RESOLUTION OF SITE CHARACTERIZATION ISSUES AT THE WASTE ISOLATION PILOT PLANT

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ABSTRACT

The Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico 40 kilometers (km) east of Carlsbad, New Mexico, is the world's first geologic repository for disposal of defense transuranic (TRU) radioactive waste. The repository has been excavated in the bedded salt of the Salado Formation at a depth of 655 meters (m) below the surface. The geologic isolation of radioactive waste containing radionuclides with long half-lives relies primarily on the geologic barriers to keep the radionuclides from leaking to the biosphere. Several geologic features and processes were identified during the characterization of the WIPP site that could impact the performance of the repository for the 10,000 - year regulatory period. These include salt dissolution, breccia chimneys, brine reservoirs, brine inflow in the repository from the Salado salt, hydrology and geochemistry of the Rustler Formation water-bearing units, karst hydrology, disturbed rock zone behavior, and the impact of mineral resources. A variety of methods were employed to understand these phenomena and how they would impact the projected performance of the repository when considered in the analysis of breach scenarios from the WIPP repository for the next 10,000-year period. These methods included additional fieldwork, laboratory analyses, and the development of conceptual models based on the results of the tests. The history of the efforts to resolve these issues should be of interest to other projects where site characterization is under way now, or will be in the near future.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is a geologic repository for permanent disposal of defense transuranic (TRU) waste located 40 km east of Carlsbad in southeastern New Mexico. The United States Department of Energy (DOE) administers the project, with Sandia National Laboratories (SNL) in charge of site characterization and most of the experiments, and Westinghouse Government Services Waste Isolation Division as the management and operating contractor. The Environmental Evaluation Group (EEG) is an oversight agency for the WIPP project. It is affiliated with the New Mexico Institute of Mining and Technology and has offices in Albuquerque and Carlsbad. It was established in 1978 as an interdisciplinary group of scientists and engineers to provide an independent technical evaluation of various aspects of the WIPP project to protect the public health and the environment of New Mexico, with full funding from the DOE. The EEG has analyzed the importance of various site characterization issues, has recommended additional field and laboratory studies to try to resolve them, and has developed conceptual models to explain the observed facts. In addition, the EEG has examined the technical issues that have been raised by other oversight agencies and public interest groups during the WIPP's site characterization and evaluation process, and has proposed further investigations and analyses to resolve these controversies.

TRU waste consists of various kinds of trash including paper, rubber, wood, metals and sludge, contaminated with radionuclides heavier than uranium with half-lives greater than 20 years and a level of contamination exceeding 100 nanocuries per gram. Although the radionuclides are disseminated in the waste, the total amount in the repository will be significant. For example, the DOE estimates about 13 metric tons of plutonium-239, the major radionuclide in the defense TRU waste, will be in the WIPP repository when the repository is full. The waste has resulted as a by-product of nuclear weapons production in the USA during the past 50 years. Only the waste retrievably stored since 1970 is presently planned to be shipped to WIPP. By current estimates, 55% of the planned capacity of waste for WIPP is yet to be produced. Two categories of the TRU waste are currently stored at the DOE-managed national laboratories and will be disposed of at WIPP. The contact-handled (CH-TRU) waste is contained in 0.21 m^3 (55-gallon) mild carbon-steel drums and standard waste boxes that have a maximum surface-dose rate of 2 millisieverts (200 millirem) per hour. The remote-handled (RH-TRU) waste will be disposed of in 0.85 m^3 capacity cylindrical canisters with unshielded surface dose rate higher than 2 millisieverts (200 millirem) per hour, and up to a maximum of 10 sieverts (1000 rem) per hour for 5% of the waste by volume.

The WIPP repository is excavated at a depth of 655 m below the surface and, when completed, will consist of 56 "rooms," each 91.5 m long, 10 m wide, and 4 m high, divided in eight panels of seven rooms each (Fig.1). The seven rooms of the first panel were excavated between 1986 and 1988, because the DOE had planned to start shipping radioactive waste to WIPP in 1988 for "operational demonstration". Those plans, and the later developed plans for conducting experiments with waste in the underground rooms, were formally abandoned in 1993. Excavation for the second panel of the repository began in October 1999. The latest estimate for the 50-hectare WIPP repository is to hold 850,000 drum-equivalent (176,000 m^3) of CH-TRU waste containing 6.5 million curies of radioactivity and 7,500 canisters (7100 m^3) of RH-TRU waste containing 1 million curies. The CH-TRU waste drums and boxes are stacked three high in the repository rooms. The RH-TRU waste canisters will be disposed of in 0.91-m diameter and 3 m deep horizontal holes in the walls of the rooms, although this waste is not expected to be available for shipment until 2003.

In addition to being radioactive, the TRU waste to be disposed of at WIPP contains hazardous chemical waste. The WIPP therefore has to satisfy the requirements of the Resource Conservation and Recovery Act (RCRA), in addition to the requirements of the U. S. Environmental Protection Agency (EPA) standards for management and disposal of TRU radioactive waste (1). After receiving the EPA's certification of compliance with their long-term radiation protection standards in October 1998, the DOE started shipping drums and boxes containing non-mixed (devoid of RCRA controlled constituents) CH-TRU waste to WIPP in March 1999. The New Mexico Environment Department issued a RCRA permit to the DOE on October 27, 1999, allowing shipment of mixed waste (containing both radioactive and chemically hazardous waste) to WIPP. The implementation of the permit is pending resolution of certain issues, included in two permit-related lawsuits against the State, one by the DOE and the other by environmental groups.

A geological repository relies primarily on the geology of the site to provide containment of waste for thousands of years. This is especially true for the WIPP project, because there is no commitment to use robust engineered barriers for disposal of the TRU waste, other than the use of backfill. Ninety-seven percent (by volume) of the waste to be disposed of at WIPP will be contained in ordinary mild-carbon-steel 55-gallon drums, or in "standard waste boxes" made of steel. The containers are expected to get crushed and corroded in a few years in the corrosive salt/brine environment of the repository and salt creep is expected to close the openings and form a cocoon around the waste. Geologic integrity and the absence of geologic and geohydrologic conditions or processes that may breach the integrity of the repository were, therefore, critical issues in assessing the suitability of the WIPP site for use as a geologic repository for long-lived radioactive waste.

The purpose of this paper is to describe and discuss the process of resolution of a number of issues that arose during the WIPP's site characterization process concerning various geological features, events, and processes that could have an impact on the integrity of the WIPP site.

GEOLOGICAL SETTING OF WIPP

The Salado Formation is about 600 m thick at the center of the WIPP site and the repository is situated at a depth of about 400-m from the top of the formation (Fig. 2). The formations of interest with respect to the WIPP project, from the oldest to the youngest, are: the Bell Canyon Formation of the Delaware Mountain Group; the Castile, Salado, Rustler and Dewey Lake Formations of the Permian Ochoan Series; the Upper Triassic Santa Rosa Sandstone Formation that tapers from the east to the west across the WIPP site, and the Pleistocene Gatuña Formation. A caliche layer known as the Mescalero Caliche is encountered underlying the surficial sands at the WIPP site.

Permian Capitan Reef bounds the Delaware Basin and the WIPP site is situated in the northern part of the basin (Fig. 3). The site lies on a generally flat plain covered with sand, caliche and desert bushes. It is located in a gypsum-karst region. A subsidence landform feature called Nash Draw lies about 5 km west of the WIPP site. It is 10 to 12 km wide in the east-west direction, about 30 km long in the north-south direction, and is thought to have resulted from erosion by solution and fill (2) of soluble rocks, a process that has occurred in the past and which is also presently active. The Pecos River flows from northwest to southeast, about 20 km west of the WIPP. The Malaga Bend of the Pecos river (Fig. 3) has been identified as an area of discharge of the Rustler water from Nash Draw and perhaps also from the WIPP site, based on (a) the presence of saline seeps along the Malaga Bend, (b) a marked increase in the salinity of the river south of the bend, and (c) the general flow direction of the water-bearing beds of the Rustler Formation.

Since all the breach scenarios from the WIPP involve groundwater in one way or another, it is essential to understand the hydrological significance of the geological formations at the WIPP site. Starting from the oldest formation shown in Fig. 2, groundwater occurs in the upper part of the Bell Canyon Formation in poorly cemented sandstone stringers (3). The Castile Formation is about 470 m thick at the WIPP site and overlies the Bell Canyon. It consists of alternating layers of anhydrite and halite, with four anhydrite and three halite members. The uppermost anhydrite member contains pressurized brine reservoirs that have been encountered by two of the boreholes drilled for the WIPP project and by several commercial oil and gas exploratory wells. The Salado Formation consists primarily of halite, with a zone of potassium-and magnesium-bearing minerals (sylvite and langbeinite) in its upper part, and thin (~1 meter) seams of clay, anhydrite and polyhalite at irregular intervals throughout. Before 1986, thick salt beds, as in the Salado Formation, were considered essentially dry and impermeable. Observations from the WIPP excavations, however, indicate that the salt beds may be saturated with brine (4) and the Salado appears to allow Darcian flow of water, albeit at very low porosity and permeability (5).

The Rustler Formation overlies the Salado and contains the most important geohydrologic units in the region. The thickness of the Rustler varies between 84 m to 130 m in the northern Delaware Basin and is approximately 95 m at the WIPP site. Lowenstein (6) and Powers and Holt (7) have described the sedimentology of the Rustler Formation. The formation contains three recognized fluid-bearing zones; in ascending order, the Rustler-Salado contact residuum, the Culebra dolomite and the Magenta dolomite. The transmissivity of the Culebra is the highest, followed by the Magenta and the Rustler-Salado contact. The water quality is highly variable within each unit. The total dissolved solids concentration is lowest in the Magenta and highest in the Rustler-Salado contact zone. Nearly all the water in the Rustler Formation at the WIPP site has total dissolved solid (TDS) concentrations greater than 10,000 mg/l.

All three Rustler hydrologic units probably discharge into the Pecos River, 22 km to the southwest near the Malaga Bend. The recharge areas are identified rather imprecisely as being up-gradient of the measured hydraulic heads, about 16 to 24 km north of the WIPP site. At the WIPP site, the three units are separated but are connected in Nash Draw, west and southwest of the site. The majority of testing in the Rustler has concentrated on the Culebra because it is more transmissive than the Magenta and the Rustler/Salado interface and therefore better suited for analyzing bounding breach scenarios.

Results of several single-hole and multi-hole flow tests at the site indicate that the transmissivity of the Culebra aquifer at and near the WIPP site ranges from $4x10^{-8}$ m^2/s to $2x10^{-3}$ m^2/s at the tested locations (8). Generally, transmissivity increases from east to west across the WIPP site, but a high transmissivity zone occurs in the southeastern part of the site, in the area of boreholes DOE-1 and H-11. High transmissivity is also found in the northcentral and northwestern parts of the site in the vicinity of boreholes WIPP-13, DOE-2 and H-6 (Fig. 4).

Chemical composition of groundwater from the Culebra aquifer varies widely within short distances at and near the WIPP site (9). Three miles south of the WIPP site, the Culebra water typically contains 3000 mg/l of TDS. At the site itself, TDS varies from 12,500 mg/l at H-2 (Fig. 4) to 139,500 mg/l at H-5. Extreme variation in the chemistry of the Culebra water within short distances is illustrated by the TDS at H-2 (12,500 mg/l), H-3 (153,500 mg/l) and DOE-1 (118,000 mg/l), within a distance of less than 3 km.

The WIPP is situated in a mineral-rich area. Potash minerals are mined around the WIPP site from the McNutt potash zone in the upper part of the Salado Formation, approximately 450-m below the surface. Oil and gas are produced around the WIPP site from the Permian Delaware Mountain Group and Pennsylvanian Atokan and Morrowan strata. Figures 5 shows the potash, oil and gas resources surrounding the WIPP site.

HISTORY OF WIPP SITE CHARACTERIZATION

The geological site characterization for the WIPP began in 1974, following the abandonment of the Lyons, Kansas site in 1972. A 3.2 km x 2.4 km rectangular site was selected by the Oak Ridge National Laboratory (ORNL) about 11 km northeast of the present site. Cores from two boreholes (AEC-7 and AEC-8, Fig. 4) penetrating through the Salado Formation drilled at the northeast and the southwest comers of that site indicated acceptable geology. Sandia National Laboratories (SNL) was given the responsibility for site characterization for WIPP in 1975. A third borehole (ERDA-6), drilled by SNL in the northwest corner of that site in 1975, encountered a pressurized brine reservoir and intense structural disturbance in the fractured upper anhydrite of the Castile Formation at a depth of 826 m. The project was then moved to the present site, which was selected by the SNL and the U.S. Geological Survey (USGS). A stratigraphic borehole (ERDA-9) was drilled in 1976 through the Salado Formation and 15 m into the Castile Formation at the center of the present site.

Early site characterization activities focused on obtaining basic data on the stratigraphy, hydrology and potash resources at the WIPP site (10,11,12). As these studies progressed, several geologic features or processes that were potentially deleterious to a radioactive waste repository were identified. The EEG organized a meeting of geoscientists in January 1980, followed by a field conference in June 1980, to discuss these geologic issues (13,14). Based on the recommendations from these meetings and independent analyses by the EEG scientists, the EEG proposed preparation of a number of topical reports to address the geological issues that had surfaced at that time. The DOE accepted these recommendations and a Stipulated Agreement between the State and the DOE was signed on 1 July 1981 that included the DOE commitment to prepare eleven "topical reports" and six "additional investigations".

As a part of additional investigations, the DOE deepened the borehole WIPP-12, located 1.6 km north of the center of the WIPP site, from its 1978 completed depth of 834.5 m at the top of the Castile, to a new depth of 1197.4 m. Pressurized brine associated with hydrogen sulfide gas was encountered at a depth of 919.5 m. At that time, the WIPP repository was designed to be located north of the center of the WIPP site and the experimental areas to the south, reverse of the configuration shown in Fig. 1. In that configuration the northern edge of the repository would have been only 170 m horizontally south from WIPP-12. As a result of encountering brine in WIPP-12, EEG recommended and the DOE accepted rotating the WIPP underground layout to place the repository south of the center and the experimental areas to the north, as shown in Fig. 1. With this relocation, the repository is now about 2 km south of the WIPP-12 borehole.

The WIPP topical studies were published in 1983 and the DOE claimed that the geologic site characterization issues were resolved. The EEG reviewed the reports and concluded (15) that the site characterization work completed until then warranted confidence in the site, but work still remained to be done to answer many remaining questions. Underground excavation began in 1982 and additional issues about the geomechanical and hydrological behavior of the repository strata came to light from the observations and measurements underground.

RESOLUTION OF ISSUES

The significant geologic issues that arose during the site characterization of WIPP are described below, and the history and current status of their resolution is discussed.

Dissolution of Salado Salt

There is indisputable evidence that the Ochoan evaporite deposits (Castile, Salado, Rustler and Dewey Lake Redbeds Formations) have undergone erosion and blanket dissolution in the Delaware Basin. The edges of the Castile and the Salado halite can be traced west of the Pecos River essentially running parallel to it in a northwest-southeast direction (16).

Bachman and Johnson 917) concluded that the horizontal rate of movement of the blanket dissolution front is about 9.5 to 13 km (6 to 8 miles) per million years. This estimate was based on the observation that the salt front in the Permian rocks has retreated eastward 40 to 56 km (25 to 35 miles) from the Capitan Reef escarpment along the western edge of the Delaware basin to its present location. They theorized this to have happened during the past 4 million years due to erosional stripping of the protective Ogallala Formation and the development of the Pecos River drainage. Jones (18) translated this proposed lateral dissolution rate into a vertical dissolution rate of about 15-cm per 1,000 years, but did not describe the basis for this calculation. Bachman

(19) concluded, however, that the fundamental assumptions underlying these estimates were faulty because the dissolution may have occurred before the Ogallala time as well.

George Bachman and Richard Kelley discovered a volcanic ash layer in the Gatuña Formation at the Livingston Ridge on the eastern margin of Nash Draw in 1979. This ash was then identified by Glenn Izett of the U.S. Geological Survey as Pearlette type "O" volcanic ash, originated in the Yellowstone region about 600,000 years ago (16). Assuming the 60-m deep Nash Draw collapse to be directly related to salt dissolution, Bachman (personal communication) informally suggested an average rate of 100 m per million years for salt dissolution vertically. These are, of course, very rough average rates of movement; the front itself may have moved faster under less arid climatic conditions. Also, an advancing "tongue" of the front may reach a point faster than the front itself. Using the above rates for horizontal and vertical dissolution, it would take at least 250,000 years for the front to travel approximately 3.2 km to reach the western edge of the WIPP site and start dissolving salt from the upper Salado, about 450 m above the repository horizon. It would then require at least 3 million years for the removal of 450 m of salt by dissolution, at the rate of 100 to 150 m per million years. In spite of the very approximate nature of the estimated rates of advance of the dissolution front, these calculated rates provide sufficient safety to the repository from an advancing front of blanket shallow dissolution of salt toward the WIPP site.

In addition to the blanket dissolution of salt described above, Anderson (16) raised the possibility of a different kind of dissolution process acting at depth from the margins of the basin. He noted that large quantities of bedded salt were missing from the middle of the evaporite sequence near the center of the basin and calculated that more than 70% of the original salt has already been removed from the lower Salado horizon in the basin. Using the correlation of acoustic logs along several lines in the Delaware Basin, Anderson (16) concluded that such dissolution has occurred around the margin of the basin where the Capitan aquifer is in contact with the Permian evaporites, and within the basin where selective dissolution in the lower Salado has undercut the overlying salt beds. He invoked the model of brine density flow (20) to explain this type of deep dissolution. According to this model, heavy saturated brine is drained away through fracture systems into the underlying Delaware Mountain Group (DMG) aquifer and lighter unsaturated water rises under artesian pressure to continue dissolution.

In 1981, a stipulated agreement to resolve a State's lawsuit against the DOE included the EEG suggestion for the DOE to prepare a series of topical reports on the subject of dissolution and other geotechnical issues. Lambert (21) examined various aspects of the dissolution issue and concluded that much of the salt thought by Anderson (16) to have been missing was never deposited. He also dismissed the DMG aquifer to be capable of providing sufficient amount of unsaturated water to carry out the Salado salt dissolution at depth. Another WIPP project report (22) examined in detail the viability of the DMG aquifer removing the dissolved salt. Wood et al. (22) concluded that the DMG aquifer does not have sufficient flow rate to supply fresh water and remove the quantities of saturated brine that would be required by the postulated mechanism.

The EEG (14, 15, 23) examined the deep-dissolution hypothesis and concluded that although the timing and the mechanism were not fully explained by the hypothesis, the evidence from geophysical well logs did indicate that a large amount of salt from the lower Salado units was missing. However, there were eight WIPP project boreholes (AEC-7 and AEC-8 to the northeast, ERDA-10 to the southwest, WIPP-11 to the north and WIPP-9, 12, 13 and DOE- 1 within the WIPP site; see Fig. 4), which had obtained cores of the Salado Formation but did not show any evidence of extensive dissolution. From this evidence the EEG concluded that the Salado Formation does not appear to have been affected in the immediate area of the WIPP site by past regional dissolution at depth. EEG did, however, recommend drilling of an additional deep borehole to resolve the suspicion of an area located 3.2 km north of the center of the WIPP site as a potential area of point-source dissolution. At that location a commercial borehole, FC-92, was drilled to assess the occurrence of potash minerals in the middle Salado. FC-92 encountered the marker beds in the upper and middle Salado at elevations about 23 m below their expected occurrences based on data from the surrounding holes. The log of at least one other nearby borehole, WIPP-34 (Fig.4), also showed this anomalous depression. At the urging of the EEG, the DOE drilled a 1319-m deep corehole (DOE-2, Fig. 4) to investigate the origin of this depression, which was suspected to be a possible area for point-source deep dissolution.

The core from the DOE-2 borehole confirmed the existence of the structural depression but showed no indication of this being due to dissolution at depth. The absence of any dissolution residue and a thickened halite section can best be interpreted as due to gravity-driven salt flow in the area (24). Two of the proponents of drilling DOE-2, Roger Anderson (25) and Peter Davies (26) concurred with Borns (24) interpretation, and after examining the cores of DOE-2, agreed that gravity-driven flow was most likely the mechanism causing subsidence and resulting structural depression observed in FC-92 and WIPP-34. EEG then concluded (27) that deep dissolution was not a threat to the WIPP repository and communicated this conclusion to the DOE.

Breccia Chimneys

A breccia chimney is a solution-subsidence structure formed by dissolution of an evaporite layer at depth that results in collapse of the overlying layers, thus forming a brecciated chimney up to several hundred meters in diameter with its base in the collapsed cavity. These features are found in many evaporite basins of the world. With respect to the WIPP, the concern was that a breccia chimney might form under the WIPP repository sometime in the future, thereby providing a potential pathway for breach of the repository.

Vine (28) identified as possible breccia chimneys several domal structures in the Delaware Basin that have been explored during the investigations for WIPP. After extensive investigation, the existence of only two chimneys (Hills A and C) was confirmed. Geophysical and geological studies show that two others (Hills B and Wills-Weaver) are also likely breccia chimneys, although they were not cored. All of these features are clustered in an area north of the WIPP site (Fig. 3) and appear to be situated over the Capitan Reef limestone, which is a prolific aquifer in the area (29). Davies (30) pointed out, however, that the Hill C breccia chimney is located at the southern edge of the buried Capitan Reef and since the borehole WIPP-16, drilled to explore this chimney, was drilled only to the level of the McNutt potash zone of the Salado Formation, it is not clear whether the Hill C breccia chimney roots in the Capitan aquifer.

Besides boreholes WIPP-31 and WIPP-16 (Fig. 4), which were drilled at Hills A and C, respectively, to investigate the breccia chimneys, three other boreholes were drilled at suspected breccia chimney locations in the basin. Borehole WIPP-32 was drilled in a small topographic high in Nash Draw, which had been described by Vine (28) as a domal karst feature. Boreholes WIPP-13 and WIPP-31 were also drilled to explore for possible breccia chimneys. There is a marked electrical resistivity anomaly at WIPP- 13 and a prominent topographic depression exists at the location where WIPP-31 was drilled. Collapsed breccia was not found in either of the wells and the WIPP-31 depression was identified as a karst sink.

Anderson and Kirkland (20) described the occurrence of collapse breccia in a borehole in Culberson County, Texas, about 90 km south of the WIPP site. Anderson (in 16) described occurrences of "castiles," which are mounds of brecciated rock that crop out a few miles south of the New Mexico-Texas border, south of the WIPP site. Both occurrences are in the exhumed western part of the Delaware Basin, which has already undergone extensive dissolution.

Snyder and Gard (29) studied the known occurrences of breccia chimneys in the Delaware Basin, including the Hill C breccia chimney which was encountered at the McNutt potash zone of the Salado Formation in the Mississippi Chemical Company potash mine, 366 m below the surface. From the study of Hill C exposure, the core of WIPP-16 drilled in this chimney, and the core of WIPP-31 drilled in the Hill A breccia chimney, Snyder and Gard (29) concluded that the breccia chimneys are formed by collapse of the overlying rocks in solution cavities in the Capitan Reef aquifer. Bachman (31) hypothesized that the location of all the known breccia chimneys in a small area over the reef is related to the presence of an old submarine canyon in the reef at this location. On the basis of the presence of Mescalero caliche over the breccia chimneys, Bachman (31) also concluded that the collapse occurred prior to the deposition of this caliche layer, i.e., more than 0.5 million years ago.

Davies (32) also studied chimneys A and C and concluded that they were produced by salt dissolution at the base and within the lowermost portion of the Salado Formation, through incremental subsidence rather than catastrophic collapse of the overlying strata. The EEG concluded (15) that the probability of a breccia chimney forming under the WIPP site was fairly remote and that this phenomenon did not appear to pose a threat to the WIPP repository.

Brine Reservoirs

Within a few kilometers of the WIPP site there are at least sixteen reported encounters of pressurized brine in the upper anhydrite layer of the Castile Formation (Fig. 6). Two of these encounters (ERDA-6 and WIPP- 12) were in the WIPP project boreholes and oil and gas drilling companies have reported the rest. When the borehole WIPP-12, located within the WIPP site, hit brine at a depth of 919.5 m in 1981, brine started flowing out of the well at a rate of 22 liters/sec and more than 4.3 million liters of brine flowed out before the well was controlled (33). Based on an extensive series of flow tests, the brine reservoirs penetrated by the WIPP-12 and ERDA-6 boreholes were estimated to contain 2.7 billion liters and 100 million liters of brine, respectively (33). Popielak et al. (33) also estimated that up to three percent of this volume, i.e. up to 80 million liters from WIPP-12, could be delivered to the surface without pumping if a man-made connection was provided. The different pressure potentials and geochemical data from the two encounters suggested a lack of communication between the ERDA-6 and WIPP-12 brine reservoirs. There was, however, no consensus on the origin and the age of the brine reservoirs. Popielak et al. (33) hypothesized that the water is the original Permian Sea water, 225 million years old, that became concentrated in the fractures associated with folding of the upper Castile anhydrite. Lambert (21), relying on the work of Barr et al. (34) and Lambert and Carter (35), interpreted the Uranium–isotope disequilibrium data to indicate the entrapment time of the brine reservoirs water. Lambert (21) concluded that the residence time of water in the WIPP-12 and ERDA-6 reservoirs may have been as low as 45,000 years, but under different assumptions, could be interpreted to be up to a maximum of 2 million years.

The configuration of the WIPP repository and the WIPP experimental areas, as originally planned, would have brought the waste within 140 m south of the WIPP-12 borehole that encountered pressurized brine in 1981. The EEG recommended moving the repository away from WIPP-12 in 1982 and the DOE rotated the repository configuration to relocate the non-waste experimental area to the north, and the repository 2-km south of WIPP-12. In 1983, EEG formally proposed geophysical investigations to delineate the extent of pressurized brine in the Castile Formation underlying the WIPP site and particularly under the new location of the repository. The work was performed in 1987, and the results gave a clear indication of the presence of brine under parts of the WIPP repository (36).

The potential presence of brine reservoirs in the Castile Formation became a major geological issue during the performance assessment and EPA certification of WIPP. Since there are good geophysical indications of the presence of brine in the Castile Formation, 250 m or so below the repository, the inadvertent drilling to a brine reservoir through the repository was the main human intrusion scenario that the WIPP project had to evaluate. Such a drilling sometime during the next 10,000 years would allow pressurized brine to flow into the repository. Several pathways for injection of such contaminated brine into the Rustler Formation or directly to the surface were evaluated as a part of the WIPP's application for compliance with the EPA standards.

Salado Brine

A reason for selecting the bedded salt deposits for isolating radioactive waste was the assumption that salt would be essentially dry. One of the surprises encountered by in situ underground studies at the WIPP is that the Salado salt yields a fair amount of water. A large percentage of boreholes drilled down from the WIPP excavations fill up with brine (37) and the walls are covered with efflorescences and encrustations resulting from brine inflow from salt into the excavation and drying up by ventilated air. Several boreholes completed in the Salado Formation indicate fluid pressure buildup (38). In situ Salado salt has low (10^{-21} m^2), but measurable, permeability.

Bredehoeft (6) proposed that the Salado salt is saturated with brine and exhibits Darcian flow. Nowak et al. (39) calculated that for salt permeabilities of 10^{-21} to 10^{-20} m^2 (1 to 10 nanodarcies), between 4 m^3 to 43 m^3 of brine would accumulate in a typical WIPP repository room with dimensions of 91.5 m x 10 m x 4 m. Since the WIPP CH-TRU containers are ordinary 55-gallon mild carbon steel drums that are not expected to last much beyond their 20-year design life, the brine would mix with the TRU waste and may form slurry. Sandia National Laboratories (40) calculated that if someone drills into such brine slurry and inadvertently brings a part of it to the surface, the EPA standards may be violated.

Corrosion of the metal containers and the metal in the waste would produce hydrogen. Microbiological degradation of the organic material in the waste would produce carbon dioxide and methane. These processes require water to produce gas and the Salado brine inflow would satisfy that need. The rate of brine flow into the repository is therefore a very important parameter for assessing breach scenarios. The DOE monitored and sampled the Salado brine from 13 boreholes in the WIPP underground from 1984 to 1993 (37). After five years of observation, five 15 m deep holes remained steady producers of brine, one showing increased brine production and five showing decreasing rates. One seep in the floor of room G produced between 0.5 to 0.75 liters of brine per day for five years. Several holes in the roof and in the walls also have been producing brine.

Hydraulic testing of the Salado Formation at the WIPP repository shows (7) the brine flow in the Salado salt to be Darcian in nature because the Darcy-flow models are able to replicate the flow and the pressure behavior observed during the entire testing sequences involving different types of tests. A 109 m long and 2.9 m diameter circular "room", Room Q (Fig. 1), was excavated at the WIPP repository level in July/August 1989 to measure the accumulation of brine inflow from the repository horizon strata. Unfortunately, much of the initial data were lost because of the ineffective temporary room seal. A permanent seal was installed in March 1991 and cumulative brine volumes were measured until April 1995. Freeze et al. (41) were able to reproduce this data through modeling with the assumptions of far field Darcy flow and a changing porosity for the disturbed rock zone (DRZ). Brine inflow from the surrounding rock into the repository was modeled in the WIPP performance assessment (42) using the BRAGFLO code and the measured parameters of permeability and porosity of the DRZ and the far-field pore pressures, using the Darcy flow assumption.

Rustler Formation Hydrology

The Culebra dolomite member of the Rustler Formation, being the most prolific of the three water-bearing zones overlying the WIPP repository, is the most likely pathway for transport of radionuclides after a breach of the repository. Based on three multi well flow tests, several single-well flow tests and non- sorbing tracer tests at four hydropads, LaVenue et al. (43) performed ground water flow modeling of the Culebra at the WIPP site. The flow model suggested that if radionuclides are injected into the Culebra directly above the repository panels near the center of the WIPP site, the fastest flow path out of the WIPP area would be to the south-southeast past the boreholes H-3 and H-11 (Fig. 4).

The calculated travel time for contaminant transport along this pathway, however, is very sensitive to assumptions of fracturing in the Culebra dolomite and distribution of contributing porosity between the rock matrix and the fractures. If double-porosity flow is assumed, with diffusion of contaminants in the rock matrix, the shortest travel time from the center of the WIPP site to the southern boundary is 14,000 years. If, on the other hand, transport is assumed through fractures only (single porosity), then the travel time may be less than 100 years. The breach scenario calculations performed in 1989-92 identified matrix diffusion and radionuclide retardation in the Culebra dolomite as sensitive parameters that control the magnitude and timing of the postulated releases of radioactivity to the environment. A multi - well tracer test was performed in 1995 at the hydropad H-19 (Fig. 4) to understand the mechanics of flow (single or double porosity) and the magnitude of matrix diffusion. The results showed (44, 8) a consistently clear evidence of double-porosity behavior.

The WIPP site is situated in a gypsum karst area. The karstic process of solution and fill (4,31,45) has formed the subsidence feature called Nash Draw. The depression in which borehole WIPP-33 (Fig. 4) was drilled is a karst sink. No positively identified karst feature has been encountered east of WIP-33 in the WIPP area, nor have hydrologic tests in the area detected any channeled flow.

Disturbed Rock Behavior

Before underground excavation at WIPP began in 1982, the DOE scientists performed calculations to predict the closure history of the excavations. These calculations used the geomcchanical properties of the rock strata at the selected WIPP repository horizon obtained from testing of the rock cores from boreholes. The calculations predicted that a WIPP room would "close slowly in a stable manner as the salt creeps" and "relative closure values of 0.21 m in the vertical direction and 0. 28 m total in the horizontal direction are seen for the isothermal room after 10 years" (46). The WIPP excavations have behaved very differently than predicted. Vertical closure in the WIPP test rooms has varied between 7.5 cm and 10 cm per year and horizontal closure has ranged between 5 cm and 7.5 cm per year. A "disturbed rock zone" of fractured rock surrounds all the excavations. In less than eight years after excavation, the roof of the first of the four test rooms fell in February 1991, due to fractures propagating above the roof and creating an up to 2 m wide unstable trapezoidal beam between the roof and a thin layer of anhydrite above the roof.

The difference between the predicted and measured closure rates has been explained on the basis of use of the wrong geomechanical models and not taking into account the details of the stratigraphy (47). While the faster closure rate will help entomb the waste sooner, it creates problems during operations. It will also create problems in maintaining retrievability of the waste. Due to its interaction with brine inflow and gas pressure from gases produced by the waste, the room closure rate also affects long-term performance of the repository. Waste emplacement in the WIPP repository began in March 1999 in Room 7 of Panel 1, which had been excavated in 1986-88 period. All rooms of panel 1 show signs of deterioration and several installments of roof support systems have been installed to maintain the roof from collapse. Excavation of Panel 2 began in November 1999 and is expected to be completed by October 2000. The new panel should be used as soon as it is ready and the Panel 1 should be abandoned. The DOE has not planned to maintain easy retrievability of waste from WIPP.

Natural Resources

The WIPP site is located in a region that contains substantial amounts of potash, natural gas and petroleum resources. Therefore, breach scenarios involving inadvertent drilling by future generations must be considered. The EPA Standards (1) prescribed a limit of assuming 30 boreholes/km^2/10,000 years, which was based on the drilling frequency in the WIPP site vicinity in 1970s. Judging by the number of producing wells, drilling activity around the WIPP site in the 1990s, and the number of applications to the U.S. Bureau of Land Management for new drilling permits, the oil and gas resources in the WIPP area are much more prolific than previously considered. In 1996, the EPA required calculation of a new projected future rate of drilling in the criteria (48) for assessing compliance with the disposal standards. The new rate based on the past 100-year history of drilling in the Delaware Basin is 46.8 boreholes/km^2/10,000 years. The WIPP application for certification showing compliance with the EPA standards, submitted to EPA in 1996 (42), assumed this rate for performance assessment.

CONCLUSIONS

Since the WIPP repository is designed to rely on geologic isolation for at least 10,000 years, consideration of the various geologic features and processes is necessary to assess the capability of the site to keep the waste isolated from the environment. EEG has been involved in trying to clarify and understand the geologic phenomena and processes since 1978. This effort has resulted in the resolution of many site characterization issues and has made the performance assessment of WIPP more robust.

REFERENCES

1. U. S. ENVIRONMENTAL PROTECTION AGENCY, "Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes", 40 Code of Federal Regulations Part 191 (1993).

2. W. T. LEE, "Erosion by Solution and Fill", U.S. Geological Survey, Bulletin 760-D, p. 107-121 (1925).

3. W. L. HISS, "Stratigraphy and Ground Water Hydrology of the Capitan Aquifer, Southeastern New Mexico and West Texas, (Ph. D dissertation)", Boulder, University of Colorado (1976).

4. J. D. BREDEHOEFT, "Will Salt Repositories be Dry?, EOS, Transactions of the American Geophysical Union, v. 69, p. 121-131(1988).

5. R. L. BEAUHEIM, T. DALE, M. FORT, R.ROBERTS, and W. STENSRUD, "Hydraulic Testing of Salado Formation Evaporites at the Waste Isolation Pilot Plant site: Second Interpretive Report", SAND92-0533, Sandia National Laboratories, Albuquerque, NM (1993).

6. T.K. LOWENSTEIN, "Post burial alteration of the Permian Rustler Formation evaporites, WIPP site, New Mexico", Environmental Evaluation Group, EEG-36 (DOE/AL/10752-36), 54 p. (1987).

7. D.W. POWERS and R.M. HOLT, "Sedimentology of the Rustler Formation near the Waste Isolation Pilot Plant (WIPP) site", Geological Society of America, 1990 Annual Meeting Field Trip, Guidebook 14, p. 79-106 (1990).

8. R. L. BEAUHEIM and G. J. RUSKAUFF, "Analysis of Hydraulic Tests of the Culebra and Magenta Dolomites and Dewey Lake Redbeds Conducted at the Waste Isolation Pilot Plant Site", SAND98-0049, Sandia National Laboratories, Albuquerque, NM (1998).

9. J. B. CHAPMAN, "Chemical and Radiochemical Characteristics of Ground Water in the Culebra Dolomite, Southeastern New Mexico", Environmental Evaluation Group, EEG-39 (DOE/AL/10752-39), 63 p. (1988).

10. G. B. GRISWOLD, "Site Selection and Evaluation Studies of the Waste Isolation Pilot Plant (WIPP), Los Medaños, Eddy County, NM", SAND77-0946, Sandia National Laboratories, Albuquerque, NM (1977).

11. D. W. POWERS, S. J. LAMBERT, S. E. SHAFFER, L. R. HILL and W. D. WEART, (Editors), "Geological Characterization Report, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico", SAND78-1596 (2 Vols.), Sandia National Laboratories, Albuquerque, NM (1978).

12. J.W. MERCER, "Geohydrology of the Proposed Waste Isolation Pilot Plant Site, Los Medaños Area, Southeastern New Mexico", U.S. Geological Survey, Water-Resources Investigations Report 83-4016 (1983).

13. Environmental Evaluation Group, "Geotechnical Considerations for Radiological Hazard Assessment of WIPP: A Report of a Meeting Held on January 17-18, 1980", EEG-6, Environmental Evaluation Group, 69 p. (1980).

14. L. CHATURVEDI, "WIPP Site and Vicinity Geological Field Trip: A Report of a Field Trip to the Proposed Waste Isolation Pilot Plant Project in Southeastern New Mexico, June 16 to 18, 1980", EEG-7, Environmental Evaluation Group, 148 p., (1980).

15. R.H. NEILL, J. K. CHANNEL, L. CHATURVEDI, M. S. LITTLE, K. REHFELDT and P. SPIEGLER, "Evaluation of the Suitability of the WIPP site", EEG-23, Environmental Evaluation Group, 157 p. (1983).

16. R.Y. ANDERSON "Deep-Seated Salt Dissolution in the Delaware Basin, Texas and New Mexico", in Environmental Geology and Hydrology in New Mexico, S. G. Wells and W. Lambert (editors), New Mexico Geological Society, Special Publication No. 10 (1981).

17. G. O.BACHMAN, and R. B. JOHNSON, "Stability of Salt in the Permian Salt Basin of Kansas, Oklahoma, Texas and New Mexico", U.S. Geological Survey, Open-file Report 4339-4 (1973).

18. C. L. JONES, "Salt Deposits of Los Medaños Area, Eddy and Lea Counties, New Mexico, with Sections on Ground Water Hydrology by M. E. Cooley, and Surficial Geology by G.O. Bachman", U. S. Geological Survey Open-File Report, USGS-4339-7, 67 p. (1973).

19. G. O. BACHMAN, "Geologic Processes and Cenozoic History Related to Salt Dissolution in Southeastern New Mexico", U. S. Geological Survey Open-File Report 74-194, 81 p. (1974).

20. R. Y. ANDERSON and D. W. KIRKLAND, "Dissolution of Salt Deposits by Brine Density Flow", Geology, v. 8, p. 66-69 (1980).

21. S. J. LAMBERT, "Dissolution of Evaporites in and around the Delaware Basin, Southeastern New Mexico and West Texas, SAND82-8461, Sandia National Laboratories, Albuquerque, NM (1983).

22. B. I. WOOD, R. E. SNOW, D. J. COSTER and S. HAJI-DJAFARI, "Delaware Mountain Group (DMG) Hydrology-Salt Removal Potential, TME-3166, U.S. Department of Energy, Waste Isolation Pilot Plant, Albuquerque NM, 136 p. (1982)

23. L. CHATURVEDI and K. REHFELDT, "Ground Water Occurrence and the Dissolution of Salt at the WIPP Radioactive Waste Repository Site, EOS, Transactions of the American Geophysical Union, v. 65, p. 457-459 (1984).

24. D. J. BORNS, "Geologic Structures Observed in Drill-Hole DOE-2 and Their Possible Origins", SAND86-1495, Sandia National Laboratories, Albuquerque, NM (1987).

25. R.Y. ANDERSON, "Report to New Mexico Environmental Evaluation Group (EEG) on Evaluation of Drillhole DOE-2", Unpublished Report dated August 29, 1987(1987).

26. P.B. DAVIES, "Letter dated June 9, 1987, to Lokesh Chaturvedi, EEG, on the subject of interpretation of DOE-2 core", Unpublished Letter (1987).

27. R. H. NEILL, "Letter from R. H. Neill, Director, EEG, to Jack B. Tillman, WIPP Prpject Manager, dated September 9, 1987, declaring the deep dissolution issue not to be a threat to the WIPP repository" (1987).

28. J. D. VINE, "Recent Domal Structures in Southeastern New Mexico", American Association of Petroleum Geologists Bulletin, v. 44, p. 190 (1960).

29. R. P. SNYDER and L. M. GARD, Jr., "Evaluation of Breccia Pipes in Southeastern New Mexico and Their Relation to the WIPP Site", U.S. Geological Survey, Open-file Report 82-968, 73 p. (1982).

30. P. B. DAVIES, "A Review of the USGS Open File Report 82-968, Evaluation of Breccia Pipes in Southeastern New Mexico and Their Relation to the WIPP Site by R.P. Snyder and L. M. Gard, Jr., prepared for EEG", Unpublished Report dated April 1993.

31. G. 0. BACHMAN, "Regional Geology and Cenozoic History of Pecos Region, Southeastern N.M.", U.S. Geological Survey, Open-file Report 80-1099, 116 p. (1980).

32. P. B. DAVIES, "Deep-Seated Dissolution and Subsidence in Bedded Salt Deposits", Ph.D. Dissertation, Stanford University, 379 p. (1984).

33. R. S. POPIELAK, R. L. BEAUHEIM, S. R. BLACK, W. E. COONS, C. T. ELLINGSON and R. L. OLSEN, "Brine Reservoirs in the Castile Formation , Southeastern New Mexico", TME 3153, U.S. Department of Energy, Waste Isolation Pilot Plant (1983).

34. G. E. BARR, S. J. LAMBERT and J. A. CARTER, "Uranium Isotope Disequilibrium in Groundwaters of Southeastern New Mexico and Implications Regarding Age-Dating of Waters", in Proc. Int. Symp. on Isotope Hydrology, STI/PUB/493, Vol 2, Int. Atomic Energy Agency, pp. 645-660 (1978).

35. S. J. LAMBERT and J. A. CARTER, "Uranium-Isotope Disequilibrium in Brine Reservoirs of the Castile Formation, Northern Delaware Basin, Southeastern New Mexico, SAND83-0144, Sandia National Laboratories, Albuquerque, NM (1983).

36. EARTH TECHNOLOGY CORPORATION, "Time Domain Electromagnetic (TDEM) Surveys at the WIPP Site", SAND87-7144, Sandia National Laboratories, Albuquerque, NM (1988).

37. D. E. DEAL, R. J. ABITZ, D. S. BELSKI, J. B. CASE, M. E. CRAWLEY, C.A. GIVENS, P. P. J. LIPPONER, D.J. MILLIGAN, J. MYERS and D.W. POWERS, "Brine Sampling and Evaluation Program: 1992-93 Report and Summary of BSEP Data Since 1992", DOE/WIPP 94-011, U.S. Department of Energy, WIPP Project Office, Carlsbad, New Mexico (1995).

38. J. W. MERCER, "Compilation of Hydrologic Data from Drilling the Salado and Castile Formations Near the Waste Isolation Pilot Plant (WIPP) Site in Southeastern New Mexico", SAND86-0954, Sandia National Laboratories, Albuquerque, 39 p. (1987).

39. E. J. NOWAK, D. F. McTIGUE, and R. BERAUN, "Brine Inflow to WIPP Disposal Rooms: Data, Modeling and Assessment", SAND88-0112, Sandia National Laboratories, Albuquerque, 76 p. (1988).

40. SANDIA NATIONAL LABORATORIES, PERFORMANCE ASSESSMENT GROUP, "Early PA Scoping calculations", Memo to Distribution, April 7, unpublished (1987).

41. G. A. FREEZE, T. L. CHRISTIAN-FREAR, S. W. WEBB, "Modeling Brine Flow to Room Q: A Mumerical Investigation of Flow Mechanisms, SAND96-0561, Sandia National Laboratories, Albuquerque, NM (1997).

42. U.S. DEPARTMENT OF ENERGY, CARLSBAD AREA OFFICE, "Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant, Final", U.S. Department of Energy, Carlsbad, NM, DOE/CAO-1996-2184, 21 vols. (1996).

43. A. M. LaVENUE, T. L. CAUFFMAN, J. F. PICKENS, and J. P. McCORD, "Ground Water Flow Modeling of the Culebra Dolomite", SAND89-7068, Sandia National Laboratories, Albuquerque, NM, 2 v. (1990).

44. L. C. MEIGS, R. L. BEAUHEIM, J. T. MCCORD, Y. W. TSANG, and R. HAGERTY, "Design, Modelling, and Current Interpretations of the H-19 and H-11 Tracer Tests at the WIPP Site", in Field Tracer Experiments: Role in the Prediction of Radionuclide Migration, Proceedings, NEA/OECD GEOTRAP Workshop, Cologne, Germany, 28-30 August 1996, pp. 157-169 (1997).

45. G. 0. BACHMAN, "Regional Geology of the Ochoan Evaporites, Northern Part of the Delaware Basin, New Mexico Bureau of Mines and Mineral Resources, Circular 184, 22 p. (1984)

46. J. S. MILLER, C. M. STONE, and L. J. BRANSTETTER, "Reference Calculations for Underground Rooms of the WIPP", SAND82-1176, Sandia National Laboratories, Albuquerque, NM (1982).

47. D. E. MUNSON, A. F. FOSSUM and P. E. SENSENY, Advances in Resolution of Discrepancies Between Predicted and Measured In Situ WIPP Room Closures, SAND88-2948, Sandia National Laboratories, Albuquerque , NM, 77 p (1989).

48. U.S. ENVIRONMENTAL PROTECTION AGENCY, " Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations," 40 Code of Federal Regulations Part 194 (1996).

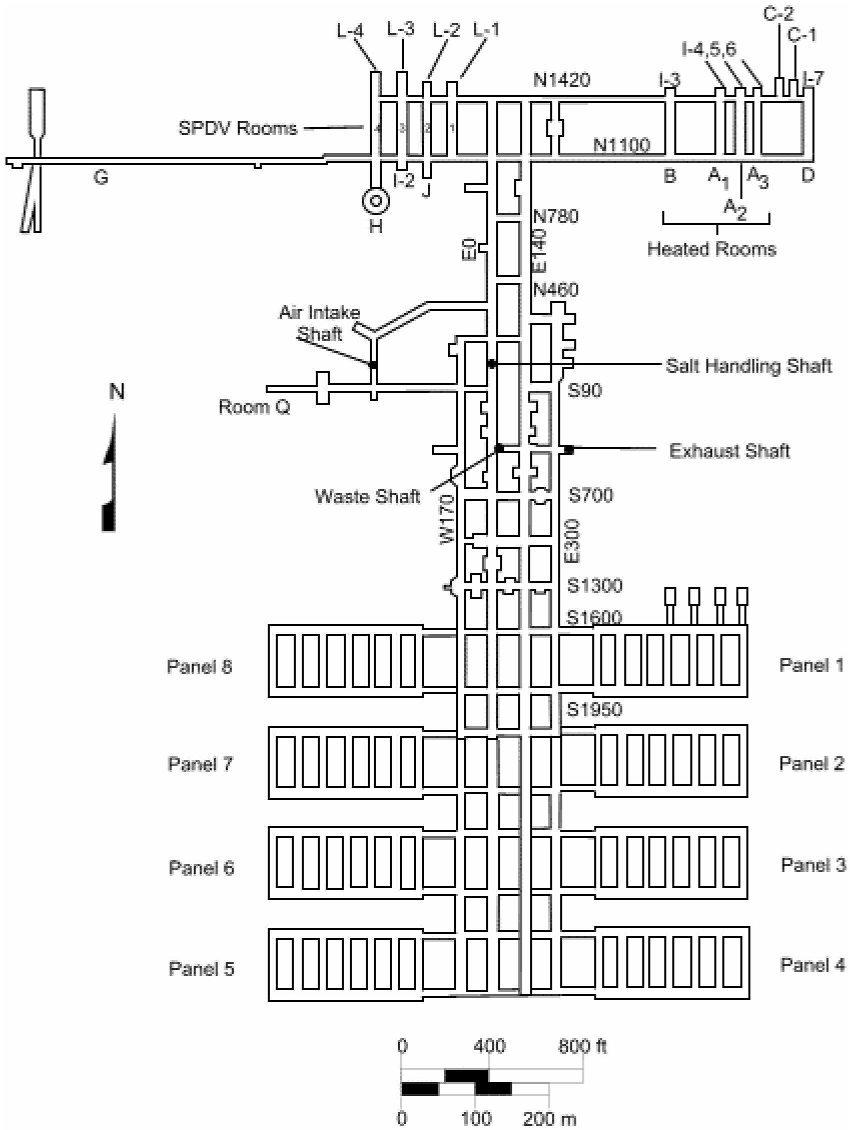

Fig.1. Underground Layout of the WIPP Repository

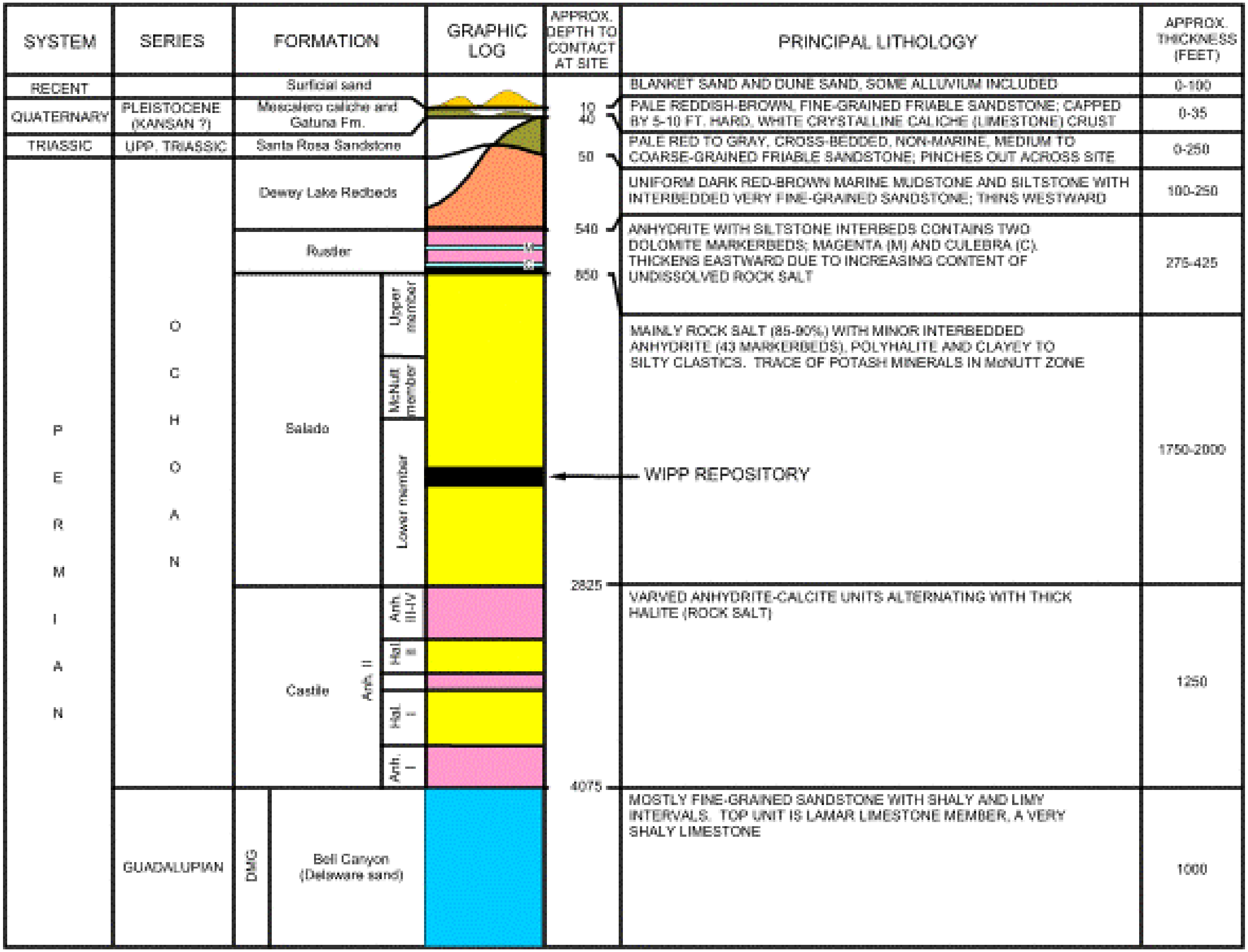

Fig. 2. Generalized Stratigraphy at the WIPP Site

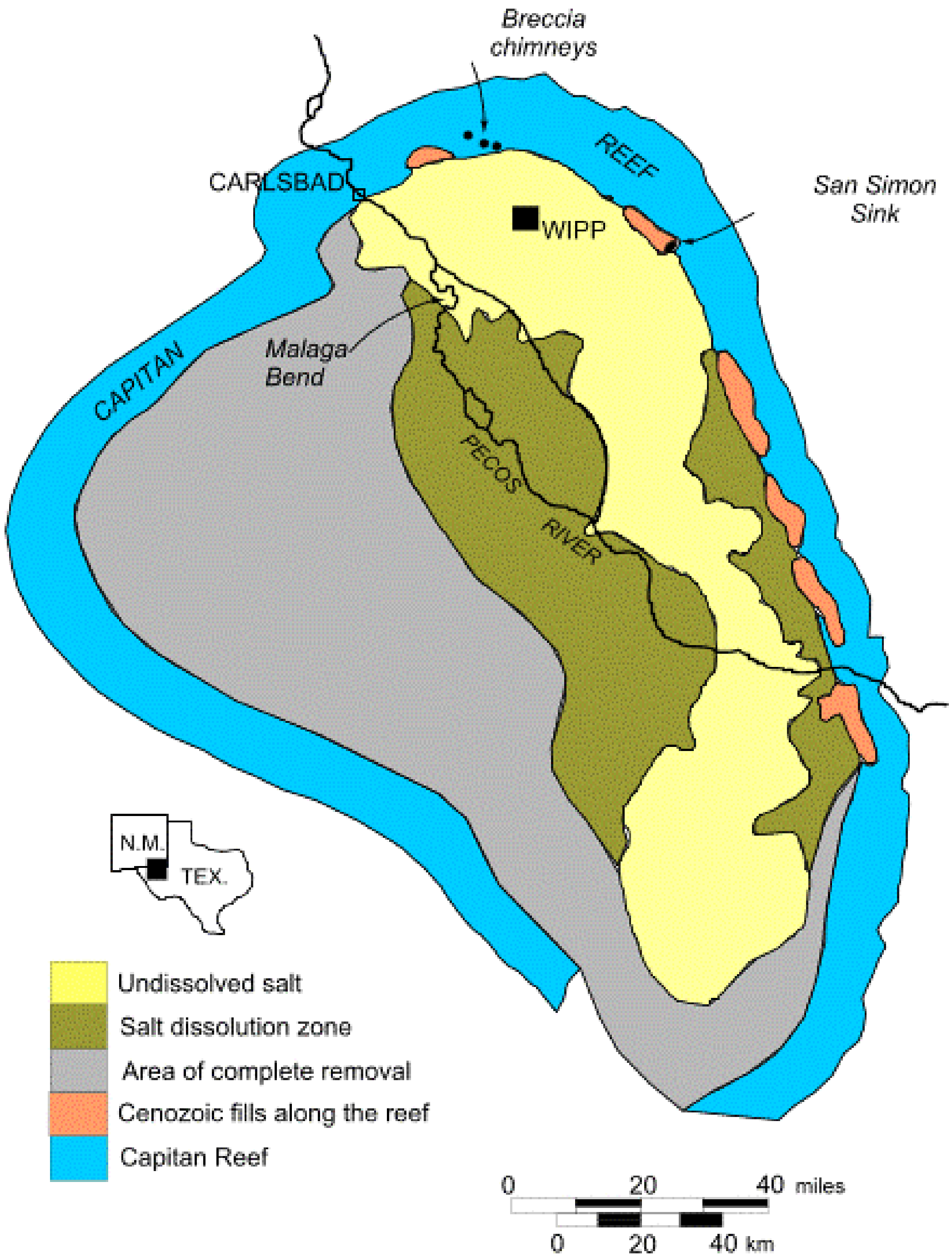

Fig. 3. Location of WIPP in the Delaware Basin

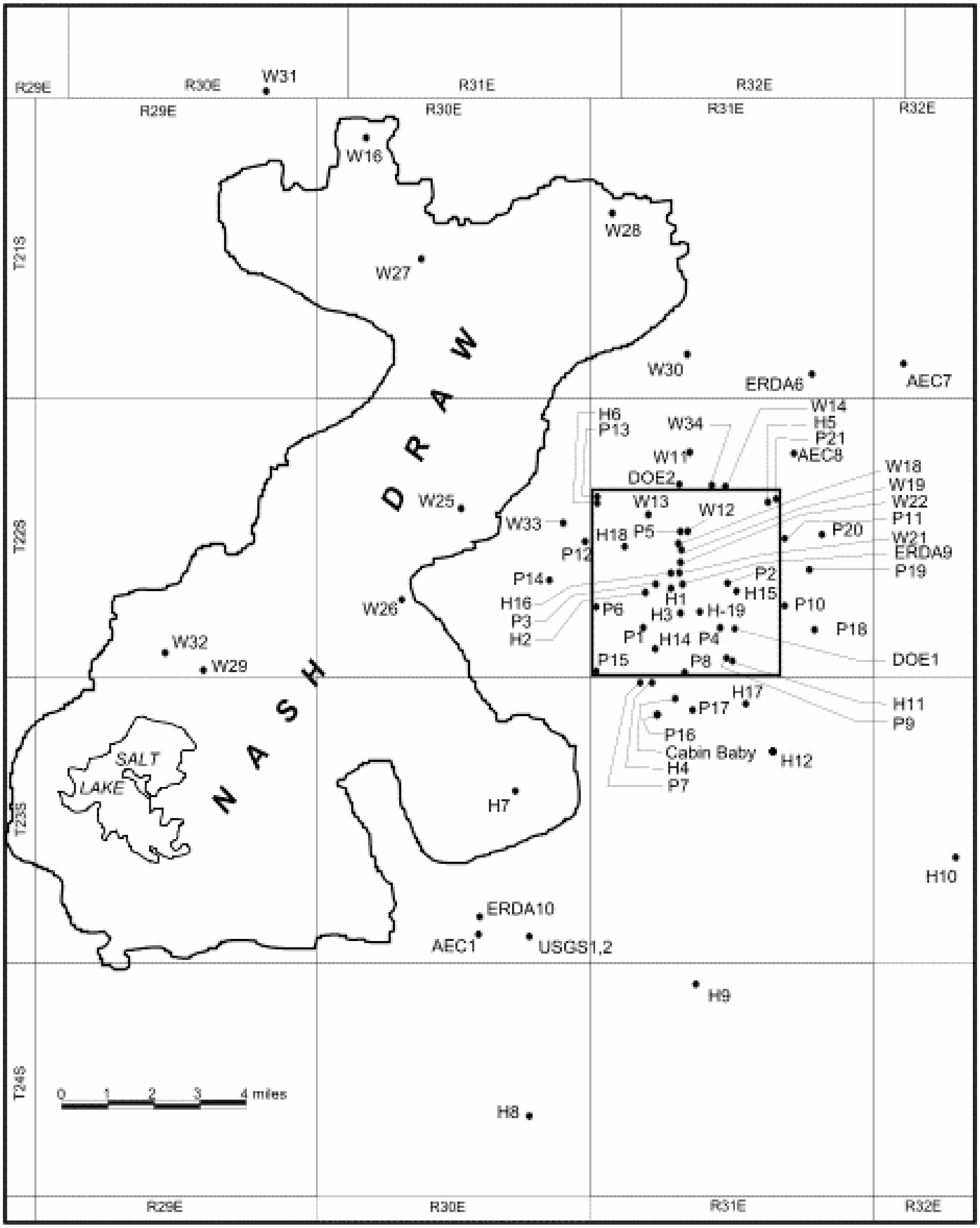

Fig. 4. Location of Project Boreholes at the WIPP Site

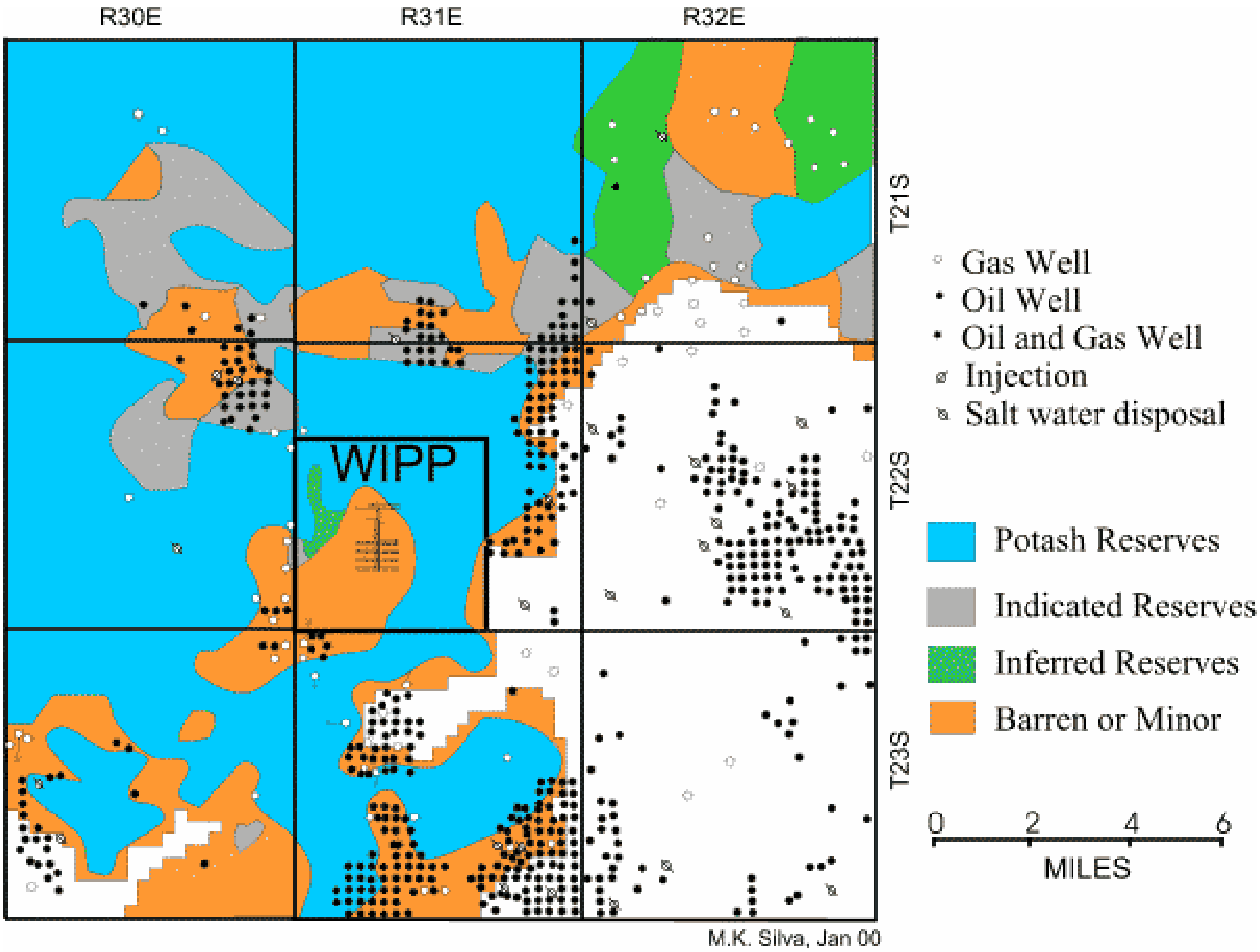

Fig. 5. Potash, Oil, and Gas Resources Surrounding the WIPP Site

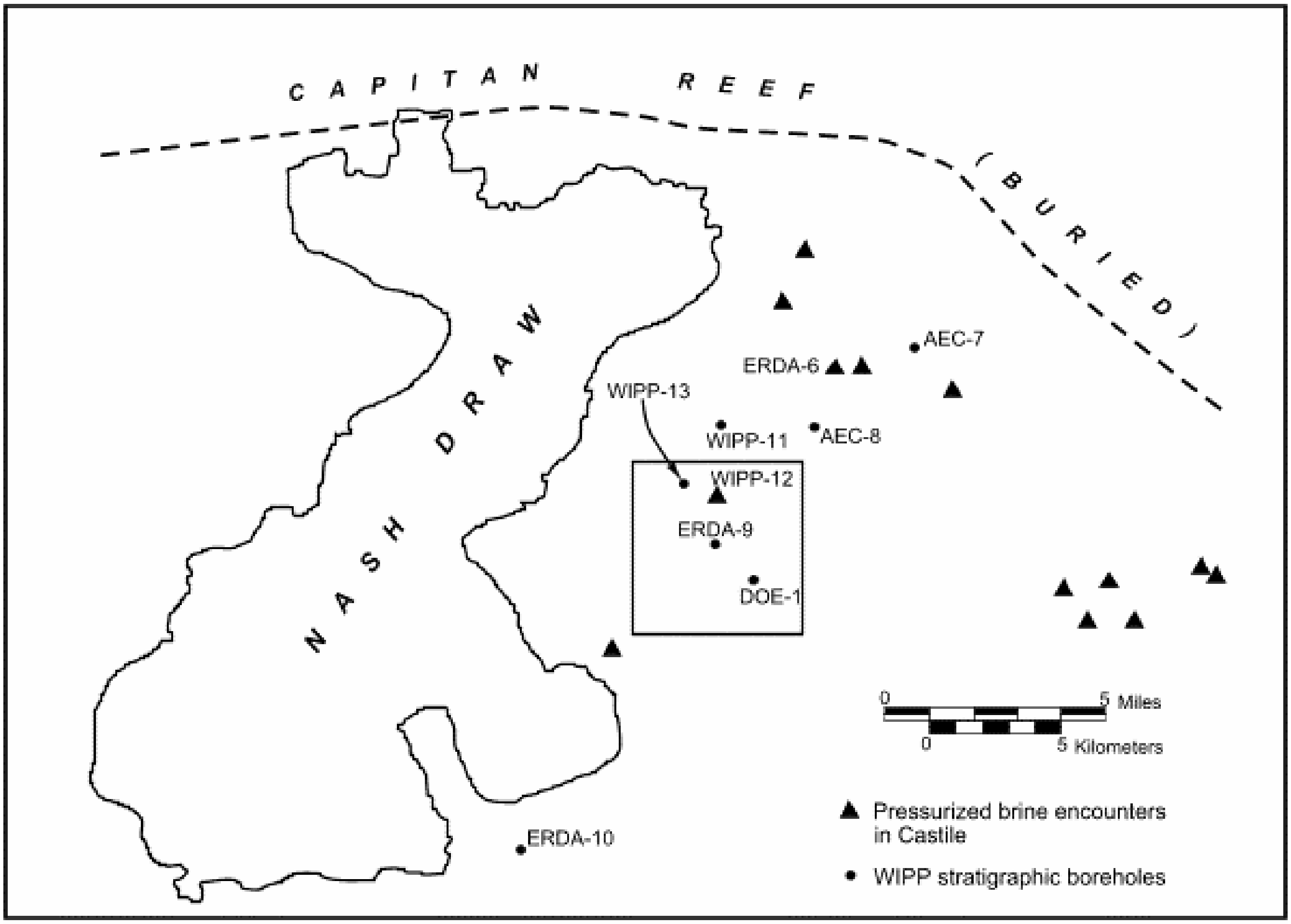

Fig. 6. Location of Boreholes which Encountered Pressurized Brine Reservoirs in the Castile Formation