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THE RUSTLER FORMATION AT THE WIPP SITE
Report of a workshop on the geology and hydrology of the Rustler Formation as it relates to the WIPP Project

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FOREWORD

The purpose of the Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the potential radiation exposure to people from the proposed Federal Radioactive Waste Isolation Pilot Plant (WIPP) near Carlsbad, in order to protect the public health and safety and ensure that there is minimal environmental degradation. The EEG is part of the Environmental Improvement Division, a component of the New Mexico Health and Environment Department -- the agency charged with the primary responsibility for protecting the health of the citizens of New Mexico.

The Group is neither a proponent nor an opponent of WIPP.

Analyses are conducted of available data concerning the proposed site, the design of the repository, its planned operation, and its long-term stability. These analyses include assessments of reports issued by the U.S. Department of Energy (DOE) and its contractors, other Federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP.

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AGENDA

Technical Meeting
on
The Rustler Formation at the WIPP site
Holiday Inn, Carlsbad

March 7, 1985

8:00 Opening Remarks - Robert H. Neill, EEG and Wendell D. Weart, SNL

8:20 Unresolved Questions of Rustler Geology - Lokesh Chaturvedi, EEG

9:00 Possible Radiological Significance of Karst Conditions in Rustler - James K. Channell, EEG

Discussion

9:50 Coffee Break

10:00 Dissolution of Halite and Gypsum and Hydration of the Anhydrites in the Rustler Formation - Richard P. Snyder, USGS

Discussion

11:00 Stratigraphy and Dissolution of the Rustler Formation - George O. Bachman, SNL Consultant

Discussion

12:00 Lunch Break

1:30 Rustler Formation in the Waste Handling and Exhaust Shafts, WIPP Site, SE New Mexico - Dennis W. Powers and Robert M. Holt, IT

Discussion

2:30 Stable Isotope Studies of Groundwaters in S.E. New Mexico - Steven J. Lambert, SNL

Discussion

3:30 A Regional Water Balance for the WIPP Site and Surrounding Area - Regina Hunter, SNL

Discussion

4:30 Chemistry of the Rustler Fluids - Dan S. Ramey, EEG

Discussion

DOE = Department of Energy
EEG = Environmental Evaluation Group, State of New Mexico
IT = International Technology Corporation,
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Technical Meeting
on
The Rustler Formation at the WIPP Site

Holiday Inn, Carlsbad
March 7, 1985

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INTRODUCTION

A workshop on "The Rustler Formation at the WIPP Site" was organized by the Environmental Evaluation Group on March 7, 1985. The workshop was held at a time when a new series of studies on the Rustler Formation was starting. It provided the scientists from Sandia National Laboratories, the U.S. Geological Survey, IT Corporation, the Department of Energy and the Environmental Evaluation Group, an opportunity to exchange and discuss the up-to-date information on the geological and hydrological characteristics of the Rustler Formation. The papers and the summaries that follow reflect the status of knowledge at the time of the workshop (March, 1985). The decision to publish the proceedings was not made until after all the papers were received by the end of 1986.

Eight papers were presented at the workshop and much of the time was spent in discussing the relevance and significance of results obtained thus far and the need for further work. Following is a brief description of each of the papers presented and a summary of the discussions.

1. Unresolved Questions of Rustler Geology by Lokesh Chaturvedi, EEG.

This paper summarized the lithologic and structural observations in the Rustler Formation which may an impact on the flow and transport characteristics of its water-bearing zones. This paper has since been published as an EEG report (Chaturvedi and Channell, 1985) and is available from the Environmental Evaluation Group.

The most credible scenarios for the transport of radioactivity to the biosphere after a breach of the WIPP repository involve transportation of radionuclides through the Rustler aquifers. All the published calculations of such scenarios (e.g., U.S. DOE, 1980; Wofsy, 1980, Channell, 1982) assume hydrologic parameters for the Rustler Formation which were obtained from a limited number of flow and tracer tests at the WIPP site. Using these values, the scenario analyses indicated a minimal or trivial radiation dose to individuals.

It has been suggested (e.g., Barrows, et al., 1983) that karst conditions may prevail in the Rustler Formation at the WIPP site with a possibility for much faster transport of contaminated water through the Rustler to the biosphere. It is well known that immediately west and south of the WIPP site, karst topography and hydrology exist. Almost 1000 tons of salts per day are discharged into the Pecos River along a 6 mile stretch from Malaga Bend to the south. This salt comes from the dissolution of the upper Salado and the Rustler Formations in the vicinity of the WIPP site. Salt is completely missing from the Rustler and the upper part of the Salado in the Nash Draw area. The resultant brine is found at the base of the Rustler in the Nash Draw wells. The unresolved questions about the Rustler, in connection with the WIPP project, relate to the extent of the Nash Draw type of processes existing east of Livingston Ridge, and can be summarized by the following questions.

A. To what distance east of Livingston Ridge have the Nash Draw type processes of dissolution and collapse affected the Rustler Formation?

The depression in which WIPP-33 was drilled is about 1-1/2 miles east of Nash Draw and clearly receives water from the surface which has caused dissolution and collapse in the

Rustler. Bachman (1985) calls this a "paleokarst system" but the depression and an arroyo draining into it clearly shows at least some continuing activity. There are other depressions scattered over the site. Could they represent WIPP-33 type of activity?

If the absence of halite is an indication of "removal by dissolution", then the "dissolution front" in the Rustler lies at the southeastern corner of the WIPP site. Wells P-18, P-10 and H-12 show a full complement of salt beds comprising about 50% of the Rustler Formation. The thickness of salt beds as well as the total thickness of the Rustler Formation decline progressively to the west, over the WIPP site, and the residual salt beds are found in a successively lower stratigraphic location to the west. The wells within zone II encounter halite beds only in the lowest member of the Rustler. If the absence of salt beds is a result of "sabkha interacting with saline to fresh water and salts" as hypothesized by Powers and Holt (1984) then the observed correlation between the karst conditions in Nash Draw (and immediately east of Nash Draw) and the absence of salt in Rustler has to be a remarkable coincidence.

B. <u>To what degree have the hydrologic properties of the Rustler aquifers been affected by dissolution and collapse</u>?

There is a pattern of increasing yield and higher transmissivity values obtained from the hydro-wells in the Rustler from east to west over the WIPP site. This corresponds with the absence of halite. Thus, P-18 is the most "tight" Rustler well and has the maximum salt thickness. On the other extreme, H-6 and P-14 to the west are the most productive with highest transmissivity values and the Rustler salt beds are missing completely at these locations. There are, however, remarkable variations within a short distance. For example, T=0.07 ft^2/day in H-1 and 19

ft^2/day in H-3 for the Culebra (Mercer, 1983). The two wells are within 1/2 mile of each other in Zone II. Do these variations within a broad pattern of increasing permeability with less halite, represent localized areas of excessive salt dissolution creating higher fracture permeability? Wide variations in the chemistry of the Rustler fluids within short distances also indicate conditions typical of karst areas.

Hydrologic investigations of the Rustler show the presence of three discrete fluid-bearing zones. There are some indications, however, that water may exist in zones other than the Magenta, Culebra and Rustler/Salado interface. The piezometers installed in the C and SH shaft in zones outside the Magenta and Culebra have shown similar pressures as those in the Magenta and Culebra. Moisture was observed seeping in the ventilation shaft from fractures in the Forty-Niner Member of the Rustler. In fact, a "salt-residue zone" was tested in the well H-1 and it produced at a rate of 0.933 gal/hour, while the Culebra produced at 0.922 gal/hour and the Rustler-Salado contact zone at 0.455 gal/hour. Also in H-3, a "salt-residue zone" produced at a rate of 0.077 gal/hour while the Culebra produced at 0.098 gal/hour and the Rustler-Salado contact at 0.11 gal/hour (Mercer and Orr, 1979).

C. To what degree are these processes continuing today and what changes may they cause to the hydrology of the Rustler Formation during the next 10,000 years?

There is obviously a great deal of merit in George Bachman's argument that a lot more water flowed at the surface and perhaps subsurface at and near the WIPP site during the Gatuna time more than 1/2 million years ago. However, the karst processes in Nash Draw are continuing phenomena and a large quantity of salt (almost 1000 tons per day) is being removed from the area. At the WIPP site proper, there is no direct evidence that such processes are active today, but there are indirect indications. These are the lack of surface drainage in spite of 12 inches of rainfall per year, the presence of several conspicuous depressions in the area and a pattern of negative gravity anomalies which is typical of karst regions (Barrows 1982). Studies aimed at providing valid alternative explanations for these observations are needed to give the Rustler a clean bill of health vis-a-vis the WIPP Project. Also needed is an understanding of the recharge and discharge areas for the Rustler, the mechanics and time of removal of salt from the Rustler (or a convincing hypothesis of syn-depositional processes of selective deposition of salt) and an understanding of the area from which the Malaga Bend salts currently originate.

The discussion on this presentation involved the geomorphology and hydrology in the WIPP-33 area, evidence of moisture in the Rustler Formation outside the Magenta and the Culebra dolomite beds and the nature of salt beds in the Rustler.

2. Possible Radiological Significance of Karst Conditions by James K. Channell, EEG

This paper summarized the results of new analyses performed to evaluate the significance of assuming karst conditions on the breach and leach scenarios involving transportation of contaminated water through the Rustler Formation.

Previous Evaluations: Both DOE and EEG have evaluated breach and leach scenarios involving injection of radionuclide contaminated water into the Rustler aquifer. These evaluations included calculations of the assumed transport of those radionuclides to either a natural outlet (presumed to be the Pecos River at Malaga Bend) or to a water supply well located several miles from the repository. The analyses of these scenarios, both by DOE and EEG, have generally concluded that radiation doses to individuals would be minimal or trivial. The assumptions used in these scenarios need to be reexamined to reflect current understandings and also to consider the implications of karst conditions.

Re-evaluations Needed: Evaluations of previous scenarios by DOE and EEG have concluded that doses following a low probability breach and leach scenario would be minimal and not occur for several thousand years. However, the assumptions used in these scenarios need to be reexamined and updated. Specifically, the following factors need to be considered:

(1) The rate of injection of radionuclides into the Rustler aquifer was not varied in the scenarios. This rate needs to be evaluated based on solubility limits and the ability of the Rustler aquifer to accept water.

(2) Radionuclides other than 239Pu.

(3) A more current repository radionuclide inventory.

(4) Breaching of the repository as early as 100 years after closure.

(5) Radionuclide travel times to the Pecos River of about 100 years with zero retardation (Kd=0).

(6) More up-to-date "radionuclide intake to dose received" conversion factors.

(7) A comparison of the quantities of the radionuclide that might reach the accessible environment with that permitted by the EPA High Level Waste Standard (40 CFR 191).

Appropriate changes in the above 7 assumptions were discussed by Channell. Calculated doses received by individuals drinking treated Pecos River and treated well waters were presented. The calculated length of leaching time required to exceed the curie release limits of the EPA Standards (40 CFR 191) was discussed.

It was concluded that the presence of significant karst conditions in the Rustler aquifer could lead to excessive radiation doses to individuals drinking from a nearby well. The limits in 10 CFR 191 for releases to the accessible environment could also be exceeded.

The discussion on this paper consisted of the plausibility of breach scenarios which would bring contaminated water to the Rustler Formation.

Detailed results of these analyses have since been published (Chaturvedi and Channell, 1985, Chapter 4).

3. Dissolution of Halite and Gypsum and Hydration of the Anhydrites in the Rustler Formation, by Richard P. Snyder, USGS.

This presentation consisted of a detailed description of the Rustler lithology, mainly with respect to the pattern of presence and absence of halite and gypsum in the Rustler. The interpretation was based on study of cores from several wells, geophysical well logs and drilling records. Snyder concluded that halite has been dissolved from progressively lower stratigraphic horizons as one moves from east to west across the WIPP site and attributed the reduction in thickness to the west to this observation. West of the WIPP site, in Nash Draw, the Rustler increases in thickness even though all the salt has been dissolved. Snyder explained this to have been caused by volume increase resulting from gypsification of anhydrite.

The discussion on this paper consisted of the process of gypsification, gypsum karst, relationship between the gypsum-filled fractures in the Dewey Lake Redbeds and the removal of salt from the Rustler, and the timing of removal of salt.

This paper has been published as a U.S.G.S. Open File Report (Snyder, 1985).

4. Stratigraphy and Dissolution of the Rustler Formation by George Bachman, SNL.

Bachman's paper is published in this report and therefore it is not necessary to summarize the presentation here.

A lively discussion followed Bachman's presentation mainly relative to the evidence for karst in Nash Draw area and its absence at the WIPP site.

5. Rustler Formation in the Waste Handling and Exhaust Shafts by Dennis W. Powers and Robert M. Holt, IT Corp.

Powers and Holt's paper is included in this report and therefore it is not necessary to summarize the presentation here.

The discussion following this presentation related to the evidence from borehole cores other than the shafts.

6. Stable Isotope Studies of Groundwaters in S.E. New Mexico by Steven J. Lambert, SNL.

Lambert's paper is also included in this report and therefore the presentation is not summarized here.

The discussion on this paper revolved around the possible mechanisms of recharge to the Rustler Formation during a more humid climate in the past. No one was able to forward a convincing hypothesis of what may have been different to allow recharge to the Rustler during the ancient time of postulated recharge compared to the present conditions.

7. A Regional Water Balance for the WIPP Site and Surrounding Area by Regina Hunter, SNL.

This paper is also published in this report and therefore the presentation is not summarized here.

The discussion on this paper consisted of evapo-transpiration rates and the difficulty of measuring or estimating them.

8. Chemistry of the Rustler Fluids by Dan S. Ramey, EEG.

The following is a summary of Dan S. Ramey's presentation. The Rustler Formation has been identified as a possible pathway for radionuclide migration and transport to the biosphere in the event of a breach of the WIPP repository. The three main water bearing units contained in the Rustler Formation include in ascending order: Rustler-Salado contact, Culebra Dolomite, and Magenta Dolomite. The Culebra and Magenta Dolomites are the most significant units hydrologically and consequently have been studied the most.

General Rustler-Salado Water Quality Description: Water samples from the Rustler/Salado contact have greater concentrations of dissolved solids than samples from either of the other two water bearing units in the Rustler Formation at the WIPP site. Total dissolved solids range from 79,800 mg/l in testhole H-7 southwest of the site to 480,000 mg/l in test hole H-1 near the center of the site. The dissolved solids content increases from Nash Draw eastward. The major dissolved ionic constituents of the brines are chloride, sodium, and magnesium with lesser amounts of sulfate, calcium and potassium. The prevalent chemical characteristic as determined by the highest millequivalent percentages of the dominant anions and cations changes from a sodium chloride water west of the WIPP site, to a magnesium chloride water to the east.

General Culebra Water Quality Description: Three identifiable zones of differing prevalent water chemistry are readily apparent from the Culebra chemistry data. Zone A is an area east of the WIPP site including the eastern side of the site itself. This zone is characterized as predominantly a sodium-chloride type water with high concentrations of potassium and magnesium. Total dissolved solids for this area are typically high with testhole P-18 having the highest TDS value (410,000 mg/l) for any Culebra sample.

Zone B lies south of the WIPP site and includes hydroholes H-7, H-8 and H-9. This zone is characterized as predominantly a calcium-sulfate water with relatively low concentrations of total dissolved solids. Wells in this zone contain the lowest concentrations of sodium, chloride, and dissolved solids of all Culebra wells.

Zone C includes most of the area north and west of the WIPP site. Sodium and chloride are the predominant chemical constituents and based upon dissolved solids concentrations (22,000 to 239,000 mg/l) the waters are classified as saline to briney. Potassium and magnesium concentrations are relatively low except at W-27 and W-29 which are located near potash mines and may be impacted by these operations.

Considerable chemical variation exists between the wells H-1, H-2 and H-3, which are closest to the site. Total dissolved solids concentrations range from 9,700 to 62,000 mg/l between these wells, a difference of over 6x, and chloride ranges from 2800 to 29,600 mg/l, an order of magnitude difference. The reasons for the abrupt chemical changes within the one square mile area surrounding wells H-1, H-2 and H-3 cannot be answered with the limited data currently available and should be considered for resampling during the upcoming water chemistry sampling period.

The differing water chemistries in Zones B and C present a problem for the currently assumed direction of flow in the Culebra. The direction of flow inferred from potentiometric surface maps is from the center of the site southward and then turning westward towards Malaga Bend. Anisotropy data collected from hydroholes H-4, H-5 and H-6 have refined the flow directions, indicating that Culebra water travels approximately southeastwardly from the center of the site before turning westward toward Malaga Bend. The observed water chemistries for Zones B and C do not support this Culebra water movement pattern. Water in Zone C moving from the center of the site would have to decrease the amount of dissolved solids from approximately 30,000 mg/l to 3,000 mg/l along its flow path into Zone B. The major constituents would have to change from sodium and chloride to calcium and sulfate from Zone C to Zone B. At present there are no likely mechanisms to effect such a chemical change, other than the mixing of low TDS water with Zone C water and there does not appear to be a source of low TDS water available for the mixing.

General Magenta Water Quality Description: The major dissolved chemical constituents of the Magenta Dolomite are chloride and sodium except in testholes H-5A, H-6A and H-9A where sulfate replaces chloride as the most prevalent anion. The total dissolved solids content ranges from 5,460 to 270,000 mg/l at testholes H-9A and H-10A, respectively, characterizing these waters as saline to briney. Total dissolved solids tend to increase from the northwest to the southeast with the exception of testhole W-27 located northwest of the site which has an extremely high dissolved solids content. Fluids in the Magenta Dolomite are significantly lower in total dissolved solids content than the other two underlying fluid bearing units.

Conclusions: Water chemistry determinations were performed on water samples collected from the three fluid bearing zones of the Rustler Formation from 20 testholes at and adjacent to the WIPP from 1976 to 1980. Analysis of the data demonstrate that the three fluid bearing zones are chemically separate from one another.

The fluids present at the Rustler-Salado contact are characterized as sodium-chloride brines that approach saturation with respect to halite. Magnesium replaces sodium as the prevalent cation east of the WIPP and may represent the approximate limit of salt dissolution at the base of the Rustler Formation.

Chemical interpretation of the fluids present in the Culebra Dolomite is a highly complex problem. Large lateral variations exist between and within testholes. A sufficient number of water chemistry samples have not been collected to adequately summarize fluid and host-rock interactions. Three zones of differing predominant chemical constituents are present in the Culebra. These zones do not support previously reported directions of water movement. The Culebra waters are undersaturated with respect to halite and have the capacity of dissolving more halite from the Rustler.

The fluids present in the Magenta Dolomite are composed predominantly of sodium and chloride. A few wells have sulfate, rather than chloride as the predominant anion.

The amount of work conducted and the degree of understanding of the chemical characteristics of the Rustler Formation have been insufficient, especially with regard to the Culebra Dolomite. Abrupt chemical changes along proposed groundwater flow paths of the Culebra have not been addressed, nor have changes in water quality with time. Water quality sampling has been too infrequent to establish a meaningful data base with which to evaluate processes of groundwater chemical evolution, and the number and type of parameters analyzed have not remained constant.

This paper has since been published as an EEG report (Ramey, 1985, EEG-31).

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SAND86-7077C

STRATIGRAPHY AND DISSOLUTION OF THE RUSTLER FORMATION

by

George O. Bachman

The Rustler Formation is the uppermost evaporite-bearing unit in the Permian Ochoan series in southeastern New Mexico. It rests on the Salado Formation which includes the salt beds where the mined facility for the Waste Isolation Pilot Plant (WIPP) is being constructed. An understanding of the physical stratigraphy of the Rustler Formation is pertinent to studies of the WIPP site because some portions of the Rustler are water-bearing and may provide paths for circulating waters to come into contact with, and dissolve, evaporites within the Ochoan sequence. Knowledge of the processes, magnitude, and history of evaporite dissolution in the vicinity of the WIPP site is important to an evaluation of the integrity of the site.

Where preserved in its entirety, the Rustler Formation includes five members which are, in ascending order, (1) an unnamed sequence of reddish-brown to medium-gray clayey siltstone with thin interbeds of gypsum; (2) the Culebra Dolomite Member; (3) the Tamarisk Member; (4) the Magenta Dolomite Member; and (5) the Forty-niner Member.

The basal unnamed member in the Rustler Formation ranges from 92 to 150 feet (28 to 46 m) thick in the subsurface in the vicinity of the WIPP site.

The Culebra Dolomite is a distinctive and persistent marker bed in the Rustler Formation. It is medium- to brownish-grey, thinly bedded, and finely crystalline. It is characterized by abundant spherical to angular vugs that range from about 2 to 10 mm in diameter. The Culebra weathers to prominent angular ledges and is preserved at many places on the surface as blocky debris in chaotic collapse breccia where other parts of the Rustler have been removed by dissolution and erosion. It ranges from about 25 to 30 feet (ca. 7.7 to 9 m) in thickness over much of the Delaware Basin. Water is present in the Culebra at places, but the hydraulic properties of the unit are extremely variable and appear to be related to fractures.

The Tamarisk Member is as much as 180 feet (54.6 m) thick in the subsurface near the WIPP site. Where well preserved it includes anhydrite and halite. At the surface it is usually represented by massive, indistinctive gypsum.

The Magenta Dolomite consists of thinly laminated reddish-brown dolomite and gray anhydrite or gypsum. It ranges from about 20 to 30 feet (ca. 6 to 9 m) thick. Permeability of the Magenta is variable and appears to be related to fracturing and dissolution of cement within the unit.

The uppermost member of the Rustler, the Forty-niner, includes anhydrite, siltstone, and halite in the subsurface. Where it is exposed at the surface in Nash Draw to the west of the WIPP site, it is massive gypsum with thin interbeds of reddish siltstone. It averages about 80 feet (25 m) in thickness in the subsurface around the WIPP site.

These five members are persistent throughout much of the Delaware Basin and northward onto the shelf, or backreef, area more than 60 miles (100 km) north of the WIPP site. The dolomite members maintain their general characteristics with little variation in thickness over thousands of square miles. However, the evaporitic and clastic members exhibit variations in facies and thickness. Some of these variations may be attributed to dissolution of the evaporites, but some are the direct result of original deposition.

Notable facies changes in the Rustler are visible in outcrops in the vicinity of Malaga Bend, about 15 miles (ca. 25 km) southwest of the WIPP site. There yellowish siltstones and fine-grained sandstones which do not appear to be present in the formation farther north are interbedded with red clays in the basal unnamed member. These fine-grained clastic rocks may be only of local extent, but they indicate an increase in clastic sedimentation southwestward from the WIPP site. Farther south along the Texas-New Mexico State Line there appears to be an increase in the thickness of red clays in the Rustler. The significance of these facies has not been studied, but they suggest that Rustler sediments were derived from a variety of sources and deposited on mudflats with some relief. Therefore, individual beds within the clastic and evaporitic members should not be expected to be as persistent as the dolomite members.

Dissolution of evaporites within the Rustler Formation has resulted in even more conspicuous variations in thickness and character of individual units than those caused by original deposition. Near the south end of Nash Draw, about 12 miles (ca. 20 km) southwest of the WIPP site, the Tamarisk Member has been removed almost entirely. Only about 5 feet (1.5 m) of silty clay separate the Culebra and Magenta Dolomites. These exposures are poorly developed, but an example of a similar diminutive stratigraphic section is well exposed about 30 miles (50 km) north of the WIPP site.

Near Crow Flat about 15 miles (ca. 25 km) east of Artesia, New Mexico, both the Culebra and Magenta Dolomites are exposed in a single arroyo wall. The intervening Tamarisk Member is about 5 feet (1.5 m) thick and consists of reddish silty clay (Fig. 1). About 3 miles (ca. 5 km) east of this locality in Turkey Track Draw gypsum is present within the Tamarisk Member. The exposures in Turkey Track Draw are poorly developed and low-dipping beds of gypsum are exposed intermittently across an area of several hundred meters. Owing to the nature of the exposures, thickness of the member in that area has not been determined.

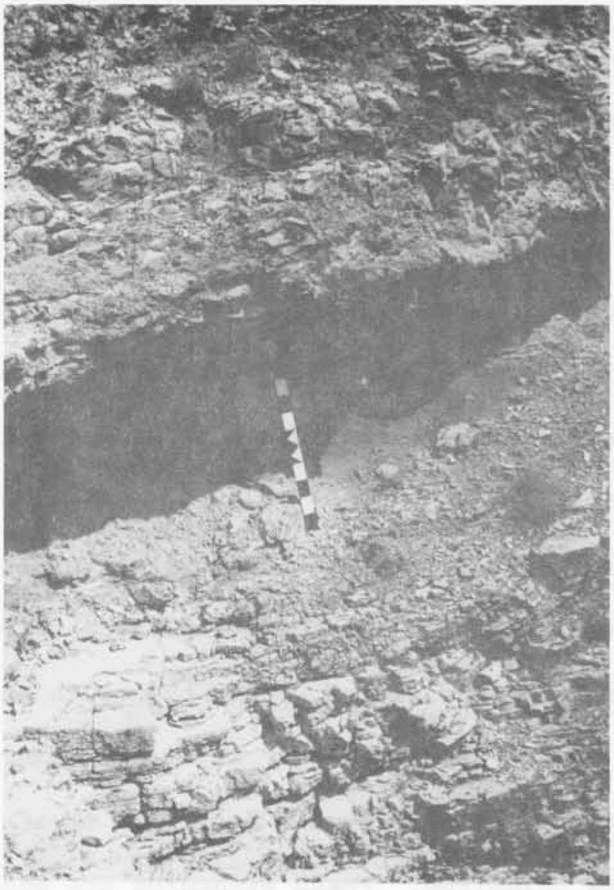

Figure 1. Outcrop of Rustler Formation in arroyo about 15 miles (ca. 25 km) east of Artesia, New Mexico, (SE 1/4 NE 1/4 sec. 15, T. 17 S., R. 28 E.). The resistant beds are formed by the Culebra Dolomite (below) and the Magenta Dolomite (above). The meter scale rests on the intervening Tamarisk Member which consists of reddish silty claystone. Adjacent to this exposure ancient collapse sinks are filled with conglomeratic redbeds of Triassic age.

Dissolution of evaporites in the Rustler Formation has contributed to the formation of innumerable karst features--landforms which result from the dissolution of soluble rocks underlying the surface. Broad karst areas underlain by the Rustler Formation are characterized by disorderly vertical and underground drainage which is in contrast to the orderly drainage of through-flowing streams and valleys found in non-karst areas. This distinctive karst topography is pitted with disconnected, enclosed hollows, collapse sinks, and caves in various stages of formation.

Among the major karst features developed on the Rustler Formation are Nash Draw, Remuda Basin, and Burton Flat. Nash Draw is a complex karst valley about 16 miles (26 km) long and ranges from 4 to 12 miles (6 to 20 km) wide. Its eastern edge is marked by Livingston Ridge which is about 4 to 6 miles (6 to 10 km) west of the WIPP shaft.

Nash Draw began to form during Pleistocene (late Gatuña) time. At that time a major tributary drainage system flowed southwesterly from the High Plains toward the main stem of the south-flowing Pecos River. Evidence of that drainage system is preserved in gravel-filled channels in Long Arroyo east of Hagerman, on Pavo Mesa east of Artesia, in Gatuña Canyon about 16 miles (ca. 27 km) northwest of the WIPP site, and along the flanks of Nash Draw itself. As this drainage system eroded downward in the vicinity of Nash Draw, it encountered the updip edge of the Rustler Formation. Dissolution was initiated in the evaporite beds of the Rustler and collapse sinks began to form. These sinks were aligned roughly northeasterly along the strike of the Rustler beds and resulted in the present alignment of Nash Draw. As these collapse sinks coalesced, Nash Draw subsided. Coincidentally, the entire Gatuña drainage system ceased to flow--probably as a result of regional tectonic adjustments--and the drainage system was disrupted. This disruption occurred after the fall of a volcanic ash in the area (Lava Creek B ash, dated at about 600,000 years BP) and before the Mescalero caliche (dated about 500,000 years BP) was formed on the surface eastward from Livingston Ridge. The main subsistence of Nash Draw occurred before the Mescalero caliche was deposited. Today the eroded edges of stream gravels in the Gatuña are as much as 200 feet (61.5 m) above the floor of Nash Draw. Dozens of collapse sinks and caves are present in various parts of Nash Draw and it continues to expand at an abbreviated rate as a karst valley.

Remuda Basin is located on the southeastern edge of Nash Draw. It is a blind valley which drains into an open cave system in the Rustler Formation. The basin is over 200 feet (62 m) deep at its deepest point and drains an area of about 3 square miles.

Burton Flat is a karst plain developed on evaporites in the Rustler Formation covering an area of more than 100 square miles (275 sq. km) about 20 to 25 miles (ca. 33 to 42 km) northwest of the WIPP site. Burton Flat is a rolling plain pocked by scores of closed depressions, collapse sinks, and caves. At places beds of Rustler gypsum are collapsed into caves in linear trends along joint sets (Fig. 2). Soils are poorly developed and the Mescalero caliche has not been observed on the karst plain. The instability of the surface, as well as the near-surface presence of evaporites such as gypsum, are unfavorable conditions for the formation of thick soils over long periods of time. If the Mescalero caliche was ever present in that area it has since been destroyed by collapse and erosion.

William Morris Davis is credited with developing the concept of geomorphic cycles in which landforms have characteristic traits during their youth, maturity, and old age. Although the concept of geomorphic cycles has many shortcomings and is often criticized, the idea of a sequential development of

Figure 2. Brecciated gypsum in Rustler Formation, Burton Flat (NE 1/4 sec. 23, T. 19 S., R. 29 E.). Gypsum has collapsed into an underground cavernous drainage system which is aligned on a joint set.

karst features is unavoidable.

Favorable outcrops are widely separated in southeastern New Mexico, but numerous exposures indicate that karst features have an orderly development. At some places evaporites in the Rustler have only recently been in the path of dissolving waters. At these places collapse sinks and caves indicate ongoing processes. At other places the remnants of extinct karst features (paleokarst) are preserved within the sedimentary sequence where they have been buried by later processes.

The remnants of some ancient karst features which involve the Rustler Formation are preserved in the southern part of Nash Draw and in Pierce Canyon about 15 miles (ca. 25 km) southwest of the WIPP site. Collapse breccia with blocks of Magenta Dolomite are intermingled with breccia of the Gatuña Formation at the south end of Nash Draw and in Pierce Canyon. Near the mouth of Pierce Canyon the Gatuña itself dips steeply into an ancient collapse sink. The collapse occurred after the Gatuña was lithified. Thick beds of stream gravel fill ancient channels in the upper part of the Gatuña Formation in Pierce Canyon and indicate that abundant surface water was available during latest Gatuña time.

Rainfall was a much more effective agent of erosion and corrosion during parts of the Pleistocene than at any time since. For example, during latest Pleistocene time, 10,000 to 25,000 years before the present, perennial lakes were common over New Mexico in places where intermittent lakes are now rare. Most of the landscape that we see today in southeastern New Mexico is the result of processes in effect since mid-Pleistocene time and are no older than about 500,000 years. Many of these landforms have been modified by later Pleistocene events. The entire Pecos drainage system in various forms is as old as Tertiary, but its present position and many of its adjacent landforms are younger than mid-Pleistocene.

Nash Draw began to form during mid-Pleistocene time, but large-scale subsidence may presently be in a relatively dormant state. Collapse sinks and caves in Nash Draw receive water during rainy seasons, and minor subsidence is active along its axis. The extensive subsidence which created the depression appears to be inactive. Late Pleistocene spring deposits were laid down along the eastern flanks of Nash Draw and do not appear to have been disturbed since their deposition. Similarly, farther north in Clayton Basin, lake beds, presumed to be late Pleistocene in age, were deposited in the floor of the basin which had been created by earlier episodes of subsidence. Those beds appear to be relatively undisturbed.

Efforts to calculate rates of dissolution of evaporites in southeastern New Mexico must consider that such rates are variable with climatic changes, changes in drainage patterns, and presence of open groundwater systems. Bachman and Johnson (1973) and Bachman (1980) based their calculations on rates of dissolution and subsidence on an assumption that these rates have been constant. Consideration of later observations show that such an assumption is invalid. The rates of dissolution and subsidence obtained in those early studies must now be considered to be invalid.

Any effort to calculate rates of dissolution and subsidence of features such as Nash Draw will fail until more absolute data are available on paleoclimate and groundwater conditions associated with ancient drainage systems. Recent observations of numerous karst features throughout southeastern New Mexico suggest that present groundwater systems are underfit with respect to these landforms. Many caves, collapse sinks, and associated groundwater systems appear to have been formed during past periods of more effective rainfall.

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RUSTLER FORMATION
IN THE
WASTE HANDLING AND EXHAUST SHAFTS,
WASTE ISOLATION PILOT PLANT (WIPP) SITE,
SOUTHEASTERN NEW MEXICO

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RUSTLER FORMATION IN THE WASTE HANDLING AND EXHAUST SHAFTS
WASTE ISOLATION PILOT PLANT (WIPP) SITE, SOUTHEASTERN NEW MEXICO

1.0 INTRODUCTION

The Permian Rustler Formation was recently examined in detail in two shafts at the WIPP Site: the waste handling shaft (waste shaft) and the exhaust shaft. The examination of the Rustler in the shafts has provided unique data previously unavailable from any other source. Fresh exposures of the Rustler in the shafts exhibited abundant primary sedimentary structures. Though some evidence of these features has been reported in outcrop and core descriptions, the abundance of primary sedimentary structures observed in the shafts is unequaled in previously described sections. These data are reported here in their stratigraphic context as an initial basis for evaluation of depositional environments of the Rustler and reevaluating the role of dissolution in the formation of the Rustler.

The waste shaft is an enlargement of the blind-bored ventilation shaft. The lithology exposed in the ventilation shaft was described in GFDR No.4 (1983). After its enlargement to become the waste shaft, the lithology described in GFDR No.4 was verified and necessary modifications to the descriptions were provided in

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This paper was presented March 7, 1985, in Carlsbad, New Mexico at a meeting of WIPP Project participitants and the EEG on the Geology of the Rustler Formation.

WTSD-TME-038 "Geotechnical Activities in the Waste Handling Shaft" (Holt and Powers, 1984). In the waste shaft, geologic data were collected during geologic inspections of the previously mapped strata and detailed mapping in identified zones of interest in the Rustler Formation. The exhaust shaft is an enlargement of an upreamed shaft. The entire exhaust shaft section was described concurrently with construction as no descriptions of the exhaust shaft geology previously existed. Data were gathered using two principal methods: reconnaissance geologic mapping and detailed, 360 degree mapping in zones of interest. The geologic data gathered in the exhaust shaft will be presented in a WTSD-TME in final preparation. A synthesis of the basic data collected in the two shafts is herein presented.

2.0 RUSTLER FORMATION

The Rustler Formation is the youngest of three Ochoan evaporite-bearing formations in the Delaware Basin (Figure 1). Richardson (1904) named the Rustler for outcrops in the Rustler Hills, Culberson County, Texas. Lang (1935) clarified the term "Rustler" to stratigraphically define the interval between the Pierce Canyon Redbeds (now recognized as the Dewey Lake Redbeds) and the Salado Formation. Lang (1935; in Adams, 1944) recognized and named two laterally persistent dolomite units. The lowermost is named the Culebra Dolomite Member, and the uppermost is named the Magenta Dolomite Member. Vine (1963) introduced the presently used five-fold stratigraphic subdivision of the Rustler. Vine named the interval above the Magenta the Forty-Niner Member and the interval between the Culebra and the Magenta the Tamarisk Member. The interval between the Rustler/Salado contact and the Culebra was not named and is herein referred to as the unnamed lower member.

The Rustler Formation is characterized by a variable lithology consisting of interbedded sulfates, carbonates, clastics, and halite. Jones (1972) reported the Rustler as consisting of 10% carbonate rocks, 30% sulphate rocks, 43% chloride rocks, and 17% clastic rocks.

3.0 WIPP SHAFT DATA

The following description is a synthesis of data collected in both the waste shaft and the exhaust shaft. It was possible to combine the data from the two shafts as the lithology varied only slightly between the two shafts. In the immediate area of the WIPP site, the Rustler is about 305 feet thick.

Unnamed Lower Member

The unnamed lower member consists of clastic sediments with subordinate amounts of bedded halite, anhydrite, and polyhalite (Figure 2). The basal contact with the Salado is distinct and apparently conformable, indicating neither significant erosion nor dissolution.

The basal contact of the unnamed lower member is marked by a change of matrix material from clay, in the Salado, to sulfate, in the Rustler. The lower one to two feet consists primarily of sulfate: anhydrite and polyhalite. The sulfates grade upward into a reddish-brown siltstone that is thinly laminated and exhibits some very small cross-laminations. This lower siltstone is variable in thickness (0.5 to 2.0 feet) because of an erosional contact with the overlying sandy siltstone.

A thin (2 to 3 inch thick) basal conglomerate with invertebrate fossil fragments overlies an undulatory and clearly erosional contact between the two siltstone units. The upper siltstone is reddish-brown at the base and grades to gray higher in the section. This siltstone (6 feet to about 61 feet above the basal contact of the Rustler) is well bedded and displays laminations, cross-laminations, trough cross-beds, channel lag, soft sediment deformation, and, near the base, anhydrite clasts or nodules that are locally aligned parallel to bedding. Portions of the gray-colored area appear similar to a stratigraphically equivalent zone observed in WIPP 19, a nearby borehole, which is disrupted by bioturbation. Higher in the section the siltstone becomes sandy and the color reverts to reddish-brown. Cross-laminations indicate a general paleocurrent direction toward the south or slightly west of south.

Two halite rich sequences, with a combined thickness of roughly 30 feet, are separated by a two-foot thick anhydrite bed and occur 61 feet above the lower contact. The halite content of the lower sequence increases upward and culminates in a 3.5 foot thick bed of relatively pure halite interbedded with minor amounts of anhydrite and claystone. The overall halite content of the upper sequence decreases upward. Halite commonly occurs as clear displacive crystals containing mud inclusions (eg. Shearman, 1978). Bedding and current bedding are common through these sequences. In the waste shaft, a trough about three feet wide and one-foot deep, with a sharp basal contact, is filled with finely bedded to laminated mudstone. Cross-bedding indicates that paleocurrents flowed nearly south.

A ten-foot thick unit of nodular to thinly laminated anhydrite with minor polyhalite overlies a sharp contact with the halitic beds. Abundant anhydrite and halite pseudomorphs after swallowtail gypsum occur. Nodular anhydrite in an argillaceous matrix occurs near the base. The polyhalite occurs near the top and is very fine grained, dense, and structureless.

The uppermost nine feet of the lower member consists of interbedded, dark gray to reddish brown claystone, silty claystone, and argillaceous siltstone. The basal contact is sharp and undulatory. Reddish-brown to gray color changes coincide with changes in grain size; both are continuous around the circumference of the the shafts. Continuous, but locally broken, thin interbeds of anhydrite are traceable around the circumference of both shafts. Abundant nodules of gypsum, up to two inches in diameter, occur in the lower part. The upper part of the bed is laminated to apparently structureless.

Culebra Dolomite Member

The Culebra consists of brown, finely crystalline, locally argillaceous and arenaceous dolomite with rare to abundant gypsum-filled and unfilled vugs (Figure 2). Bedding ranges from massive to laminated; some cross-bedding exists. In the waste shaft, a scour channel from the middle of the unit is oriented nearly east-west, but the direction of paleocurrents has not been determined. In the waste shaft, the uppermost one foot is a black to golden laminated claystone and carbonate that is very rich in organic carbon (W. C. Cornell, pers. comm., 1984). Some laminae at the upper contact of this layer are truncated.

Tamarisk Member

The Tamarisk Member is about 86 feet thick in the shaft areas (Figure 2). It consists of a lower (about 16 feet) and an upper anhydrite separated by six to nine feet of claystone.

The anhydrites are gray, finely crystalline, and they are banded to laminated to nodular. The anhydrites locally contain carbonate interbeds which are often associated with anhydrite pseudomorphs after swallowtail gypsum. Contacts with the claystone are undulatory and sharp.

The claystone unit is poorly bedded to apparently structureless. The lower part is reddish brown and the upper part is gray. The color change is diffuse or gradational and undulatory over about six feet of thickness. In the waste shaft, fractures in the claystone record at least two episodes of fracturing and subsequent filling with gypsum. Older vertical and subvertical fractures are crosscut by younger horizontal to subhorizontal fractures. In the exhaust shaft, nodules of gypsum and subangular, irregularly shaped clasts of anhydrite occur throughout the claystone, and in general, the concentration of both decreases higher in the section. In WIPP 19, this claystone rests upon the Culebra and displays reddish-brown to gray mudstone and siltstone clasts that are round to angular and clast-supported. In some zones, the clasts appear to become smaller in size upward.

Magenta Dolomite Member

The Magenta in the shafts is a light to dark brown gypsiferous and arenaceous dolomite about 25 feet thick (Figure 2). The purplish cast to the Magenta apparently only develops after surficial exposure and weathering.

The Magenta displays abundant bedding and primary sedimentary structures. Bedding is tabular to lenticular, discontinuous, frequently convoluted, and occasionally is erosionally truncated. Small cross-bedding and/or cross-laminations in light brown material are commonly draped with finer-grained dark carbonate. Subunits in the upper Magenta contain basal sands or small pebble conglomerates of carbonate. Isolated gypsum nodules are locally abundant. The bedding locally resembles flaser bedding and wavey and lenticular bedding (after Reineck and Singh, 1980). A zone containing mound-shaped structures occurs in the lower two feet. The mounds consist of thinly laminated to laminated dolomite interbedded with dark brown, probably organic-rich, claystone. The lower contact is gradational into the underlying anhydrite.

Forty-Niner Member

The Forty-Niner is about 57 feet thick in the shaft areas (Figure 2). It consists of lower (16 feet) and upper (29 feet) anhydrites with a claystone (12 feet) sandwiched between the anhydrites.The anhydrites are relatively hard, gray, and finely crystalline. They range from laminated to nodular. Contacts with the claystone are sharp to slightly gradational. The upper contact with the Dewey Lake

Redbeds is sharp and undulatory with a relief of about one-foot. Laminae within the upper anhydrite are erosionally terminated at the upper contact with the Dewey Lake Redbeds.

The silty claystone in the middle of the Forty-Niner exhibits fine discontinuous bedding, color banding, and some cross-laminations. Gypsum locally occurs throughout the section with an enterolithic or nodular morphology. The bedding surrounding gypsum occurrences is commonly displaced and distorted. Lithologically distinct units are individually distinguishable on the basis of color, bedding morphology, and erosional surfaces. The basal two feet is greenish-gray with reddish-brown clasts near the base.

4.0 SUMMARY

The large number of primary sedimentary structures and related primary features that have been observed in the shafts are described in detail in the geotechnical reports concerning the two shafts (Holt and Powers, 1984; in preparation). This paper summarizes those reports. Primary features occur throughout the Rustler and have been observed occuring in zones previously interpreted as dissolution residues. The authors are undertaking a complete detailed reexamination of Rustler core to provide the basis for an evaluation of Rustler depositional environments and a reevaluation of the extent of dissolution of the Rustler in the vicinity of the WIPP site.

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STABLE-ISOTOPE STUDIES OF GROUNDWATERS IN SOUTHEASTERN NEW MEXICO

SAND85-1978C

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ABSTRACT

Oxygen-18/16 and deuterium/hydrogen ratio measurements have been made on groundwaters sampled according to specific field criteria applied during pump tests of the Rustler Formation (the uppermost Permian evaporite unit) in Nash Draw, a solution-subsidence valley west of the WIPP site in the northern Delaware Basin of southeastern New Mexico. Comparison of these data with similar measurements on other groundwaters from the northern Delaware Basin indicates two nonoverlapping populations of meteoric groundwaters in delta-O-18/delta-D space. Most of the Rustler waters in Nash Draw and at the WIPP site and older waters from the eastern two-thirds of the Capitan Limestone constitute one population, while unconfined groundwaters originating as observable modern surface recharge to alluvium, the near-surface Rustler in southwestern Nash Draw, and the Capitan in the Guadalupe Mountains (Carlsbad Caverns) constitute the other. The isotopic distinction suggests that Rustler groundwater in most of Nash Draw and at the WIPP site is not receiving significant modern meteoric recharge. A likely explanation for this distinction is that meteoric recharge to most of the Rustler and Capitan took place in the geologic past under climatic conditions significantly different from the present.

INTRODUCTION

Oxygen-isotope ratios have been measured on all waters collected during the Nash Draw investigations of 1980 (cf. Lambert and Robinson, 1984). In addition, other relevant waters were analyzed and those results are included in this preliminary discussion. A map of borehole locations in Nash Draw and over the WIPP site is given in Figure 1; the localities for Nash Draw samples whose isotopic compositions are reported herein may be found on the map, which also shows the geographic relationships among the Nash Draw holes, other boreholes, natural occurrences of surface water, and the scarps bounding Nash Draw. Deuterium/hydrogen ratios were previously determined by C. J. Yapp (University of New Mexico) under the auspices of the Sandia/University Research Program, but until the stable-isotope facility was established at Sandia the oxygen isotope data were not available, and the data could not be plotted in the customary delta-D vs delta-O-18 space.

Most of the data reported here are relevant to the Rustler Formation in Nash Draw, but delta-values of other related waters are reported and discussed here as well, such as Surprise Spring, San Simon Sink, and some of the more recently collected waters from Carlsbad Caverns.

METHODS

Hydrogen.

Waters were converted to hydrogen gas by reaction with uranium metal at 800 C, (Bigeleisen, et al, 1952). The hydrogen was collected by means of a Toepler pump and the HD/HH ratio was determined by mass spectrometry (see below). Corrections were made for background, port leakage, mass tail, and contribution of the triatomic hydrogen ion.

Oxygen.

Water was first distilled in vacuum to obviate the necessity of correcting for salinity in later treatments. Quantitatively distilled water was analyzed for oxygen by the equilibration of carbon dioxide with water at 25.4 degrees C (Epstein and Mayeda, 1953). After a full week of equilibration an aliquot of gas was extracted and dried, and then its O-18/O-16 ratio was measured with a 90-degree sector single-focusing double-collecting dual gas-fed mass spectrometer of the type described by A. O. Nier (1947) with modifications by C. R. McKinney et al. (1950). The instrument used to measure oxygen was a Micromass Model 602E manufactured by VG Isogas, Ltd., Middlewich, Cheshire, United Kingdom. Corrections for background, mass tail, and valve leakage are negligible on this instrument, but corrections were made for oxygen-17, carbon-13, and carbon dioxide exchange in the equilibration between gas and water. The hydrogen instrument at the University of New Mexico was a Nuclide 3-60-RMS. Results for both the new oxygen data and the previously existing hydrogen data are reported in the usual delta notation, expressed as the deviation of the isotopic ratio from that of Vienna Standard Mean Ocean Water (V-SMOW) in parts per thousand (per mil). The delta value of the working machine standard for oxygen (Harding Iceland Spar) was determined by comparison with NBS-18 (Fen Carbonatite) and NBS-19 (Taum Sauk Marble) whose values were reported by Coplen et al (1983). Details of the determination of the delta-O-18 value of Harding Iceland Spar are given in Table 1.

DATA

The data for both oxygen and hydrogen are provided in Table 2. Replicate analyses were done on a spot basis and for those results that were different in some way from the bulk of the results. Replicates represent entirely independent distillations, equilibrations, extractions, purifications, and mass spectrometric measurements. Since most of the results lie close together in delta-D/delta-O-18 space, oxygen measurements were not replicated for the greater bulk of the water samples.

DATA VALIDITY

The validity of these data from Nash Draw holes and resulting interpretations are subject to the limitations of the sampling conditions as described and discussed by Lambert and Robinson (1984). It is not possible to derive a quantitative estimate of the degree of contamination remaining in any of the samples discussed (ibid.). Several sources of contamination of water samples taken from a pumped (or swabbed or bailed) well have been discussed previously, including, but not limited to, introduction of alien water, introduction of alien solids that may slowly leach, dissolve, react with or infuse the water, products of reaction between water and equipment in the hole, and scaling of coatings on pipe in the hole. In any man-made hole, it is virtually impossible to obtain an unperturbed sample; the very act of drilling the hole irreversibly alters the local hydrologic system. A well-known example of such long-term unmitigable perturbations is given by McNitt (1963) for The Geysers geothermal field. In Nash Draw pump times varied from 17 to 184 hours, during which several solution parameters were measured in the field, including Eh, pH, specific conductance, specific gravity, bicarbonate and/or carbonate, chloride, divalent cations, calcium, hydrogen sulfide, sulfate and total iron. Based on the long-term observations in the pumped wells, the best indicators of achievement of steady state in solution parameters were divalent cations and chloride. The length of time required for these solutes to achieve steady state values was typically greater than 24 to 48 hours, even at pump rates of several gallons per minute. During some of the pump tests, there was no indication of an asymptotic approach of some parameters to a steady-state value. This was particularly true of bicarbonate. In one case, the flow rate was consistently less than 100 mL/min (WIPP-30 Magenta), and Lambert and Robinson (1984) determined that after 184 hours chloride, divalent cations, and calcium were still monotonically decreasing with no indication of approach to steady-state. Even during long pump times at low pump rates, however, there is little likelihood of stable-isotope fractionation of the water due to partial evaporation (because of the relatively small amount of water exposed to dry air in the hole), rock-water interaction (as illustrated below by the coincidence of data from "tight" units with the meteoric field), or reaction with pipe (also because of coincidence with the meteoric field). The close juxtaposition of isotopic data from units of low productivity with data from units of high productivity (some of which were several miles apart) shows that contamination of the low productivity units did not affect the isotopic results as much as it may have affected some other solution parameters.

Thus isotopic data for even low-flow-rate waters are expected to be accurately representative of their actual compositions at their sampling locations to within approximately 0.5 per mil for delta-O-18 and approximately 10 per mil for delta-D, based on the clustering of most of the Rustler data points in Table 2. For high-flow-rate waters, the "accuracy" is no better than the limits of reproducibility for the analytical methods, i.e., 0.1 per mil for delta-O-18 and 1 per mil for delta-D. As pointed out by Lambert and Robinson (1984), however, certain solution parameters (particularly trace constituents) are more susceptible to contamination than others, and the mitigation of contamination for some constituents is more difficult than for others. Thus, while the effects of small amounts of contamination may be small for the stable isotope measurements, the same is not necessarily true for certain ultratrace radioisotopes.

For simple homogeneous systems most replicate delta-O-18 analyses lie within 0.1 per mil of one another. The differences between the two replicates of oxygen for Surprise Spring and the New Mexico Room are larger than usual, and one of the measurements in each case may reflect incomplete distillation. At least one additional replicate of each of these samples will be analyzed in order to resolve the variation.

DISCUSSION

The Meteoric Field.

The data from this work are plotted in delta-D/delta-O-18 space in Figure 2. Included in Figure 2 are the worldwide meteoric lines, defined by

delta-D = 8 x delta-O-18 + 5 (Epstein, et al., 1965;1970)

and

delta-D = 8 x delta-O-18 + 10 (Craig, 1961a)

The intervening area bounded by these lines is called the meteoric field.

Not included in Figure 2 are the isotopic data obtained previously for the various Delaware Basin groundwaters, as the resulting diagram would be excessively cluttered by their inclusion. Data have been previously reported by Lambert (1978;1983a;1983b); the individual data points from previous work are given in Figure 3. The approximate ranges of (1) Carlsbad Caverns waters from the Guadalupe Mountains, and (2) Rustler waters at and near the WIPP site and deep Capitan waters east of the Pecos River, as defined by the previous data, are depicted as fields in Figure 2.

Waters from Nash Draw.

Figure 2 shows that with the exception of WIPP-29 Culebra, all Nash Draw well waters are clustered together on or near the meteoric field. They occupy the same general position in delta-D/delta-O-18 space as do many other waters from the Rustler Formation and the eastern Capitan Limestone (Lambert, 1978). This shows that these waters have undergone minimal rock-water interaction since they originated as precipitation. [Note: Groundwaters having undergone rock-water interaction are probably represented by the Rustler/Salado waters in H1, H2, H3, H4, H5, H6, and the Culebra waters in P-17 and P-18 (see Figure 3), all of which are from zones of lower permeability, and whose isotopic compositions define a trajectory away from the meteoric field, but still have a meteoric origin, as indicated by the intersection of this trajectory with the meteoric field at isotopic compositions representative of much of the Rustler. For additional discussion of rock-water interaction in the Rustler Formation, see Lambert (1983a).]

WIPP-29 Culebra neither lies near the meteoric field nor bears any similarity to any of the other waters in Nash Draw. This isotopic isolation may be related to the very shallow depth of the Culebra water in WIPP-29 (about 12 feet), in contrast to the equivalent depth of a few hundred feet in the other Nash Draw holes. At this time it is not possible to uniquely determine a cause for the isotopic isolation of WIPP-29 Culebra. If, for example, the shallowness of the water makes it susceptible to kinetic fractionation by partial evaporation, such a process could conceivably lead to the evolution of a water such as this from isotopic values characteristic of the rest of the Rustler. Evaporation-induced fractionation would tend to make residual liquids more enriched in deuterium and oxygen-18. In addition, a water of this isotopic composition could reflect a completely different origin from that of the rest of the Rustler, such as locally derived recharge from the surface, with or without some degree of rock-water interaction tending to enrich the water in oxygen-18 (see discussion below). Only a few tens of feet from WIPP-29, for example, is a relatively permanent pond that came into being since the beginning of local potash-refining activity. Thus there is a case for locally derived surface runoff recharging the Rustler in the vicinity of WIPP-29. Nevertheless, the isotopic isolation demonstrates a profound hydraulic isolation of WIPP-29 from the rest of the Culebra; the supply of water here is less influenced by the rest of the Rustler (by at least an order of magnitude) than by purely local effects, whether those effects be local recharge (see discussion below), isotope shift, or evaporation.

Evaporation is not a likely cause for the isotopic isolation of water from WIPP-29 Culebra; the high transmissivity of the Culebra at WIPP-29 (1000 feet squared per day; Gonzalez, 1983) together with the little enrichment in solutes relative to the rest of the Culebra (Lambert and Robinson, 1984) shows that water is in quantity much greater than that probably necessary to offset loss by evaporation. Thus, partial evaporation of water with an isotopic composition characteristic of the Culebra in the rest of Nash Draw is not a likely cause for the observed isotopic isolation. It is also possible that the isotopic composition of WIPP-29 Culebra could have arisen by oxygen-isotope shift, a process whereby the oxygen isotope composition of a water changes by isotope exchange with local oxygen-bearing minerals, with little change in hydrogen (Craig, 1966); given the apparently high water/rock ratio, this is unlikely.

The geologic and isotopic observations together indicate that the source of Culebra water at WIPP-29 is not dominated by the Culebra water in other parts of Nash Draw, but may be locally derived; this in turn implies that either the Culebra does not have as uniformly connected a porosity in Nash Draw as formerly believed, or local surface effects dominate the groundwater in very shallow occurrences of the Culebra, which is 12 feet below the surface at WIPP-29. In any case the isotopic differences between the Culebra and the Rustler/Salado in WIPP-29 (6.5 per mil for oxygen, 20 per mil for hydrogen) preclude the plausibility of a direct vertical connection between these two horizons in this hole.

Perhaps a more profound observation is the isotopic isolation of Surprise Spring from the rest of the Rustler. Barrows (unpublished) has proposed that Surprise Spring, and by implication, nearby Laguna Grande de la Sal (both of which are a significant distance upstream from Malaga Bend) are discharge points for the Rustler. Surprise Spring discharges from the surface outcrop of the gypsiferous Tamarisk Member of the Rustler Formation, between the Magenta and Culebra Members, and the profound difference in isotopic composition between Surprise

Spring and all the rest of the Rustler groundwaters (excluding WIPP-29 Culebra) shows that Surprise Spring cannot be a discharge point for water in either the Culebra or the "brine aquifer". The degree of isotopic isolation of Surprise Spring from the rest of the Rustler in Nash Draw is consistent with the earlier conclusion of Lambert (1983a) that "the water of Surprise Spring is not derived from either the Culebra dolomite or the 'basal brine aquifer', both of which in that vicinity have chloride contents at least 60000 mg/L chloride" (Surprise Spring has 30000). The origin of the water in Surprise Spring is probably more akin to modern meteoric recharge than is WIPP-29 Culebra (which may be strongly influenced by mixing) or any of the rest of the Rustler. Oxygen-isotope shift could conceivably be a mechanism by which water with the isotopic composition of Surprise Spring might be derived from the inferred modern meteoric water represented by the Carlsbad Caverns data. This mechanism alone does not, however, provide a means to derive Surprise Spring water from the other, obviously meteoric, Rustler groundwaters in Nash Draw and the WIPP site.

The isotopic data in Table 2 and Figure 2 also show that different parts of the Rustler Formation even within the same hole can be isotopically (and probably hydraulically) isolated from one another. For example, the Culebra and Rustler/Salado waters in WIPP-28 are isotopically different by 1.4 per mil in oxygen and 11 per mil in hydrogen, even though they both lie in the meteoric field. Thus, as will be discussed in a subsequent argument, the isotopic data show that waters of different isotopic compositions entered their respective horizons of the Rustler Formation under different climatic regimes.

There are other cases of both similarities and differences among waters in a single well in different parts of the Rustler. Connections cannot be argued solely on the basis of isotopic similarities; a case can be made for vertical connection only if superposed occurrences of water in the Rustler have simultaneous isotopic, solute, and potentiometric similarities. Such may be the case in WIPP-25 for the Magenta and Culebra. As the complete data sets become available, such possible vertical connections will be evaluated.

Other Waters.

The waters remaining to be discussed form a chain of data points alongside but slightly to the right of the meteoric field (Figure 2): the three new points for Carlsbad Caverns, summer rain, and San Simon Sink. We first note that the new Carlsbad Caverns points generally correspond to the range previously reported for the Caverns. The small yet analytically significant deviation of the three new points from the meteoric field is tentatively attributed to partial evaporation. It is fairly well known that most Caverns water comes from infiltration on outcrops (Ronal Kerbo, pers. comm.), but most of the isotope shift away from the meteoric field is probably attributable to evaporation from cavern pools. Nevertheless, the overall isotopic distribution of Caverns waters is not changed by the new data.

Note that there is considerable nonsystematic variation between isotopic composition of Caverns waters and depth. The Caverns waters probably carry seasonal (climatically induced) variations that give rise to the relatively wide spreading of the isotopic compositions along the meteoric field. Thus, a seasonally integrated record of the modern recharge must be obtained in such a way as to (1) average out the annual climatic variations and (2) mitigate the effects of partial evaporation in the Caverns air.

At the upper extreme in deuterium is the summer rain, collected during a storm at WIPP-29. This point falls into the Caverns ("modern") field, but must be viewed as a single climatic incident. It is probably, however, more representative of modern rainfall (especially in the summer when most of the precipitation falls in the Delaware Basin) than, say, the waters in most of the Rustler in the lower left part of Figure 2, or that of the "May storm" in the lower left part of Figure 3. Individual climatic events, even when combined into a weighted average over a year, should not be used to infer the isotopic composition of modern recharge, as (1) the recharge water may be most dominant in a particular season, and (2) a single year may not be representative of precipitation that has occurred over tens to hundreds of years.

The San Simon Sink (WIPP-15) water occupies a somewhat anomalous position. It was sampled, apparently, under water-table conditions. It could have arisen by partial evaporation of Capitan- and Rustler-like waters. Based on potentiometric levels (R. L. Hunter, pers. comm.), however, a leakage path from the underlying Capitan is unlikely. Indeed, water in WIPP-15 may be a product of older Rustler waters mixing with modern recharge from the surface; this may also be the case for WIPP-29 Culebra. San Simon's position slightly off the meteoric field suggests it has undergone either partial evaporation or oxygen-isotope shift by exchange with local minerals.

The isotopic composition of the Pecos River, sampled at Lake Carlsbad in June (Figure 3), probably represents the period of highest runoff feeding the river's tributaries upstream. This isotopic composition falls near the field of the other surface-derived waters, and its distance (in delta-D/delta-O-18 space) from the Rustler waters of Nash Draw (except WIPP-29 Culebra) and points east does not make the Pecos River water a likely candidate for major modern recharge to the Rustler near the WIPP site or in much of Nash Draw.

One additional point in Figure 3 deserves some attention: the one marked "Dewey Lake ?". This water originated from a very shallow well on the James Ranch property due south of the WIPP site. Its isotopic composition is very near the meteoric field, and very near the field of Carlsbad Caverns. The well's proximity to a large area of sand dunes implies that infiltration can readily proceed there, and thus it probably represents conditions conducive to active modern recharge, as does Carlsbad Caverns. The isotopic composition of this water is similar to that of groundwater from the alluvium in San Simon Sink. This suggests that San Simon Sink may be less dominated by mixing of Capitan water coming up from below, and more dominated by modern surface recharge. It is unlikely that the James Ranch well is influenced by mixing from the Capitan, given its great distance from the Capitan (about 13 miles) and the barrier posed by the Rustler and Salado Formations between the Dewey Lake and the

Capitan.

It is interesting to note that C. J. Yapp (unpublished written communication) reported several delta-D values for water from the Ogallala Formation from eastern New Mexico. They all fall within the range -39 to -41 per mil. The proximity of the Ogallala to the surface implies (as in the case of Carlsbad Caverns and San Simon Sink) that the Ogallala is receiving modern recharge in the region, and its delta-D value is at the lower limit of the Carlsbad Caverns field, but still within it. Thus, regardless of the values of meteoric precipitation collected at the surface in the northern Delaware Basin, the delta-D values of groundwaters that have meteoric origins (as the Ogallala is here inferred to have) should be considered representative of meteoric waters that actually recharge groundwater bodies. Hence, Carlsbad Caverns should not be considered atypical of demonstrably modern meteorically derived recharge to groundwater in the northern Delaware Basin.

The Climatic Influence.

Under the assumption that all major meteoric precipitation originates as water evaporated from the oceans, there are several factors that can govern the oxygen- and hydrogen-isotopic composition of meteoric water. These include temperatures of evaporation and condensation, latitude, elevation, and the previous precipitation history of the air mass; the last is generally considered to be the most important.

As a moist air mass moves from its oceanic source area over the land and begins to precipitate, the isotopic equilibrium fractionation factors between water liquid and vapor for oxygen and hydrogen indicate that the liquid (or solid) precipitation is slightly enriched in O-18 and deuterium with respect to the water vapor remaining in the air mass. By the interacting processes of (1) equilibrium isotopic exchange between vapor and precipitate, and (2) Rayleigh fractionation, the airmass becomes increasingly depleted in heavier isotopes as precipitation proceeds, leaving subsequent precipitation progressively more depleted. Under extreme conditions, such as at the South Pole, depletions can become as large as -56 per mil in oxygen and -430 per mil in hydrogen with respect to ocean water. This progressive rainout accounts for the distribution of isotopic compositions along the meteoric field. Combinations of factors such as elevation and distance inland from the ocean can contribute large geographic variations in isotopic composition (see Figure 4). The isotopic compositions of local groundwaters in Figure 4 were deduced by Craig (1963) to be representative of local meteoric precipitation; he reasoned that mixing in the local groundwater reservoir homogenized the seasonal variations induced by annual climatic cycles. Thus, while summer precipitation would be different from winter precipitation, with a climate stable for hundreds of years the isotopic composition of local groundwater would remain within a fairly narrow range. Figure 4 shows that the different climatic regimes represented by the geographic variations (from desert Niland to temperate Italy to mountainous Lassen) do not overlap. This need not always be the case; some combinations of climatic conditions can give rise to the same isotopic composition for local meteoric precipitation. The inverse, however, is axiomatically true: different isotopic compositions of meteoric precipitation are always indicative of different climatic conditions. Other than evaporation and reprecipitation involving large (necessarily atmospheric) air masses, there is no known natural process of fractionation that will move isotopic compositions along the meteoric field. Figure 4 also illustrates the phenomenon of oxygen-isotope shift under temperatures typical of active hydrothermal systems. Note that the isotopically shifted waters clearly have their origins traceable to their meteoric parents, but no longer plot near the meteoric field.

In the groundwaters in southeastern New Mexico whose isotopic compositions fall on or near the meteoric field, those waters that have penetrated only to very shallow depths under water-table conditions (e.g., WIPP-29 Culebra, Surprise Spring, the Dewey Lake (?), and San Simon Sink) and waters from caverns in the Guadalupe Mountains (whose demonstrable source is modern meteoric precipitation) have isotopic compositions that overlap, and they occupy a position in Figure 2 that tends toward higher delta-O-18 and delta-D values. This was first discovered by Lambert (1978), who at the time thought that a different air mass was supplying the Guadalupe Mountains with precipitation that was isotopically distinct from that supplying the rest of the Delaware Basin. The correspondence of the modern Guadalupe Mountains values with those of waters well within the Delaware Basin both west and east of the WIPP site (e.g., WIPP-29 Culebra, Surprise Spring, Dewey Lake (?), and San Simon Sink) shows that an air-mass difference is probably not the explanation for the isotopic distinction; it would be highly fortuitous if one airmass selectively but perennially supplied the Guadalupe Mountains, the southwestern part of Nash Draw, the Dewey Lake due south of the WIPP site, and San Simon Sink, while another supplied the rest of Nash Draw and the WIPP site. Thus if the juxtaposition of two different air masses at the same time (separated by a somewhat convoluted boundary, but never more that 50 km apart) is not the explanation, the only alternative is to have different air mass patterns governing the climate of southeastern New Mexico at different times. Time-dependent variations in climate at a given location would result in different ranges of isotopic compositions of waters available to recharge various bodies of groundwaters at different times.

The data in Figures 2 and 3 appear to represent at least two generations of meteoric recharge to the groundwater systems in the Delaware Basin. Considering only the waters whose isotopic compositions lie on or near the meteoric field (i.e., those which have not lost their meteoric character by isotope-shift due to advanced partial evaporation or rock-water interaction), there is a gap in values between those associated with demonstrably modern meteoric recharge now being derived from the surface (the "heavier" group with a delta-D value greater than -40 per mil) and the others. No data points have yet been found that occur in the gap. The individual data points on either side of the gap do not statistically overlap. Thus the isotopic compositions of the meteorically-derived groundwaters that have demonstrable recent recharge from the surface also have an isotopic signature that is characteristically heavier.

Implications.

Robinson and Lang (1938) postulated that "water percolating into the ground in the vicinity of Bear Grass Draw may pass into the truncated edges of the lower Rustler formation and may migrate south and east as porosity and structure determine." If we consider the isotopic composition of the modern precipitation that actually infiltrates to be somewhere in the "Carlsbad Caverns" field in Figure 3 (and that such water is represented not only by caverns waters but also by waters from San Simon Sink, Surprise Spring, WIPP-29 Culebra, and Dewey Lake (?)), and we assume that this composition prevails near Bear Grass Draw as well as in other parts of the northern Delaware Basin, then modern recharge at Bear Grass Draw, or anywhere else in the northern Delaware Basin, if any, is minimally contributing to the groundwater in the Rustler Formation at the WIPP site or in Nash Draw. Recharge to the Rustler Formation could have taken place near Bear Grass Draw, however, during an erosional cycle that stripped the overburden from the Rustler in that area (J. W. Mercer, personal communication). The climatic conditions that governed that hypothetical episode of recharge would probably have been significantly different from those prevailing in the present cycle of intermittent fluvial and eolian alluvial and colluvial deposition; we would expect that recharge episode's isotopic signature as well to be different from that of the present. A few prominent erosional/depositional cycles are preserved in the geologic record, such as that around Gatuna time, 600,000 years ago (Bachman, 1985); others may have existed before and after that time, but evidence of them may have been since obliterated.

In any case, it is probably not possible to infer a modern recharge area in the Rustler simply by following the potentiometric contour lines upgradient, as the water now being recovered may be a relic of past climatic conditions no longer prevalent, and the present potentiometric distribution in the Rustler may be a transient response to continued or enhanced discharge. Furthermore, potentiometric contour lines are interpolated generalizations of the pressure distribution in a given hydrostratigraphic unit, and at any specific point it may not be valid to draw flow lines perpendicular to the local inferred hydraulic gradient.

On a physical basis alone it is difficult to infer the area upgradient to the east of the WIPP site to be an active recharge area; in spite of the fact that the potentiometric levels are higher there, the permeability is significantly lower (cf. Mercer, 1983). Similarly (again, on a physical basis alone) it is difficult to infer a significant amount of direct infiltration at or near the WIPP site, since the impermeable Mescalero caliche is virtually unbreached, except at borehole WIPP-33 west of the WIPP site, where an obvious surface depression is underlain by a zone of cavities and inferred collapse in the Rustler gypsum (Bachman, 1985). To the north and east, where the potentiometric levels in the Rustler Formation are generally higher, the caliche is regionally continuous, except in the northern lobe of Nash Draw due north of the WIPP site (see Figure 1).

Another possible reason for the lack of apparent recharge to the deeper Rustler groundwaters may be underflow, implying multiple channels of flow within a single layer such as the Culebra. This would imply that a different system of channels is carrying groundwater derived from modern meteoric precipitation, while the main channel system sampled thus far carries fossil water. This possibility is not likely, given the isotopic homogeneity of the Rustler groundwaters over a wide area (i. e., in the many holes sampled, only near-surface Rustler waters bear an isotopic resemblance to modern recharge). Also, the many geophysical and hydrologic tests performed in holes drilled with air have sought to identify all possible detectable fluid-bearing zones (cf. Mercer and Orr, 1979), and in each case each 8-m thick dolomitic Culebra member appears to have only one main saturated horizon within it that could be tested and sampled. Results of radioiodine tracer surveys, however, have suggested that the thickness of the saturated fluid-producing zone within the Culebra, for example, may be less than half its total thickness.

One could also argue that groundwater in the Rustler Formation is flowing from a modern recharge area outside the immediate vicinity of the WIPP site and Nash Draw; there are, however, observations that limit the credibility of such an argument. Due to the virtually identical isotopic compositions of Rustler groundwaters and Capitan groundwaters east of the Pecos River (i.e., older Capitan waters discussed by Barr et al., 1979, as opposed to actively recharged Capitan water in Carlsbad Caverns first characterized isotopically by Lambert, 1978), these two regionally pervasive bodies of groundwater must have been recharged under similar climatic conditions. One could argue that recharge to much of the Rustler and Capitan occurred at significantly different times, between which a much different climate prevailed. In view of the identical isotopic compositions, it would be extremely fortuitous to reproduce climatic conditions and isotopic compositions at different geologic times to such a precise degree, given the high sensitivity of isotopic compositions to local conditions. I thus consider recharge to the Capitan east of the Pecos and the deeper Rustler horizons to be contemporaneous. Lambert (1978) argued that rain presently falling on conspicuous outcrops of Capitan limestone in the Guadalupe Mountains has not altered the isotopic composition of groundwater in the rest of the Capitan. If modern recharge is thus somehow inhibited within such a permeable unit as the Capitan, it is difficult to infer a significant amount of modern recharge entering the Capitan from adjacent hydrostratigraphic units (the lagoonal-facies section including the Tansill to the San Andres, for example), since permeability contrasts would be greater across stratigraphic boundaries than within a unit such as the Capitan (cf. Hiss, 1975). Thus, even though areas such as the Sacramento Mountains to the west would be expected to receive isotopically lighter recharge, areas far removed from the northern Delaware Basin are not considered likely active recharge points for the Rustler Formation (or the Capitan) within the northern Delaware Basin.

CONCLUSIONS

The isotopic data suggest that modern meteorically derived water that can be shown to recharge local groundwater bodies at the present time is distinct from that in most of the Rustler near the WIPP site. The corollary of this conclusion also appears to be true: the Rustler groundwaters tapped by WIPP holes (with the possible exception of WIPP-29 Culebra) are not receiving significant amounts of modern meteoric recharge. The water that actually infiltrates, ultimately to recharge local groundwater bodies is not necessarily identical in isotopic composition to any inferred weighted-average value of the modern precipitation accumulating at the surface.

One possible implication of a trivial amount of recharge is that groundwater may be draining from the Rustler Formation with a large change in storage, i.e., with no recharge and an inferred discharge at Malaga Bend on the Pecos River, the change in storage would be the dominant non-trivial variable in the water balance equation. This in turn implies that the Rustler groundwater system over the WIPP site and in much of Nash Draw may not be at steady-state with respect to a "water balance".

Another implication that cannot be entirely dismissed is permeability changing with time. Although the permeability that is measurable in holes today is relatively low by commercial water-well standards, the permeability may have been higher in the past, decreasing as dissolved material precipitated in pore space when the recharge rate fell. Conversely, the paleopermeability may have also been lower at various times in the past, rising with the influx of fresh recharge that could have dissolved additional rock and enlarged the pore space. Although such has not yet been demonstrated, portions of the Rustler Formation may contain stagnant fossil water entrapped during an episode of permeability reduction. Through a meticulous examination of secondary mineralization (such as gypsum veining), it may be possible to deduce a paragenetic sequence of multiple generations of permeability changes; it may even be possible to characterize the waters that participated in these changes, and determine their age from the isotopic systematics of the secondary mineralization. Thus, the possibility of multiple generations of water migrating through the Rustler Formation may even ultimately account for the dissolution patterns of the halite and gypsum, and may also ultimately account for the complex distribution of solutes in the groundwaters observed today.

The concept of "fossil" (i. e., relic of former recharge conditions) water being "mined" (removed without replacement) is not unique to the northern Delaware Basin. Yapp (1985) reported a body of groundwater in the Albuquerque Basin whose isotopic composition was distinct from inferred recharge from either the Rio Grande or the Sandia Mountains. None of the three groundwater bodies had isotopic compositions that corresponded exactly with the weighted-average value of modern surface precipitation.

There is a fairly wide distribution of isotopic compositions in waters in Carlsbad Caverns, and a profound separation between inferred isotopic values of modern meteoric recharge (including waters from San Simon Sink, Surprise Spring, WIPP-29 Culebra, and the shallow Dewey Lake (?) as well as from Carlsbad Caverns) and values of most Rustler groundwaters. These observations emphasize the need to obtain an accurate representation of the isotopic composition of modern infiltrating precipitation for the Delaware Basin, in order to provide additional testing of the hypothesis that groundwaters in the Rustler Formation over the WIPP site and in most of Nash Draw are not receiving significant modern recharge.

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Table 1

Delta-Values of Stable-Isotope Standards
(expressed in parts per mil)

Individual values versus Harding Iceland Spar (HIS)
obtained by analyses on various dates.
(measurements made by this laboratory)

	Delta-O-18	Delta-C-13
*NBS-18 (Fen Carbonatite)		
8 Dec 83	-4.84	-0.35
13 Dec 83	-4.84	-0.34
16 Dec 83	-4.84	-0.35
16 Aug 84	-4.83	-0.37
Mean (3 degrees of freedom)	-4.84	-0.35
Standard Deviation	0.01	0.01
*NBS-19 (Taum Sauk Marble)		
8 Dec 83	16.29	6.89
13 Dec 83	16.45	6.89
16 Dec 83	16.35	6.87
22 Jun 84	16.46	6.87
Mean (3 degrees of freedom)	16.39	6.88
Standard Deviation	0.08	0.01

Mean values versus Standard Mean Ocean Water (SMOW)
(values reported by Coplen et al, 1983)

NBS-18 (2 degrees of freedom)	7.20
NBS-19 (1 degree of freedom)	28.65
HIS (this laboratory, calculated)	**22.39 carbon dioxide **12.02 total carbonate

*Corrections were applied to raw measurements to obtain these numbers according to the procedures of Craig (1957) based on the working standard of this laboratory. The correction was made for the contribution of carbon-13 and oxygen-17 to the mass 45 and 46 beams.

**Conversion algorithms have been applied according to the relevant fractionation factors and standard values given by Coplen et al (1983) to obtain these numbers from the corrected data.

Correction and conversion calculations are contained in the original laboratory notebooks.

Carbon dioxide was quantitatively liberated from carbonates by reaction of carbonate with 100 % phosphoric acid at 25.4 C according to the procedure of McCrea (1950).

Table 2.

Stable-Isotope Values for Waters from Nash Draw and Surroundings.
(in per mil versus V-SMOW)

Locality		delta-O-18 (Lambert)	delta-D (Yapp)
WIPP-25,	Magenta	-6.2	-44,-43
	Culebra	-6.4	-43,-44
	Rustler/Salado	-7.1	-52,-52
WIPP-26	Culebra	-6.5	-43,-44
	Rustler/Salado	-6.7	-46,-47
WIPP-27	Magenta	-6.3	-46,-47
	Culebra	-6.1	-44,-47
	Rustler/Salado	-7.0	-48,-49
WIPP-28	Culebra	-6.6	-46,-46
	Rustler/Salado	-8.0	-58,-57
WIPP-29	Culebra	-0.5,-0.4	-27,-27
	Rustler/Salado	-7.0	-47,-48
WIPP-30	Magenta	-6.5	-43,-41
	Culebra	-7.1	-50,-50
	Rustler/Salado	-7.1	-53,-51
Surprise Spring		-2.9,-1.8	-31,-30
Carlsbad Caverns			
New Mexico Room, elev. ~3670 ft.asl		-4.2,-3.7	-37,-37
Music Room, elev. ~4100 ft.asl		-4.0,-4.0	-32,-31
Naturalist's Room, elev. ~3620 ft.asl		-3.5	-24,-23
WIPP-15, San Simon Sink		-4.5	-40,-37
Rainwater, summer, WIPP-29 pad		-2.3	-18,-20

FIGURE CAPTIONS

Figure 1. Map of Nash Draw, WIPP site and vicinity, showing borehole localities.

Figure 2. Delta-D versus delta-O-18 for some Delaware Basin waters.

Figure 3. Delta-D versus delta-O-18 for some Delaware Basin waters (pre-1980).

Figure 4. Variations in delta-O-18 and delta-D values of near-neutral chloride-type thermal waters and geothermal steam from geothermal areas (after Craig, 1963). Solid circles are local meteoric groundwaters, showing geographic (climatic dependent) variation. Note horizontal "oxygen-isotope shift" of thermal waters from the worldwide meteoric line of Craig (1961a).

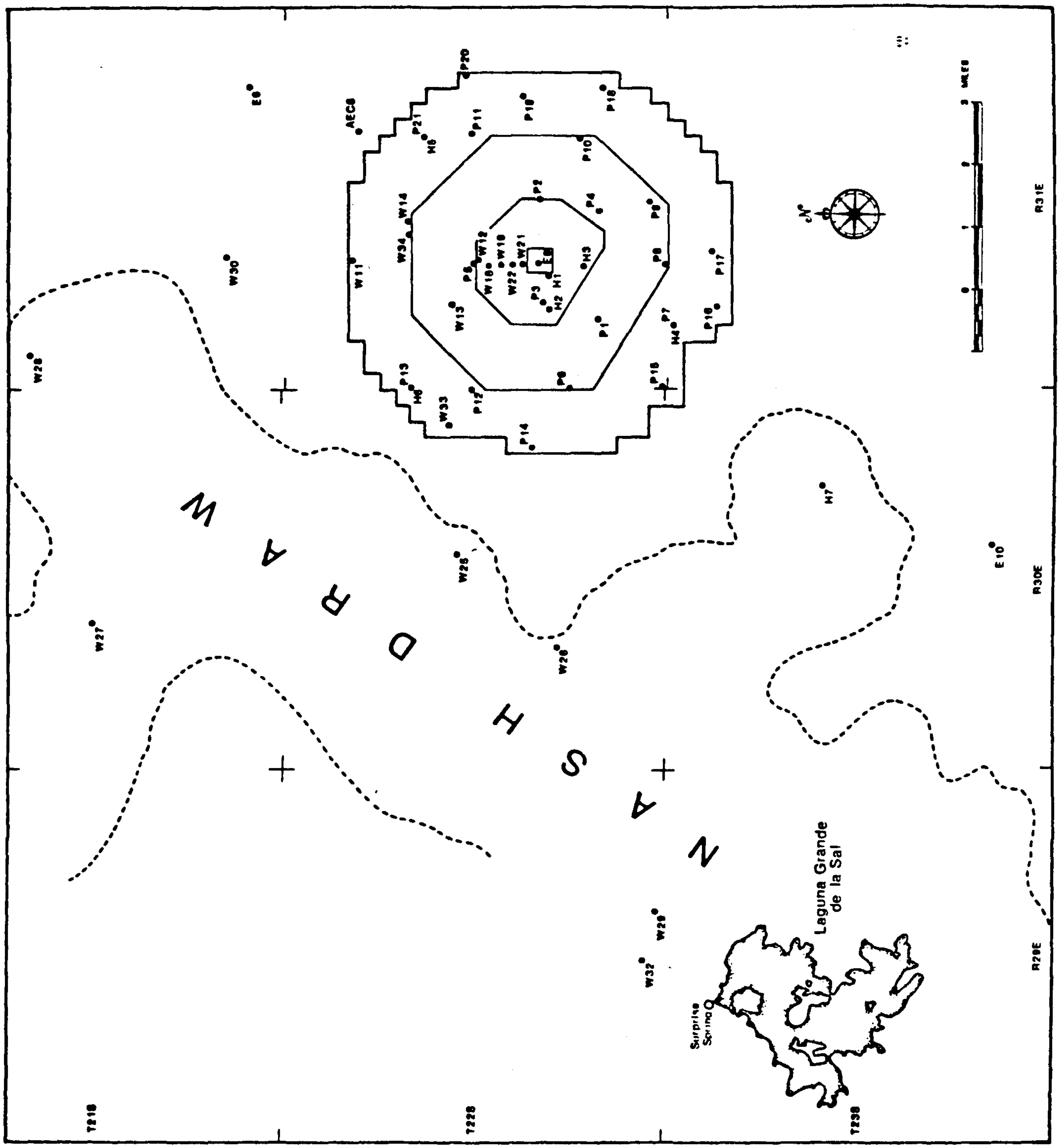

NASH DRAW
Laguna Grande de la Sal
Surprise Spring
T21S
T22S
T23S
R29E
R30E
R31E
MILES
AEC8
E9
E10
W30
W28
W27
W25
W26
W29
W32
H7
P20
P21
P11
P18
P10
P9
P8
P17
P16
P15
P14
P13
P12
P7
P6
P4
P2
P1
P3
P5
H1
H2
H3
H4
H5
H6
W11
W12
W13
W14
W15
W18
W21
W22
W33
W34
EB

Fig. 1

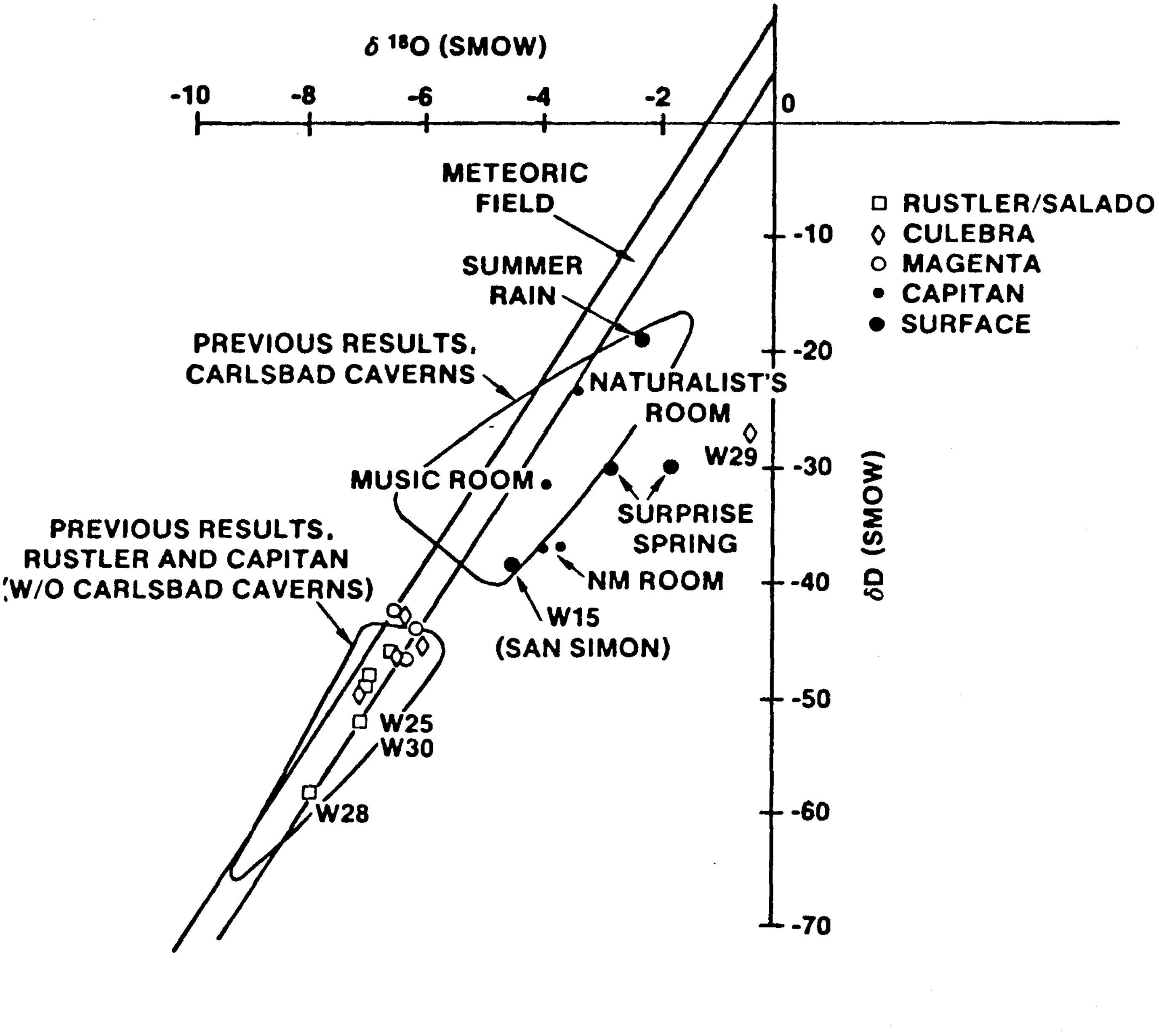

δ 18O (SMOW)
-10
-8
-6
-4
-2
0
METEORIC FIELD
SUMMER RAIN
PREVIOUS RESULTS, CARLSBAD CAVERNS
NATURALIST'S ROOM
MUSIC ROOM
PREVIOUS RESULTS, RUSTLER AND CAPITAN (W/O CARLSBAD CAVERNS)
W29
SURPRISE SPRING
NM ROOM
W15 (SAN SIMON)
W25
W30
W28
□ RUSTLER/SALADO
◊ CULEBRA
○ MAGENTA
• CAPITAN
● SURFACE
-10
-20
-30
-40
-50
-60
-70
δD (SMOW)

Fig. 2

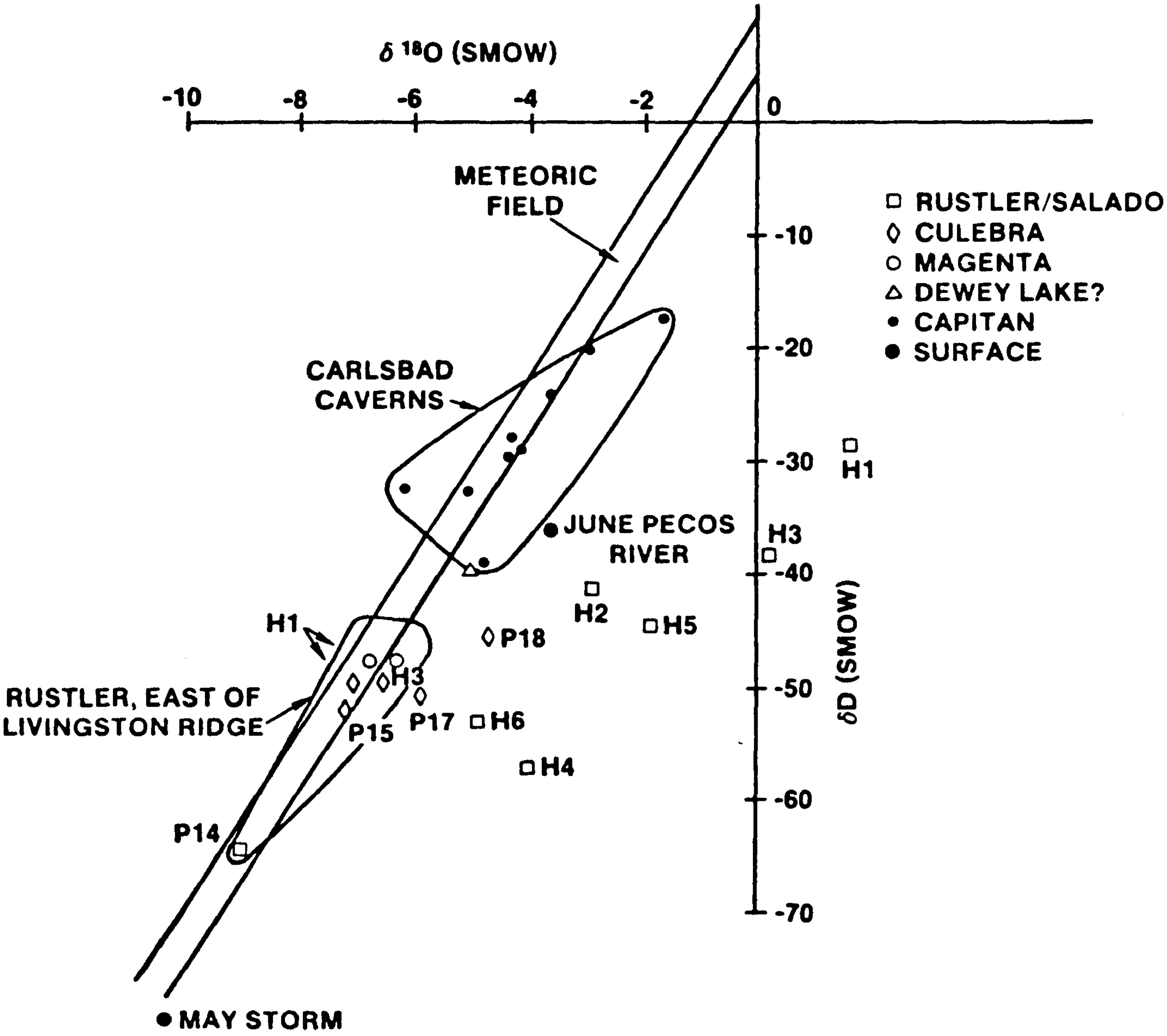
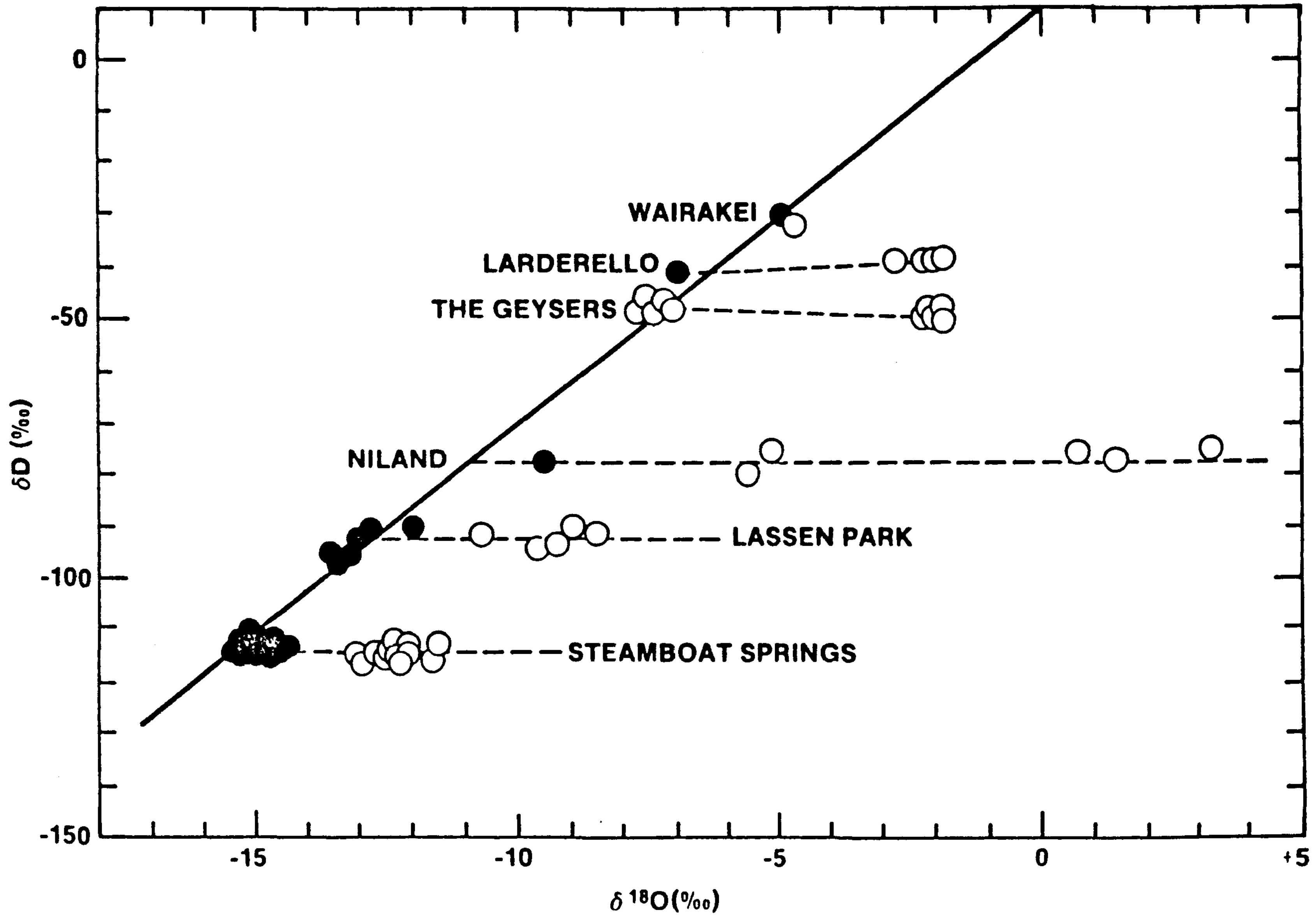

δ 18O (SMOW)
-10
-8
-6
-4
-2
0
METEORIC FIELD
□ RUSTLER/SALADO
◊ CULEBRA
○ MAGENTA
△ DEWEY LAKE?
• CAPITAN
● SURFACE
-10
-20
-30
-40
-50
-60
-70
δD (SMOW)
CARLSBAD CAVERNS
H1
JUNE PECOS RIVER
H3
H2
H5
P18
H1
H3
RUSTLER, EAST OF LIVINGSTON RIDGE
P15
P17
H6
H4
P14
MAY STORM

Fig. 3



WAIRAKEI
LARDERELLO
THE GEYSERS
NILAND
LASSEN PARK
STEAMBOAT SPRINGS
0
-50
-100
-150
δD (‰)
-15
-10
-5
0
+5
δ¹⁸O(‰)

Fig. 4

A REGIONAL WATER BALANCE FOR THE WIPP SITE AND SURROUNDING AREA

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INTRODUCTION

A water balance or budget is developed as an accounting of the components of a closed hydrologic system. In the WIPP study area (Figure 1), water-budget techniques have previously been used to compute leakage from Lake Avalon (National Resources Planning Board 1942, p. 60) and from potash refinery spoil ponds (Geohydrology Associates 1978b). Although many variations of the water-budget equation can be written, a general expression for a closed hydrologic system is

$$\sum_{1}^{n} I_i + \sum_{1}^{n} O_i + \Delta S = 0 \qquad \text{(Eq. 1)}$$

where I_i is a given inflow volume,
O_i is a given outflow volume,
and ΔS is change in storage within the region.

The simplicity of this equation tends to be misleading for two reasons. First, the components may not be easily or adequately quantified. Second, in a developed area like the WIPP region, the water budget must include many usage factors, such as municipal or industrial pumpage. In the WIPP water-budget study area, inflows are precipitation, surface- and ground-water inflow, and the artificial addition of surface and ground water. Outflows are surface runoff, evaporation and transpiration, and ground-water outflow. Changes in storage in the WIPP region have also been documented. The WIPP water balance described here is based on a combination of long-term averages and figures for 1980.

HYDROLOGY

The development of a water balance begins with a detailed examination of the component inflows to, outflows from, and changes in storage inside the study area. Some of these components must be calculated using data on use of water inside the study area by various agencies. This section examines the data available on precipitation; agricultural, municipal, and industrial water usage; stream flow; evapotranspiration; ground-water flow; and change in storage.

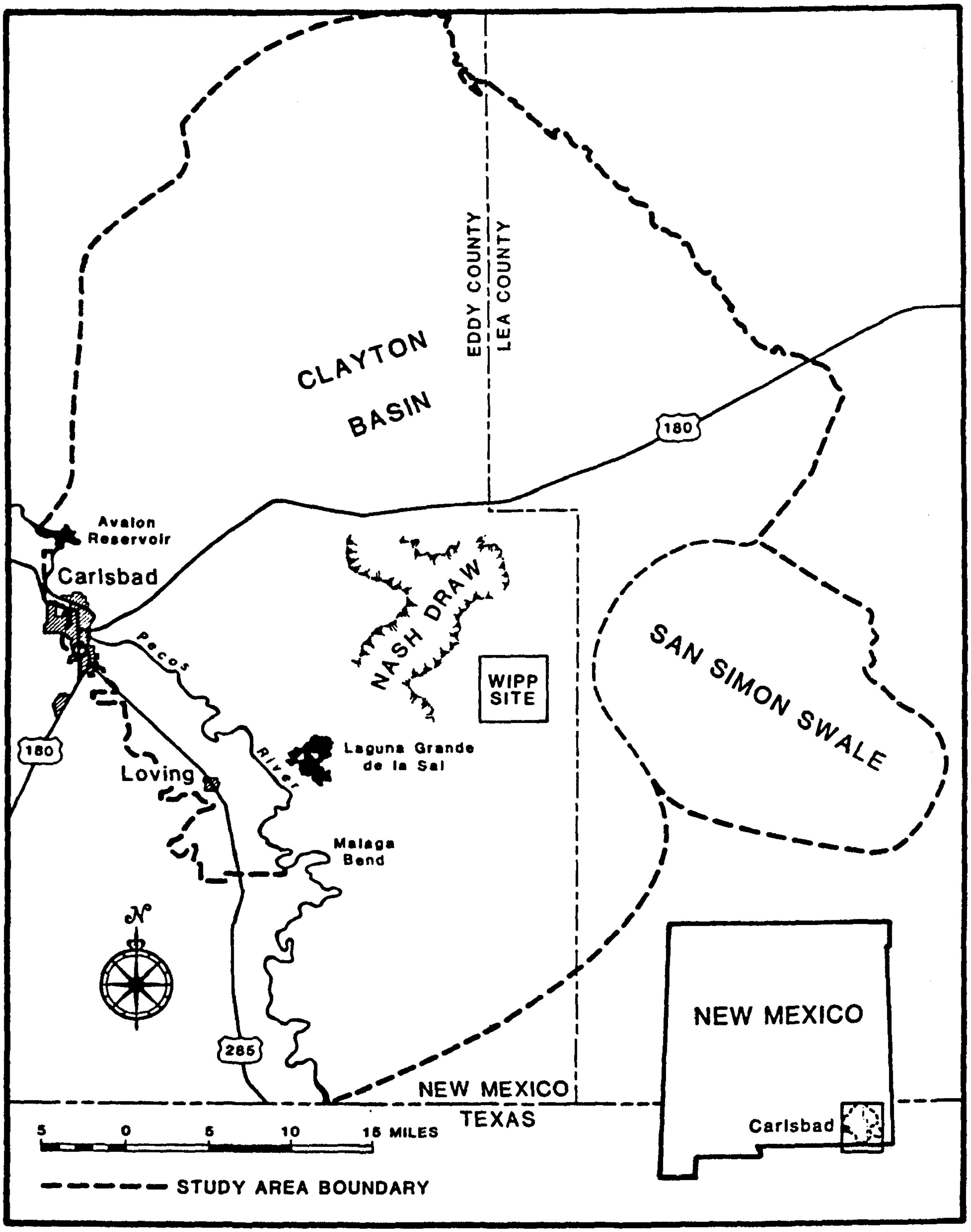

Figure 1. Study area for the WIPP water balance.

Precipitation

Precipitation is the second largest item in the water budget, easily dwarfing surface-water inflow, ground-water pumpage, and all forms of water use in the study area. Precipitation falling on the study area was calculated in four ways to indicate the uncertainty associated with the available data. Calculated volumes ranged from 1,241,000 ac-ft/yr for the main part of the study area and 155,700 ac-ft/yr for San Simon Swale to 1,317,000 ac-ft/yr for the main part and 192,000 ac-ft/yr for San Simon Swale. The mean value for the total study area is 1,466,450 ac-ft/yr. The uncertainty in long-term average total precipitation is ~6% for the main part of the study area ~20% for San Simon Swale. This uncertainty is not caused by errors in the data, but rather by sparsity of and resulting ambiguities in the data.

Agricultural, Municipal, and Industrial Water Use

In order to determine the ground-water discharge to the Pecos River, usage of water by various human agencies must be assessed. Agriculture is the biggest water user in the area. The total amount of water devoted to irrigation in 1980 was 83,100 ac-ft. Water is diverted in large quantities from the Pecos River, is applied to fields in the Carlsbad Irrigation District, and then flows back through the shallow alluvial aquifer to the River. About two-thirds of the agricultural water evaporates during this process.

Municipal water is pumped from the Capitan Ls. or from the alluvial aquifer and returned either directly to the Pecos River after treatment or indirectly through the alluvial aquifer after disposal in septic tanks. About half of the municipal water evaporates during this process. The total municipal usage is small, about 10,300 ac-ft/yr in 1980.

In 1978, the potash industry imported 19,768 ac-ft of water into the area (Geohydrology Associates 1978b). Industrial water is pumped either from the Ogallala Fm. outside the study area or from Pre-Ochoan oil fields. It is disposed of either in water-flooding operations in the oil fields or in brine tailings ponds. Currently all or nearly all of the industrial water is ultimately evaporating, although past disposal has caused large increases in storage in Nash Draw. Apparently very little of the production and consumption of water by the oil industry has an effect on the aquifers above the Salado Fm.

Surface-Water Inflow and Outflow

Surface-water inflow can vary enormously from year to year. The available data describing surface-water inflow and outflow are of good quality and quantity; however, the Pecos River is such a highly regulated stream that applying the outflow data directly in the water budget is impossible. The primary usefulness to the WIPP project of stream-flow data is in the bounds that they place on ground-water discharge from the study area, an important parameter in ground-water modeling.

An upper bound on the ground-water discharge from the study area to the Pecos River was calculated using

$$Q_g = \Delta Q_s + E + I - R - M - S \qquad \text{(Eq. 2)}$$

where Q_g is ground-water discharge to the reach,
ΔQ_s is change in flux in the river between gages at the ends of the reach,
E is net evaporative loss,
I is diversion for irrigation,
R is return flow from irrigation,
M is return flow or direct addition of municipal effluent,
and S is surface runoff.

Using Eq. 2, the total gain of the Pecos River in 1980 that might be attributable to ground-water inflow between Avalon Dam and station 4075, near Red Bluff Draw, was calculated to be 23,600 ac-ft. This quantity should be an upper bound on ground-water discharge to the River in the study area.

Additions to the flow of the Pecos River come from ground-water discharge, irrigation and municipal return flow, and surface-water inflow. Ground-water discharge to the Pecos River tends to be high in dissolved solids and in some places may be nearly saturated in sodium chloride; a reasonable lower bound can be obtained by assuming that the increase in dissolved solids in any reach results entirely from the discharge of saturated brine into the river. The minimum discharge of ground water to the Pecos River in the study area is estimated using the increase in dissolved solids to be 2,200 ac-ft/yr.

Because the Pecos River probably also receives ground-water discharge from the aquifers west of the study area, both lower and upper bounds are probably higher than the volumes discharged to the river from the study area alone.

Evapotranspiration from Range Land and Brine Lakes

Evapotranspiration is the largest item in this water budget, because most precipitation in the study area returns almost immediately to the atmosphere, without ever becoming incorporated into the ground- or surface-water systems, and because much of the imported water also evaporates. On unirrigated range land, much of the precipitation that does not evaporate immediately is taken up fairly rapidly by plants and transpired. Roughly half of the water used by municipalities and the potash industry and for irrigation undergoes evapotranspiration. Large volumes of water also evaporate from fresh and saline lakes and rivers in the area. Table 1 summarizes evapotranspiration from all processes.

Ground-water Flow

Ground water is recharged in the northwestern part of the study area and enters from the northeast. It appears that the ground-water system that

Table 1. Evapotranspiration in the study area

		Water Committed or Acreage	Rate of Evapotranspiration	Total Evapotranspiration (ac-ft/yr)
Municipalities		10,533 ac-ft	50%	5,266
Potash-Related*				26,350
Spoil ponds (including Laguna Uno)		1,560 acres	4.4 ft/yr	6,850
Spoil piles		1,290 acres	4.0 ft/yr	5,100
Mud flats and dense vegetation		4,804 acres	3.0 ft/yr	14,400
Brine Lakes				
Laguna Grande de la Sal		2,880 acres	4.4 ft/yr	17,200
Other (excluding Laguna Uno)		1,035 acres		
Fresh-Water Bodies				
Lake Avalon		470 acres	6.1 ft/yr	10,900
Pecos River (station 4040 to station 4075)		1,320 acres		
Irrigated Acreage (applied water)		27,700 acres	58.8%	48,900
Unirrigated Acreage**				
Main Part of Study Area:	high	1,317,000	98%	1,291,000
	low	1,241,000	89%	1,104,000
	best	1,290,500	96%	1,239,000
San Simon Swale	high	192,000	98%	188,000
	low	155,700	89%	139,000
	best	175,950	96%	169,000

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*Geohydrology Associates 1978b, p. 59.

**including precipitation on irrigated acreage.

includes flow through the WIPP site is much smaller than the WIPP water-budget study area. Much or all of the ground water that enters the study area north of Highway 180 evaporates from Clayton Basin. Ground water in the area of San Simon Swale seems to percolate slowly downward and leave the study area to the southeast. Based on the available data, the only part of the study area genuinely connected hydrologically to the WIPP site is 400 mi^2 south of Highway 180, west of The Divide, and east of the Pecos River. This area includes all of Nash Draw. Recharge to this area seems to occur at the Divide and in the vicinity of Mimosa Ridge. Discharge occurs from Laguna Grande de la Sal, by evaporation, and to the Pecos River. If these are the only recharge and discharge areas, then the rate of evapotranspiration is higher in the WIPP site-Nash Draw area than in the rest of the study area. Details of the pre-development water levels in Nash Draw are unknown.

Ground-water Flow near Clayton Basin

The water table in the vicinity of Clayton Basin appears to be hummocky. The 3250-foot contour opens broadly to the south. The water-level contour at 3200 ft in Clayton Basin is closed (Figure 2). Water levels rise gently to the north, east, and west. An east-west ground-water divide, roughly 25 ft in height, is present in the vicinity of Mimosa Ridge on the southern edge of Clayton Basin. Water levels in the alluvium, the Rustler Fm., the Dockum Group, and Triassic rocks are between 3169 ft and 3200 ft inside the closed contour. The water table is at the surface in parts of Clayton Basin. The depth to water is less than 50 ft in much of the Basin (Geohydrology Associates 1978a, Figure 15). A second 3200-foot contour runs roughly east and west in Ts. 20 and 21 S.

If the ground-water divide between Clayton Basin and Nash Draw blocks the flow of water to Nash Draw from the north, then a very large volume of water must be discharged from Clayton Basin. The volume must be at least as large as the sum of the recharge to the study area north of Highway 180 and the discharge of the PCA, AMAX, and possibly Duval and National refineries. Water is removed from Clayton Basin by evaporation from the industrial spoil ponds and piles and natural ponds and wetlands. Transpiration by phreatophytes can easily remove water from depths of 25 ft. The total evapotranspiration is estimated to be 26,000 ac-ft/yr. PCA, AMAX, Duval, and National discharge a total of 10,000 ac-ft/yr, but probably not all of the Duval and National wastes enter Clayton Basin. Clearly, a substantial amount of natural ground water, at least 16,000 ac-ft/yr, is removed from the study area by evapotranspiration from Clayton Basin. Using Theis's estimate (1934, p. 152) for recharge to the Ogallala Fm., 16,000 ac-ft/yr is equivalent to the recharge to at least 380,000 acres, or the northern third of the WIPP water-balance study area. Ground-water flow into the study area from the north and east is offset by water flowing west from the ground-water ridge between Clayton Basin and the Pecos River. No ground-water need flow into Nash Draw from the north in order to maintain equilibrium between inflow to and evapotranspiration from Clayton Basin. If the ground-water ridge underlying the divide between Clayton Basin and Nash Draw is an artifact of potash refining, Clayton Basin could discharge into Nash Draw in the future.

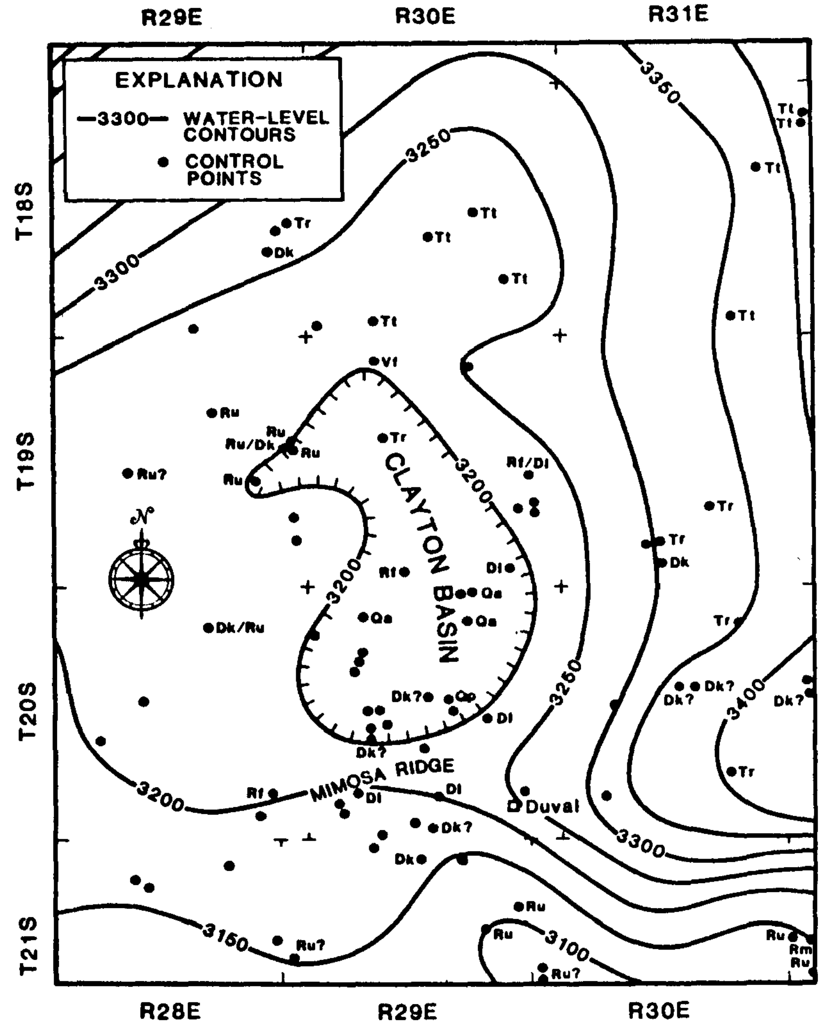

Figure 2. Water-levels in and near Clayton Basin, in feet. Aquifers: Qa, Quaternary alluvium; Vf, Valley fill; Tt, Tertiary rocks, undivided; Dk, Dockum Group; Tr, Triassic rocks, undivided; Dl, Dewey Lake Redbeds; Ru, Rustler Fm., undivided; Rf, Rustler Fm., Forty niner Member; Rm, Rustler Fm., Magenta Member.

Ground-Water Flow near San Simon Swale

The water-level contour at 3150 ft in San Simon Swale is closed (Figure 3). The 3200-foot contour opens to the southeast. Water levels rise fairly rapidly to the northeast, southwest, and northwest. It appears that San Simon Swale is not connected hydrologically to the WIPP site. It is topographically separated from the site by The Divide. Water in the Triassic aquifer is separated from the site by a ground-water divide. Any water recharging the Capitan Ls. flows to the southeast. If there is no connection to the Capitan Ls., then water is flowing to the southeast in the Triassic aquifer or discharging to the surface by evapotranspiration, in spite of the comparatively great depth to water.

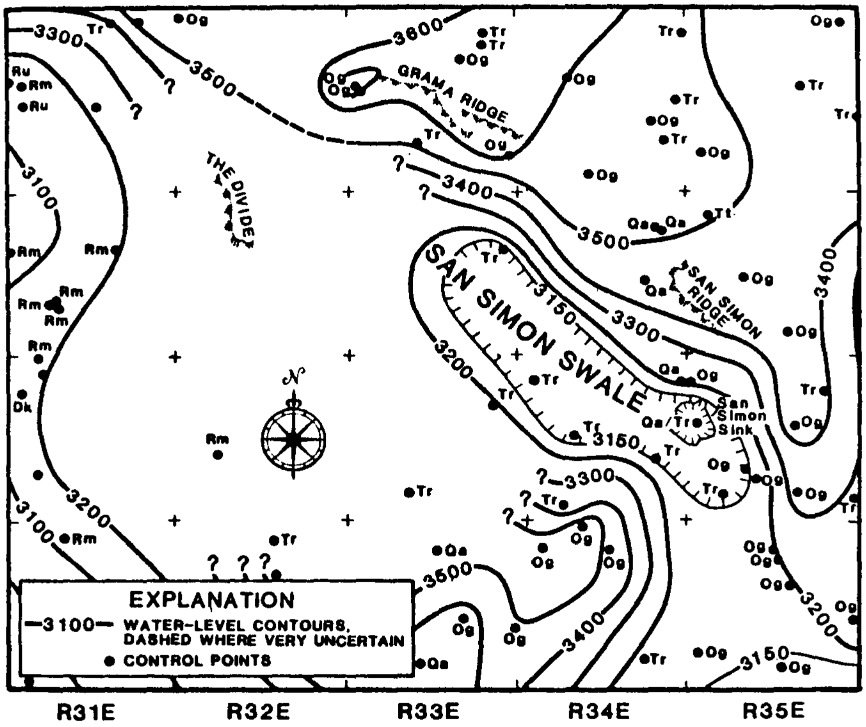

Figure 3. Water levels in and near San Simon Swale, in feet. Aquifers: Qa, Quaternary alluvium; Og, Ogallala Fm.; Tt, Tertiary rocks, undivided; Dk, Dockum Group; Tr, Triassic rocks, undivided; Ru, Rustler Fm., undivided; Rm, Rustler Fm., Magenta Member.

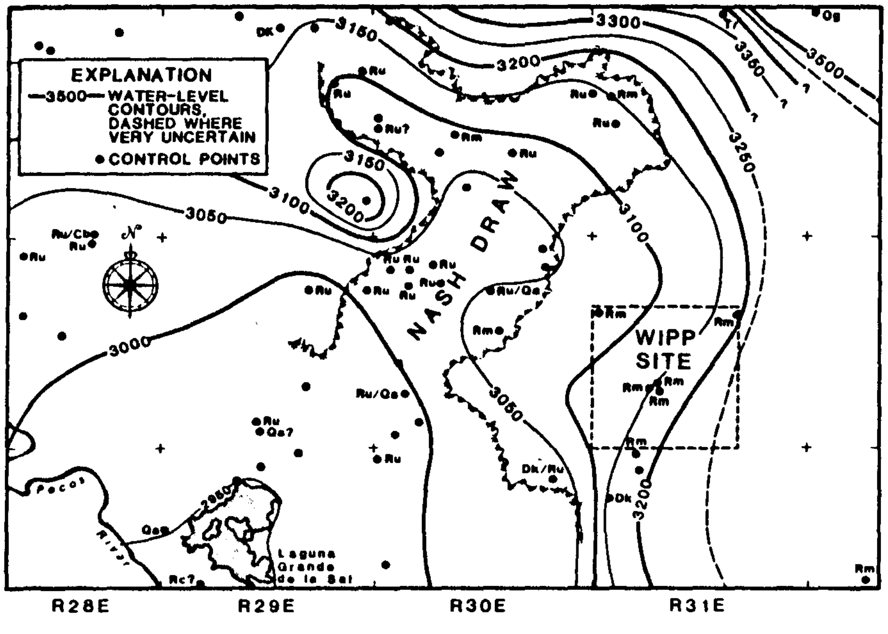

Figure 4. Water levels in and near Nash Draw and the WIPP site, in feet. Aquifers: Qa, Quaternary alluvium; Og, Ogallala Fm.; Tr, Triassic rocks, undivided; Dk, Dockum Group; Ru, Rustler Fm., undivided; Rm, Rustler Fm., Magenta Member; Rc, Rustler Fm., Culebra Dolomite Member.

Ground-Water Flow near Nash Draw and the WIPP Site

Ground-water flow in and near Nash Draw and the WIPP site has been discussed by Mercer (1983) and Geohydrology Associates (1979, 1984). Figure 4 summarizes the information presented by those authors for the aquifers nearest the land surface. There are ground-water divides in the general vicinities of The Divide, separating flow near the WIPP site and Nash Draw from flow near San Simon Swale, and of Mimosa Ridge, separating the flow from flow near Clayton Basin. Near-surface flow in and near Nash Draw appears to be directed toward Laguna Grande de la Sal, although this may be a coincidence rather than an indication that the lake is a primary discharge area. The Pecos River at Malaga Bend could be the primary discharge area, rather than the lake. Flow is to the south, north of the lake; water flows down the Draw toward the lake; and water in the Magenta Member flows to the west, more or less east of the lake.

At a finer level of examination, the water levels in Nash Draw are hummocky. The aquifers form a complex of water-table, semi-perched, semi-confined, and stratified areas, but it is unlikely that any aquifer above the Rustler-Salado brine aquifer is truly confined or separate from the others throughout Nash Draw. Several factors support this conclusion. First, geologic units in the Draw are broken and rubbley, and some units are missing in places. Second, available data indicate that in any one area in Nash Draw, heads in wells of different depths are about the same. Finally, the best available chemical data (Lambert and Robinson 1984, Table 6-1) show that water in the Magenta and Culebra Dolomite Members is nearly indistinguishable between members in WIPP-25 and -27, although there are differences between wells.

In Nash Draw, the Rustler/Salado brine aquifer is under a slight artesian head in some areas in the vicinity of Laguna Grande de la Sal (Havens 1972), although brine under water-table conditions is also continually present there. Current water levels near the lake indicate that there may be some flow from the lake to the Pecos River (Geohydrology Associates 1979, p. 72). The current water levels (under water-table conditions) in Nash Draw directly to the west of the WIPP site are about 3000 ft. Water levels have risen in this part of Nash Draw some 135 ft in the last 30 years, apparently in response to discharge from potash refineries.

At the WIPP site, water in the Magenta Member of the Rustler Fm. is confined. The head is about 3150 ft in the center of the site and about 3100 ft at the western edge (Mercer 1983), giving rise to a gradient of approximately 16 ft/mi across the site. Water in the Culebra Dolomite Member is also confined at the site; water-level altitudes are roughly 3,000 ft.

Change in Storage

A hydrologic system that is in equilibrium has no long-term change in storage. Any inflow of surface water, ground water, or precipitation recharge is balanced by surface- or ground-water outflow and evapotranspiration.

Changes in storage are thus prima facie evidence that a hydrologic system is not in equilibrium.

In the vicinity of the Carlsbad Irrigation District, pumpage for irrigation caused water levels to decline markedly between 1947 and 1955 (Bjorklund 1959). At this time, ground-water withdrawals in the vicinity of the CID from both the limestone and alluvial aquifers appear to be roughly in equilibrium with recharge from precipitation and irrigation seepage. The water-table gradient is presumably lower than it was before large-scale irrigation and municipal pumpage began. If irrigation and municipal pumpage were to cease, water levels would rise and the natural gradient would be restored. The natural gradient is unknown.

Old and new data on water levels in domestic and stock wells throughout the range land of the study area (Geohydrology Associates 1978a, Appendix A) suggest that there has been no large-scale lowering of the water levels outside the CID.

Rising water levels in Nash Draw are well documented. The rise is apparently due to the discharge of industrial brines by the potash industry. In 1942, when the only refinery in operation was the U. S. Potash Co. (T. 23 S., R. 29 E., sec. 18), Laguna Grande de la Sal was apparently the only perennial lake in Nash Draw (National Resources Planning Board 1942). At that time the lake had been receiving the plant effluent for several years. The area of the lake (National Resources Planning Board 1942, Figure 12, p. 66) was 1,970 acres. By 1965, the area of the lake had increased to 2,890 acres, and ephemeral lakes had developed, with a total acreage of 497 acres. By 1979, Laguna Grande de la Sal remained about the same, at 2,880 acres and the other, now permanent, lakes increased to about 1,745 acres. The depth to water in the J Bar F well, now inundated by Laguna Uno, was 134.0 ft in 1948 (Hendrickson and Jones 1952, p. 134-135).

The total increase in storage, including both ground water and surface water, has been roughly 139,000 ac-ft, based on calculations of existing volumes. Geohydrology Associates (1978b, p. 59) calculated a rate of increase in storage of 3,327 ac-ft/yr, based on inflow and outflow. Considering that the refineries have been operating for about 40 years, these two calculations give almost identical results.

MODEL OF THE WATER BUDGET

A model of the WIPP regional water balance is shown in Figure 5. Ground water and surface water are represented as partially connected conduits flowing through the study area. Evapotranspiration is represented as a sink. All other water-budget parameters are represented as pools that can give water to or receive water from the conduits or the sink. The model can be viewed as a detailed, concrete representation of Eq. 1. Uncertainties in the model arise from three qualitatively distinct sources: measurement error, parameter variability, and interpretation. The difference between the calculated recharge to and discharge from the total hydrologic system, a useful check of the completeness of the model, is within the limits of accuracy of the basic data.

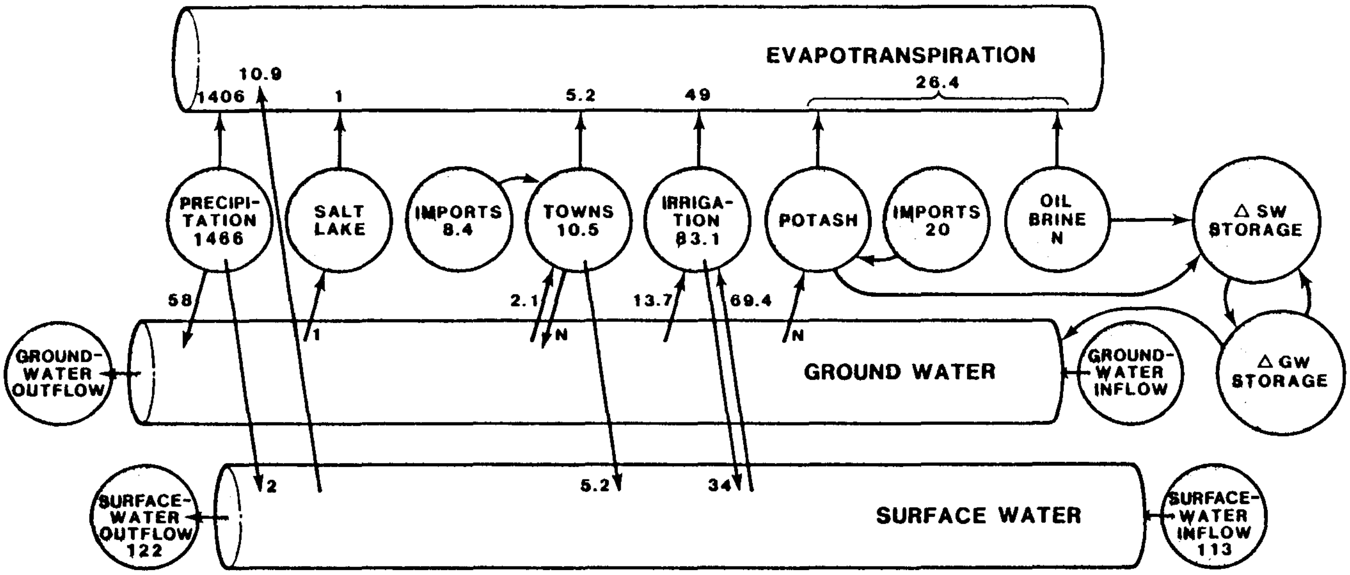

Figure 5. Model of the WIPP regional water balance (format for the model after Geohydrology Associates 1978c). Values are in thousands of acre-feet/year and are more fully explained in the parent water budget, SAND-2233.

Inflows

Water enters the regional hydrologic system from several distinct sources. Precipitation, ground- and surface-water inflow, and imported water are represented by I in Equation 1. Conclusions drawn from hydrologic studies of the WIPP region must take into account the volumes and origins of the various waters in the region. The largest inflow of water is precipitation. Much of the precipitation evaporates or is transpired immediately. A small portion runs off and joins the Pecos River. A very small portion recharges the ground water. Surface water enters the study area from the north in the Pecos River and from the west in the Black River. Ground water flows into the study area along the northeastern boundary and may flow out to the south; the volume has not been estimated in this report. Minor amounts of ground water are imported into the study area by artificial means. Agricultural, industrial, and municipal imports are shown separately in the model to emphasize that their origins may differ. Small volumes of imported water may cause major perturbations in flow in the natural hydrologic system, depending on the point of discharge into the system. Imported waters probably differ chemically from each other and from the waters that they join inside the study area.

Outflows

Water leaves the regional hydrologic system in three ways. Evapotranspiration and surface- and ground-water outflow are represented by O in Eq. 1. Evapotranspiration is by far the largest sink. Ground-water outflow is uncertain because no potentiometric-surface maps are available for aquifers below the topmost aquifer for most of the study area. Surface water is gaged at the Red Bluff gaging station, about nine river miles before leaving the study area. Presumably the Pecos River continues to gain water between the final gaging station and the point at which it leaves the study area. The volumes of ground-water and surface-water outflow are important primarily because of the bounds they place on parameters used in ground-water modeling.

Changes in Storage

Changes in storage are represented by ΔS in Equation 1. Changes in surface- and ground-water storage in Nash Draw are well documented, although it seems that a new equilibrium has been reached between industrial additions and losses from newly formed lakes.

Usage

Only inflow, outflow, and changes in storage are explicitly included in Eq. 1. In a developed region, however, it may be difficult to determine the value of each term of the equation without carefully examining the usage of water in the study area. In the WIPP area, water usage changes the inflow to the region by artificially importing water for municipal, agricultural, and industrial purposes. Water usage changes the outflow both by adding water to the Pecos River as municipal and agricultural return flow and by consumptive use. Water usage changes the volumes of ground water and surface water in storage by raising and lowering the water table. In addition, usage may divert water from one flow stream to another. For example, irrigation diverts water that would normally leave the study area by ground-water outflow to surface-water outflow and evapotranspiration.

SUMMARY

The WIPP water-balance study area defined here comprises about 2,000 mi^2 in Eddy and Lea Counties, southeastern New Mexico. Inflows to the study area are precipitation ($\sim 1.47 \times 10^6$ ac-ft/yr), surface water ($\sim 1.1 \times 10^5$ ac-ft/yr), water imported by municipalities and industries ($\sim 3 \times 10^4$ ac-ft/yr), and ground water (volume not estimated). Outflows are evapotranspiration ($\sim 1.5 \times 10^6$ ac-ft/yr), surface water ($\sim 1.2 \times 10^5$ ac-ft/yr), and possibly some ground water. The volume of surface and ground water in storage in Nash Draw has increased since the beginning of potash refining. Regional ground-water flow in most aquifers above the Salado Formation is from the northeast to the southwest, although this pattern is interrupted by Clayton Basin, Nash Draw, and San Simon Swale. The Pecos River is the only important perennial stream. Most of the area has no integrated surface-water drainage.

It seems from the available data that ~1,600 mi^2 of the study area are hydrologically separate from Nash Draw and the WIPP site. Ground water north of Highway 180 apparently discharges into Clayton Basin and evaporates. Water in San Simon Swale apparently percolates downward and flows to the southeast.

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