STABLE ISOTOPES IN SOUTHEASTERN NEW MEXICO GROUNDWATER: IMPLICATIONS FOR DATING RECHARGE IN THE WIPP AREA

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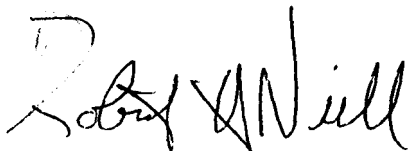Santa Fe, New Mexico 87503

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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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EXECUTIVE SUMMARY

The first geologic repository for nuclear waste in the United States, the Waste Isolation Pilot Plant (WIPP), is being excavated at a depth of 2150 ft below ground surface in the Salado Formation in southeastern New Mexico. If a breach of the repository occurs, the water-bearing zones of the Rustler Formation, overlying the Salado, are considered to be the most likely pathways for the transport of radionuclides to the biosphere. A thorough characterization of the hydrology of the Rustler Formation is crucial to the evaluation of the consequences of a breach of the WIPP repository.

The Department of Energy is currently conducting studies of the Rustler Formation (many at the request of the State of New Mexico) that should significantly improve knowledge about the radionuclide contaminant transport ability of the Rustler. One recently completed study examined stable isotope data from Rustler groundwater and concluded that Rustler groundwater in the vicinity of the WIPP Site is not receiving significant modern meteoric recharge (Lambert, 1986). In addition, Lambert (1986) concludes that the stable isotope data reveal an hydraulic isolation of two possible discharge areas (well WIPP-29 and Surprise Spring) from the Rustler Formation elsewhere in Nash Draw and near the site. The conclusions of Lambert's

(1986) stable isotope study allow longer residence time of water in the Rustler Formation and reduce the calculated consequences of a breach of the WIPP repository.

The present study compiles stable isotope data from throughout southeastern New Mexico and compares them to data from the WIPP area. The stable isotopic compositions of most samples of groundwater from the Rustler Formation are similar to the composition of other, verifiably young, groundwater in the area. Though the stable-isotope data cannot indicate ages for water in the various aquifers, neither do the data show any distinction between most Rustler groundwater and verifiably young groundwater.

A small number of samples, primarily from the Rustler/Salado contact east of Nash Draw, have isotopic compositions that are not characteristic of recently recharged meteoric water. These waters' enrichment in heavy isotopes may be due to mixing with deeper groundwater (supported by the stable isotopic composition of Salado fluid inclusions and Castile brine) or to exchange between the groundwater and hydrous minerals.

A comparison of the heavy isotope enrichment observed in evaporating waters and the composition of the water at WIPP-29 and Surprise Spring shows that the isotopic composition of these

Nash Draw waters could be derived by evaporating Rustler ground-water. Based on stable isotopes, both WIPP-29 and Surprise Spring could be discharge areas for Rustler groundwater moving from elsewhere in Nash Draw and the east.

The enrichment in heavy isotopes found in water from pools in Carlsbad Caverns was used by Lambert (1986) as evidence that the relatively depleted Rustler water was recharged during a past, more pluvial, time. However, the uniqueness of the isotopic composition of water in the Caverns' pools suggests that rather than representing the composition of recent recharge, the heavy isotopes are enriched by evaporation and equilibrium isotope exchange in the humid cave environment. Recharge in the extreme karst environment near the cavern may also favor isotopically heavy precipitation.

The age of water in the Rustler Formation and the presence or absence of modern recharge cannot be determined on the basis of stable isotopic composition alone. Physical measurements of the flow system of the Rustler are the best way to locate and quantify recharge to the Rustler. Regional hydrologic testing of the Rustler fluid-bearing zones has begun and will provide data on the transmissivity and degree of fracture connection.

Additional water-level measurements in more locations are needed to refine potentiometric surface maps and determine the location of recharge and discharge areas and groundwater divides. Unsaturated zone studies of infiltration in suspected recharge areas are also needed.

CONTENTS

LIST OF FIGURES

STABLE ISOTOPES IN SOUTHEASTERN NEW MEXICO GROUNDWATER:

IMPLICATIONS FOR DATING RECHARGE IN THE WIPP AREA

STATEMENT OF PROBLEM

The first geologic repository for nuclear waste in the United States, the Waste Isolation Pilot Plant (WIPP), relies on geologic isolation to separate the waste from the biosphere. The water-bearing zones in the Rustler Formation, overlying the Salado Formation salt, are generally considered the most likely pathways by which waste could be transported to the biosphere. Therefore, a thorough characterization of the hydrology of the Rustler Formation is crucial to the proper evaluation of the consequence of a radionuclide release from the WIPP.

A recent evaluation of stable isotope data from Rustler groundwater (Lambert, 1986) concludes that "...Rustler groundwater in most of Nash Draw and at the WIPP site is not receiving significant modern meteoric recharge." The implications of this conclusion are suggested by Lambert (1986) to be: 1) the Rustler may contain fossil water (relic of former recharge conditions) that is being removed without replacement at Malaga Bend, resulting in a large change in storage; and 2) the Rustler may contain stagnant fossil water entrapped during an episode of permeability reduction. Both of these scenarios result in reduced discharge, and eventually no natural discharge, from the Rustler, with corresponding increased residence time of water in the aquifer. The impact of this characterization of the Rustler hydrology on radionuclide-release consequence analysis is obvious and significant.

In addition to the conclusions concerning recharge to the Rustler, Lambert (1986) also concludes that the isotopic data reveal an hydraulic isolation of well WIPP-29 and Surprise

Spring, both in Nash Draw, from the rest of the Rustler. The implication of this conclusion is that Surprise Spring and the area around WIPP-29 are not discharge points for Rustler groundwater. All discharge from the Rustler is concluded to occur near Malaga Bend and release scenarios can take credit for this longer flow path before radionuclides are released to the environment.

Lambert's (1986) basis for concluding that the Rustler is not receiving significant amounts of modern meteoric recharge is a difference between the stable isotopic composition of water in pools in Carlsbad Caverns and of groundwater in the Rustler Formation. Lambert considers Carlsbad Caverns water as being typical of modern recharge. Lambert's evidence for the lack of discharge is the difference between isotopic data from Surprise Spring and WIPP-29 and the majority of Rustler isotopic compositions. He attributes this difference to hydraulic isolation. The data used in Lambert (1986), as well as additional isotopic data published for southeastern New Mexico, are used here to examine the timing of recharge to the water-bearing zones of the Rustler and the possibility of discharge at WIPP-29 and Surprise Spring.

HYDROGEOLOGIC SETTING

The focus of this study, the WIPP site and vicinity, is located in the northern Delaware Basin of southeastern New Mexico (Figure 1). The stratigraphy and water-bearing properties of units in the Delaware Basin are discussed below to acquaint the reader with the hydrogeology of the area. In addition to the data from the vicinity of the WIPP site, isotopic data from the Roswell Underground Water Basin are also presented. The hydrogeology of the Roswell Basin will be briefly described following the discussion of the northern Delaware Basin.

Delaware Basin

The term "Delaware Basin" refers to the area in Southeast New Mexico and West Texas where vast amounts of clastic sediments and evaporites were accumulated in a slowly sinking shallow sea during late Paleozoic time. The basin is bounded by, and includes, the Capitan Reef. The following discussion is based on these investigations of water-bearing zones in the Delaware Basin: Hiss (1975), the Capitan Aquifer; Nicholson and Clebsch (1961), groundwater in southern Lea County; Hendrickson and Jones (1952), groundwater in Eddy County; and Mercer (1983), groundwater in the WIPP area.

The Delaware Basin consists of the arcuate Capitan Limestone reef complex and up to 13,000 feet of limestone, shale, and evaporites. The basin was tilted to the east and the Guadalupe Mountains uplifted during the Cenozoic. The reef and water-bearing formations above the Salado are the primary consideration in this study (Table 1 and Figure 2). The limited data available from deeper aquifers suggest that water-rock reactions have altered the isotopic composition of the groundwater (Lambert, 1978), reducing these water's relevance to a discussion of recent meteoric recharge.

3
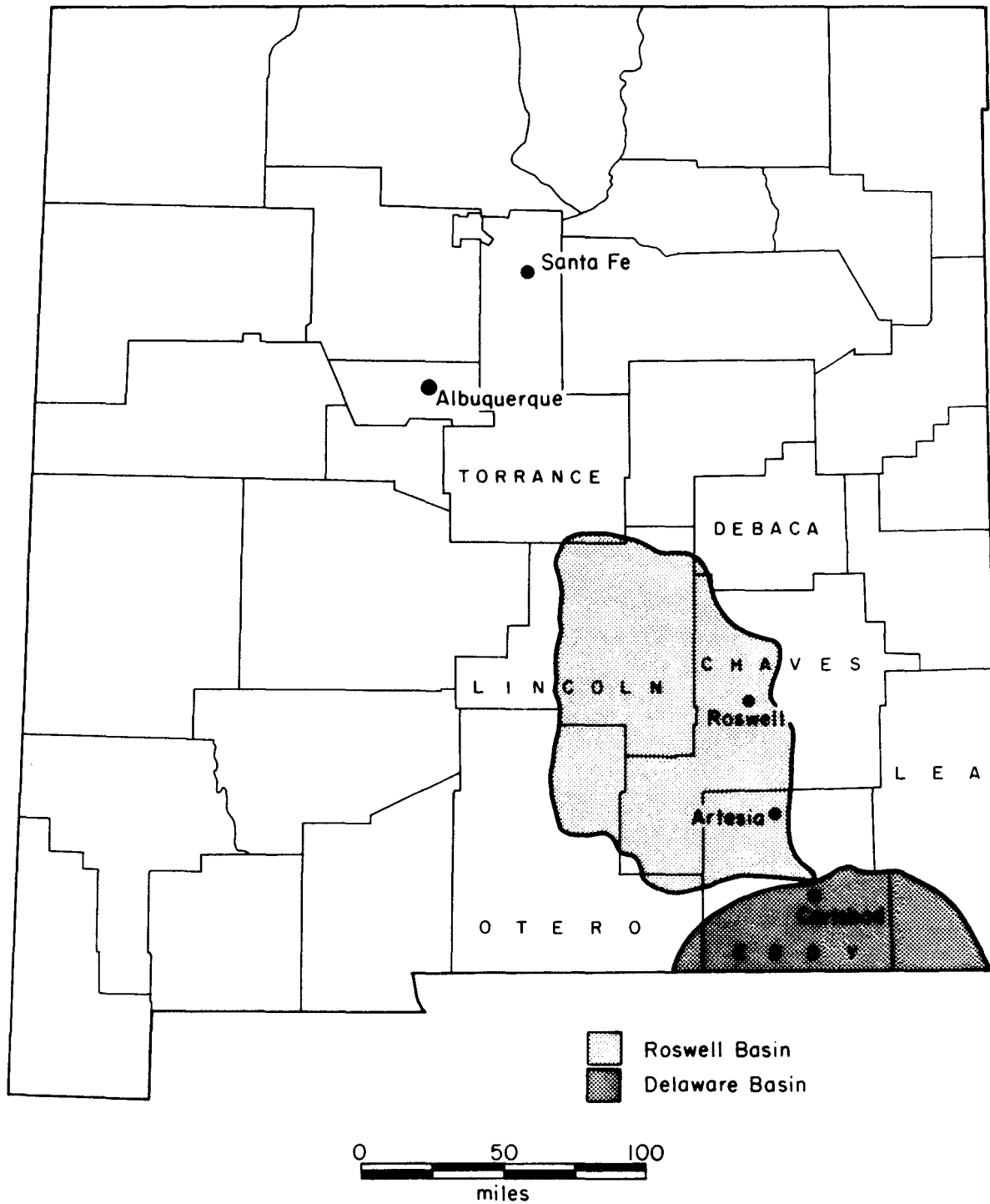
Figure 1. Map of New Mexico showing counties in southeastern New Mexico and the location of the Delaware Structural Basin and the Roswell Groundwater Basin.

4

TABLE 1

Delaware Basin Post-Ochoan Stratigraphy

PERIOD	FORMATION	LITHOLOGY
Quaternary	Alluvium and surficial sand	gravel, sand, clay
Quaternary	Mescalero caliche	caliche
Quaternary	Gatuna	gravel, sand, clay
Tertiary	Ogallala	calcareous sand, minor clay and gravel
Cretaceous	Scattered outcrops	limestone and re-worked sediments
Triassic	Dockum Group (Chinle and Santa Rosa)	mudstone, siltstone, and sandstone with conglomerate
Permian	Dewey Lake	red beds of mudstone siltstone, minor sandstone
Permian	Rustler	anhydrite, dolomite, halite, siltstone
Permian	Salado	halite, anhydrite, clay, polyhalite, potash minerals
Permian	Capitan Limestone	limestone reef

9
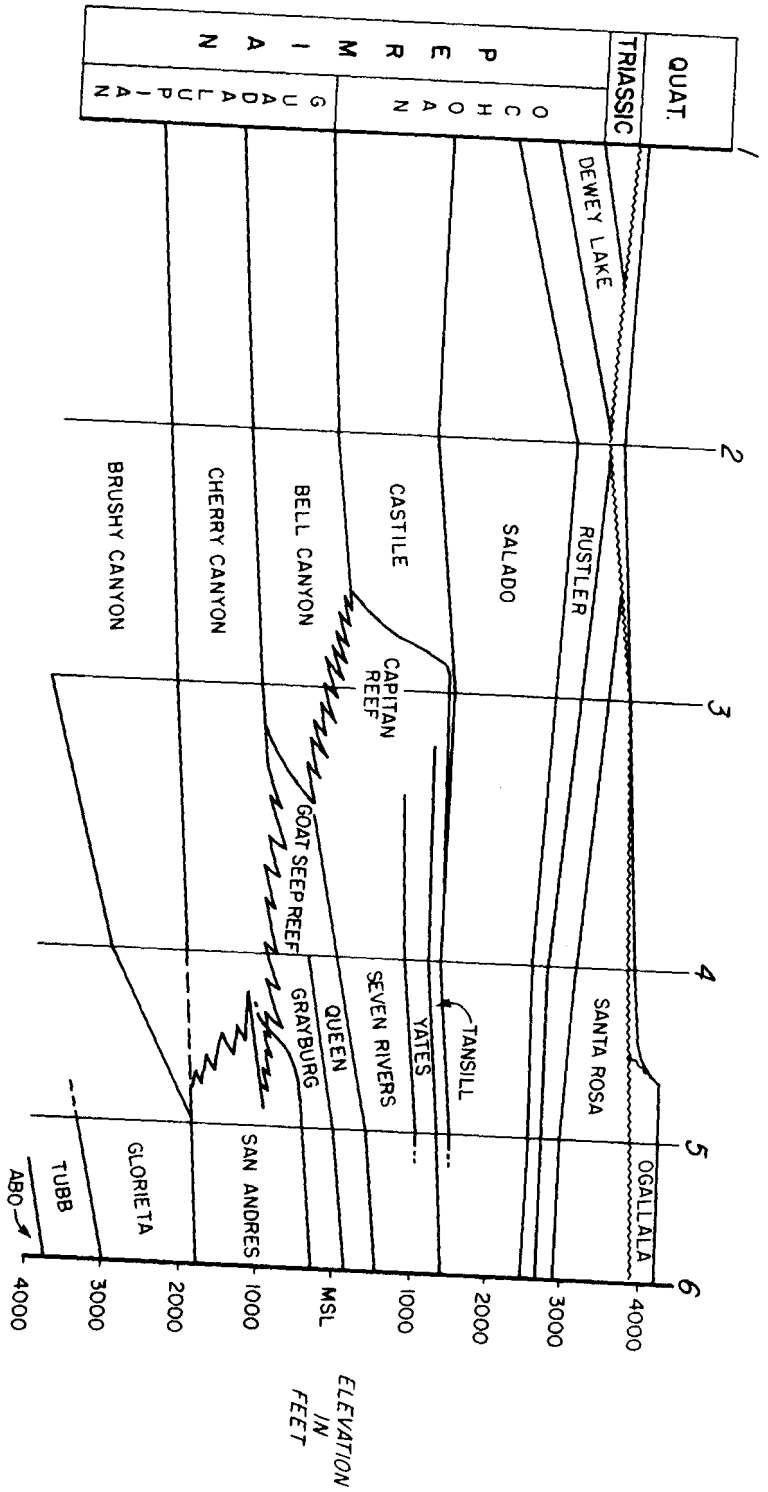
Figure 2. North-south stratigraphic cross-section through the Delaware Basin and Northern Shelf.
Modified from U. S. DOE (1984).

Capitan Limestone

The Capitan Limestone aquifer is a productive and important aquifer in southeastern New Mexico and western Texas, supplying groundwater for municipal and industrial use. The aquifer has high porosity and permeability developed along solution features, though permeability is lower in the vicinity of submarine canyons and in areas where the calcium carbonate content is relatively low (Hiss, 1975). In the western part of the basin, water enters the Capitan in the Guadalupe Mountains and flows through the karstic system to discharge points at springs along the Pecos River at Carlsbad. Leakage from adjacent shelf and basin aquifers and infiltration of water on Capitan outcrops in the Glass Mountains of Texas provide water to the aquifer east of the Pecos River. Discharge occurs by leakage into shelf aquifers to the east and by pumping.

Carlsbad Caverns

Water in Carlsbad Caverns is part of an isolated, perched hydrologic system within the Capitan Reef (Hendrickson and Jones, 1952). The Caverns extend from the surface to a depth of 900 feet, with the most extensive caves developed between the depths of 600 and 800 feet below the surface. Though the caves were formed by circulating groundwater, and the cave levels were probably controlled by past, higher, water tables, the caves are above the Capitan water table today and no streams or springs flow in the explored part of the caverns. The relatively small amount of groundwater that enters the caverns is discharged by evaporation (Hendrickson and Jones, 1952; Ron Kerbo, National Park Service at Carlsbad Caverns, personal comm., 1986). For instance, one of the larger cavern pools, the "Lake of Clouds", located at the lowest known point of the caverns, has no apparent drainage and its level remains nearly constant

(Barnett, 1980). Though the relative humidity in the cave is high, the evaporation surface is large and changes in barometric pressure result in active air circulation.

Rustler Formation

The primary water-bearing zones in the Rustler Formation are the Rustler/Salado contact zone, the Culebra Dolomite, and the Magenta Dolomite (from stratigraphically lowest to highest). The Rustler/Salado contact water-bearing zone is composed of clay with interlayered gypsum and sandstone and is considered to be the result of the dissolution of clay-bearing halite and other evaporites. The Rustler/Salado contact aquifer was formerly assumed to be confined to the dissolution/collapse feature of Nash Draw, but "...data from WIPP boreholes shows that the aquifer extends east of Livingston Ridge on to the WIPP site and is not confined by the physiographic depression of Nash Draw" (Chaturvedi and Channell, 1985). Water in all zones of the Rustler Formation in Nash Draw may have experienced contamination by introduced water. Disposal of oil-field brines and effluent from potash mining operations may have altered the original water chemistry in Nash Draw.

Water in the Rustler fluid-bearing zones is generally considered to discharge at Malaga Bend on the Pecos River, and possibly at Laguna Grande de la Sal in Nash Draw (Figure 3). Potentiometric levels in wells show the water movement in the Magenta to be primarily to the west, and to the southwest in the Culebra and Rustler/Salado contact (Figures A-1, A-2, and A-3 in the Appendix). The proposed recharge area for these aquifers in Clayton Basin (Mercer, 1983) has recently been questioned due to an apparent groundwater divide immediately south of Clayton Basin (Hunter, 1985). Other potential recharge areas exist in

8
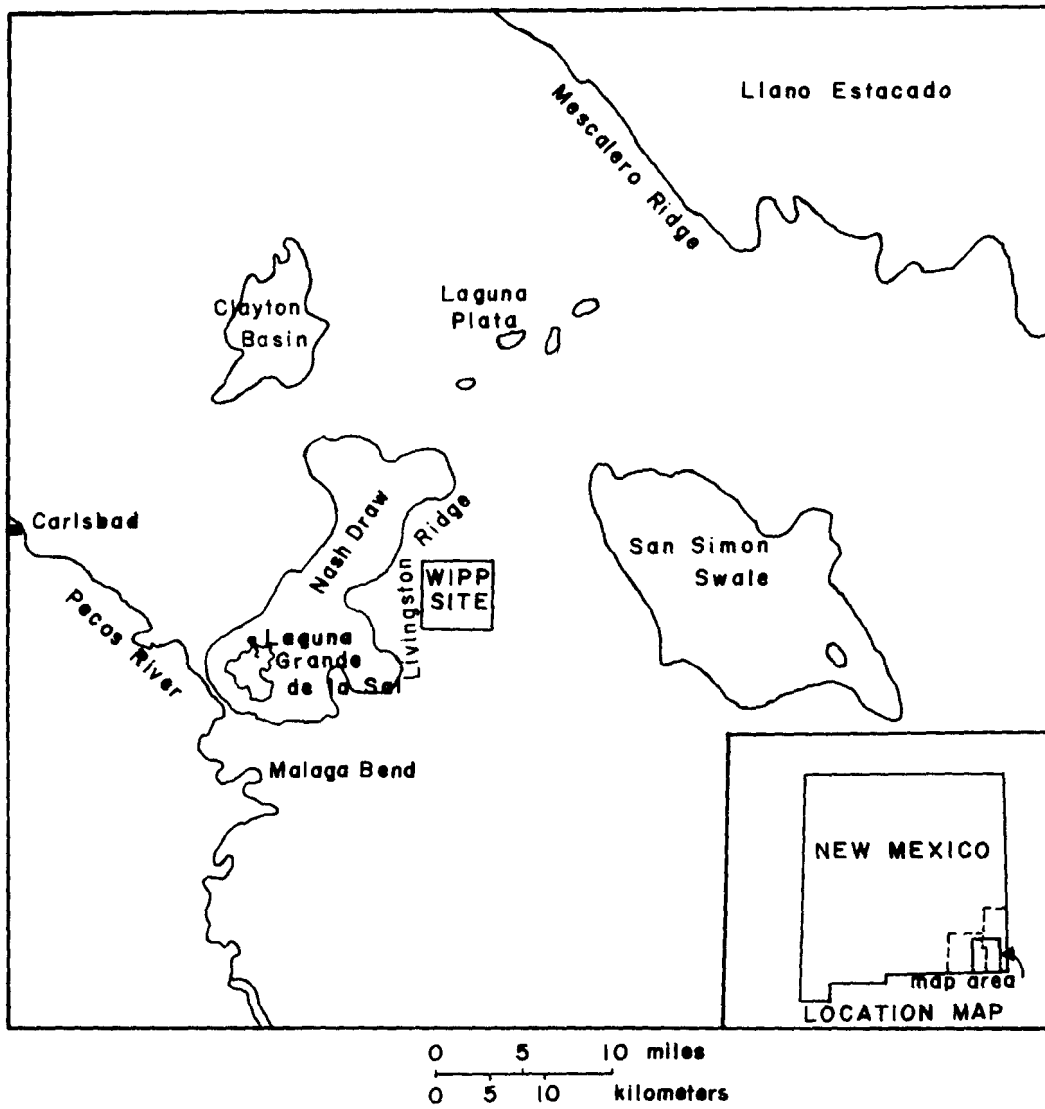
Figure 3. Location of geographic features in the vicinity of the WIPP site.

the Laguna Plata and San Simon Swale areas of eastern Lea County
(Figure 3), though a groundwater divide may separate the San
Simon region from the WIPP site (Nicholson and Clebsch, 1961;
Hunter, 1985). The potential for recharge to the Rustler
through the overlying Dewey Lake Redbeds remains unknown. Also
unknown are the hydrogeologic conditions in the Rustler
immediately to the east of the WIPP site.

Dewey Lake Redbeds

The Dewey Lake Redbeds Formation overlies the Rustler Formation
and locally contains perched water within lenticular sand units.
Recharge may take place through local dune sands and along
fractures or bedding planes in the mudstone and siltstone.
Movement of water in the Dewey Lake is considered to be
restricted due to the overall low permeability of the formation
(Mercer, 1983).

Santa Rosa Sandstone

The Triassic Santa Rosa Sandstone is the principle aquifer in
the western third of southern Lea County. The Santa Rosa is
recharged by precipitation and runoff directly on the outcrop
and through sand dunes in Lea and Eddy Counties (Nicholson and
Clebsch, 1961). Recharge probably also occurs by groundwater
flow through the Ogallala Formation where the Ogallala overlies
the Santa Rosa. Groundwater in western Lea County moves to the
south and southwest in the Santa Rosa Formation, toward Laguna
Plata (Figure 3). Discharge may occur in this area from the
Santa Rosa to Permian units through zones of increased
permeability due to collapse (Nicholson and Clebsch, 1961).
Elsewhere in southwestern Lea County, flow in the Santa Rosa is
strongly influenced by San Simon Swale. The Triassic Chinle
Formation also contains water in Lea County, but no isotope data
are available from that unit.

Ogallala Formation

The Ogallala Formation is a large and very productive aquifer across the High Plains of the United States. In southeastern New Mexico, the Ogallala represents a continuous and productive unit only east of the Pecos River. The recharge of the Ogallala is due entirely to precipitation. Water movement is predominantly southeastward, though in the area of Mescalero Ridge (Figure 3), some water moves southwestward across the ridge and into the Santa Rosa Sandstone (Nicholson and Clebsch, 1961). The water that moves southeast is eventually either intercepted by wells or discharges along the eastern edge of the Llano Estacado.

Quaternary Deposits

Quaternary deposits, including the Gatuna Formation, playa deposits, and alluvium, contain localized water in the Delaware Basin. Recharge to these units occurs by infiltration of precipitation, streams, canals, and irrigation return water. Leakage from the Capitan aquifer also contributes water to the alluvium west of the Pecos River. Alluvium associated with the Pecos River contains a productive aquifer yielding water to irrigation wells. The Gatuna Formation is reported to yield water (Cooper and Glanzman, 1971), but the discontinuous nature of the unit restricts water movement and the quantity of water is small (Mercer, 1983). Where the Gatuna overlies the Santa Rosa Sandstone, it probably contributes recharge to the Santa Rosa. Elsewhere, discharge probably occurs by transpiration. The occurrence of water in other Quaternary deposits is variable and localized.

Roswell Basin

The following discussion of the Roswell Basin is derived primarily from Hoy and Gross (1982) and Welder (1983). The term

"basin" here refers to a groundwater basin (an area containing a large aquifer and any related aquifers), rather than a structural basin like the Delaware Basin. The Roswell Groundwater Basin covers approximately 6000 square miles in southeastern New Mexico (Figure 1). It contains an eastward-dipping limestone aquifer which consists of the San Andres and Grayburg Formations (Table 2), overlain in the east by the leaky confining beds of the Artesia Group and an alluvial water-table aquifer. Water in the carbonate aquifer is unconfined in the western part of the basin and confined to the east. Along the Pecos River between Roswell and Artesia, flowing artesian conditions were encountered in wells completed in the limestone, prior to the extensive use of irrigation for farming.

Water movement in the Roswell Basin is generally eastward to the Pecos River, with an additional southward component in some areas. Recharge to the limestone aquifer occurs as infiltration of precipitation and streamflow to the karstic San Andres outcrops and as upward leakage from underlying sedimentary beds. The underlying beds (Glorieta sandstone and Yeso Formation), are recharged at their exposures in the Sacramento Mountains. Recharge to the alluvial aquifer occurs by infiltration of precipitation, surface runoff, and irrigation return flow. Under pre-irrigation conditions, the alluvial aquifer also received recharge through the leaky confining layer from the limestone aquifer. Since the onset of irrigation, however, the flow is reversed during periods of large withdrawals from the carbonate aquifer, and the alluvial aquifer recharges the carbonate aquifer during these periods. The major discharge from all units in the basin is by pumping for irrigation water. Additional discharge occurs from both the alluvial and the carbonate aquifers to the Pecos River.

12

TABLE 2

Roswell Groundwater Basin Stratigraphy

PERIOD	FORMATION	LITHOLOGY
Quaternary	Alluvium and surficial sand	caliche, gravel, sand, clay
Quaternary	Gatuna	gravel, sand, clay

Permian	Artesia Group:
	    Tansill
	    Yates
	    Seven Rivers
	    Queen
	    Grayburg
		Upper portion:
		clay, sand, evaporites
		
		Lower portion:
		clay, sand, carbonates

Permian	San Andres	Upper portion: evaporites, sand, carbonate Lower portion: carbonate, shale, sand (Glorieta Sandstone)
Permian	Yeso	Shale, carbonate

(See Figure 2 for stratigraphic relationship with Delaware
Basin Formations)

13

STABLE ISOTOPES AND HYDROGEOLOGY

Interpretation of stable isotope ratios in water is an established method of supplementing information derived from conventional hydrogeologic techniques. Detailed information on the theory and application of stable isotope studies to hydrogeology can be found in Gat and Gonfiantini (1981) and Faure (1977). Hoy and Gross (1982) also discuss the stable isotope approach to hydrology, with special emphasis on applications to the Roswell Basin. The isotopic data are represented as the relative difference in the ratio of the heavy isotope to the light isotope with respect to a reference, using the δ-notation:

$$\delta = \frac{R \text{ sample} - R \text{ reference}}{R \text{ reference}}$$

with R as the $^{18}O/^{16}O$ or D/H isotope concentration ratio. The reference is usually Standard Mean Ocean Water (SMOW). The δ-values are presented as per mil $[\delta\ (\%) = \delta \times 1000]$. Discussions of the δ-notation can be found in the references given above.

The usefulness of stable isotope ratios lies in the fact that because of the mass differences between oxygen-16 and oxygen-18 and between protium and deuterium, the thermodynamic properties are different between water molecules of varying isotopic composition. This difference results in isotopic fractionation during many reactions. The fractionation which results during physical processes such as evaporation and condensation, and fractionation which results from exchange reactions such as between water and limestone, are of primary concern to this discussion.

14

Isotopic Fractionation During Condensation

The isotopic composition of precipitation has been related to temperature, amount of precipitation, latitude, distance from the ocean, and altitude. The most important factor is the temperature of condensation (Yurtsever and Gat, 1981). A strong linear relationship exists between δ D and δ^{18}O values of precipitation worldwide. This relationship is often referred to as the Meteoric Water Line (MWL) (Figure 4), and can be described by the equation:

$$\delta D = 8\delta^{18}O + 10$$

(Craig, 1961).

The δD-δ^{18}O relationship for a given region can differ from the global equation, usually in the value of the D-axis intercept (deuterium excess). Water with relatively low values of δD and δ^{18}O indicate that they condensed at relatively cool temperatures. Conversely, higher values of δD and δ^{18}O indicate condensation in warm temperatures.

The impact of latitude, distance from the ocean, and altitude on the isotopic composition of precipitation is related both to the relationship with temperature of these variables, and to the "rain-out" effect. As water vapor in an air mass moves away from the point of evaporation, the heavy isotopes condense first and are said to be "rained-out" of the cloud. Subsequent precipitation becomes isotopically lighter as the cloud becomes successively depleted in the heavy isotopes. The same process relates to the amount of precipitation in a single event. The initial precipitation will be relatively isotopically heavy, but as more water condenses, the rain becomes depleted in heavy isotopes. Therefore, large-volume rainfall events are characterized by relatively light isotopic compositions.
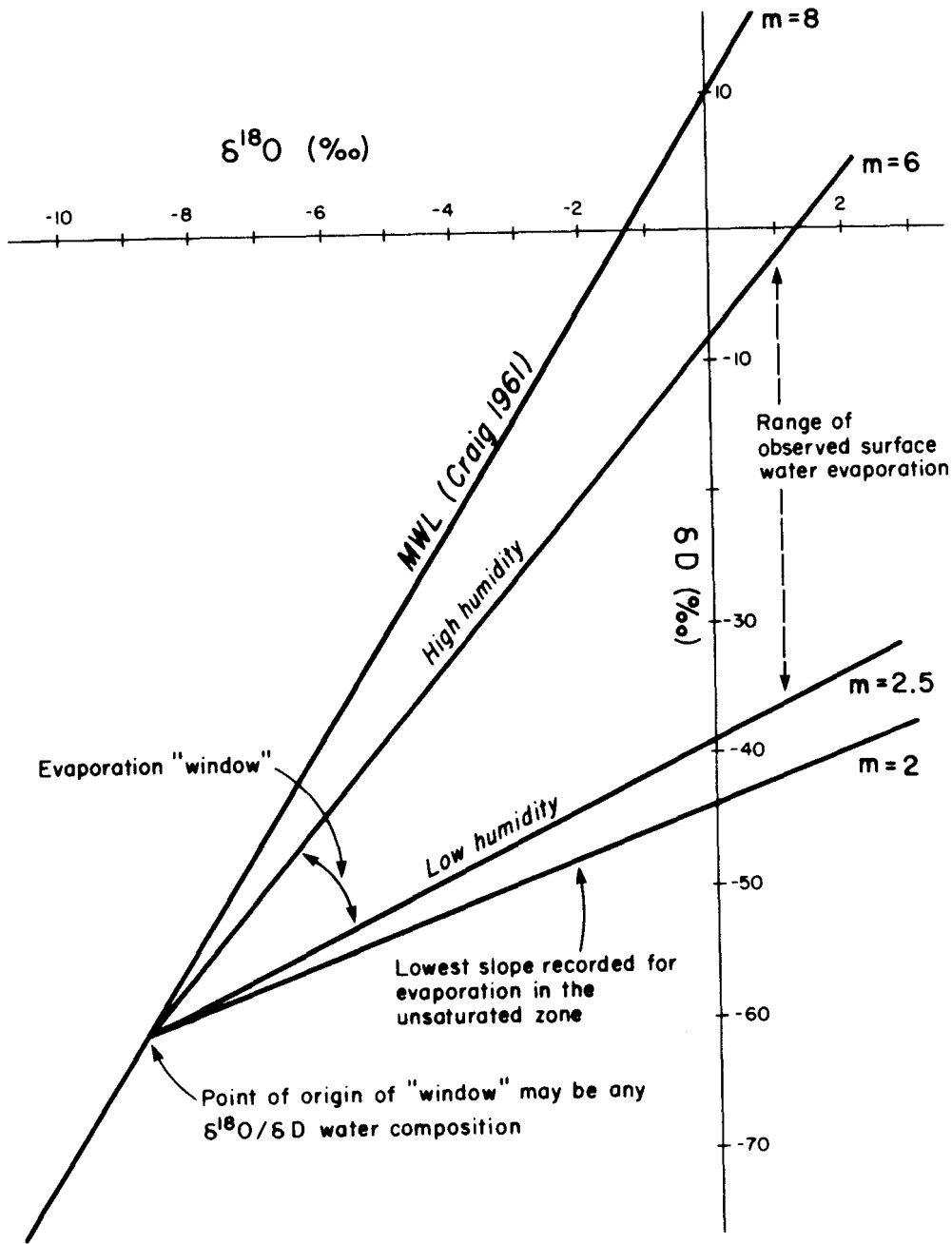
Figure 4. Plot of δD vs δ^{18}O showing the observed range in isotopic paths (evaporation "window") traced by a residual water as it undergoes evaporation. See text for a discussion of the factors that determine which evaporation-line slope a water will follow.

The impact of altitude on the isotopic composition of precipitation is pertinent to this discussion because some of the recharge to the Roswell Basin occurs in the Sacramento Mountains. The question is whether the isotopic composition of groundwater that receives part of its recharge from precipitation at high altitudes in the Roswell Basin can be compared to groundwater in the Rustler Formation which probably receives most of its recharge at lower elevations. Hoy and Gross (1982) attempted to identify the relative contribution of recharge from higher and lower elevations to the Roswell Basin limestone aquifer on the basis of isotopic composition. They found that the groundwater data, irrespective of altitude, fell in a tight cluster within the range of the isotopic composition of precipitation at lower to intermediate elevations in the basin. They concluded that in this semi-arid, continental environment, the temperature effect due to altitude is masked by the large, rapid temperature fluctuations that occur at all elevations across the basin. Nevertheless, caution is taken here to use data only from low to intermediate elevations in the Roswell Basin and the potential impact of high-elevation recharge is recognized.

Isotopic Fractionation During Evaporation

Evaporation of water, whether from a surface-water body or from the unsaturated zone, leaves the residual water enriched in the heavier isotopes of oxygen and hydrogen (Figure 4). The isotopic path traced by the residual water as successively more water is evaporated is characterized by a slope of less than 8 in δD-$\delta^{18}O$ space. The lower slope reflects the greater fractionation of oxygen, compared to hydrogen, during the evaporation process. The slope of the evaporation path depends upon the relative humidity of the air, the fractionation factor, the excess separation factor (amount of isotopic fractionation

in excess of the appropriate equilibrium process), and the ratio of the isotopic compositions of the air and liquid. The relative humidity and fractionation factor are both temperature dependent. Lower slopes indicate evaporation under conditions of lower relative humidity and higher slopes indicate evaporation in relatively high humidity environments.

Gat (1981) reported that most observed slopes are within the range of 3.5 to 6. Lloyd (1966) reported a somewhat larger range of 2.5 to 6 for evaporating seawater. Allison (1982) reported evaporation line slopes between 2 and 4.7 for the condition of evaporation in the unsaturated zone of sand columns. The lower slopes of unsaturated zone evaporation are attributed to the greater role of kinetic fractionation during vapour-phase movement through the dry surface layer. In addition to the controlling factors for surface-water evaporation slopes listed above, the slope for evaporation in the unsaturated zone probably also depends on the thickness of the zone of vapour-phase transport (Allison, 1982). The range of evaporation-line slopes is traced in δD-$\delta^{18}O$ space on Figure 4.

Isotopic Fractionation During Exchange Reactions

The isotopic composition of water can also be modified by exchange reactions. The typical case of isotopic exchange involves hydrothermal systems in which high temperatures increase the rate of isotopic exchange between groundwater and rocks. In lower temperature environments, isotopic exchange reactions generally require long periods of water-rock contact (i.e., slow-moving groundwater systems) and a large rock-to-water ratio. Isotopic exchange between water and carbonates results in an oxygen-18 enrichment of the groundwater. This shift is the result of the oxygen-18 enriched nature of

18

carbonates (+20‰ to +30‰ for limestone, slightly higher for dolomite). Both the deuterium and oxygen-18 content can be affected in a water that reacts with hydrous minerals such as gypsum. All of these rock-water reactions result in an oxygen-18 enriched water, plotting to the right of the Meteoric Water Line in δD-$\delta^{18}O$ space.

The isotopic composition of water that has exchanged isotopes with rock may mimic that of water that has undergone evaporation. In practice, however, the environment in which the sample is collected (surface water, shallow groundwater, or deep formation water removed from atmospheric contact) dictates which fractionation scenario is more likely. The interpretation is more difficult in the case of a remnant evaporitic brine that subsequently undergoes rock-water reactions.

Stable Isotopes and Fossil Water

Stable isotopes can be used in hydrogeologic investigations to help identify the presence of fossil water (paleowater) in aquifers. However, no simple correlation exists between variations in the stable isotope content of precipitation and past climatic patterns. Paleoclimatic interpretations of isotopic data in the absence of groundwater-age measurements are risky because of the number of variables affecting the isotopic composition of precipitation (e.g. isotopic content of vapor sources, precipitation history of the air mass, humidity, and temperature profiles in the lower atmosphere). For instance, groundwater recharged by rain during polar front occlusions could be depleted in heavy isotopes and misinterpreted as paleowater if no tritium or carbon-14 measurements are available (Fontes, 1981).

Paleowater investigations usually rely on the popular concept that the glacial episodes during the Quaternary were characterized by low temperatures, low evaporation, and/or high rainfall in the mid-latitudes. Presumably, this would result in precipitation during glacial periods having a lighter stable-isotope content. Successful applications of stable isotopes to investigations of paleowaters have shown that a given aquifer may have a much lower deuterium and oxygen-18 content than present-day precipitation and often a different deuterium-excess value. The use of hydrogeologic evidence and carbon-14 dates to support the hypothesis is a consistent feature of valid paleoclimate studies.

STABLE ISOTOPE DATA FROM SOUTHEASTERN NEW MEXICO

The data used in this report are presented in Table 3.   The three primary sources for published stable-isotope data for aquifers in southeastern New Mexico are Lambert (1986), Lambert (1978), and Hoy and Gross (1982).   Isotopic data are also presented graphically in Lambert (1983), but the identity of wells is not listed.   Popielak and others (1983), O'Neil and others (1986), and Knauth and Beeunas (1986) present isotope data from the Salado and Castile Formations.   Additional data from rainfall samples and WIPP-area groundwater have been obtained by the EEG.

On some samples, Hoy and Gross (1982) have reported only the oxygen-18 analysis and the Ogallala data in Lambert (1986) consist only of deuterium analyses.   To facilitate presentation, the other isotope for these data is calculated by using the local meteoric water line determined by Hoy and Gross (1982) for the Roswell Basin.   The local line is based on data from aquifers, springs, snow, and surface water, and three years of precipitation and is expressed by the following equation:

$$\delta D = 7.27 \ (\pm \ 0.38) \ \delta^{18}O + 5.36 \ (\pm \ 1.25) \quad (\text{Hoy and Gross, 1982}).$$

The potential error introduced by calculating a $\delta^{18}O$ or δD value is small because the samples involved are generally accepted as recent, unaltered meteoric water by virtue of either their tritium contents or their location in shallow aquifers.   The exception to this is the data point from the Pecos River at Artesia (sample number S-13, Hoy and Gross, 1982) which probably should plot to the right of the meteoric water line due to evaporation.   The meteoric water line will be discussed further in the section on the isotopic composition of precipitation, surface water, and groundwater in southeastern New Mexico.

21

TABLE 3

Stable Isotopic Data and Tritium Values of Water from
Southeastern New Mexico

FORMATION	MEMBER	WELL	DATE	δO-18	δD	T.U.	SOURCE
Capitan		Carlsbad	pre-1977	-7.9	-54		Lambert, 1978
Capitan		Middleton	"	-7.5	-55		"
Capitan		Hackberry	"	-6.5	-46		"
Capitan	Caverns		"	-3.6	-24		"
Capitan	Caverns		"	-4.3	-28		"
Capitan	Caverns		"	-4.2	-29		"
Capitan	Caverns		"	-3.0	-20		"
Rustler	?	Duval Mine	"	-6.4	-48		"
Rustler	?	James Ranch	"	-5.0	-40		"
Rustler	?	Fairview	"	-7.1	-53		"
Rustler	?	Indian	"	-6.3	-46		"
Rustler	?	Mobley	"	-6.9	-44		"
Rustler	?	Mobley #3	"	-5.9	-44		"
Rustler	Magenta	H-1	"	-6.8	-48		"
Rustler	Culebra	H-1	"	-7.0	-50		"
Rustler	Magenta	H-3	"	-7.3	-53		"
Rustler	Culebra	H-3	"	-7.0	-53		"
Santa Rosa		Smith L.R.	"	-7.2	-52		"
Salado		Duval Mine	"	+3.0	-10		"
Salado		Duval Mine	"	+2.6	-12		"
Morrow		Todd State	"	+2.7	-15		"
Morrow		Todd Federal	"	+9.2	-18		"
Bell Canyon		Todd Federal	"	+2.2	-13		"
Castile		ERDA-6	"	+10.3	0		"
Weighted Mean ppt			pre-1982	-6.0	-38*		Hoy & Gross, 1982
Snow	location: Sierra Blanca		1-16-79	-21.2	-146		"
Snow	location: Sierra Blanca		1-14-79	-21.8	-158		"
Snow	location: Sierra Blanca		1-14-79	-15.4	-102		"

22

FORMATION	MEMBER	WELL	DATE	δO-18	δD	T.U.	SOURCE
Rain	location: Roswell		4-76	-10.0	-71		Hoy & Gross, 1982
Rain	location: Roswell		7 & 8-76	-4.8	-35		"
Rain	location: Roswell		9 & 10-76	-6.2	-50		"
Rain	location: Roswell		3 & 4-77	-6.4	-44		"
Rain	location: Roswell		7-77	-0.8	-5		"
Rain	location: Roswell		10-77	-6.4	-28		"
Rain	location: Roswell		9-78	-5.2	-37		"
Alluvial Aquifer Hageman-Artesia mean				-7.15	-47*		"
Pecos River @ Artesia		S-13	4-1-78	-5.5	-35*	36.0	"
Pecos River @ Roswell		S-10	4-1-78	-12.6	-86*	40.7	"
Glorieta/Yeso		07	77-78	-7.4	-48*	12	"
Glorieta/Yeso		08	77-78	-8.2	-56	33	"
San Andres		WR5	78	-9.2	-64	16	"
San Andres		WP14	mean	-6.5	-42*	7	"
San Andres		WP14	4-78	-7.3	-42.6		"
San Andres		WP14	4-79	-7.9	-48.6		"
San Andres		WP16	7-77	-7.5	-48.4	16.4	"
Alluvium/Gatuna		WA10	75-78	-7.1	-46*	6.3	"
Alluvium/Gatuna		WA11	77	-7.2	-51.1	6.8	"
San Andres		WP4	76-78	-7.1	-46*	7.3	"
San Andres		WP2	4-79	-7.7	-55.4	10.4	"
San Andres		WR14	5-77	-7.2	-47.3	9.1	"
Spring		F5	77-78	-2.7	-34.3	36.9	"
Bitter Lakes		S23	78	-4.1	-29.5		"
Bitter Lakes		S23	78	±0.6	-6.0		"
Rustler	Magenta	W-25	84?	-6.2	-43.5		Lambert, 1986
Rustler	Culebra	W-25	"	-6.4	-43.5		"
Rustler	R/S	W-25	"	-7.1	-52		"
Rustler	Culebra	W-26	"	-6.5	-43.5		"
Rustler	R/S	W-26	"	-6.7	-46.5		"
Rustler	Magenta	W-27	"	-6.3	-46.5		"
Rustler	Culebra	W-27	"	-6.1	-45.5		"
Rustler	R/S	W-27	"	-7.0	-48.5		"
Rustler	Culebra	W-28	"	-6.6	-46		"
Rustler	R/S	W-28	"	-8.0	-57.5		"
Rustler	Culebra	W-29	"	-0.45	-27		"

FORMATION	MEMBER	WELL	DATE	δO-18	δD	T.U.	SOURCE
Rustler	R/S	W-29	"	-7.0	-47.5		Lambert, 1986
Rustler	Magenta	W-30	"	-6.5	-42		"
Rustler	Culebra	W-30	"	-7.1	-50		"
Rustler	R/S	W-30	"	-7.1	-52		"
Surprise Spring			"	-2.4	-30.5		"
Capitan	Caverns		"	-4	-37		"
Capitan	Caverns		"	-4	-31.5		"
Capitan	Caverns		"	-3.5	-23.5		"
?-San Simon Sink		W-15	"	-4.5	-38.5		"
Summer rain			"	-2.3	-19		"
Ogallala		Eastern New Mexico	pre-1986		-39 to -41		"
Pecos River			June	-3.5	-36		"
Dewey Lake (?)			pre-1980?	-5	-40		"
Rustler	R/S	H1		+1.8	-28		"
Rustler	R/S	H3		+0.2	-38		"
Rustler	R/S	H2		-2.7	-41		"
Rustler	R/S	H5		-1.7	-44		"
Rustler	R/S	H6		-4.8	-52		"
Rustler	R/S	H4		-4	-57		"
Rustler	R/S	P14		-9	-63		Lambert, 1986
Rustler	Culebra	H1		-7.2	-49		"
Rustler	Culebra	H3		-6.5	-49		"
Rustler	Culebra	P15		-7.2	-52		"
Rustler	Culebra	P17		-5.8	-50		"
Rustler	Culebra	P18		-4.5	-46		"
Rustler	Magenta	H1		-6.8	-47		"
Rustler	Magenta	H3		-6.1	-48		"
Capitan	Caverns			-1.6	-17		"
Capitan	Caverns			-3	-20		"
Capitan	Caverns			-3.5	-24		"
Capitan	Caverns			-4.2	-28		"
Capitan	Caverns			-4.0	-29		"
Capitan	Caverns			-4.3	-30		"
Capitan	Caverns			-5	-33		"
Capitan	Caverns			-6.1	-32		"
Capitan	Caverns			-4.8	-39		"

24

FORMATION	MEMBER	WELL	DATE	δO-18	δD	T.U.	SOURCE
Rustler	Culebra	DOE-2	1985	-7.07	-55		EEG, 1985
Rustler	Culebra	H-3	"	-6.76	-55		"
rain	location: Carlsbad		11-24-84	-14.06	-97		"
rain	location: WIPP site		12-04-84	-5.12	-25		"
rain	location: WIPP site		12-18-84	-4.36	-31		"
snow	location: Carlsbad		1-01-85	-22.54	-162		"
snow	location: WIPP site		1-31-85	-10.95	-71		"
snow (?)	location: Carlsbad		2-24-85	-15.95	-122		"
rain	location: WIPP site		2-28-85	-6.22	-52.5		"
rain	location: WIPP site		3-19-85	-7.59	-62		"
rain	location: WIPP site		6-85	-3.6	-19		"
rain	location: WIPP site		7-85	-3.1	-13		"
Castile		ERDA-6	1982	+9.51	-5		Popielak, et al, 1983
Castile		WIPP-12	1982	+10.45	-0.8		"
Salado		ERDA-9	1983	+3.4	-21		O'Neil, et al, 1986
Salado		ERDA-9	"	+1.2	-28		"
Salado		ERDA-9	"	+8.4	-14		"
Salado		ERDA-9	"	+8.0	-10		"
Salado		ERDA-9	"	+5.8	-14		"
Salado		ERDA-9	"	+9.9	-2		"
Salado		ERDA-9	"	+7.5	-8		"
Salado		ERDA-9	"	+8.1	-4		"
Salado		ERDA-9	"	+9.5	-5		"
Salado		WIPP Mine	1985	+4.7	-9		Knauth & Beeunas, 1986
Salado		WIPP Mine	"	+3.5	-6		"
Salado		WIPP Mine	"	+2.9	-7		"
Salado		WIPP Mine	"	+3.2	-9		"
Salado		WIPP Mine	"	+3.7	-5		"
Salado		WIPP Mine	"	+2.9	-5		"

*denotes values calculated from $\delta D = 7.3 \, \delta^{18}O + 10$ (Hoy & Gross, 1982)

**EEG analyses performed by Global Geochemistry Corp., Canoga Park, California

Only selected data from Hoy and Gross (1982) are presented here. The selection is based on tritium values higher than 4 Tritium Units (TU) to include only water which has been recharged in the last thirty years, and based on locations as geographically and topographically similar to the Carlsbad area as possible. Only lower altitude wells in the Roswell Basin are used in this study (<5000 ft msl). The impact of potentially higher elevation recharge to some of the Hoy and Gross wells is discussed in the section on "Isotopic Fractionation During Condensation." The Roswell Basin, Carlsbad Caverns, and the WIPP area are all located in the Southeastern Plains of New Mexico and experience fairly uniform climatic conditions. For instance, the towns of both Roswell and Carlsbad receive 13 inches of average annual precipitation, with virtually the same seasonal distribution (Figure 5)(Tuan et al, 1973).

The tritium values of the Hoy and Gross (1982) groundwater samples reported here range from 5 to 33 Tritium Units (TU). The last precipitation before extensive atmospheric tests of nuclear bombs occurred in 1951 and the natural activity (between 4 and 20 TU) of this precipitation will have decayed down to about 1 to 4 TU in the 1980's. Therefore, groundwaters recharged and removed from contact with the atmosphere before 1951 will now have tritium values of less than or equal to 1 to 4 TU (Fontes, 1983). There are difficulties in using tritium data to obtain quantitative ages because mixing with older groundwater, hydrodynamic dispersion, and variation in the amount of tritium in rainfall complicate the analysis. However, any groundwater with a tritium level over 4 TU has had contact with the atmosphere (the tritium source) within the last 30 years, establishing a recent meteoric connection for the Roswell Basin samples reported here.
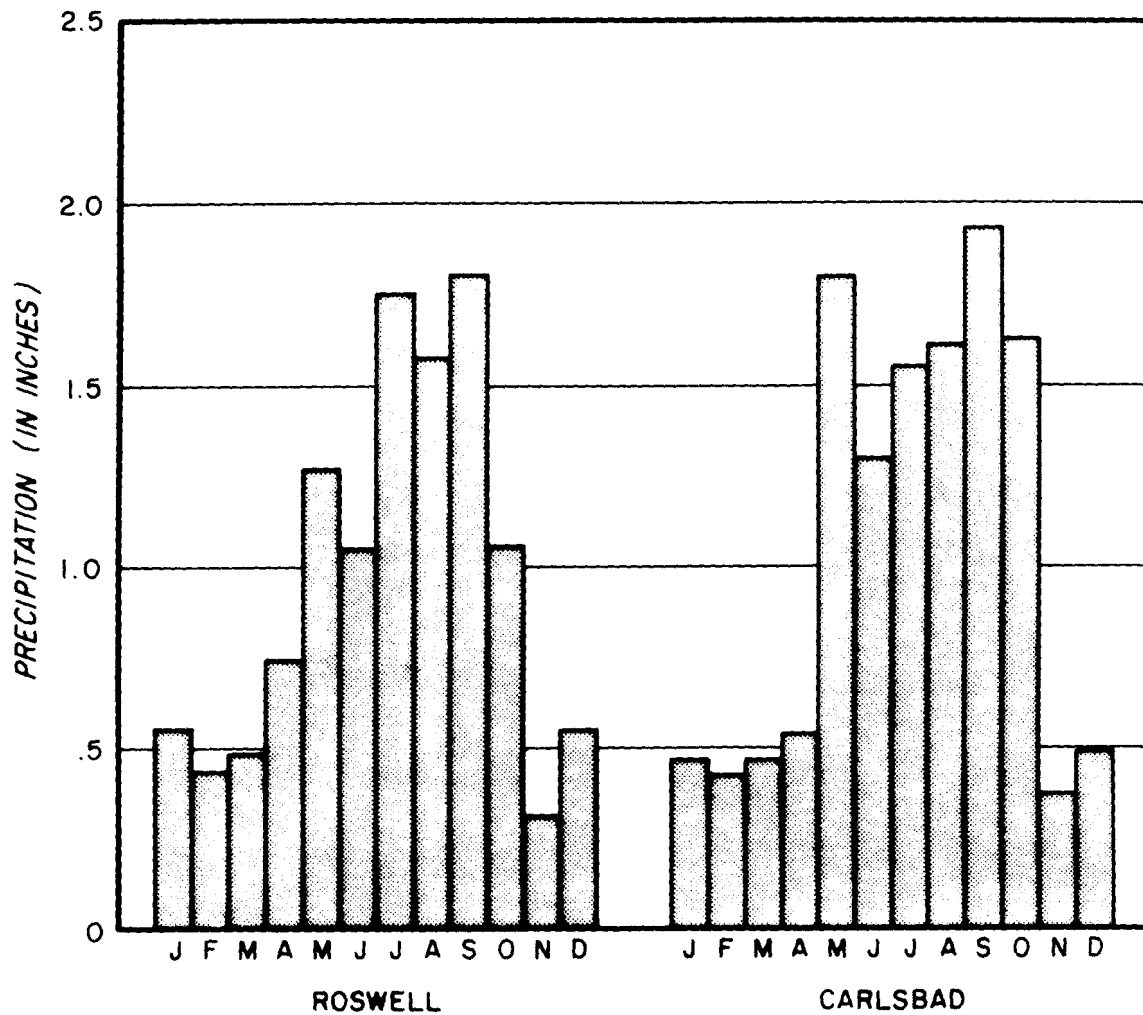
26

Figure 5. Monthly average precipitation recorded at weather stations in the towns of Roswell and Carlsbad. Modified from Tuan and others (1973).

27

Mixing may have affected the tritium results from the Roswell
Basin limestone-aquifer wells reported here (denoted by "WP" in
Table 3). The presence of more than 4 TU tritium documents
recent recharge, but this recharge may have mixed with older
groundwater in the limestone aquifer (Hoy and Gross, 1982; Gross
et al. 1976). However, the "older" groundwater in the limestone
aquifer is believed to have an age of one hundred to several
hundred years (Gross, pers. comm., 1985), a time period too
short to encompass the large scale climatic changes necessary to
dramatically alter the isotopic composition of precipitation.
Water from the alluvial aquifer wells ("WA" wells) and the
observation wells ("O" wells) may be affected by mixing with
irrigation returns from Pecos River water and from well water
from the limestone aquifer. However, water levels in the
observation wells responded rapidly to runoff events in nearby
stream courses, indicating that recharge from surface water is
important in the system (Hoy and Gross, 1982). Hoy and Gross
(1982, p. 70) have concluded that "Groundwaters in the Roswell
Basin, therefore, represent present climatic conditions".

In addition to the numerical data obtained for this analysis,
sixteen points have been taken from a graph presented in Lambert
(1986, Figure 3). These are presumably the same data shown in
Lambert (1983) in which the identity of the individual data
points is not listed. The numbers assigned to these points may
be slightly in error since they were interpreted from the graph.

Data Presentation

The isotopic data used in this study are presented in Table 3.
The sample locations in southeastern New Mexico are shown on
Figure 6, with a more-detailed map of wells in the WIPP vicinity
presented in Figure 7. The large quantity of data is presented
in a series of graphs for clarity. Maps modified from Mercer
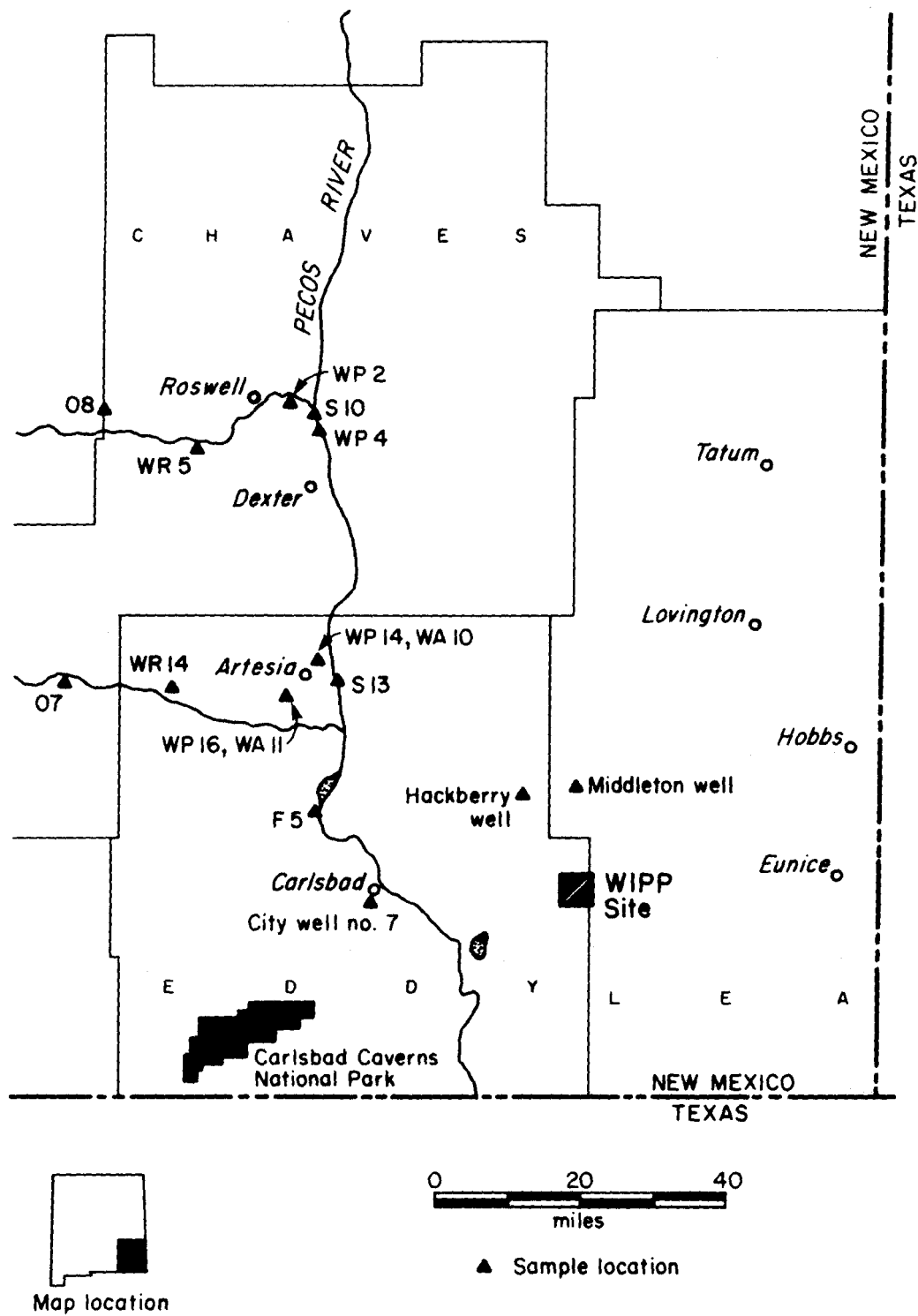
28

Figure 6. Location of wells (exclusive of the WIPP area) and surface water samples for which stable isotope data are available.
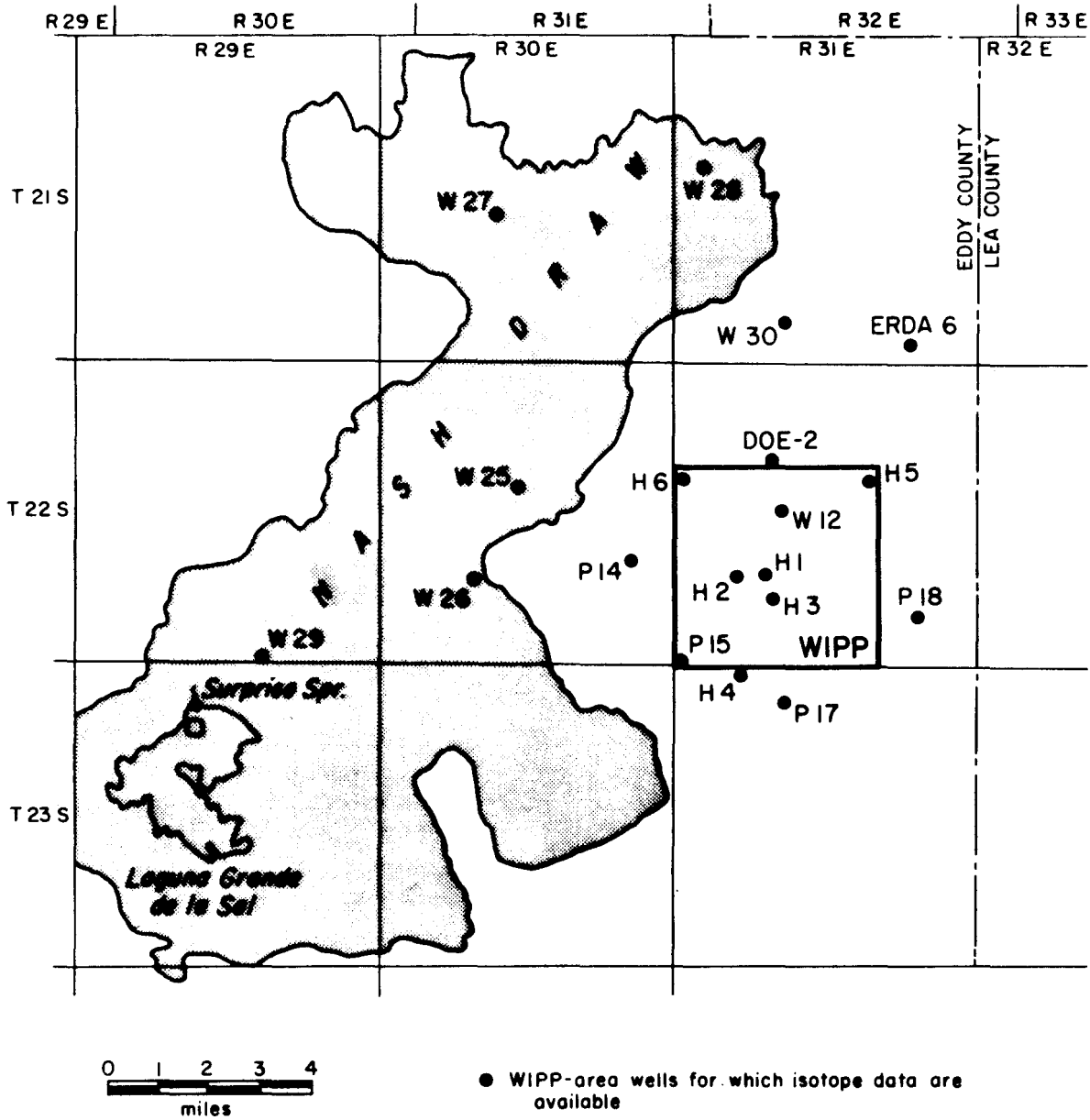
29

Figure 7. Location of wells in the WIPP area for which stable isotope data are available.

(1983), showing potentiometric contours of the Rustler water-bearing units are included as Appendix A for easy reference.

STABLE ISOTOPES IN RUSTLER FORMATION GROUNDWATER

Figure 8 displays two groups of δD-$\delta^{18}O$ compositions. There is a group of Rustler data points paralleling the meteoric water line and a group of additional Rustler points (primarily from the Rustler/Salado contact) that stretch from the light end of the meteoric water line toward oxygen-18 and deuterium enriched values. The slight offset from Craig's (1961) meteoric water line exhibited by the first Rustler group could be the expression of a local meteoric water line. As discussed more fully in the next section, data from the Roswell basin indicate that the local meteoric water line does not differ significantly from the global line defined by Craig (1961). It is probable that the offset from the meteoric water line reflects partial evaporation of water either as it falls through the atmosphere, or as it infiltrates through the unsaturated zone.

The group of Rustler points (Group A) outlined near the meteoric water line (MWL) in Figure 8 contains all of the Magenta samples, almost all of the Culebra samples, and Rustler/Salado Interface zone samples that were collected from wells located in Nash Draw. The trend of this group along and close to the MWL indicates that none of these samples have undergone extensive isotopic exchange with the aquifer matrix. There is also no obvious isotopic distinction marking Nash Draw water that has been contaminated by oil-field brine or potash-mine effluent. Most potash-refining water is imported from the Ogallala Formation in the vicinity of Hobbs, New Mexico. Water from the

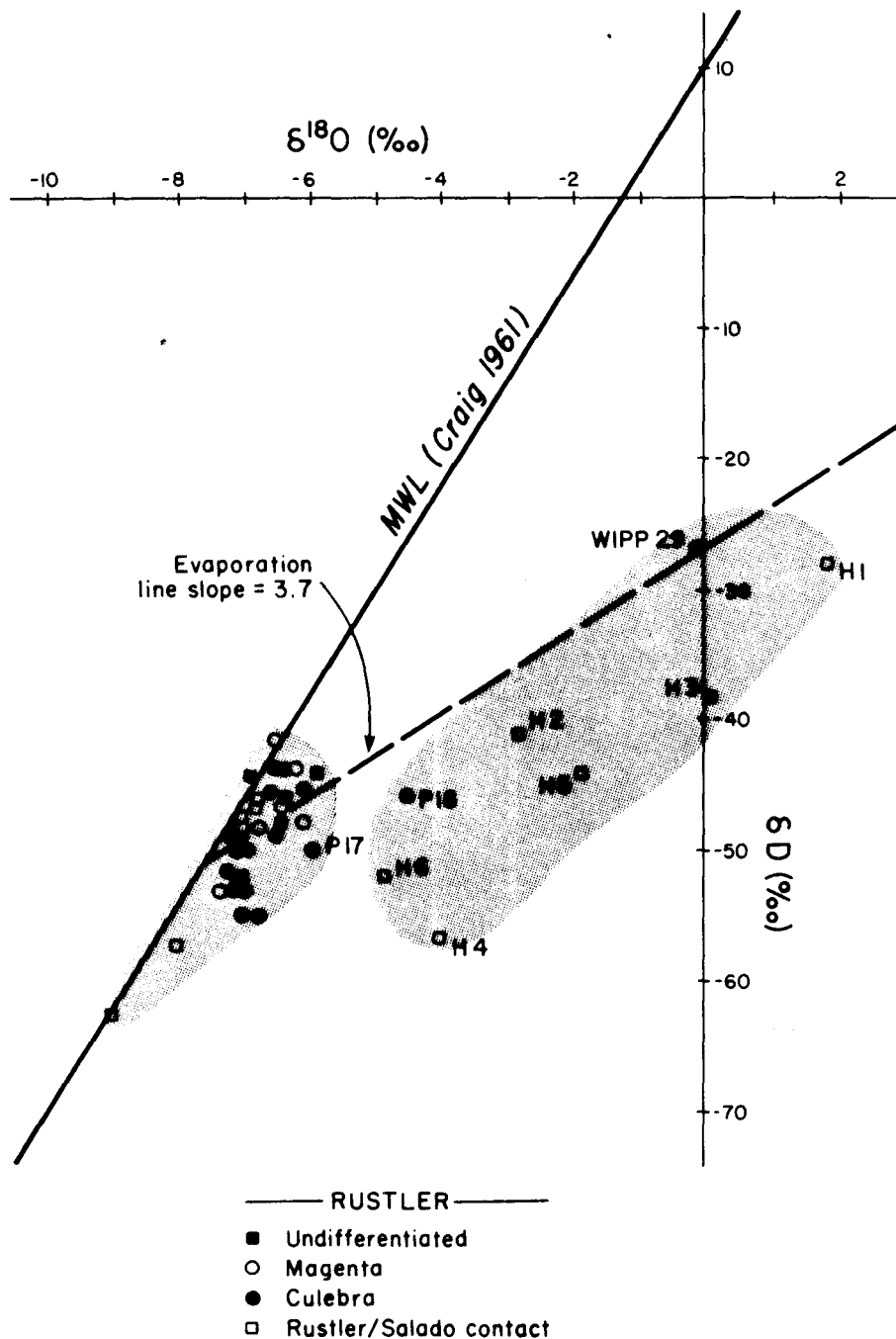**Figure 8.** Plot of δD vs $\delta^{18}O$ for groundwater from units in the Rustler Formation. Two groups are identified: Group A near the meteoric water line, and Group B enriched in heavy isotopes relative to the meteoric water line. A hypothetical evaporation line from Group A to WIPP-29 is also shown. The data are listed in Table 3.

Ogallala in southeastern New Mexico is not drastically different in isotopic composition from Rustler groundwater (Ogallala δD = -39 to -41 and most Group A Rustler values of -42 to -50), making the identification of contamination difficult. In the case of oil-field brine, there is no heavy-isotope enrichment indicating significant contamination of Nash Draw water by enriched oil-field brine (Figure 9). Isotopic analysis of brine from the major hydrocarbon-producing unit in the area, the Pennsylvanian Morrow Formation, revealed $\delta^{18}O$ values in excess of +2 per mil (Lambert, 1978).

The Rustler/Salado Interface East of Nash Draw

The trend of the Rustler/Salado Interface data that plot far from the meteoric water line suggests four possibilities: 1) the aquifer is composed of reactive materials that are exchanging oxygen-18 and deuterium. 2) the residence time of water is substantially longer in this aquifer, as compared to the Culebra and Magenta, allowing more time for water-rock reactions. 3) evaporation is occurring during the recharge process, or 4) mixing is occurring with remnant, evaporitic brines. All of the enriched samples were collected east of Nash Draw and therefore are not expected to be affected by contamination from introduced water. The four possibilities for the isotopic enrichment are discussed below. The offset of these points from the meteoric water line has also been discussed by Lambert (1983). He relates the heavy-isotope enrichment to a reduced water-to-rock ratio and well production rates and concludes that interaction of rock and water involving the exchange of both hydrogen and oxygen accounts for the enrichment.

33

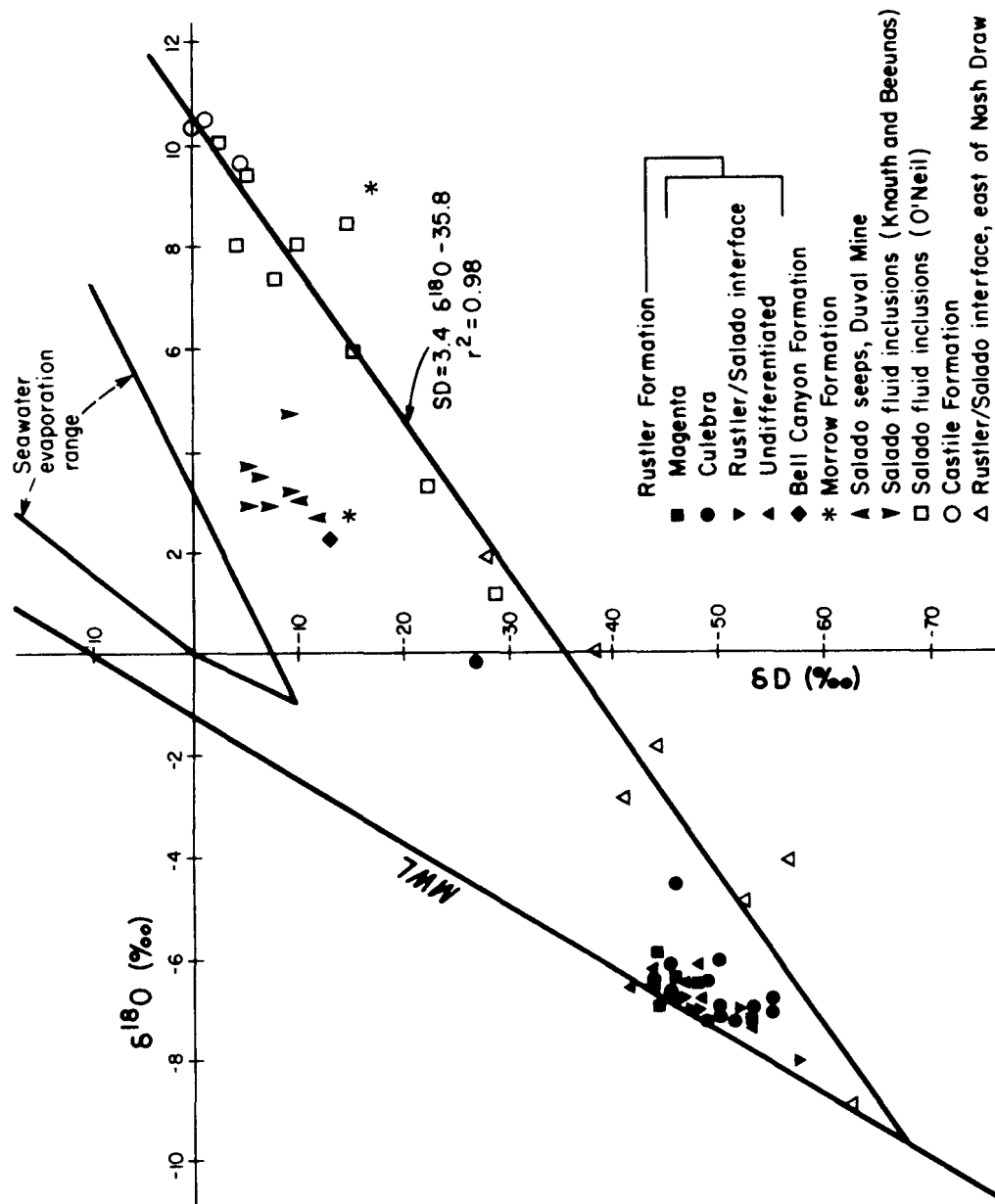Figure 9. Plot of δD vs $\delta^{18}O$ for groundwater from the Rustler Formation and deeper formations in the Delaware Basin. The least-squares linear regression line was calculated using the data shown in open symbols. A range is used for seawater composition to account for melting of ice sheets during the Permian. The data are listed in Tables 3.

Isotopic Exchange Between Water and Rock

The Rustler/Salado Interface matrix is a layer of primarily fine-grained clastic material with smaller amounts of anhydrite, halite, and polyhalite. The lack of limestone and dolomite precludes O-18 enrichment by exchange between water and carbonates. Exchange between the groundwater and petroleum hydrocarbons or hydrogen sulfide could affect the deuterium concentration, but not oxygen (Clayton et al, 1966). Exchange with hydroxide-bearing clay minerals could conceivably alter both the hydrogen and oxygen isotopic compositions (Clayton et al, 1966; Taylor, 1974) and is consistent with the mineralogy of the matrix.

O'Neil and Kharaka (1976) observed rapid hydrogen isotope exchange between clay minerals and water in the laboratory and concluded that this must be an active process in nature even at low temperatures. They also concluded that the mechanism of oxygen isotope exchange between minerals and waters usually involves a solution/redeposition step, and therefore, oxygen isotope exchange between clays and water at low temperatures is negligible under most conditions. Appreciable exchange of both oxygen and hydrogen was observed in montmorillonite clays where the presence of interlayer water facilitates isotopic exchange (O'Neil and Kharaka, 1976). However, most clays in the world's modern ocean basins have not reached isotopic equilibrium with the marine environment in hundreds of thousands of years, but rather the clays continue to reflect their detrital origin (Savin, 1980).

Aside from reaction kinetics, a major problem with invoking isotopic exchange between clay minerals and water to account for

the enriched nature of the eastern Rustler/Salado Interface
samples is the original isotopic composition of the clay. No
isotopic measurements are available from minerals in the
Interface matrix, so published values for clay minerals
(principally kaolinite, illite, montorillonite, and gibbsite)
must be used. Though enriched in O-18 relative to meteoric
water, published values for clays show a depletion in the
minerals' deuterium content (Savin and Epstein, 1970; Taylor,
1974; O'Neil and Kharaka, 1976). Fractionation factors for
kaolinite and montmorillonite reveal that the mineral is about
27 per mil enriched in O-18 and about 30 per mil depleted in
deuterium relative to the coexisting meteoric water (Taylor,
1974). All of the clay minerals analyzed by Savin and Epstein
(1970) were depleted in deuterium with respect to sea water,
including those which apparently formed in isotopic equilibrium
with the ocean. Most of their clay samples had δD values
between -50 and -80 per mil and $\delta^{18}O$ values between +13 and +29
per mil (Savin and Epstein, 1970).

Even if exchange between Rustler/Salado Interface groundwater
and clay minerals occurs, it is not a guaranteed mechanism to
account for the enriched water compositions. Given the range in
published values for clays, equilibrium fractionation between
clay and groundwater could leave the water depleted in oxygen -
18 and only slightly enriched in deuterium, relative to the
water's original composition. It is possible that clays
deposited in an evaporitic brine are enriched in heavy isotopes
and that exchange with such clays could enrich the coexisting
water. Exchange with other hydrous minerals, such as
polyhalite, is another possible enrichment mechanism. However,
relying on exchange between minerals and water to explain the
Rustler/Salado Interface isotopic composition will remain
tenuous until the isotopic composition of the matrix minerals is
determined.

Residence Time

The rate of water movement through the Rustler/Salado Interface has been interpreted as being extremely slow, especially in the eastern area where the enriched isotopic compositions occur (Mercer, 1983). Therefore, the period of contact between the water and the matrix minerals could be long enough for isotopic exchange to occur, even at relatively low temperatures. However, as discussed in the previous section, there are no isotope exchange reactions consistent with the Rustler/Salado Interface mineralogy that will assuredly enrich the water in both oxygen-18 and deuterium.

There is a rough correlation between Rustler/Salado potentiometric contours and stable isotope content. The heaviest group, including the data from H1, H2, H3, and H5 (Figure 8), all fall up-gradient from the 3100 foot contour on Mercer's (1983) map (Figure A-1 in Appendix A). A more meaningful correlation is the coincidence between all of the Rustler/Salado points that fall on the meteoric water line on Figure 8 (P14, W-25, 26, 27, 28, 29, and 30) and the zone of "active circulation" on Mercer's (1983) water-quality map (Figure 10). Mercer's boundary between the more-developed flow system to the west and the less-developed to the east is given strong support by the isotopic data.

Evaporation During Recharge

Water that has undergone evaporation exhibits a similar oxygen-18 and deuterium enrichment as displayed by some of the groundwater from the Rustler/Salado Interface. The trend away from the meteoric water line may reflect evaporation of recharging water as it moves through the unsaturated zone. If evaporation is the explanation for the heavy-isotope enrichment, this implies either a different recharge area or different
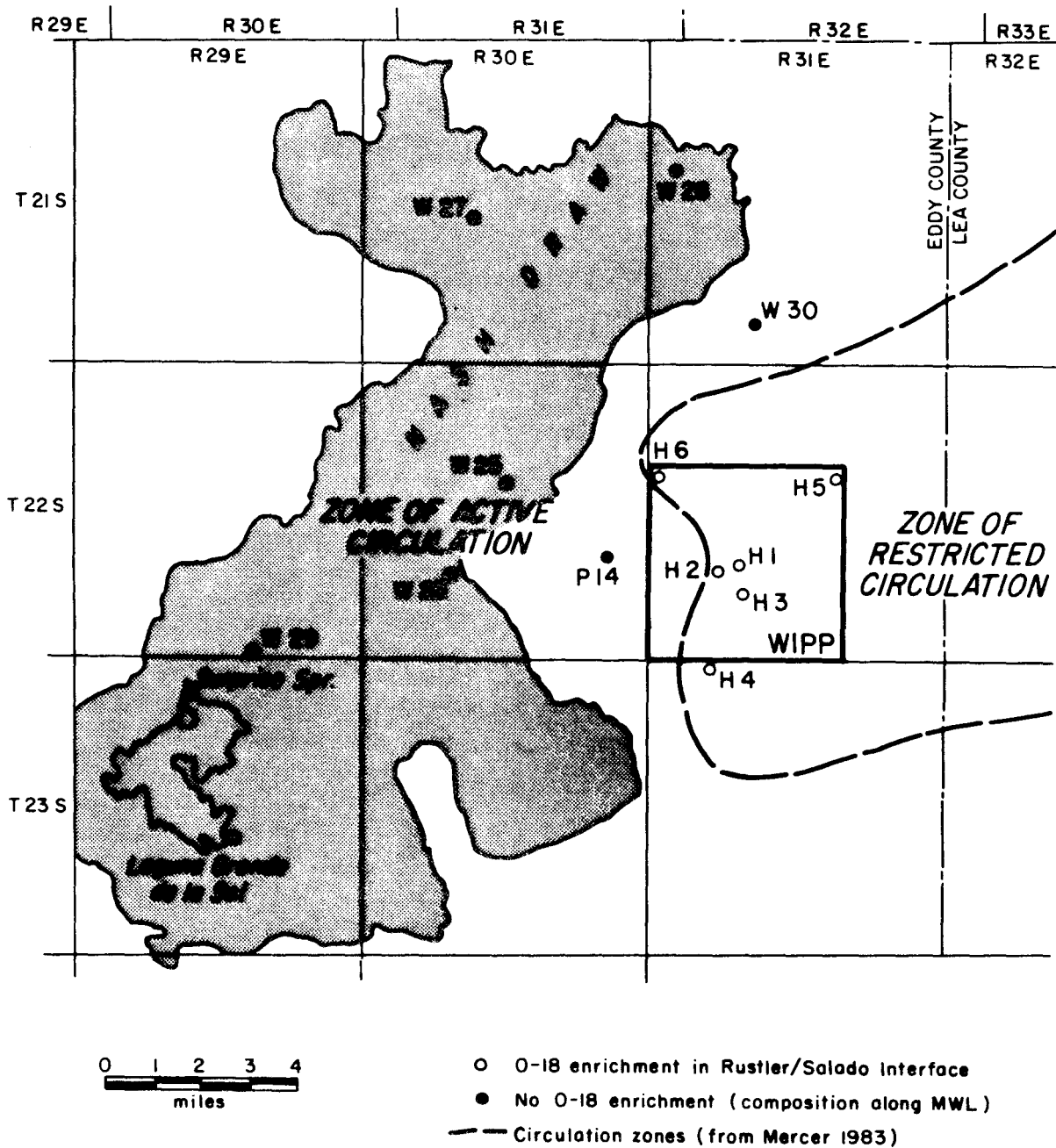
Figure 10. Stable isotope interpretations superimposed on Mercer's (1983) division of the Rustler/Salado Interface groundwater flow system. Adapted from Mercer (1983).

recharge conditions (perhaps temporally controlled) for the eastern Rustler/Salado Interface groundwater compared to the non-enriched Rustler samples. A different recharge area need not be a great distance away; slight differences in geomorphology and sediment type can have a large impact on the isotopic characteristics of recharge (Allison et al. 1985; Stephens, 1985).

Though evaporation of recharging water could account for the heavy-isotope enrichment of the eastern Rustler/Salado Interface brines, it is difficult to infer a recent meteoric origin for these samples. Though the trend of these data back toward the meteoric water line suggests a meteoric origin, the least-squares best-fit line through the Rustler/Salado Interface heavy-isotope enriched points leads to a source water on the meteoric water line with an approximate composition of $\delta D = -74$ and $\delta^{18}O = -10$ (Please note that the best-fit line shown on Figure 9 includes data in addition to that from the Rustler/Salado Interface). This source composition is within the range of presently observed precipitation (discussed in a following section), but it is considerably more depleted in heavy isotopes than the Rustler groundwater that is clustered about the meteoric water line.

The lighter source water could be explained by recharge either during the cooler season or from heavy rainfalls depleted in heavy isotopes, but this explanation seems contradictory to the evaporation during recharge needed to account for the deviation from the meteoric water line. The most simple explanation is that these waters were recharged at some time in the past when the mean isotopic composition of rainfall was more depleted in the heavy isotopes of oxygen and hydrogen than today, and that the water has had a long residence time during which its

39

isotopic composition has changed either due to rock/water
interaction or mixing of different waters.

Mixing With Heavy-Isotope Enriched Water

Mixing with a remnant evaporitic brine could produce a water
enriched in heavy isotopes. However, the Rustler/Salado
Interface samples do not lie on a mixing line between the non-
enriched Rustler groundwater and an evaporation window leading
from a range of the isotopic composition of seawater (Figure 9).
A range of seawater is shown on Figure 9 because Permian
seawater may have been slightly depleted in heavy isotopes
relative to modern seawater due to melting of the polar ice
caps. Complete melting of all ice sheets could lower the $\delta^{18}O$
value of seawater to -1‰ and the δD to -10‰ (Taylor, 1974). The
maximum evaporative enrichment of seawater in $\delta^{18}O$ is probably
near +6‰, limited by back exchange between the brine and
atmospheric water vapor (Lloyd, 1966).

The remnant evaporitic brine would not necessarily have to be a
simple evaporated seawater brine. Based on the isotopic
composition of fluid inclusions from the Permian-age San Andres
salt in the Palo Duro Basin, Knauth and Beeunas (1985 and 1986)
concluded that the salt precipitated from a mixed meteoric-
marine evaporative brine. A modern example of such a mixed
continental/oceanic system in the coastal salt pans of the
Salina Ometepec, Baja California, contains brines with similar
isotopic compositions to the Palo Duro Basin fluid inclusions
(Knauth and Beeunas, 1985; Kreitler et al, 1984). Mixing
between the meteoric Rustler water and remnant brine with a
mixed meteoric-marine evaporative isotopic composition could
produce enriched brines similar to the eastern Rustler/Salado
Interface brines. However, water in the Rustler/Salado
Interface probably does not represent anything approaching pure
Permian water. The nature of the Interface (a contact residuum

40

from the dissolution of evaporites) and the trend of these data back toward the meteoric water line suggests that flushing of original fluids has occurred.

The trajectory of the enriched Interface samples points through the isotopic composition of fluid inclusions from the Salado Formation (O'Neil et al. 1986) toward the very enriched brine samples collected from brine reservoirs in the Castile Formation (Figure 9). This trend has been discussed by Roedder (1984) and O'Neil and others (1986), though the trend now appears stronger with the addition of Lambert's (1986) data. O'Neil and others (1986) conclude that the isotopic trend reflects mixing between evaporated Permian seawater (perhaps in the form of gypsum dehydration water) and later meteoric water possibly introduced during salt recrystallization. Though Roedder (1984) agrees that mixing is one interpretation of the data. he suggests that the trend in the Salado fluid inclusion data may represent deposition in a mixed meteoric/marine Permian environment. such as postulated by Knauth and Beeunas (1985 and 1986) for the Palo Duro Basin.

The trajectory of the Rustler/Salado Interface data on Figure 9 cannot be due simply to deposition in a mixed meteoric/marine Permian environment because the interface is the result of post-Permian dissolution of salt by meteoric water. The trend indicates that either the Rustler/Salado Interface water has mixed with a Castile-like brine or that the Interface water is undergoing a similar isotopic evolution as the deeper brines. Both of these hypotheses are complicated by the radically different major ion chemistries (particularly SO_4. Mg. and K) in the Rustler/Salado Interface and the Castile (Table 4). However. mineral precipitation/solution might account for the ion discrepancies in the mixing model. and the isotopic and

41

Table 4

Chemical Analyses of Groundwater from the Castile Formation and the Rustler/Salado Interface East of Livingston Ridge

| | Castile | Castile | Castile | R/S | R/S | R/S | R/S | R/S | R/S | R/S |
Formation / Well	ERDA-6	ERDA-6	WIPP-12	H1	H2	H3	H4	H5	H6	P14
TDS (mg/L)	321,000	330,000	328,000	325,000	311,000	326,000	320,000	411,000	315,000	313,000
Cl^- (mg/L)	186,100	170,000	178,000	210,000	200,000	210,000	210,000	290,000	200,000	180,000
$SO_4^=$ (mg/L)	16,000	16,000	18,000	520	1,300	370	1,400	2,000	2,000	10,000
HCO_3^- (mg/L)	1,310	2,600	2,700	675	199	467	1	300	-	220
Ca^{++} (mg/L)	130	490	350	13,000	9,200	18,000	8,300	2,100	4,200	570
Mg^{++} (mg/L)	350	450	1,800	30,000	25,000	25,000	27,000	82,000	21,000	1,200
Na^+ (mg/L)	112,000	112,000	138,000	56,000	66,000	59,000	66,000	14,000	80,000	120,000
K^+ (mg/L)	5,100	3,800	2,900	17,000	9,100	14,000	8,600	21,000	8,000	13,000
Source	Lambert '78	Popielak, '83	Popielak '83				Mercer '83			Salado fluid

42

major solute evolution paths do not have to be identical in the evolution model. Considering the large uncertainty in the cause of the isotopic enrichment of the Castile brine (O'Neil et al, 1986; Popielak et al, 1983; Lambert, 1978) and the lack of application of some of the Castile-enrichment hypotheses to the Rustler/Salado Interface (e.g. gypsum hydration water), the mixing of deeper brine and meteoric water seems the best explanation for the Rustler/Salado Interface isotopic compositions. The mechanism of this mixing could be related to the slow movement of water through approximately two thousand feet of low-permeability evaporites, or to a major salt recrystallization event, or to a tectonic event that produced conduits for flow in the form of fractures. It should be noted that the isotopic composition of Salado fluid inclusions analyzed by Knauth and Beeunas (1986) do not plot on the Rustler/Salado Interface-Castile brine mixing line. There are apparently at least two types of isotopically distinct water in inclusions, perhaps related to the two groups of fluid inclusions identified by Stein and Krumhansl (1986) on the basis of major ion composition.

Isotopic exchange between minerals and water (coupled with a long residence time), evaporation during recharge, and mixing with enriched brine could all produce the heavy-isotope enrichment observed in some of the Rustler/Salado Interface samples. Given the lack of a well-defined recharge area and the low permeabilities encountered in the eastern part of the Rustler/Salado Interface (Mercer, 1983), exchange and mixing seem more likely to be the cause of the enrichment than evaporation. Whatever the cause of the enrichment in heavy isotopes, the Rustler/Salado groundwater from the eastern part of the study area does not seem to be closely related to modern meteoric water in the area.

The Culebra and Magenta Dolomites

Of the water from the Culebra and Magenta dolomites, only the groundwater from the Culebra in wells P-18 and W-29 plot outside the area defining the typical non-enriched Rustler isotopic composition. The measured hydraulic properties in the Culebra, which identify P-18 as having the lowest transmissivity, and the dolomite composition of the Culebra, suggest that the isotopic deviation of P-18 is probably due to water-rock interaction. Considering the aquifer matrix, oxygen-isotope exchange between the groundwater and dolomite is the most reasonable reaction. Both P-17 and P-18 are within Mercer's (1983) zone of restricted circulation in the Culebra (Figure 11). Well P-17 shows a slight oxygen-18 enrichment, and it may be that P-17 belongs outside the typical Rustler group. There are not enough isotopic data to either support or deny Mercer's (1983) division of the Culebra flow system. However, as discussed by Chaturvedi and Channell (1985, p. 37), recent hydrologic tests have revealed high transmissivities within the "zone of restricted circulation", indicating that the previous division of the flow system is not valid.

Well WIPP-29

The location of WIPP-29 within the zone of active circulation in Nash Draw and the very shallow water level measured in this well (8.2 ft below the surface, Mercer, 1983), indicate that evaporation is a probable cause for this sample's deviation from the MWL. Though the top of the Culebra dolomite is actually four feet below the water level, the loss of core in the limestone above the Culebra indicates that the overlying limestone is fractured (SNL and USGS, 1979), and the Culebra and overlying units probably behave as a single hydrologic unit in the WIPP-29 area (Chaturvedi and Channell, 1985). As discussed earlier, evaporation-line slopes usually vary between 2.5 and 6 for surface water (Gat, 1981; Lloyd, 1966) and have been
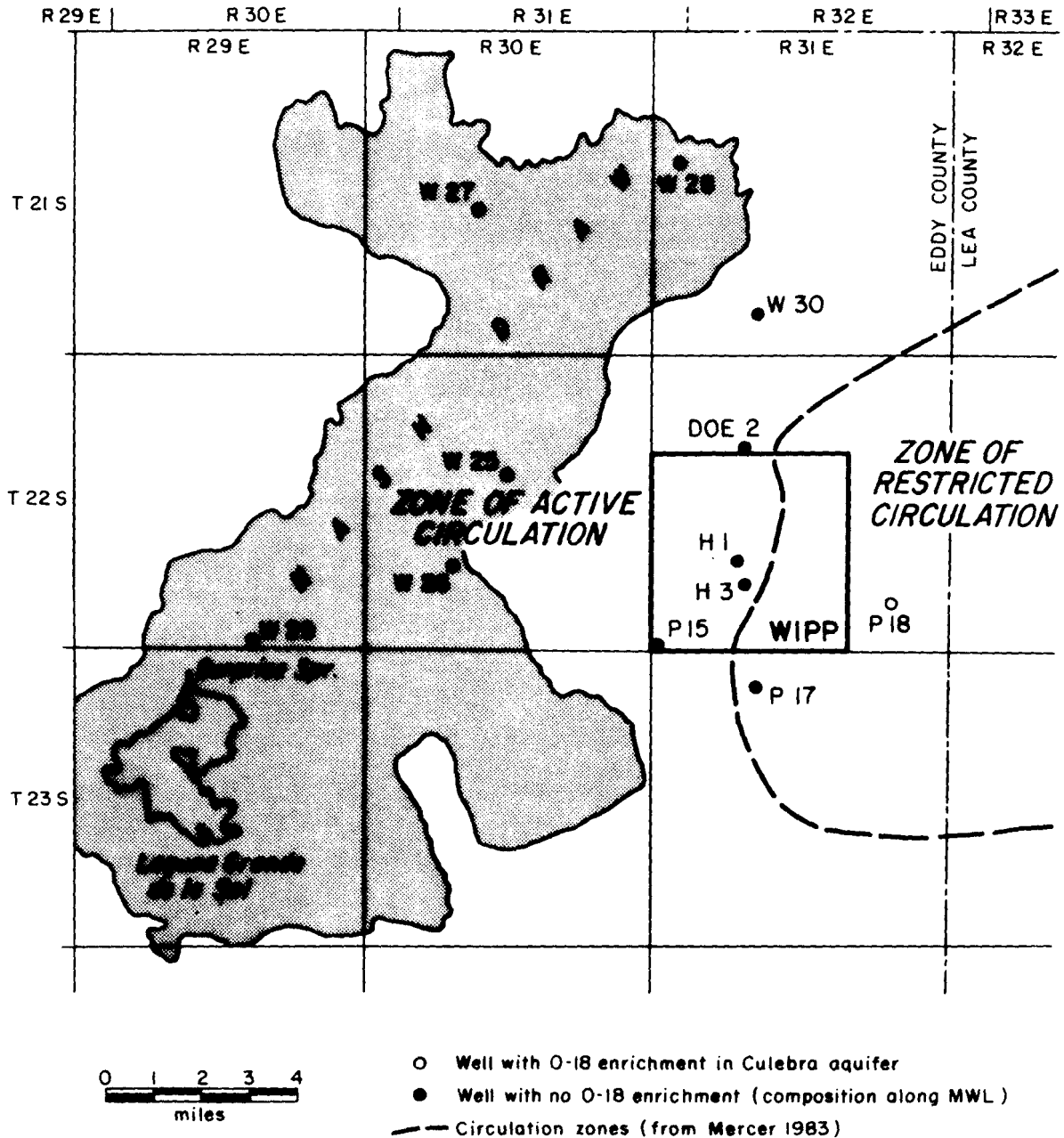
44

Figure 11. Stable isotope interpretations superimposed on Mercer's (1983) division of the Culebra flow system. Recent hydrologic tests have revealed high transmissivities within the "zone of restricted circulation", indicating that the division of the flow system is not valid. Adapted from Mercer (1983).

45

observed to be slightly lower for evaporation in the unsaturated zone (Allison, 1982). A postulated evaporation line leading from the Rustler grouping to WIPP-29 has a slope of 3.7, which lies in the smaller end of the range of usually observed evaporation-line slopes reported by Gat (1981) (Figures 4 and 8). The low slope is indicative of evaporation in a low-humidity, continental environment, such as is found in Nash Draw, and is consistent with the lower slopes observed for unsaturated-zone evaporation (Allison, 1982). The isotopic composition of WIPP-29 must be interpreted with caution due to the possibility of contamination of the Nash Draw area with potash-refining effluent and oil-field brine. Most of the water used for potash refining comes from the Ogallala Aquifer near Hobbs and would not cause an enriched heavy-isotope composition. Mixing between Rustler water and enriched oil-field brine similar to the samples from the Morrow Formation (Figure 9) could result in an isotopically heavy water; however, the dissolved solids in the mix would not be as high as the dissolved solids reported in the Culebra at WIPP-29 (Table 5).

Lambert (1986) believes that the WIPP-29 isotopic composition is evidence of a "profound hydraulic isolation of WIPP-29 from the rest of the Culebra." Though Lambert (1986) states that the isotopic composition of WIPP-29 can be derived by evaporating water with an isotopic composition representative of the Culebra, he discounts the evaporation mechanism because "...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" (Lambert, 1986). Though the water must be abundant

Table 5

Total dissolved solids content of groundwater in the Culebra member in WIPP-area wells and groundwater from the hydrocarbon-producing Morrow Formation in southeastern New Mexico

Rustler Formation Culebra Member

Well	H1	H2	H3	H4	H5
TDS (mg/L)	97,300	8900	51,600	18,200	144,000

Rustler Formation Culebra Member

Well	H6	H7	H8	H9	H10
TDS (mg/L)	52,000	3200	3000	3300	66,000

Rustler Formation Culebra Member

Well	P14	P15	P17	P18	W25
TDS (mg/L)	33,700	23,700	92,500	118,000	17,000

Rustler Formation Culebra Member

Well	W26	W27	W28	W29	W30
TDS (mg/L)	16,000	126,000	56,000	239,000	109,000

Morrow Formation

Well	Todd State	Todd Federal
TDS (mg/L)	35,600	92,400

47

enough to offset loss by evaporation (otherwise the water table
would be dropping), that does not preclude evaporation-induced
enrichment of the heavy isotopes in the residual water. The
situation of water flowing in the Culebra from an unknown
recharge point to the area around WIPP-29 where partial
evaporation takes place, and then on to its ultimate discharge
at Laguna Grande de la Sal, can be modeled as a constant volume
lake with both inflow and outflow. In this model:

$$\delta_L^{ss} = \bar{\delta}_{in} \frac{F_{in}}{F_{out}} - \bar{\delta}_E \frac{E}{F_{out}}$$

<div align="right">(Gat, 1981)</div>

with δ_L^{ss} = the steady state isotopic composition of the lake

$\bar{\delta}_{in}$ = the mean isotopic composition of the inflow

$\bar{\delta}_E$ = the mean isotopic composition of evaporation

F_{in}, F_{out} = the amount of flow in and out

E = the amount of evaporation

If evaporation is negligible, the steady state isotopic
composition of the lake approaches that of the inflow and no
enrichment in heavy isotopes occurs. However, as evaporation
becomes more important than outflow ($E > F_{out}$), the steady state
isotopic composition of the lake is increasingly modified from
that of the inflow. Therefore, though the lake volume remains
constant (with adequate inflow to offset evaporation loss), and
there is outflow from the lake, the lake can become enriched in
the heavy isotopes due to evaporation.

Applying this model to WIPP-29 reveals that the abundance of
water noted at WIPP-29 does not contradict heavy-isotope
enrichment by evaporation. The large dissolved solids content

at WIPP-29 Culebra, relative to the rest of the Culebra, also supports an evaporation hypothesis (Table 5). Given the shallow depth to groundwater at WIPP-29, partial evaporation in the unsaturated zone is the most likely cause of the observed isotopic enrichment. The stable isotope content of groundwater from WIPP-29 is consistent with the existence of a hydraulic connection between the Culebra at WIPP-29 and the Culebra elsewhere in Nash Draw and to the east.

Summary

The Rustler Formation groundwater shown in Figure 8 falls into two distinct groups of water. There is a group that closely parallels the MWL, collected from active flow systems in the Rustler Formation. The second group deviates substantially from the MWL, being enriched in oxygen-18 and deuterium. The enriched samples come from areas of restricted circulation or high evaporation and presumably reflect mixing with enriched brine, interaction between the water and rocks, or evaporation of water in the unsaturated zone. The isotopic compositions of the Rustler samples that plot along the meteoric water line do not indicate a long residence time for the water, as would be indicated if there was an enrichment in the heavy isotopes due to exchange with the aquifer matrix. Considering that the matrix is dolomite, enrichment of the water in oxgen-18 would be expected if there were long residence times and a large rock-to-water ratio. The lack of enrichment does not prove, however, that the water was recharged under current climatic conditions. Modern precipitation and verifiably young groundwater in the area must be examined to evaluate if the isotopic composition of Rustler groundwaters could be derived from modern meteoric recharge.

STABLE ISOTOPES IN PRECIPITATION, SURFACE WATER, AND OTHER GROUNDWATER IN THE AREA

Precipitation

The isotopic composition of samples of precipitation in southeastern New Mexico is presented in Figure 12. The samples from the WIPP site and from Carlsbad are grab samples from individual storm events. Likewise, the snow samples from Sierra Blanca (on the western border of the Roswell Basin) are also grab samples (Hoy and Gross, 1982). The Roswell precipitation data are monthly or bimonthly composites collected at the Roswell National Oceanographic and Atmospheric Administration weather station (Hoy and Gross, 1982).

The data plotted from Hoy and Gross (1982) include only those samples for which both oxygen-18 and deuterium measurements were made. In addition to these data, Hoy and Gross (1982) analyzed oxygen-18 for monthly composites of precipitation for three years. These data were weighted according to volume of precipitation and a weighted mean δO-18 composition for precipitation at Roswell was computed (Hoy and Gross, 1982). This weighted mean is also plotted on Figure 12, estimating the corresponding δD value from the local meteoric water line.

The weighted mean isotopic composition for precipitation at Roswell is relatively enriched in the heavy isotopes compared to the range of values. This reflects the season of maximum rainfall (Figure 5). Moisture in southeastern New Mexico originates in both the Pacific and the Gulf of Mexico; however, the isotopically heavier Gulf moisture predominates in the summer months, when the majority of rainfall occurs (Tuan et al. 1973).
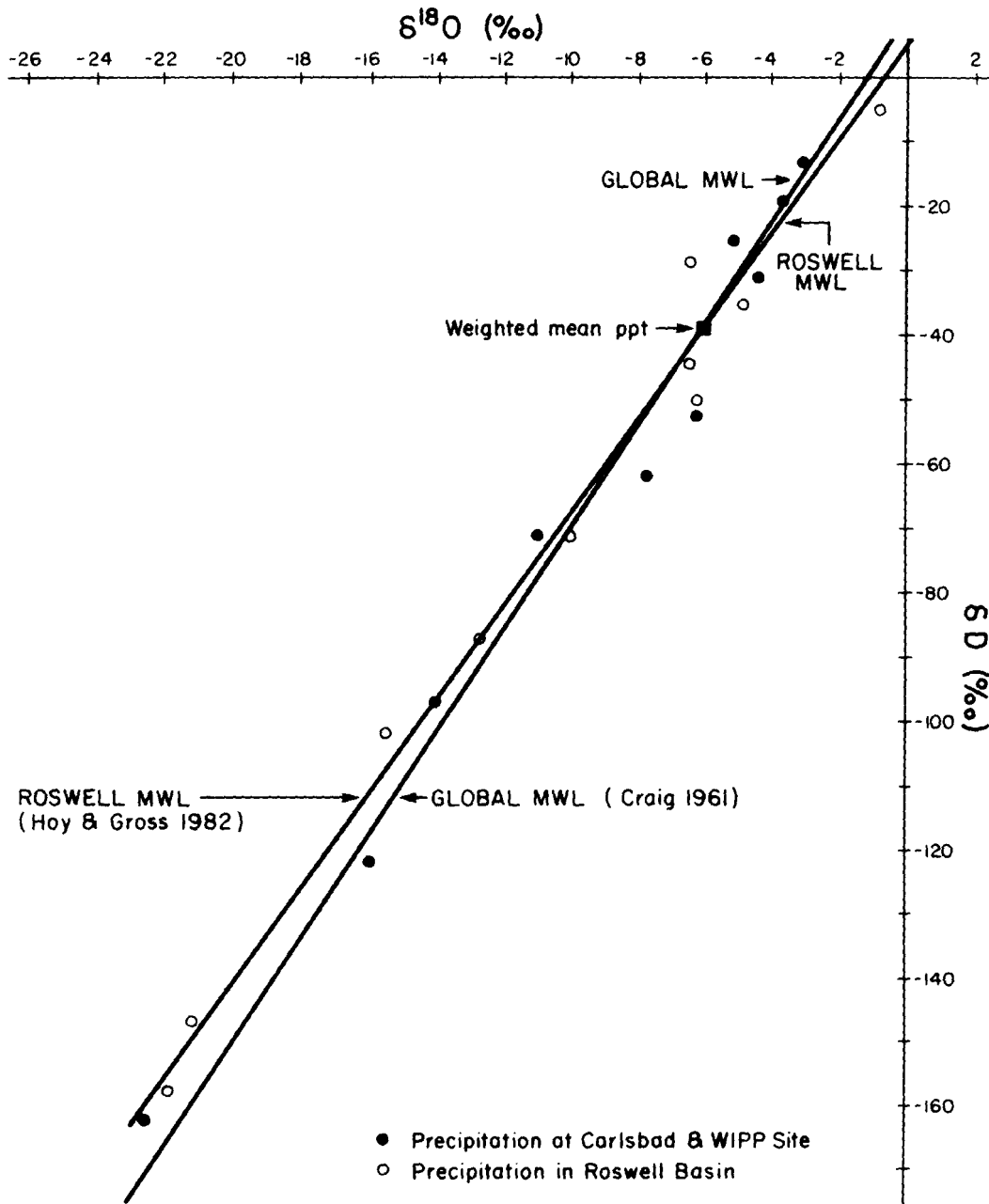
Figure 12. Plot of δD vs $\delta^{18}O$ for precipitation at Carlsbad, the WIPP Site, and in the Roswell Basin. Hoy and Gross (1982) calculated the local meteoric water line for the Roswell Basin and the weighted mean precipitation value for the town of Roswell. Data are listed in Table 3.

51

The isotopic composition of isolated precipitation events in Carlsbad and at the WIPP site falls in a range that coincides well with observed rains and snows in the Roswell Basin. The snow samples collected in Carlsbad exhibit the same extreme depletion in heavy isotopes that is seen in the snow samples from Sierra Blanca, while the summer rain is enriched in heavy isotopes similar to the summer rain in Roswell.

The global meteoric water line shown on Figure 12 was established by Craig (1961) on the basis of about 400 meteoric water samples collected worldwide. The line is defined by:

$$\delta D = 8\delta^{18}O + 10 \qquad \text{(Craig, 1961)}.$$

Since the global line was identified, it has been noted that different areas of the world have unique δD-axis intercepts and occasionally different slopes than the global meteoric water line. The meteoric water line in North America is defined by a line with a slope similar to the global line, but with an intercept of 6 ± 3 rather than 10 (Yurtsever and Gat, 1981).

Using data from precipitation, groundwater, and surface water in the Roswell Basin, Hoy and Gross (1982) identified a local meteoric water line described by:

$$\delta D = 7.27\ (\pm\ 0.38)\ \delta^{18}O + 5.36\ (\pm\ 1.25).$$

According to Hoy and Gross (1982), the difference between Craig's (1961) line and the Roswell data may not be statistically significant. If significant, the minor departure of the Roswell Basin data from the global meteoric water line may be due to a slight evaporation effect. A least-squares linear regression through the data from the random precipitation sampling in the Delaware Basin (Carlsbad and the WIPP site) gives a line defined by:

$$\delta D = 7.54\ \delta^{18}O + 5.07$$

with a correlation coefficient of 0.989. Though not based on a

statistically sound sample distribution, there appears to be a similarity in the $\delta D/\delta^{18}O$ relationship between meteoric water in the Delaware and Roswell Basins. This suggests that if there is any slight evaporation effect on the isotopic composition of rainfall, it is similar in both basins.

Groundwater

In many areas, the isotopic composition of meteoric groundwater approximates the mean composition of precipitation over the recharge area (Gat, 1981). However, some groundwater is either more enriched or more depleted in heavy isotopes than the mean composition of local rainfall. Such differences are often larger under more arid conditions and are usually the result of the recharge process (Gat, 1981). In order to determine the isotopic composition of water that actually infiltrates to recharge aquifers in arid areas, it is useful to sample shallow groundwater that can be proven to receive modern recharge. The presence of modern recharge can be determined by radiometric age dating (principally using tritium), or by observing fluctuating water-table levels with variations in rainfall. Unfortunately, no indisputably young groundwater has been identified in the immediate WIPP area. However, groundwater in the Roswell Basin has been dated with tritium and can be documented as receiving recharge within the last thirty years (Hoy and Gross, 1982). In addition, water found in pools in Carlsbad Caverns is generally considered to come from the infiltration of modern precipitation on outcrops (Lambert, 1986).

Roswell Basin

The isotopic compositions of groundwater and surface water in southeastern New Mexico are plotted on Figure 13, along with the outline of the non-deviated Rustler samples and the weighted mean precipitation point from Hoy and Gross (1982). The
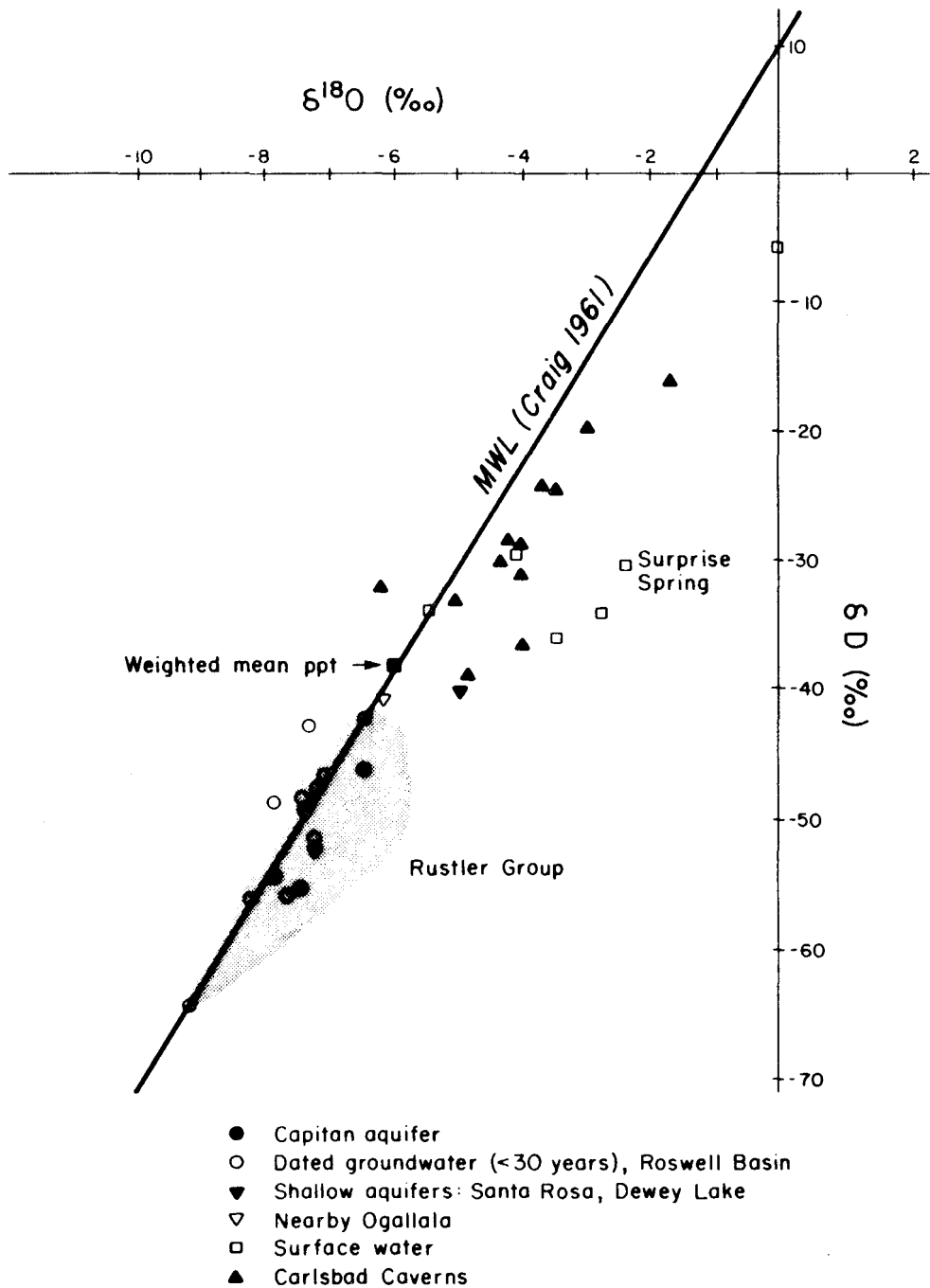
Figure 13. Plot of δD vs $\delta^{18}O$ for groundwater and surface water in southeastern New Mexico. Rustler Formation water is not shown, but the area occupied by most Rustler groundwater is shaded. The Roswell Basin groundwater has been dated with tritium as receiving recharge within the last thirty years. The data are listed in Table 3.

54

coincidence between the isotopic composition of the verifiably young Roswell Basin groundwater and the composition of the Rustler water is striking (Figures 8 and 13).

The isotopic composition of the weighted mean precipitation in the Roswell Basin is somewhat enriched in heavy isotopes compared to groundwater from both the Roswell and Delaware Basins. The lighter composition of the groundwater relative to the weighted mean precipitation could be related to either, or both, of the following processes. First, though the majority of rainfall may occur in the summer, this is also the time of the highest evapotranspiration rate. Because of cooler temperatures, lower evaporation, and reduced plant activity, recharge from isotopically lighter winter precipitation may be favored over recharge from summer rain. A second possibility is that recharge in this arid area may occur primarily from intense, infrequent storms. Rainfall events with high total precipitation volumes are characterized by lighter isotopic compositions (Gat and Gonfiantini, 1981; Vogel, 1963). Therefore, the lighter isotopic composition of groundwater relative to the composition of weighted mean precipitation could be due to either a seasonal or an amount effect.

A similar discrepancy between the isotopic composition of groundwater and of the mean precipitation has been noted in the Kalahari Desert in southern Africa. Vogel and others (1963) found that groundwater in South Africa contained considerably less deuterium than either the area rain or river water. After confirming that low deuterium concentrations were associated with heavy precipitation, they concluded that the groundwater supply was not being continuously replenished by precipitation, but was recharged primarily from occasional heavy downpours

55

(Vogel et al., 1963). The possibility that the depleted
Kalahari groundwater was recharged in a previous climatic regime
by rain of a different isotopic composition than present was
contradicted by the C-14 ages of the groundwater (Mazor et al.,
1974).

Carlsbad Caverns

The isotopic composition of water from pools in Carlsbad Caverns
is markedly enriched in the heavy isotopes relative to the
composition of groundwater in units of the Rustler Formation
(Figure 13). This difference between the isotopic content of
water from the Caverns and groundwater from the Rustler is the
basis for Lambert's (1986) conclusion that the Rustler is not
receiving recent meteoric recharge. Lambert (1986) assumes that
the relatively heavy content of the Caverns' water is
representative of modern meteoric recharge in southeastern New
Mexico. However, the Caverns' water is more enriched than both
the mean precipitation and verifiably young groundwater in the
Roswell Basin, and therefore is not representative of all young
groundwater in the area.

The difference between the isotopic composition of the Roswell
Basin water and the Caverns' water could be attributed to the
influence of isotopically lighter high-altitude recharge in the
Roswell Basin. However, as discussed previously in greater
detail, Roswell Basin groundwater has an isotopic content
consistent with that of precipitation at low to intermediate
elevations in the basin. In addition, some of the data,
particularly from the alluvial aquifer in the Artesia area, are
from aquifers that receive major portions of their recharge by
direct infiltration of precipitation at low elevations and these
groundwaters are also substantially lighter isotopically than
the Caverns' water.

56

The heavy-isotope enriched nature of the Carlsbad Caverns' water may be related to the Caverns' unique hydrologic environment, in which recharge occurs on a karstic terrain and discharge is almost entirely by evaporation from seeps along the walls and from pools (Hendrickson and Jones, 1952). The recharge mechanism for the Caverns may favor isotopically heavy water, presumably by allowing the infiltration of more summer precipitation. National Park Service personnel at Carlsbad Caverns have observed increased dripping in the Caverns in the summer months, relative to the rest of the year, and have noted an increase in drip rate in the Big Room within a few weeks of large, sustained storms (Ron Kerbo, National Park Service, personal communication, 1986). The extreme karst conditions at the Caverns may allow rapid infiltration of all precipitation, whereas infiltration elsewhere in southeastern New Mexico may favor recharge during cooler months when evaporation is less effective or only during heavy storms.

The enrichment in heavy isotopes in water in Carlsbad Caverns could also be explained by evaporation from pools in the humid environment of the cave. Evaporation could also occur as the water moves through the 600 feet of unsaturated zone and as water slowly drips from and along speleothems. The humid environment of the cave (usually at 96% relative humidity in the main body of the cave; Ron Kerbo, National Park Service, personal communication, 1986) would result in a higher evaporation-line slope, leading back to an original isotopic composition for the water approximating that of the value for weighted mean precipitation. Indeed, an evaporation "window" leading from the value for weighted mean precipitation and outlined by evaporation-line slopes between 2.5 and 6, encompasses almost all of the Caverns' data (Figure 14). The data cluster about the higher slope (6) and are not markedly
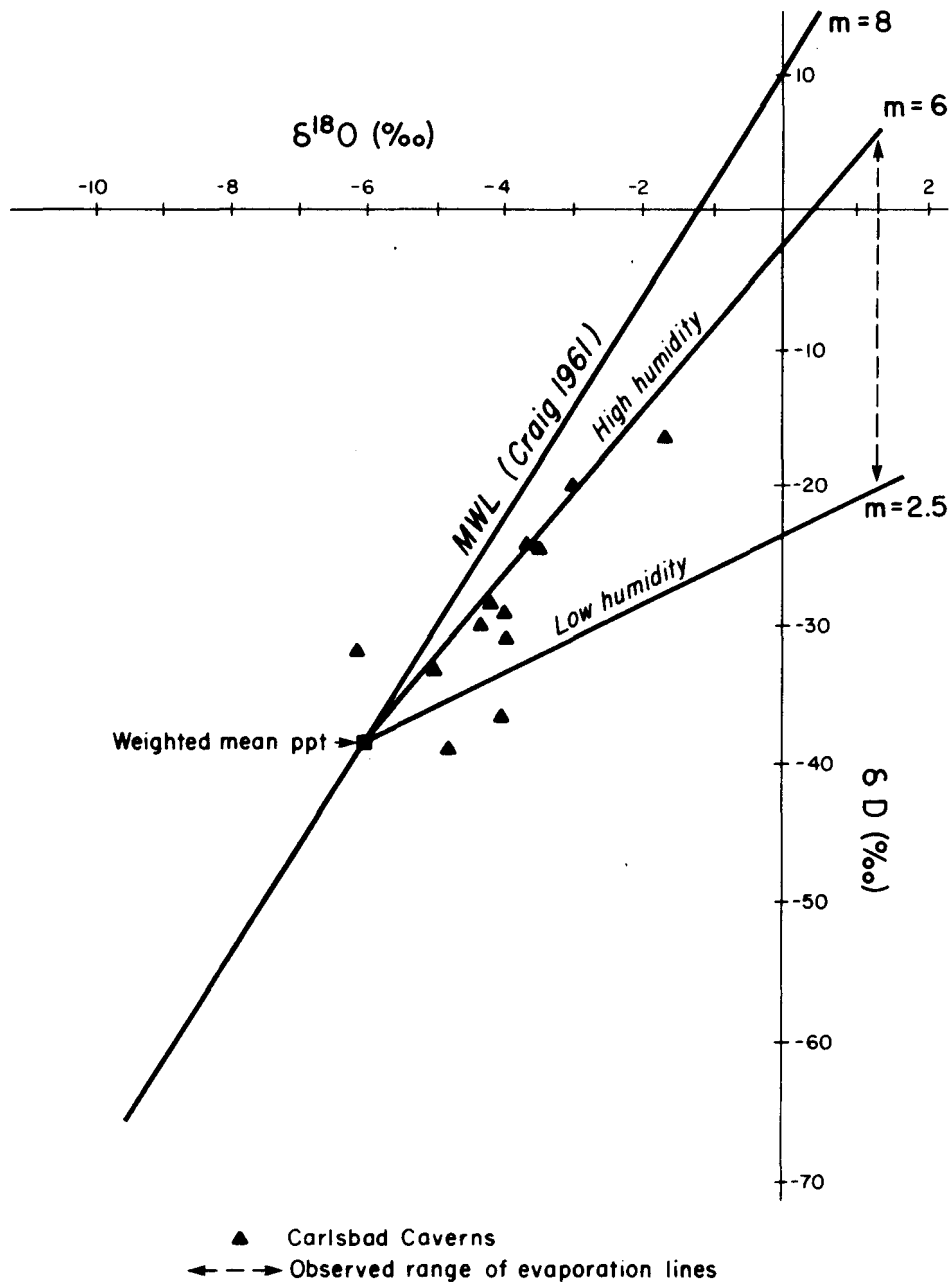
57

Figure 14. Plot of δD vs $\delta^{18}O$ for water from pools in Carlsbad Caverns, overlain by an evaporation window leading from the weighted mean composition of precipitation. The clustering of data about the higher slope is consistent with evaporation in the humid cave environment.

offset from the local meteoric water line observed by Hoy and
Gross (1982) (with a slope of approximately 7.3). This lack of
notable deviation from the meteoric water line reflects the fact
that when the relative humidity approaches 100%. an equilibrium
isotopic fractionation (exchange reaction) occurs between the
atmospheric moisture and the liquid (Gat. 1981). An equilibrium
isotopic exchange reaction between atmospheric moisture and the
liquid also occurs under lower relative humidity conditions. but
it is masked by the kinetic separation (non-equilibrium
component) resulting from fractionation during evaporation.

Ogallala Formation

Data from other groundwater in southeastern New Mexico are also
presented in Figure 13. though none of these waters have been
documented as receiving recent recharge. The isotopic data from
the Ogallala and the Dewey Lake (?) fall between the areas
defined by the Caverns and Rustler isotopic compositions. The
Ogallala point represents the composition of nine municipal
water systems in southeastern New Mexico that draw from the
Ogallala. The Ogallala receives recharge by direct infiltration
of precipitation and probably represents recent recharge. The
lighter isotopic composition of the Ogallala. compared to that
of water found in Carlsbad Caverns. further demonstrates that
the Caverns are not isotopically representative of all young
groundwater in southeastern New Mexico.

Dewey Lake Redbeds

The Dewey Lake (?) sample (question mark notation is from
Lambert. 1986) has unclear origins. Lambert (1978) reported
groundwater from the Rustler Formation (member unidentified).
collected from a well on the James Ranch. that had an isotopic
composition identical to the Dewey Lake (?) point (collected
from a well on the James Ranch) reported in Lambert (1986).

Presumably, the data reported for the James Ranch well in Lambert (1978) and Lambert (1986) are identical. The zone of completion of the James Ranch wells has been a matter of speculation, though a recent investigation concluded that rather than being completed in the Rustler, as previously thought, the wells were possibly completed in the Dewey Lake (Mercer, 1983).

The uncertainty of the sampled interval necessitates caution in using the Dewey Lake (?) data. The data plot toward the heavier end of the space between the Rustler and Caverns fields. If the water is from the Rustler, the distinction between the Rustler and Caverns isotopic compositions is much less distinct than interpreted by Lambert (1986). If the point is from the Dewey Lake, the age and history of the water are still uncertain. Because of its low permeability, the Dewey Lake is not known to contain significant amounts of groundwater and has no detected continuous zone of saturation (Mercer, 1983). The presence of moist cuttings was usually the only indication of groundwater in the Dewey Lake during drilling for WIPP-site hydrogeologic investigations (Mercer, 1983).

Santa Rosa Sandstone

The other aquifers in southeast New Mexico for which isotopic data are available are the Santa Rosa Aquifer and the Capitan Aquifer. The isotopic compositions of water from both of these units plot within the Rustler field on Figure 13. The Santa Rosa receives recharge directly from precipitation and possibly by groundwater flow from the overlying Ogallala Formation. The water in the Santa Rosa probably represents modern recharge, as does water in the Ogallala, and is similar isotopically to water in the Rustler.

Capitan Limestone

The data from the Capitan Aquifer also coincide with the composition range found for the Rustler groundwater and are lighter than Caverns' water. Lambert (1986) concluded that modern recharge is inhibited within the Capitan, just as he postulates recharge is inhibited in the Rustler. Though highly permeable, the recharge conditions to the Capitan east of the Pecos River are not well understood. However, one of the Capitan points is from Carlsbad City Well #7 (Lambert, 1978), located west of the Pecos River. The Capitan flow system west of the Pecos is well-developed in highly karstic limestone, receiving recharge on outcrops along the Guadalupe Mountains and discharging at large springs in the Pecos River (Hiss, 1975).

Surface Water

The isotopic composition of most of the surface water data (from lakes, springs, and the Pecos River) shows the effect of evaporation. The greater degree of oxygen-18 enrichment seen in the surface waters as compared to water from Carlsbad Caverns is due to the surface waters' evaporation in the semi-arid desert environment, resulting in a lower evaporation-line slope. Overlaying the evaporation "window" shown on Figure 4 onto the surface water points presented in Figure 13 results in evaporation lines for these river and spring points leading back to isotopic compositions that fall in the Rustler groundwater group.

Surprise Spring

It should be noted that the isotopic composition of the water from Surprise Spring could be obtained by the evaporation of Rustler groundwater (Figure 13). Therefore, based on the stable isotopes, Surprise Spring could be a discharge point for Rustler groundwater. Lambert (1986) has asserted that Surprise Spring

61

could not be derived isotopically from Rustler groundwater and that oxygen isotope shift (presumably due to water/rock reactions) may be responsible for the spring's composition. Given the spring's surface exposure, the aridity of the area, and the ability to draw reasonable evaporation lines from the Rustler isotopic composition to the Surprise Spring isotopic composition, evaporation of Rustler groundwater seems a more likely method of deriving the enriched isotopic composition of Surprise Spring than water/rock reactions. As discussed earlier, such water/rock isotopic exchange would be extremely slow at the relatively low temperatures encountered outside of geothermal areas.

Summary

It is clear from Figures 8 and 13 that most of the isotopic compositions of groundwater in southeastern New Mexico fall in the same range as that observed in the Rustler aquifers. It is important to note that the Roswell Basin waters have been dated, proving that they were recharged during current climatic conditions, and that these waters have the same range of stable isotopic compositions as the water from the Rustler Formation. The Roswell Basin water, as well as undated groundwater from the Ogallala, Santa Rosa, and Capitan Formations, all have isotopic compositions consistent with those measured in groundwater from the Rustler Formation. No groundwater in southeastern New Mexico has been found that has an isotopic composition within the range defined by water from Carlsbad Caverns. The Caverns' water appears to be closely related isotopically to surface water in the area. Both the Caverns' water and surface water has undergone evaporation, but the surface water exhibits more deviation from the meteoric water line because of evaporation in a lower relative-humidity environment.

CONCLUSIONS AND RECOMMENDATIONS

The isotopic compositions of most of the samples of groundwater from the Magenta and Culebra aquifers, and for the Rustler/Salado Interface Zone west of the WIPP site, are similar to that of other groundwater in southeastern New Mexico. The isotopic compositions of recently recharged, dated groundwater in the Roswell Basin, of water in the shallow, active Ogallala and Santa Rosa aquifers east of the WIPP site, and of the Capitan and Rustler aquifers in the Carlsbad area, are all lighter than the isotopic composition of water found in Carlsbad Caverns. The isotopic similarity between the aquifers indicates that all of the systems were recharged by isotopically similar waters produced by similar climatic conditions. Though the stable-isotope data in no way indicate absolute ages for water in the various aquifers, neither do they show any distinction between most Rustler groundwater and verifiably young groundwater.

Some groundwater samples can be argued to be part of relatively old, slow-moving groundwater systems. This distinction is based on an observed shift away from the meteoric water line and toward enrichment in the heavy isotopes. Most of the shifted samples are from the Rustler/Salado contact east of Nash Draw, and their positions agree favorably with Mercer's (1983) distinction between more- and less-developed flow systems in the contact. The waters' enrichment in heavy isotopes may be due to mixing with deeper groundwater (supported by the stable isotopic composition of Salado fluid inclusions and Castile brine) or to exchange between the groundwater and hydrous minerals. In contrast, it is significant that most of the Culebra and Magenta waters do not exhibit an oxygen-18 excess, indicating that the waters' residence time has not been long enough for isotopic exchange between the water and dolomite.

63

The isotopic compositions of water from WIPP-29 and from Surprise Spring can be derived by partially evaporating a water with an isotopic composition representative of water found in the Rustler aquifers. Therefore, the stable isotope data are consistent with the concept of discharge from the Rustler by evaporation in the unsaturated zone in the area of WIPP-29 and discharge by direct evaporation from Surprise Spring outflow.

The stable isotope data from water in southeastern New Mexico indicates that water from Carlsbad Caverns is not isotopically representative of groundwater recharge in the area. The isotopic composition of the Caverns' water is more similar to that of surface water in the area rather than groundwater. There are two possible explanations for the unique, heavy, composition of the Caverns' water. First, evaporation and equilibrium isotopic exchange in the humid environment of the cave could produce the Caverns' isotopic composition from a starting fluid with approximately the same isotopic composition as the area's weighted mean precipitation. Second, the Caverns may receive disproportionately more recharge from isotopically heavy summer rains than the aquifers in the area, perhaps due to the unique hydrologic system imposed by the extreme karst conditions.

There is currently no basis for concluding that the Rustler aquifers are not receiving significant amounts of modern meteoric recharge. The concept that the Rustler contains slow-moving, fossil water is not supported by the isotopic data except in the eastern part of the Rustler/Salado Interface. In fact, the isotopic similarity between the Rustler water and verifiably young groundwater in the area, and the lack of isotopic exchange between Culebra and Magenta water and the carbonate matrix, imply that there is a good possibility that the Rustler is currently receiving recharge.

64

Stable isotopes, though valuable tools in interpretive hydrology, are best applied in situations where the basic hydrology of the system is understood, but refinement of interpretations is desired. However, there are many uncertainties remaining concerning the physical hydrology of Rustler flow systems, especially in relation to recharge. Unfortunately, the question of recharge cannot be answered on the basis of stable isotopes alone.

Additional data on the isotopic composition of precipitation at the WIPP, of infiltrating precipitation, and of shallow, young groundwater in the area will certainly aid in the interpretation of the current data base. However, actual physical measurements of the flow system of the Rustler are probably the only way the amount and location of recharge to the Rustler can be defined. Such studies have been recommended and outlined by Hunter (1985) and include water-level measurements and sampling to determine the location of groundwater divides and measurements of infiltration in the unsaturated zone of suspected recharge areas. These studies should be conducted.

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APPENDIX A

Potentiometric Surface Maps (freshwater heads) for water-bearing zones in the Rustler (modified from Mercer, 1983).

A-1. Rustler-Salado Interface
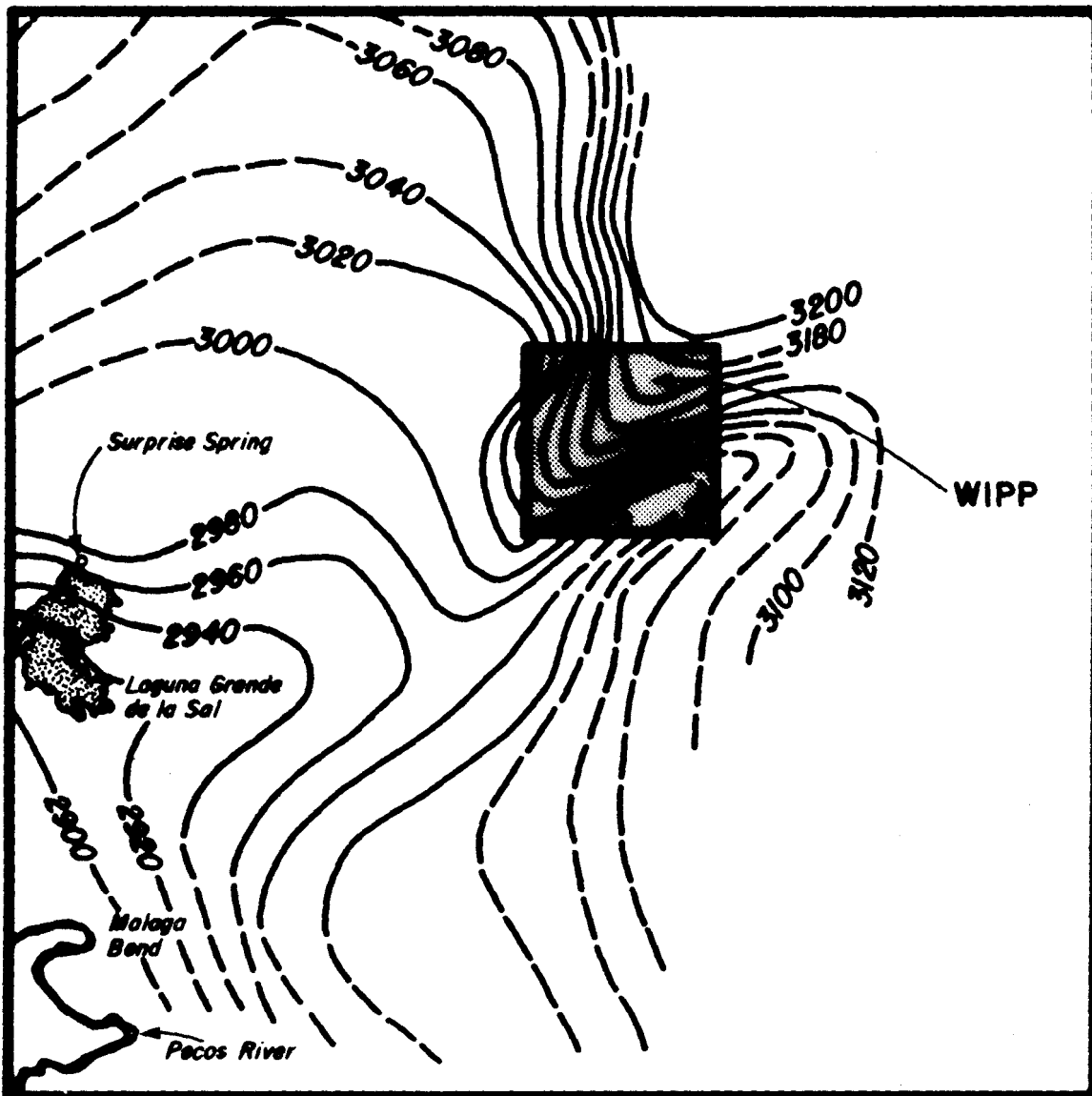
A-2. Culebra Dolomite

A-3. Magenta Dolomite
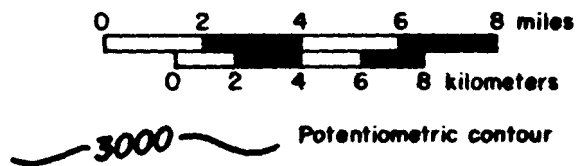
Figure A-1. Adjusted potentiometric contours of the Rustler/Salado contact residuum (modified from Mercer, 1983).
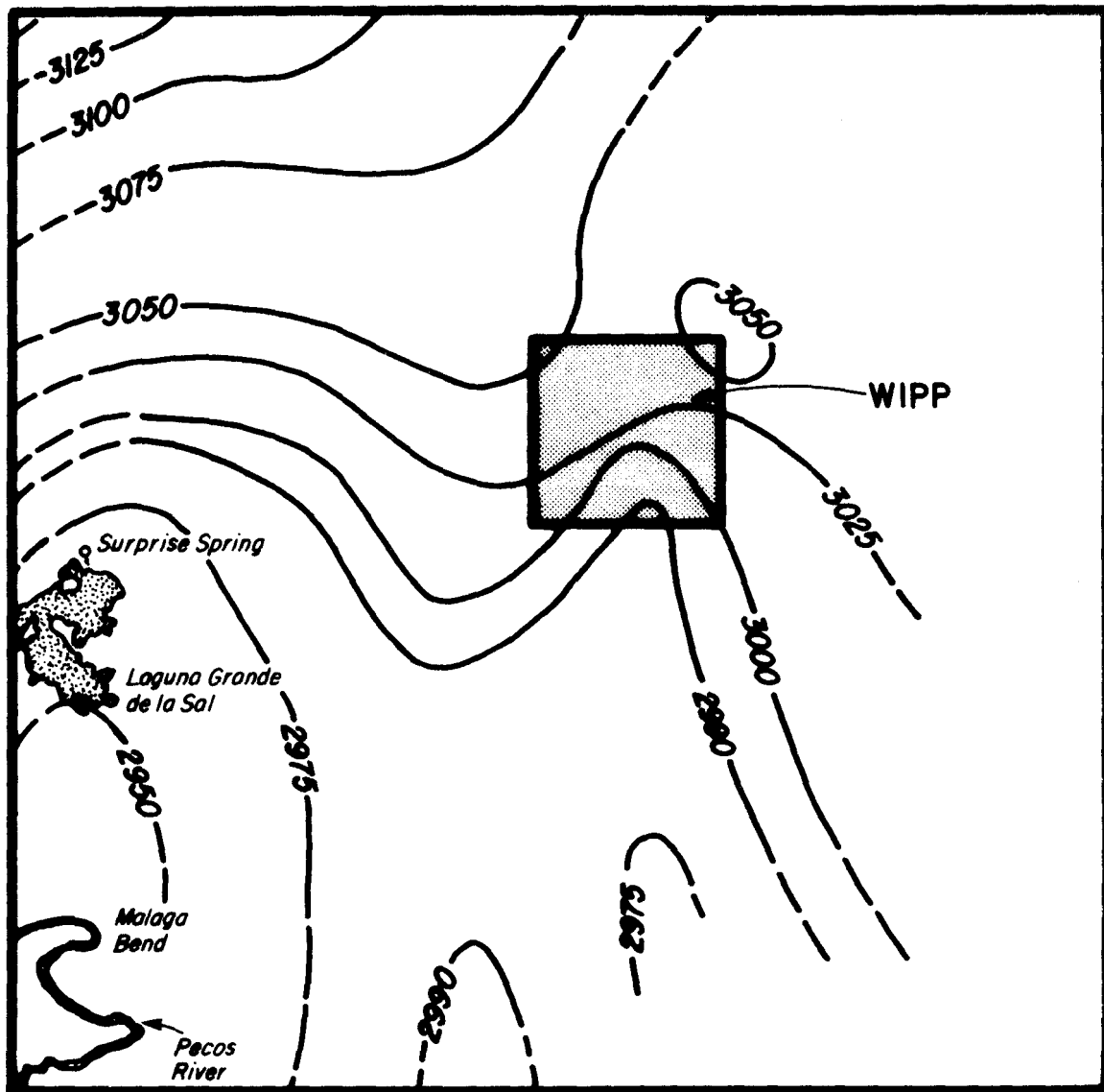
Figure A-2. Adjusted potentiometric contours of the Culebra Dolomite Member of the Rustler Formation (Modified from Mercer, 1983).
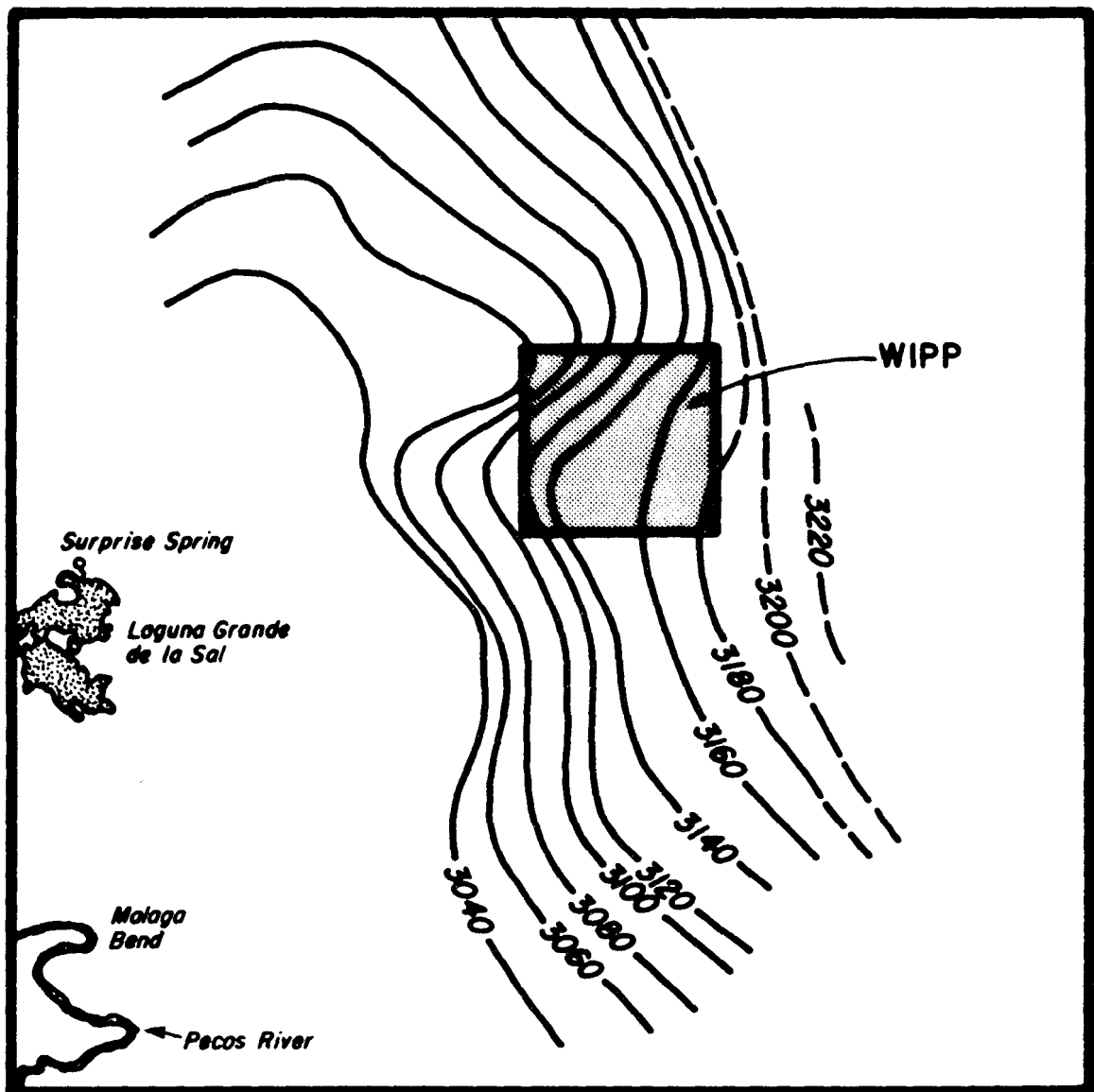
Figure A-3. Adjusted potentiometric contours of the Magenta Dolomite Member of the Rustler Formation (modified from Mercer, 1983).