPERTY VALUE, FY1986-87 ($000s)	$725,498.3
TOURISM, 1986	
Lodging Employment	469
Eating and Drinking Employment	888
Gross Receipts of Hotels, Motels, Trailer Parks and Other Lodging Places ($000s)	$6,295.3
Gross Receipts of Eating and Drinking Places ($000s)	$19,712.5
Lodgers Tax Receipts, FY1985-86 ($000s)	
Carlsbad	$140.3
Artesia	$26.6
County of Eddy	$62.6

Source: UNM, 1989

1981-1989). The recent establishment, in 1988, of a United States Border Patrol office in Albuquerque to monitor the northern section of the state reflects the significance of this increase. Although the U.S. government has not compiled the statistics necessary to assess immigration to southeastern New Mexico, Mexican immigration has undoubtedly affected the southeastern quadrant, including Eddy County, during the twentieth century. The presence of a Border Patrol office in Carlsbad reflects this continuing immigration.

Conclusion

For most of the prehistoric and historic eras, Indian groups have predominated in southeastern New Mexico. Land use among Paleo-Indians, Archaic Indians, the Mescalero Apaches, and the Comanches of the southern Great Plains including Eddy County was limited to hunting and gathering activities. Contact with the Pueblo farming cultures and later, with the Spaniards, did little to alter the cultural profile and dominant subsistence strategy in southeastern New Mexico.

The introduction of cattle ranching in southeastern New Mexico during the 1860s, and the construction of an irrigation system during the 1880s, brought the first significant alteration of cultural and land-use patterns in Eddy County. Anglo- and Mexican-American settlers migrated to the Carlsbad area as ranching and irrigated farming made the area more economically promising. Although Carlsbad never developed into a major agricultural center, by the 1920s, oil, gas, and potash mining were added to the area's economic base, surpassing agriculture and cattle ranching in importance.

Today, land use in Eddy County includes mining, agriculture, and cattle ranching. Mining and cattle ranching predominate in the vicinity of Carlsbad and the study area. Anglo-Americans and Mexican-Americans represent the dominant cultural groups in Eddy County.

The evolution of the cultural development and land use in southeastern New Mexico is summarized in Figure IX-18.

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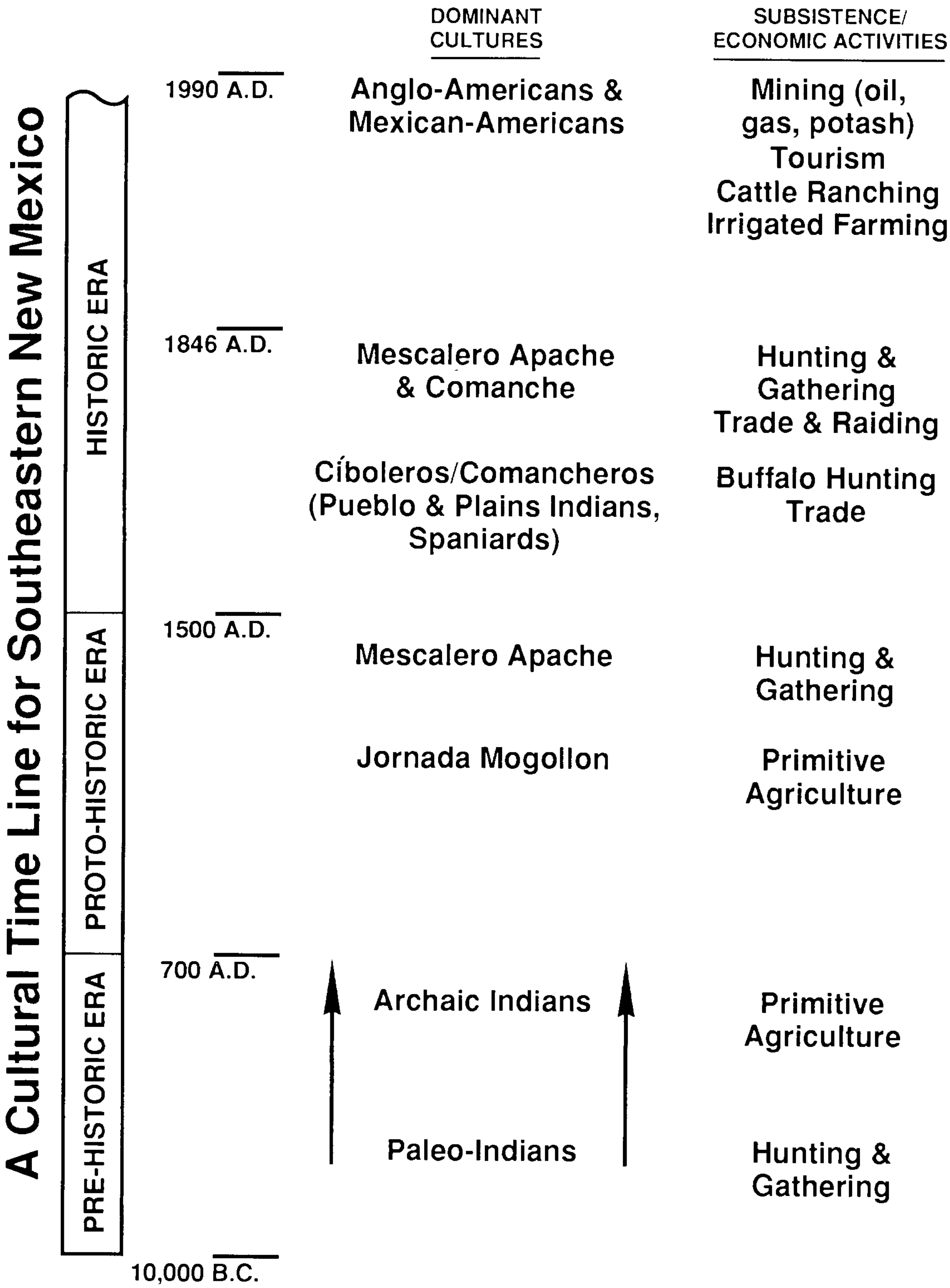

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Figure IX-18. Changes in Dominant Cultures and Land-Use Activities in Southeastern New Mexico from Earliest Records to Present.

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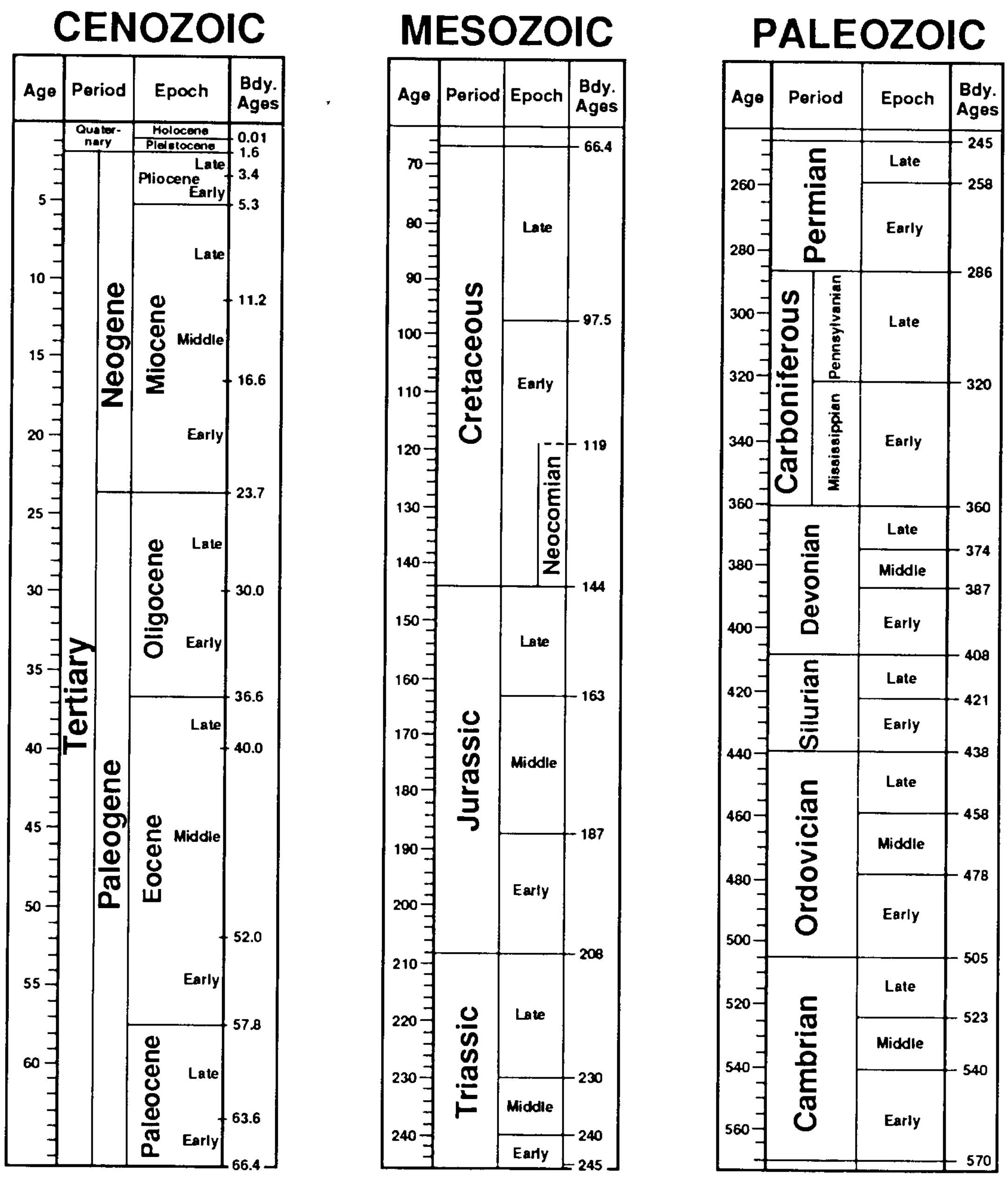
GEOLOGIC TIME SCALE



All Ages in Millions of Years

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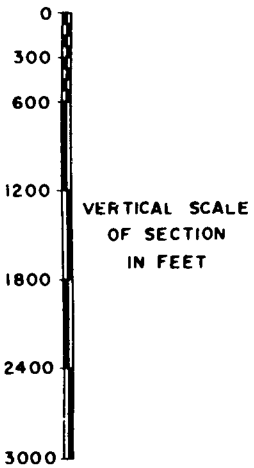
Source: simplified from Geological Society of America, 1984

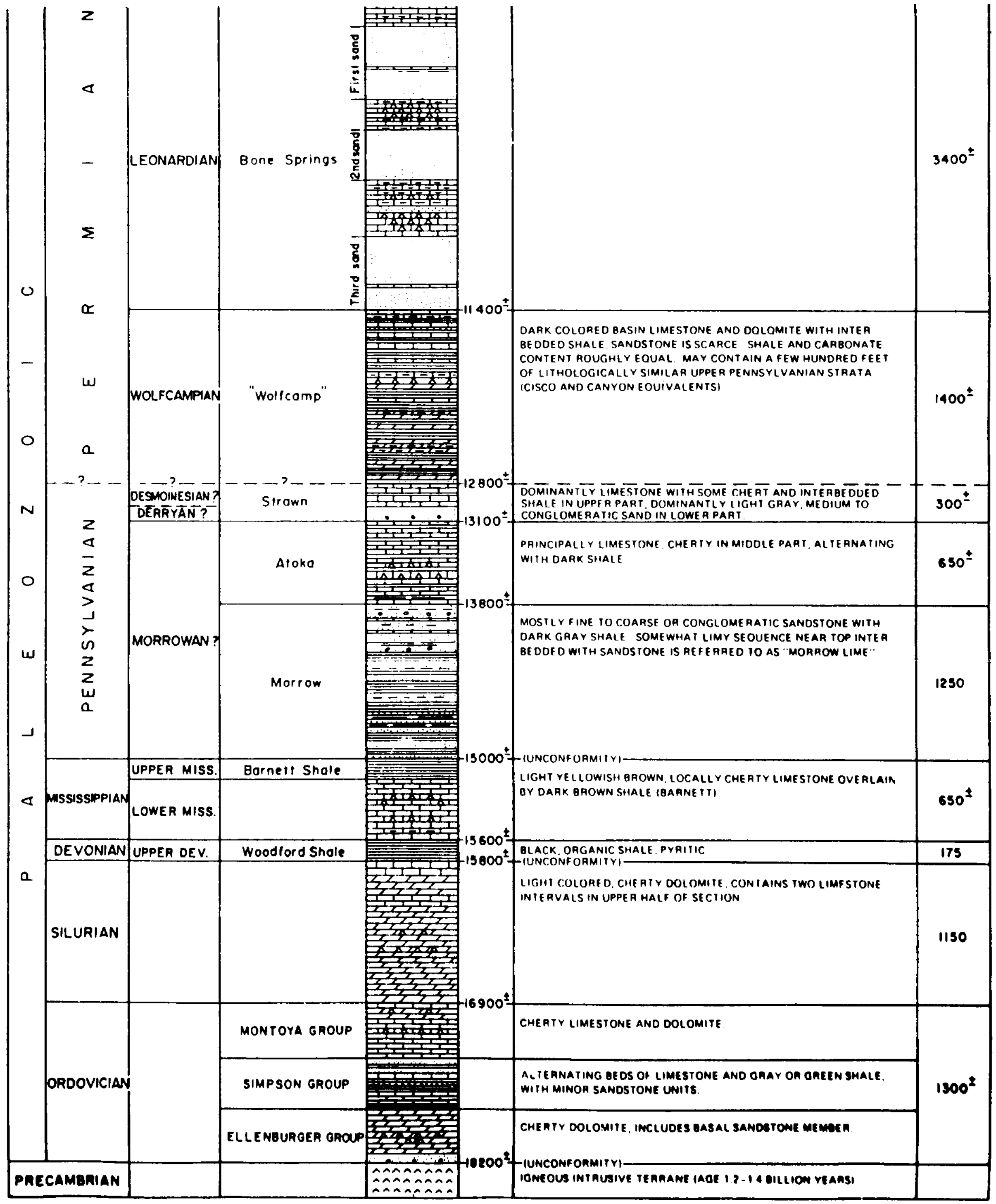
EXPLANATION

LITHOLOGIC SYMBOLS

- Sandstone
- Mudstone; siltstone; silty and sandy shale.
- Shale
- Limestone
- Dolomite
- Cherty limestone and dolomite
- Shaly limestone
- Anhydrite (or gypsum)
- Interlaminated anhydrite-calcite
- Halite, (rock salt)
- Granitic rocks

ERA	SYSTEM	SERIES	FORMATION	GRAPHIC LOG	APPROX. DEPTH TO CONTACT AT SITE	PRINCIPAL LITHOLOGY	APPROX THICKNESS (feet)
CENOZOIC	RECENT		Surficial sand			BLANKET SAND AND DUNE SAND; SOME ALLUVIUM INCLUDED	0-100
CENOZOIC	QUATERNARY	PLEISTOCENE (Kansan?)	Mescalero caliche & Gatuna Fm.		10 40	PALE REDDISH BROWN, FINE GRAINED FRIABLE SANDSTONE. CAPPED BY 5 10 FT. HARD, WHITE CRYSTALLINE CALICHE (LIMESTONE) CRUST.	0-35
MESOZOIC	TRIASSIC	UPPER TRIAS	Santa Rosa Sandstone		50	PALE RED TO GRAY, CROSS BEDDED, NON MARINE, MEDIUM TO COARSE GRAINED FRIABLE SANDSTONE; PINCHES OUT ACROSS SITE	0-250
PALEOZOIC	PERMIAN	OCHOAN	Dewey Lake Redbeds		540	UNIFORM DARK RED BROWN MARINE MUDSTONE AND SILTSTONE WITH INTERBEDDED VERY FINE GRAINED SANDSTONE; THINS WESTWARD	100-550
			Rustler	M C	850	GRAY, GYPSIFEROUS ANHYDRITE WITH SILTSTONE INTERBEDS IN UPPER PART, REDDISH BROWN SILTSTONE OR VERY FINE SILTY SANDSTONE IN LOWER PART, HALITIC NEAR BASE. CONTAINS 2 DOLOMITE MARKER BEDS MAGENTA (M) IN UPPER PART AND CULEBRA (C) IN LOWER PART. THICKENS EASTWARD DUE TO INCREASING CONTENT OF UNDISSOLVED ROCK SALT.	275-425
			Salado (Upper member; McNutt member; Lower member)	CA	CH ZONE RH ZONE 2825	MAINLY ROCK SALT (85 90%) WITH MINOR INTERBEDDED ANHYDRITE, POLYHALITE AND CLAYEY TO SILTY CLASTICS. TRACE OF POTASH MINERALS IN MC NUTT ZONE. THE MINOR INTERBEDS ARE THIN AND OCCUR IN COMPLEXLY ALTERNATING SEQUENCES. THICKEST NON HALITE BED IS THE COWDEN ANHYDRITE (CA), 17 FT THICK. MULTIPLE ANHYDRITE INTERBEDS ARE MOST COMMON IMMEDIATELY BELOW THE COWDEN AND IMMEDIATELY ABOVE BASE OF SALADO	1750-2000
			Castile (Anh. III-IV; Hal. II; Anh. II; Hal. I; Anh. I)		4075±	THICK MASSIVE UNITS OF FINELY INTERLAMINATED ("VARVED") ANHYDRITE CALCITE ALTERNATING WITH THICK HALITE (ROCK SALT) UNITS CONTAINING THINLY INTERBEDDED ANHYDRITE. TOP ANHYDRITE UNIT LACKS CALCITE INTERLAMINATIONS.	1250±
		GUADALUPIAN	DELAWARE MOUNTAIN GROUP: Bell Canyon (Delaware sand)		5100±	MOSTLY LIGHT GRAY FINE GRAINED SANDSTONE WITH VARYING AMOUNT OF SILTY AND SHALY INTERBEDS AND IMPURITIES. CONTAINS CONSIDERABLE LIMESTONE INTERBEDS AND LIME RICH INTERVALS. TOP UNIT IS LAMAR LIMESTONE MEMBER, A PERSISTENT SHALY LIMESTONE OR LIMY SHALE.	1000±
			DELAWARE MOUNTAIN GROUP: Cherry Canyon		6200±	MOSTLY GRAY TO BROWN, FINE TO VERY FINE GRAINED SANDSTONE SIMILAR TO BRUSHY CANYON, INTERBEDDED WITH SHALE, DOLOMITE AND SOME LIMESTONE	1100±
			DELAWARE MOUNTAIN GROUP: Brushy Canyon		8000±	PREDOMINANTLY FINE GRAINED, GRAY TO BROWN SANDSTONE INTERBEDDED WITH MINOR BROWN SHALE AND DOLOMITE	1800±
		LEONARDIAN	Bone Springs			THICK, PARTLY CHERTY BASIN LIMESTONE SEQUENCE IN UPPER PART UNDERLAIN BY ALTERNATING UNITS OF FINE TO VERY FINE GRAINED SANDSTONE AND LIMESTONE. SHALE IS NOT COMMON BUT THE LIMESTONES ARE COMMONLY ARGILLACEOUS	3400±





GEOLOGIC COLUMN FOR THE WIPP AREA

Source: from Powers and others, 1978

GLOSSARY

accessible environment -"The accessible environment means (1) the atmosphere, (2) land surfaces, (3) surface waters, (4) oceans, and (5) all of the lithosphere that is beyond the controlled area" (40 CFR 191.12[k]).

acidic volcanics - A descriptive term applied to those igneous rocks that contain more than 60% silicon dioxide (SiO_2), as contrasted with intermediate and basic; applied loosely to any igneous rock composed predominantly of light-colored minerals having a relatively low specific gravity.

active institutional control - "Active institutional control means (1) controlling access to a disposal site by any means other than passive institutional controls, (2) performing maintenance operations or remedial actions at a site, (3) controlling or cleaning up releases from a site, or (4) monitoring parameters related to disposal system performance" (40 CFR 191.12[f]).

activity ratios - Comparison of the radioactivities of isotopes.

alluvial - Pertaining to poorly consolidated gravels, sands, and clays deposited by streams or running water.

alpha-emitting - Ejection of positively charged particles from an atom's nucleus during the radioactive decay of certain nuclides.

anaerobic - Living, active, or occurring in the absence of free oxygen.

Anasazi - A prehistoric farming culture of northwest New Mexico that reached its peak development between A.D. 950 and 1100, with its center located near what is now Chaco Culture National Historical Park.

Anglos - Anglo-Americans, especially a Caucasian resident of the United States who is not of Latin descent.

anhydrite - A mineral consisting of anhydrous calcium sulfate ($CaSO_4$); it is gypsum without water, and is denser, harder, and less soluble.

anoxic - Without free oxygen.

anthropogenic - Pertaining to the scientific study of the origin of man.

Apaches - A formerly nomadic tribe of North American Indians inhabiting the southwestern United States and northern Mexico.

aquifer - A body of rock that is sufficiently permeable to conduct ground water and to yield significant quantities of ground water to wells and springs.

Archaic - In New World archaeology, a prehistoric cultural stage that follows the Lithic and is characterized in a general way by a foraging pattern of existence and numerous types of stone implements.

aseismic - Said of an area that is not subject to earthquakes.

Athapaskan - A group of related North American Indian languages including Navajo and Apache and languages of Alaska, northwestern Canada, and coastal Oregon and California.

backfill - Material filling a former excavation (e.g., salt placed around the waste containers, filling the open space in the room).

barrel - As used in the petroleum industry, a volumetric unit of measurement equivalent to 42 U. S. gallons (158.76 liters).

basement complex - The undifferentiated complex of igneous or metamorphic rocks that underlies the sedimentary rocks in an area. In many places the rocks of the complex are of Precambrian age, but in some places they are Paleozoic, Mesozoic, or even Cenozoic.

brine reservoir - A higher porosity volume of rock that contains pressurized brine.

caliche - A soil horizon composed predominantly of calcium carbonate of secondary origin.

ciboleros - Buffalo hunters.

Classic Mimbres phase - A prehistoric cultural stage corresponding to the peak development of the Anasazi (between A.D. 950 and 1100) and generally referring to the villages in southern New Mexico.

Classic Period - In New World archaeology, a cultural stage that follows the Formative and is characterized by the rise of civilizations such as the Mayan. It is followed by the Post-Classic.

claystone - An indurated clay having the texture and composition of shale but lacking the fine lamination and fissility.

Clovis Period - A prehistoric cultural stage from approximately 9500 to 9000 B.C., characterized by family bands of hunters whose territories covered hundreds of square miles in northern and western New Mexico.

comancheros - Originally members of Plains Indian tribes during the 1800s who traded horses, buffalo meat and hides, and slaves for foodstuffs from the Pueblo Indians of New Mexico. Over time, Anglos joined the comancheros, and trade goods included guns, ammunition, and whiskey.

conceptual model - The set of hypotheses that postulates the description and behavior of the natural and/or engineered systems (e.g., structural geometry and all significant physical processes that affect behavior).

creep - The usually slow deformation of solid rock without failure in the presence of differential stresses.

Darcy model - Pertaining to a formula derived by Darcy for the flow of fluids through porous media, which states that flow is directly proportional to the hydraulic gradient, the cross-sectional area through which flow occurs, and the hydraulic conductivity.

decommission - Actions taken to reduce potential environmental, health, and safety impacts upon abandonment of the repository, including sealing of the engineered subsurface facility as well as activities to stabilize, reduce, or remove radioactive materials or to demolish surface structures.

deuterium - An isotope of the element hydrogen with one neutron and one proton in the nucleus and an atomic weight of 2.0144. Designated as D, d, H^2, or ^2H.

disposal site - As it pertains to Subpart B of 40 CFR 191, the controlled area for the WIPP. "The controlled area means (1) a surface location, to be identified by passive institutional controls, that encompasses no more than 100 km and extends horizontally no more than 5 km in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system; and (2) the subsurface underlying such a surface location" (40 CFR 191.12[g]).

disposal system - "Any combination of engineered and natural barriers that isolate spent nuclear fuel or radioactive waste after disposal" (40 CFR 191.12[a]). The natural barriers extend to the accessible environment.

distillate - Liquid hydrocarbons, generally clear or pale straw-colored and of high API gravity (above 60°), that are produced with wet gas; also referred to as condensate.

disturbed rock zone (DRZ) - That portion of the geologic system of which the physical or chemical properties may have changed significantly as a result of underground construction.

dolomites - Carbonate sedimentary rocks consisting of more than 50% of the mineral dolomite [$CaMg(CO_3)_2$].

drifts - Horizontal passageways in a mine.

dryland farming - A type of farming practiced in arid areas without irrigation by maintaining a fine surface of tilled earth or mulch that retards the natural moisture of the soil from evaporating.

entradas - Spanish expeditions into the southwestern U. S. during the 1700s and 1800s.

eolian - Pertaining to the wind; especially said of sedimentary deposits and features formed by wind action.

evapotranspiration - Loss of water from a land area through transpiration of plants and evaporation from the soil.

faunal assemblages - Groups of fossils that occur at the same stratigraphic level, used to determine relative time intervals.

fission - A nuclear reaction in which an atomic nucleus splits into fragments of comparable mass accompanied by the release of energy.

fissionable material - Said of nuclei, such as uranium and plutonium, that are capable of being induced to undergo nuclear fission by slow neutrons, accompanied by the release of energy.

fluvial - Of or pertaining to a river or rivers.

Folsom-Midland Period - Of or relating to an early North American culture of the Pleistocene period (9000 to 8000 B.C.) flourishing predominantly east of the Rocky Mountains and notable chiefly for the use of leaf-shaped flint implements.

foraminifera - Any of various fossil and living species of marine and freshwater protozoans, class Foraminifera, characterized by calcite, silica, aragonite, or agglutinated shells.

full-glacial maximum - The time or position of the greatest extent of any glaciation; most frequently applied to the greatest equatorward advance of Pleistocene glaciation.

gas diffusion - Migration on a molecular or atomic scale in response to a concentration gradient.

gastropod - Any mollusk belonging to the class Gastropoda, characterized by a distinct head with eyes and tentacles and, in most, by a single calcareous shell that is closed at the apex, sometimes spiralled, not chambered, and generally asymmetrical (e.g., a snail).

geomorphology - The study of the classification, description, nature, origin, and development of present landforms and their relationships to underlying structure, and of the history of geologic changes as recorded by these surface features.

granitic - Pertaining to or composed of granite (a coarse-grained, crystalline rock of igneous origin primarily composed of feldspar and quartz.

gravels - An unconsolidated, natural accumulation of rounded rock fragments resulting from erosion, consisting predominantly of particles larger than sand (diameter greater than 2 mm or 1/12 in), such as boulders, cobbles, pebbles, granules, or any combination of these fragments.

ground water - That part of the subsurface water that is in the zone of saturation; loosely, all subsurface water as distinct from surface water.

gypsiferous dolomites - A dolomite containing gypsum, hydrous calcium sulfate ($CaSO_4 \cdot 2H_2O$), a mineral frequently associated with halite and anhydrite in evaporitic rocks.

half-lives - The time necessary for a radioactive substance to lose half of its radioactivity (provided there are a large number of atoms involved). Each radionuclide has a characteristic half-life.

halite - A dominant mineral in evaporites; salt, NaCl.

high-level wastes - "(A) The highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and (B) other highly radioactive material that the Commission [Nuclear Regulatory Commission], consistent with existing law, determines by rule requires permanent isolation" (Public Law 97-425).

Hispano - Of or pertaining to the language, people, and culture of Spain, Portugal, or Latin America.

Homestead Act - An act passed by Congress in 1862 promising ownership of a 160-acre tract of public land to the head of a family after he had cleared and improved the land and lived on it for five years.

host rock - The geologic medium in which radioactive waste is emplaced.

Humanos - A North American Indian tribe that inhabited southeastern New Mexico, specifically the area near Gran Quivira, during the 1500s.

hydrocarbons - Organic compounds, gaseous, liquid, or solid, consisting solely of carbon and hydrogen. Crude oil is essentially a complex mixture of hydrocarbons.

infiltration - The flow of a fluid into a solid substance through pores or small openings; specifically, the movement of surface water or precipitation into soil or porous rock.

interbeds - Sedimentary beds that lie between or alternate with other beds having different characteristics.

Jornada Mogollon - A prehistoric farming culture of the eastern plains of New Mexico and the Llano Estacado of Texas during approximately A.D. 950 to 1100.

Jumano Plains Indians - A North American tribe that inhabited the plains areas of Texas and New Mexico in the 1500s.

karst - A type of topography formed from solution of limestone, dolomite, or evaporite minerals; characterized by sinkholes, caves, and underground drainage.

lacustrine - Pertaining to a lake or lakes.

langbeinite - A colorless to reddish mineral [$K_2Mg_2(SO_4)_3$] used as a source of potassium in fertilizers and formed as a saline residue from evaporation.

limestones - Sedimentary rocks consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite and with or without magnesium carbonate; specifically, carbonate sedimentary rocks containing more than 95% calcite and less than 5% dolomite.

Lipan Apaches - A tribe of North American Plains Indians that inhabited southeastern New Mexico during the 1700s.

lithosphere - The solid portion of the earth as opposed to the atmosphere and the hydrosphere.

lithostatic pressure - Subsurface pressure caused by the weight of overlying rock or soil, about 14.9 MPa at the WIPP repository level.

mescal - A spineless, globe-shaped cactus, Lophophora williamsii, of Mexico and the southwestern United States, having buttonlike tubercles that are dried and chewed as a drug by certain Indian tribes.

Mescalero Apaches - A tribe of North American Plains Indians that inhabited southeastern New Mexico during the 1700s.

metamorphosed - The mineralogical, chemical, and structural adjustment of solid rocks due to heat or chemical action at depth below the surface zones of weathering and cementation, and which differ from the conditions under which the rocks in question originated.

millirems - One-thousandth (0.001) of a rem. A rem is a unit of radiation that charges atoms, equal to the amount that produces the same damage to humans as 1 roentgen of high-voltage x-rays. Derived from roentgen equivalent man.

Mogollon-Mimbres culture - A prehistoric farming culture of southern New Mexico, contemporary to the Anasazi of northwest New Mexico, from approximately A.D. 950 to 1100.

monsoonal climate - The type of climate that is found in regions subject to monsoons. A monsoon is a type of wind system whose direction changes with the seasons, for example, over the Arabian Sea, where the winds are from the northeast for six months and then from the southeast for the next six months.

overburden - The loose soil, silt, sand, gravel or other unconsolidated material overlying bedrock.

oxygen-18/oxygen-16 ratio ($^{18}O/^{16}O$) - Comparison of the amount of oxygen-18 and oxygen-16 in a substance. Ratios in sea water reflect global volume of glacial ice.

packrat middens - Any organic debris or soil deposited by any of various small North American rodents of the genus Neotoma that collect in their nests a variety of small objects.

paleoclimatic - The climate of a given interval of time in the geologic past.

Paleo-Indians - Hunter-gatherers that inhabited New Mexico about 10,000 to 5000 B.C.

passive institutional control - "Passive institutional control means (1) permanent markers placed at a disposal site, (2) public records and archives, (3) government ownership and regulations regarding land or resource use, and (4) other methods of preserving knowledge about the location, design, and contents of a disposal system." (40 CFR 191.12[e])

pelagic - Pertaining to the water of the ocean as an environment; said of marine organisms whose environment is the open ocean rather than the bottom or shore areas.

performance assessment - Performance assessment is defined by Subpart B of 40 CFR 191 as "an analysis that (1) identifies the processes and events that might affect the disposal system, (2) examines the effects of these processes and events on the performance of the disposal system, and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events. These estimates shall be incorporated into an overall probability distribution of cumulative release to the extent practicable." (40 CFR 191.12[q])

polyhalite - An evaporite mineral: $K_2MgCa_2(SO_4)_4 \cdot 2H_2O$, which is a hard and poorly soluble mineral.

Post-Folsom Period - A time period from about 8000 to 6000 B.C. characterized by a diminished presence of Paleo-Indians in the New Mexico area.

potable - Fit to drink, as in water that is safe and palatable for human use.

potash - Specifically K_2CO_3. Also loosely used for many potassium compounds, especially as used in agriculture or industry.

Pueblo - A community dwelling up to five stories high, built of stone or adobe by Indian tribes of the southwestern United States; a tribe such as the Hopi or Zuni that inhabited pueblos; an Indian village of the southwestern United States.

quality assurance - All those planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily in service.

radiolysis - Chemical dissociation of molecules as a result of radiation.

radionuclide - A species of atom having an unstable nucleus, which is subject to spontaneous decay.

rancheria - A Mexican herdsman's hut; a village of such huts; an Indian village.

recharge - The processes involved in the addition of water to the ground-water zone of saturation.

reserves - Identified resources of mineral- or fuel-bearing rock from which the mineral or fuel can be extracted profitably with existing technology and under present economic conditions.

resources - Reserves plus all other mineral deposits that may eventually become available--either known deposits that are not economically or technologically recoverable at present, or unknown deposits, rich or lean, that may be inferred to exist but have not yet been discovered. They represent the mineral endowment, global, regional, or local, ultimately available for man's use.

sandstone stringers - Relatively thin, laterally narrow layers or beds of rock composed of sand-sized particles.

scenario - A combination of naturally occurring or human-induced events and processes representing realistic future changes to the repository, geologic, and geohydrologic systems that could cause or promote the escape of radionuclides from the repository.

seal - An engineered barrier designed to isolate the waste panels or to impede ground-water flow in the shafts.

sensitivity analysis - An evaluation to determine the contribution of individual input variables to the uncertainty in model predictions or to identify those parameters for which variability in the sampled value has the greatest effect on the results.

Seven River Apaches - Dominant group of Mescalero Apaches in southeastern New Mexico during the late 1600s and early 1700s.

shales - Fine-grained, detrital sedimentary rocks, formed by the consolidation (especially by compression) of clay, silt, or mud. Shale is characterized by a finely laminated structure that splits approximately parallel to the bedding, along which the rock breaks readily into thin layers, and that is commonly most conspicuous on weathered surfaces and by an appreciable content of clay minerals and detrital quartz.

Shoshonean - A group of Uto-Aztecan languages that includes most of the Uto-Aztecan languages found in the United States.

siltstone - A sedimentary rock composed of at least two-thirds silt-sized grains (1/256 to 1/16 mm); it tends to split into flat layers that are hard, durable, and generally thin.

slant drilling - The intentional drilling of a well at controlled departures from the vertical.

spent nuclear fuel - Nuclear reactor fuel that has been irradiated to the extent that it can no longer effectively sustain a chain reaction because its fissionable isotopes have been partially consumed and fission-product poisons have accumulated in it.

sulfide ores - Mineral compounds characterized by the linkage of sulfur with a metal or semimetal, such as galena, PbS, or pyrite, FeS_2.

summed normalized release - Method for determining release limits for compliance with the Containment Requirements of Subpart B of 40 CFR 191: for each radionuclide released, the ratio of the cumulative release to the total release limit is determined; ratios for all radionuclides released are then summed for comparison to the requirements.

sylvite - A white or colorless mineral (KCl), the principal ore mineral of potassium compounds, that occurs in beds as a saline residue from evaporation.

transuranic (TRU) wastes - Radionuclides having an atomic number greater than 92. In the current regulatory environment, the term is used for waste that, without regard to source or form, is contaminated with more than 100 nCi of alpha-emitting transuranic isotopes with half-lives greater than 20 years, per gram of waste, except for (1) high-level wastes; (2) wastes that the DOE has determined, with the concurrence of the EPA Administrator, do not need the degree of isolation required by 40 CFR 191; or (3) wastes that the NRC has approved for disposal on a case-by-case basis in accordance with 10 CFR 61. Heads of DOE field organizations can determine that other alpha-contaminated wastes, peculiar to a specific site, must be managed as TRU waste.

tritium - A radioactive isotope of hydrogen having two neutrons and one proton in the nucleus.

TRUPACT-II - The transportation container for trucking contact-handled (CH) transuranic (TRU) waste to the WIPP. The waste inside the TRUPACT-II container is stored in 55-gallon steel drums packed in metal standard waste boxes (SWBs) and experimental bins overpacked in SWBs.

uncertainty analysis - An evaluation to determine the uncertainty in model predictions that results from imprecisely known input variables.

undisturbed performance - "The predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events." (40 CFR 191.12[p])

verification - The process of assuring (e.g., through tests on ideal problems) that a computer program (computational model) correctly performs the stated capabilities (such as solving the mathematical model). Given that a computer code correctly solves the mathematical model, the physical assumptions of the mathematical model must then be checked through validation.

vugs - Small cavities in a rock.

weeps - Pertaining to a porous rock from which water oozes.

NOMENCLATURE

Abbreviations and Symbols

MaBP - mega-annum (million years) before present

MPa - mega-pascal

Acronyms and Initialisms

DRZ - disturbed rock zone

ppm - parts per million

TRUPACT-II - TRansUranic PACkage Transporter-II

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