A BASELINE STUDY OF OXYGEN 18 AND DEUTERIUM IN THE

ROSWELL, NEW MEXICO, GROUNDWATER BASIN*

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Partial Technical Completion Report
Project No. B-059-NMEX

May 1982

New Mexico Water Resources Research Institute
in cooperation with the
Geophysical Research Center
New Mexico Institute of Mining and Technology

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ABSTRACT

The isotopic ratios of deuterium and oxygen 18 were measured in pre-
cipitation, surface, and groundwater samples from the Roswell Artesian
groundwater basin in south-central New Mexico. The purpose was to deter-
mine recharge and circulation patterns. The results would supplement
earlier studies based on tritium ratios and hydrogeologic surveys. The
study area comprises about 8000 square miles with elevations ranging from
3,400 ft a.m.s.l. to almost 12,000 ft. Except for minor deviations due
to evaporation, the samples measured for this study conform to the
meteoric water line. No exchange reactions with aquifer rock seem to
have taken place. While the δD vs. $\delta^{18}O$ values of precipitation are spread
over the whole usual range of the meteoric water line, well and spring
samples (reflecting groundwater) lie within a relatively narrow range
($\delta D = -30^{o}/oo$ to $-80^{o}/oo$ and $\delta^{18}O = -60^{o}/oo$ to $-10^{o}/oo$, all with respect
to Standard Mean Ocean Water). Exceptions outside of this range are minor
and can be attributed to evaporation effects. Well waters of the
Principal Artesian Aquifer average $\delta D = -51^{o}/oo$, $\delta^{18}O = -8^{o}/oo$. The
narrow range of δD and $\delta^{18}O$ indicates mixing effects which are ascribed
to one or more of the following factors: long groundwater flow paths; large
temperature fluctuations affecting all parts of the Basin and which over-
whelm the influence of elevation on precipitation, especially in summer;
two sources of atmospheric moisture (Gulf of Mexico and Gulf of California);
interaquifer leakage; and recharge from intermittent streams with the flow-
length expanding and contracting over large distances (tens of miles) de-
pending on climatic conditions. Groundwaters in the southern part of the
Basin seem to be, on the average, heavier in oxygen 18 by one per mil as

compared to those from the northern part. This may reflect a larger contribution of high-mountain runoff in the north. It is concluded that a more precise definition of circulation patterns on the basis of stable isotope differences will require a much greater sampling frequency in both space and time, as well as a more sophisticated statistical evaluation of the results than was possible in this preliminary baseline study of a very large basin.

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Dr. Gary Landis and Mr. H. R. Northrop of the Geology Department, University of New Mexico, did most of the deuterium analyses used in this work. On repeated occasions, we were privileged to confer with them and observe them at work in their excellent laboratory. All of the oxygen 18 analyses, and a small number of deuterium tests, were performed by Geochron Laboratories of Cambridge, Massachusetts.

PROBLEM STATEMENT

A continued investigation of the Roswell artesian groundwater basin has furnished evidence of complex groundwater recharge and circulation patterns. Tritium activity in groundwater from many sampling points located in all parts of the Basin have been carried out over the last 25 years. They suggest that groundwater in the Basin is made up of "fast" and "slow" recharge components. The former consist of direct recharge from downward percolating precipitation or streamloss. "Slow" recharge is believed to originate as precipitation along the Sacramento mountain front and is transmitted into the Basin proper by a variety of pathways (upward leakage from deep formations, springs discharging into streamchannels and subsequent streamchannel loss, lateral percolation through an unconfined aquifer). In addition to a regional aquifer system (regional water table and piezometric surface) one or more systems of perched localized aquifers have been recognized. They are the source of a large number (perhaps the majority) of springs in the Sacramento Mountains and along the mountain front and seem to play a major role in the recharge process.

The stable isotopes oxygen 18 and deuterium, which form part of the water molecule, undergo fractionation as atmospheric (meteoric) water condenses to form precipitation and then runs off along the surface of or percolates through the ground. Exchange processes between groundwater and aquifer rock may also alter the

stable isotope makeup. Thus, the stable isotope composition may give important clues concerning the environment and climatic characteristics of groundwater formation and history of groundwater flow.

The purpose of this work was to establish baseline criteria for such a study and to attempt a broad interpretation of the data.

The detailed objectives will be introduced in the section on Stable Isotope Approach to Hydrology.

THE ROSWELL GROUNDWATER BASIN

Geography

The Roswell Groundwater Basin, as defined here, covers approximately 8000 square miles in Chaves, Eddy, Lincoln, and Otero counties in southeastern New Mexico (Figure 1). On the north and south it is somewhat arbitrarily bounded by Arroyo del Macho and Seven River Hills, respectively, and more distinctly bounded on the east and west by the Pecos River and the crest of the Sacramento Mountains, respectively (Figure 2).

Three relatively distinct geographic zones are crossed in travelling from east to west in the basin. The most heavily populated and water dependent region with the city of Roswell (the Chaves County seat), is a narrow strip of approximately 1500 square miles on the west bank of the Pecos River, which is the basin's major drainage. At this zone's average elevation of 3400 feet, the mean annual air temperature is 58°F (15°C). Precipitation, averaging on the order of 10 inches per year, falls mostly in small, intense thundershowers in the summer months. This region grades into a long rangeland slope, covering the largest part of the basin, approximately 4500 square miles, up to the Sacramento Mountains. Three major tributaries of the Pecos River cut almost due east across this section from their sources in the most western, mountainous and forested geographic zone (Sacramento Mountains/Sierra
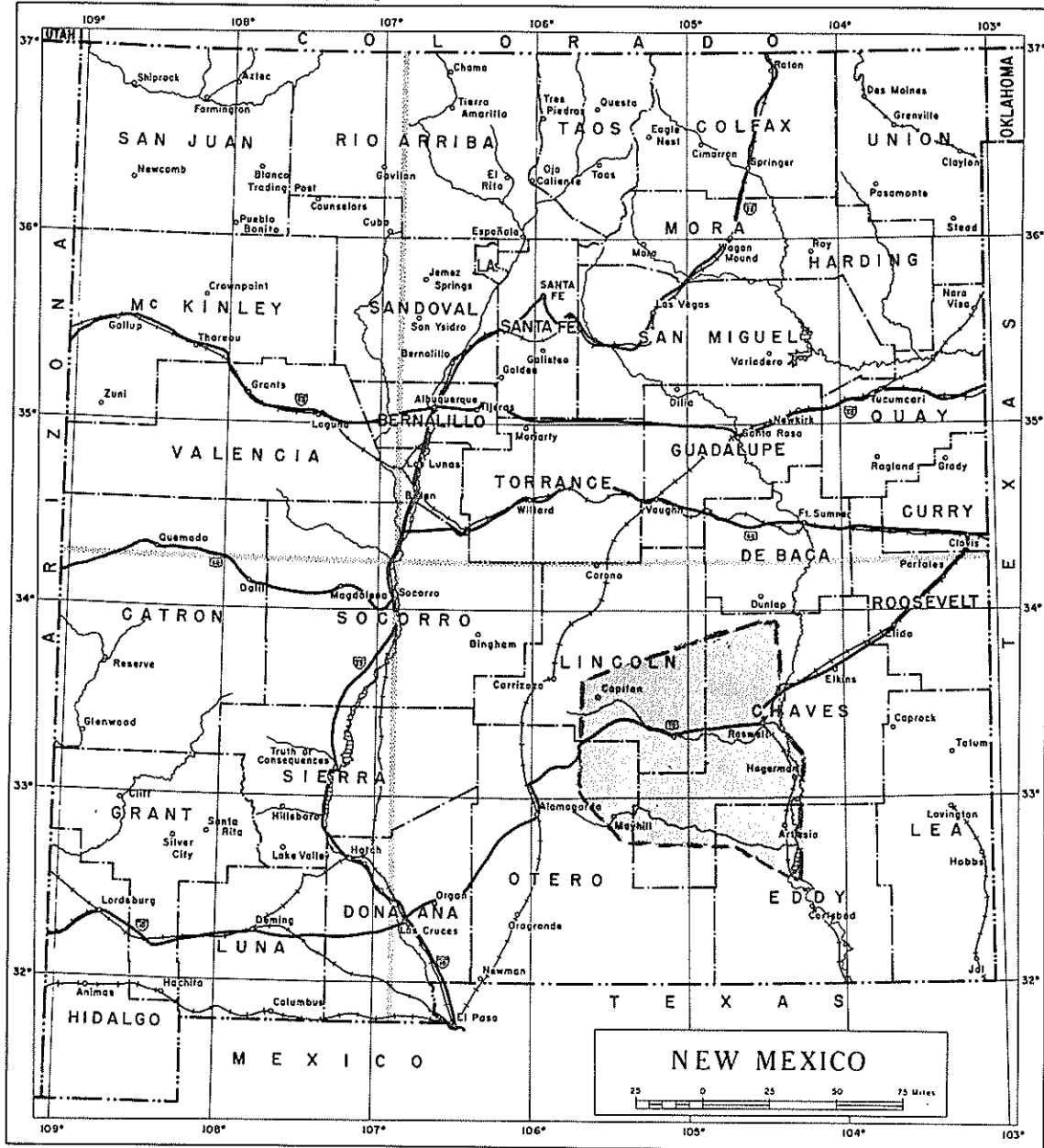
Figure 1:   The study area and its location.

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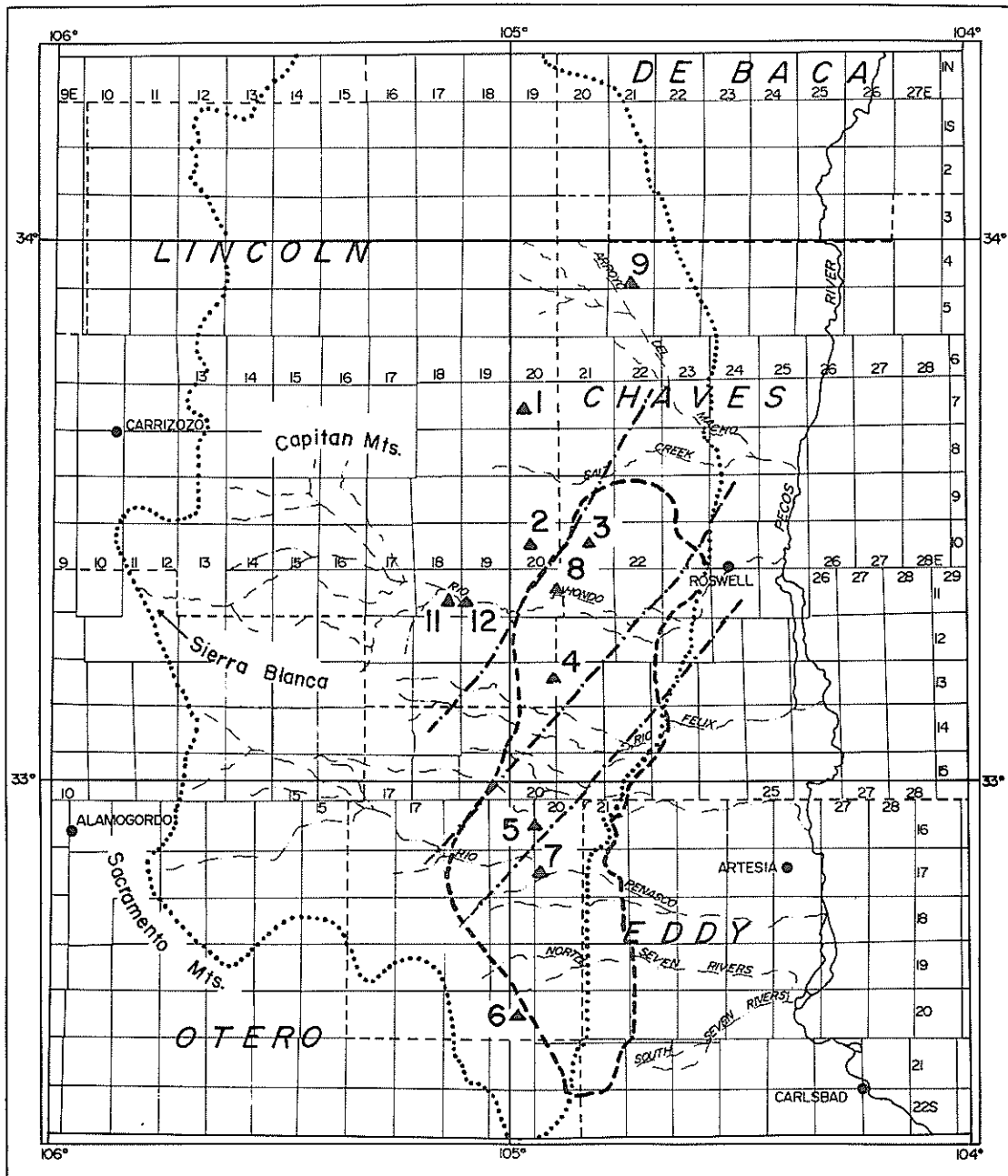
Figure 2: The Roswell Basin. Hydrologic and geographic boundaries.
Dotted: total intake area (after Bean, 1949). Dashed:
Principal Intake Area (after Fiedler and Nye, 1933, Plate 2).
Dash dot: Structure zones (from north to south: Border Hill,
Six-Mile Hill, Y-0). Triangles: observation wells, numbered
1-12 (Duffy et al., 1978). Obs. well 10 (drilled in the Macho
drainage at T.8, R.24) no longer exists. Wells 5 and 6 were
not used for this study.

Blanca). The tributaries are, from north to south respectively, the Rio Hondo, the Rio Felix, and the Rio Peñasco. At the average elevation of 9000 feet in the Sacramento Mountains, the mean annual air temperature is 47°F (8°C). Precipitation again occurs as intense, localized thunderstorms, but winter precipitation, especially at the higher elevations, contributes a greater percentage than in Roswell to the annual total of up to 20 inches.

Geohydrology

The major geohydrologic divisions of the area follow the above defined geographic limits quite well (Figure 3). A simplified stratigraphic column for the basin in shown in Table I.

The Agricultural Belt

The narrow eastern strip is the primary artesian water source in the basin. The major aquifer, referred to as the Principal or the Carbonate Aquifer, is primarily in the Permian San Andres Formation which is encountered at depths from 400 to 800 feet below the surface in this region. In the study area, it is predominantly limestone and dolomite, with minor components of gypsum and sandstone. The Permian Artesia Group (shales, sandstones, evaporites, some carbonates) forms the confining to semi-confining layer on the San Andres, due to the large quantities of clay and silt in this group. In some portions of the basin, parts of the Artesia Group (formerly called the Chalk Bluff), notably the Grayburg, Queen, and Seven Rivers Formations, either form part of the

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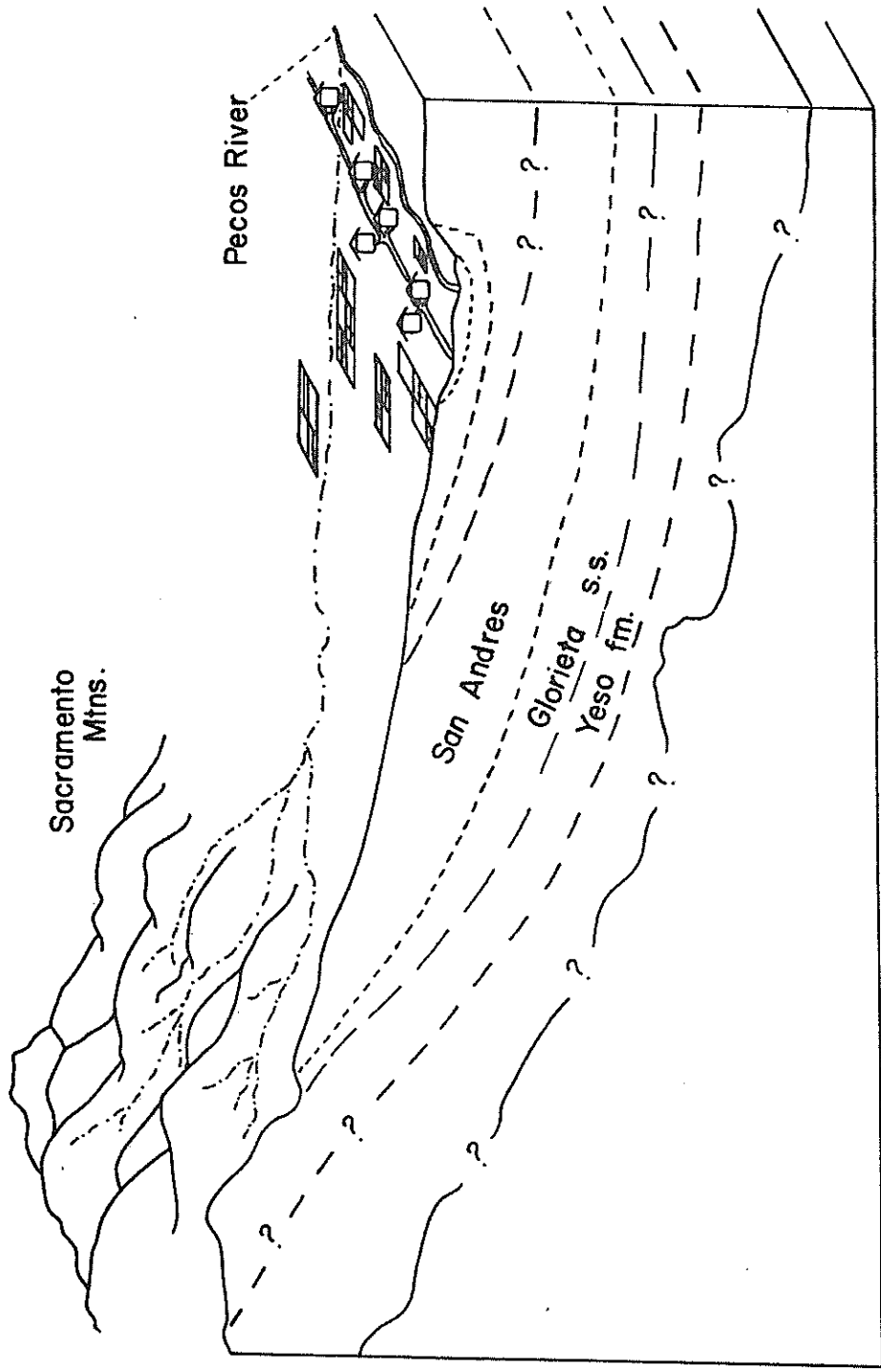
Figure 3: Schematic cross section of the Basin.

Sacramento Mtns.

Pecos River

San Andres

Glorieta s.s.

Yeso fm.

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TABLE I. Simplified Stratigraphic Column for the Roswell Basin
(after Kelley, 1971, modified)

AGE	GROUPS,FORMATIONS, MEMBERS	DESCRIPTION
Holocene and Pleistocene	Alluvium	0-300 ft. thick Caliche, gravels, sands some clays
Pleistocene and Pliocene	Gatuna Formation	0-200 ft. thick Sands, clays, gravels, red color, thin layers of carbonates.

Permian	Artesia Group
	   Tansill Formation
	   Yates Formation
	   Seven Rivers Formation
	   Queen Formation
	   Grayburg Formation
		0-2100 ft. thick Upper portion: Clays, sands, evaporites. Lower portion: Clays, sands, carbonates. The Queen Formation is usually considered to form the aquitard.

	San Andres Formation
	   Fourmile Draw Member
	   Bonney Canyon Member
	   Rio Bonito Member
	   Glorieta Sandstone
		250-1350 ft. thick Upper portion: Evaporites, sands (Lovington sandstone),carbonates (lime-stone, dolomite). Lower portion: Carbonates, sands (Glorieta Sandstone), shales.

	Yeso Formation	$\leq$ 1400 ft.

Precambrian

Note: Only those formations that outcrop are listed.

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Principal Confined Aquifer or are aquifers in their own right (the Shallow Confined Aquifer of Saleem and Jacob, 1971; cf. Kinney et al., 1968, p. 23). According to Kinney et al. (1968), the Seven Rivers aquifer grades into the overlying alluvium (and its aquifer) in some parts of the Basin.

The Cenozoic Gatuna Formation overlies the Artesia and sometimes has been mapped as Artesia because of its lithologic similarities. The Gatuna also is part of the confining layer in some areas, and, in others, it forms part of the shallow phreatic aquifer, known as the Alluvium Aquifer due to its predominant aquifer material. The recent alluvium and underlying Gatuna Formation comprising the Alluvium Aquifer average a bottom depth of 150 to 200 feet in this region.

Dipslope or Principal Intake Area

As one moves west in the Basin, the top three formations (the alluvium, the Gatuna Formation, and the Artesia Group) thin rapidly, and 20 miles west of the Pecos River, the San Andres forms the long slope to the Sacramento Mountains, 30 miles further west. Simplistically, the San Andres is unconfined in this area, however, a few of the Pecos Valley Artesian Conservancy District (PVACD) water level observation wells have provided evidence of at least partly confining conditions (Gross et al., 1976, p. 32). The San Andres Formation is characterized by strongly developed solution features (karst). Almost all surface runoff disappears and is

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incorporated into the groundwater system. This is especially true of the three major rivers that cross the dipslope, the Hondo, Felix, and Peñasco. Fiedler and Nye (1933) proposed that this is the belt where most of the groundwater recharge occurs in the basin and called it the Principal Intake Area.

The Mountain Zone

Underneath the San Andres Formation, as one moves farther west to the Sacramento Mountains, two lower units become important. The Glorieta Sandstone, which is commonly taken to be a basal unit of the San Andres Formation, and the Yeso Formation gain importance due to their increasingly higher position and observed water producing potential, as evidenced by numerous springs (Davis, et al., 1980; Gross et al., 1979) and producing zones in the PVACD observation wells (Crawford & Borton, 1958; Gross et al., 1976). Until recently, the Yeso Formation was considered relatively unimportant as an aquifer (Fiedler & Nye, 1933; Mourant, 1963), but there is increasing evidence as to the long-term contributions of this formation (Davis, et al., 1980; Duffy et al., 1978). Mesozoic and Cenozoic volcanics and clastics outcrop elsewhere in the Sacramento Mountains, but their contributions to the overall hydrologic system of the basin are considered relatively unimportant.

Underlying Formations

Another geologic setting which has been considered relatively

unimportant in the hydrologic system of the basin is the material beneath the Yeso Formation. Northwest of the Six Mile Buckle (see Figure 2), pre-Permian formations are absent between the Precambrian basement rocks and the Yeso. Southeast of the Six Mile Buckle, Paleozoic formations older than Permian (Wolfcampian, notably the Abo Formation) for a southeastward-thickening wedge beneath the Yeso Formation (Kelley, 1971, p. 5). These pre-Yeso formation have been omitted from consideration in the present report because we have no data about their hydrological characteristics in the study area. These pre-Yeso formations are important, however, because they may contribute deep leakage components to the Principal Aquifer (Rehfeldt and Gross, 1982).

Structural Relationships

Three distinct structural relationships must be considered in defining the aquifer characteristics in the basin. The most important structure is, of course, the regional bedrock slope (dip-slope) from the Sacramento Mountains down to the Pecos River, resulting in the overall eastward movement of water in the basin. Three complex fault zones cut the dipslope diagonally from north-east to southwest. They are the Border Hill Buckle, the Six Mile Buckle, and the Y-O Buckle (Figure 2). In addition to secondarily creating channels for water flow, these three zones complicate the groundwater flow patterns near the Pecos River due to differential displacement of the intervening blocks. This displacement is evidenced by the range of depths down to the top of the San Andres

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Formation: on the order of 400 feet near Roswell to over 800 feet near Hagerman and Dexter (Gross et. al., 1976). The third structural relationship of importance is the presence of erosional unconformities between the Yeso and the San Andres and between the San Andres and the Artesia Group. These unconformities, combined with the collapsed, brecciated nature of the Yeso, the karstic nature of the San Andres, and solution features in all the units contribute to interaquifer leakage, variable hydraulic conductivities, and difficulty in defining confined and unconfined zones; all of which complicate characterizing the overall aquifer properties.

The Water Supply Problem and Previous Studies

Water Usage

Since 1950, over 100,000 acres have been under irrigation each year. Water consumption by the city of Roswell has been on the order of 10,000 acre-feet per year during the same time period. Water well levels have declined almost continuously from 1942, and the city of Roswell has moved some of its wells from north to southwest of the city to an area of better water quality, due to encroachment of saline waters north and east of the city. In truth, the term 'artesian basin' is no longer quite correct, since very few wells flow anymore, spring flow into the Pecos River has all but ceased, and the base flow of the Pecos River has dropped considerably. At the same time, water quality has been declining

steadily throughout the Basin. In the 1930's, the State Engineer closed the basin, restricting pumpages and imposing other limitations. Continued study of the basin is indicated for regional water management.

Emphasis of Previous Studies

Water resources along the eastern edge of the basin are obviously heavily taxed. In order to understand and project the water budget, the recharge relationships in the basin must be defined. Until recently, the major amount of recharge has been considered to occur in an area known as the 'Principal Intake Area', located on the structural slope connecting the Sacramento uplift and the Pecos Valley, and dominated by the San Andres Formation. This area was originally defined by Fiedler and Nye (1933) in a detailed study of the geology and hydrology of the entire basin. It is here, in the Principal Intake Area, that all major streams crossing it lose their surface flow, indicating the great capacity of the San Andres Formation to absorb and transmit groundwater through solution features. Several studies reported on the hydrogeology of one or the other of the principal tributaries to the Pecos River, i.e. Rio Hondo, Rio Felix, Rio Peñasco (Renick, 1926; Bean, 1949; Theis, 1951; DeWilde, 1961; Mourant, 1963). Quantitative estimations of the basin's water resources have been made by Hantush (1957), Motts and Cushman (1964), Saleem and Jacob (1971), Rabinowitz et al. (1977). The subsurface hydrogeology of the eastern agricultural belt has

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been studied in more detail by Havenor (1968) and by Kinney et al. (1968).

Through the years, the importance of a recharge contribution from the far western regions of the basin has been increasingly emphasized. According to this view, a substantial fraction of the artesian basin's groundwater enters the Principal Aquifer not by downward percolation of surface water (precipitation or surface runoff) but by upward leakage from the Yeso or possibly even deeper formations. Four recent studies (Gross et al., 1976; Duffy et al., 1978; Gross et al., 1979; Davis et al., 1980) have been particularly concerned with this problem. Tritium measurements throughout the basin and spectral analysis of the stream-aquifer recharge process in the central region of the basin provided evidence of 'fast' (i.e. water 'younger' than the tritium half-life of 12.4 years) and 'slow' recharge components and brought up the question of interaquifer leakage. Rehfeldt and Gross (1982) have suggested that this upward leakage may occur through fractures or faults, such as the three 'structure zones' mentioned earlier. The present work was undertaken with the hope that in investigation of stable isotopes in basin water would shed additional light on the processes of recharge and interaquifer leakage.

THE STABLE ISOTOPE APPROACH TO HYDROLOGY

Physical and Chemical Basis

General

The measurement of stable isotope ratios in natural waters can provide information about circulation and recharge patterns that supplements conventional hydrologic and geologic techniques and, in some cases, may not be obtainable from these methods.

The stable isotope composition of groundwater is generally considered as a conservative property, related to the original isotopic composition of the recharging water and its 'history' upon entering the groundwater system. If different components, such as snowmelt and summer rains, contribute to the groundwater, they can in principle be distinguished by their varying compositions. These variances arise from basic, though slightly manifested, physical and chemical differences in molecules of the same chemical species but different isotopic composition. All of the variations in the physical and chemical properties are due to slight mass differences between isotopes of a particular element. The mass differences are due to the presence or absence of extra neutrons in the nuclei of the isotopes.

The two elements considered in this study are hydrogen and oxygen, which make up the water molecule. Each of these elements has three naturally-occurring isotopes: for hydrogen they are protium (H or ^{1}H), deuterium (D or ^{2}H), and tritium (T or ^{3}H) with

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mass numbers of 1, 2, and 3, respectively; and for the oxygen isotopes, there are mass numbers 16 (^{16}O), 17 (^{17}O), and 18 (^{18}O). Table II shows the natural abundance of each of these isotopes. Tritium is an unstable (radioactive) isotope of hydrogen and is considered here with respect to previous studies of tracing and dating groundwater in the Roswell Basin (Gross et. al., 1976; Rabinowitz et al., 1977). Using only the stable isotopes, there are nine isotope combinations theoretically possible in a water molecule: $H_2^{16}O$, $H_2^{17}O$, $H_2^{18}O$, $HD^{16}O$, $HD^{17}O$, $HD^{18}O$, $D_2^{16}O$, $D_2^{17}O$, and $D_2^{18}O$. Molecules containing ^{17}O are generally omitted due to the relatively small amounts of ^{17}O present, and, in addition, only those molecules in which at least one ^{1}H atom is present need to be considered in natural occurrences, e.g.: $D_2^{16}O$ is disregarded.

The stable-isotope composition of a water sample is measured as the ratio of the heavy to the light isotope (i.e.: $^{18}O/^{16}O$ or D/H) and presented as a fractional difference with respect to a standard. This 'delta' notation will be introduced more formally in the section on EXPERIMENTAL TECHNIQUES.

TABLE II

Natural Abundances of Hydrogen and Oxygen Stable Isotopes (from Faure, 1977)

Element	Isotope	Abundance (% of occurrence of element)
Hydrogen	H	99.985%
	D	0.015%
	T	too small for this scale
		100.000%
Oxygen	^{16}O	99.756%
	^{17}O	0.039%
	^{18}O	0.205%
		100.000%

Fractionation Factor

Since the thermodynamic properties of molecules depend upon the constituent masses, the similar molecules containing different isotopes separate slightly in changing environments. This separation is termed isotope fractionation, and the primary environmental factor is temperature. More precisely, the energy of a molecule is proportional to the temperature, but similar molecules with different isotopes will have slightly different energies at the same temperature due to nucleon and electron interactions. The internal energy of a molecule consists of contributions from rotational, vibrational, and electronic energies. Both rotational and vibrational energies are inversely proportional to the mass (actually the reduced mass) of the molecule. The contributions of the electronic energies are secondary to this discussion. As the temperature increases, molecules will have more energy, but the lighter molecules will have slightly higher energies, making them slightly more reactive (Daniels and Alberty, 1975).

Two types of reactions in which this isotopic fractionation is of interest are exchange reactions, such as the isotopic exchange of an ^{18}O for an ^{16}O atom between water and limestone, and physical processes such as evaporation and condensation of water vapor. A fractionation factor (α) is used to express the extent to which such reactions must go to attain equilibrium, i.e.:

$$\alpha = \frac{R_A}{R_B}$$

where: R_A = ratio of heavy to light isotope in phase A

R_B = ratio of heavy to light isotope in phase B.

This fractionation factor is temperature dependent in the range of environmental temperatures of interest in many hydrologic applications.

Condensation and Evaporation

As mentioned, the fractionation factor may be applied to reactions involving water vapor. When water evaporates, the remaining liquid is enriched in the molecular species containing heavier isotopes, such as HDO or $H_2^{18}O$, since these molecules have a lower vapor pressure than $H_2^{16}O$. Similarly, when water condenses, the first liquid is enriched in the heavier isotopes for the same reason. Applying this to precipitation, summer thundershowers experiencing a great deal of evaporation will have initial rainfall enriched in the heavier isotopes since the lighter ones evaporate first. Also, precipitation at lower altitudes is enriched in the heavier isotopes, and subsequent precipitation at higher altitudes, such as from an air mass moving up a mountain slope, will be depleted in the heavier isotopes since they have already been 'rained out' (Faure, 1977). Latitude, and distance from the moisture source also influence isotopic composition over very large areas due to 'rain out', but these effects would not be noticeable within this basin.

The temperature dependence of the fractionation factor, resulting in a seasonal fluctuation of the isotopic composition, is best shown by an example. Starting with water vapor of a given ^{18}O composition, $\delta\ ^{18}O_V = -10^O/oo$, and the fractionation factor between water vapor and liquid,

$$\alpha = \frac{R_\ell}{R_V} = \frac{\delta^{18}O_\ell + 1000}{\delta^{18}O_V + 1000} \, ,$$

at $0°C$, $\alpha = 1.0110$. Then

$\delta^{18}O_\ell = (1.0110)(-10^O/oo + 1000) - 1000 = 0.89^O/oo$. At $20°C$, $\alpha = 1.0090$ and $\delta^{18}O_\ell = (1.0090)(-10^O/oo + 1000) - 1000 = -1.09^O/oo$. This would imply that, with isothermal condensation and equilibrium conditions, summer precipitation is isotopically lighter than winter precipitation, a condition not seen in nature. In fact, the converse is true. More realistically, condensation is the result of some kind of cooling process under non-equilibrium conditions. One of the most common non-equilibrium effects consists in the separation of the phases by "kinetic effects", i.e. motion (Dansgaard, 1964). For simplicity, the non-equilibrium process is assumed to be a Rayleigh process, i.e. slow condensation with the immediate separation of the condensate from the vapor after formation (Faure, 1977, p. 327). In such a process, the oxygen 18 content of the condensate decreases with decreasing condensation temperature (Dansgaard, 1964, p. 438-441 and Table 2). The non-linear increase of the fractionation factor with decreasing temperature requires that, under Rayleigh conditions,

water vapor of a given initial isotopic composition and producing condensate as it cools from a specified temperature,be depleted in heavier isotopes more rapidly than water vapor of the same initial composition condensing from a higher temperature,resulting in a more negative or isotopically lighter product overall, provided both water vapors cool the same number of degrees.

The Rayleigh process is sufficient to explain the general trends in deuterium and oxygen 18 contents of natural water in many instances. In other cases it is clearly inadequate. Thus, for instance, other kinetic effects may complicate the picture. One such process is fractionation by re-evaporation. This might be expected to occur where water droplets condensing from a mass of moist air fall through an air mass that is undersaturated with respect to water vapor, a chronic condition in semiarid environments such as this basin. Another such process is diffusion of water vapor at a static air-water interface. The isotopically lighter molecules in the water vapor diffuse more rapidly; this causes isotopic fractionation. Air currents complicate the results. Fractionation by diffusion may occur in soil pores or in open water bodies, such as lakes (Siegenthaler, 1979, p. 271). For a detailed discussion of processes and their effects on isotopic fractionation the reader is referred to a classical paper by Dansgaard (1964).

The "amount effect" (Dansgaard, 1964, especially Figure 21) is
the observation that a heavy rainfall tends to be isotopically
lighter than a light rainfall. This may explain part of the scatter
of $\delta^{18}O$ values in precipitation at the two weather stations to be
discussed. Reasons for the "amount effect" are complex and not well
understood. Clearly, then, the isotopic composition of natural
waters can provide a wealth of information about the water's history
if the composition can be related to the controlling factors.

The complexity of the situation is obvious, even under simpli-
fied conditions. Fortunately, the condensation temperature is the
easiest factor to take into account, and, in most instances, has
more influence on the isotopic composition of precipitation than
kinetic factors and other complications.

Evaporation not only affects the isotopic composition of pre-
cipitation, but it can also alter recharging surface water as it
enters the groundwater system. The result is isotopically heavier
water since the lighter isotopes evaporate more readily. In
general, the effects of evaporation can be distinguished by simul-
taneous oxygen 18 and deuterium measurements because oxygen 18 is
more affected by evaporation than deuterium. In a δD vs. $\delta^{18}O$ plot
(Figure 9), the evaporation effect causes a flattening of the slope.
This plot, and the so-called 'meteoric water line', will be discus-
sed in the section on <u>Relationship Between Oxygen 18 and Deuterium</u>
<u>Ratios</u> (p. 33).

Exchange Reactions

Craig et. al. (1963) concluded that at low temperatures (polar climate) isotope fractionation due to molecular exchange between a water body and atmospheric water vapor predominates over fractionation caused by simple evaporation. The effect on isotopic composition is qualitatively the same for both processes, i.e. enrichment of the liquid in the heavier isotopes. In a dry, warm climate such as characterizes most of our study area, evaporation and atmospheric exchange are important considerations. Both of these processes enrich the heavier isotopes in the liquid phase and are therefore usually lumped together. As mentioned earlier, air currents complicate the picture so that equilibrium conditions are not applicable for predictive purposes.

The other important exchange is between water and aquifer material. Water exchanges isotopes with clay material more readily than with carbonate or primary rock silicates. Exchange with carbonate only occurs either at high temperatures, (e.g.: great depth of burial or anomalous thermal gradients) or where the water is stagnant for geologic periods of time. Neither condition is known to have existed in this basin. The result is O^{18} enrichment in groundwater.

An exchange with clay minerals or with hydrated evaporites of marine origin will enrich the water in both oxygen 18 and deuterium. Such an effect will therefore qualitatively move the isotope composition in the same direction as evaporation and warmer condensation

temperatures do (that is, into the northeast quadrant of the δD vs. $\delta^{18}O$ graph and below the meteoric line). Where the exchange is slight it can, therefore, not be easily separated from evaporation and climatic effects. Such an exchange with clay and evaporite minerals was suggested by Lambert for certain groundwaters (brines) of the Delaware Basin (Lambert, 1978, see especially his Figure 3). The Roswell Basin has large amounts of marine shales and evaporites in its geologic column (Table I). They occur in all of the formations that are aquifers in the basin but are especially prominent in the Yeso. Such exchange processes would therefore be very much within the realm of possibility. Neither the geochemical characteristics nor the isotope values of the waters investigated for this report indicate, however, that such exchange processes with marine shales or evaporites have, in fact, taken place.

History Effects

This term designates peculiar isotopic ratios in natural waters reflecting exposure to past environments, especially climatic conditions, different from the ones in which the waters are presently found. For example, brackish groundwaters in Southern Israel "reflect the inflow of meteoric water that occurred during the humid Pleistocene" (Issar, 1981). No such effects can be inferred from our data.

Based on the results to be presented here, we believe that the groundwaters investigated for this report purely reflect the

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climatic conditions of the present and, furthermore, have not under-
gone appreciable exchange with aquifer matrix.

Previous Studies

These principles have been applied to a variety of hydrologlic
problems, some of which deal with precipitation, others with surface
or groundwaters, and some are directed toward analyzing varied
sources of water as in this study. A few of these studies are
reviewed here.

Gonfiantini et. al. (1975) related tritium and stable isotope com-
position to the chemistry of well and spring samples from the
volcanic terrain of Gran Canaria Island to demonstrate the comple-
mentary nature of such data and to determine the altitude of re-
charging precipitation for the various sites. In addition, the
overall pattern of moist air circulation over the island was sub-
stantiated, i.e. the north part of the island receiving most of
the precipitation on the mountain front and the south side of the
island being in the 'rain shadow'.

Payne and Ortiz (1979) studied groundwaters of the Los
Naranjos Area of Mexico to determine the relative contributions of
precipitation and stream losses from the Rio Blanco to recharge in
the heterogeneous aquifer materials of the river basin. The
results of this study were used to establish that precipitation
infiltration is the dominant source of groundwater recharge, a
fact that could not be ascertained from conventional measurements

of river discharge, evapotranspiration, evaporation and precip-
itation in the basin. On the basis of isotope indices, the rel-
ative proportions (mixing ratios) of recharge sources (precipitation
and stream losses) were computed.

Dincer et. al. (1970) studied snowmelt runoff in a small basin
in northern Czechoslovakia using snowpack measurements plus tritium
and oxygen 18 data. They were able to determine the contributions
of meltwater to surface runoff and to subsurface water, and res-
idence times for subsurface storage in the basin. Based on the
success of the study, they hoped to stimulate the use of isotope
techniques in snow hydrology.

Dincer and Payne (1971) studied the southwestern karst region
of Turkey and successfully established the existence of a hydraulic
link between inland lakes and coastal springs. This study is of
great interest because they determined two flow components in the
reservoir, a seasonal flow through solution features and a slower
base flow. This situation is somewhat analogous to the condition
thought to exist in the Roswell Groundwater Basin.

One of the most comprehensive isotope studies is that by
Arnason (1976) in Iceland. All hydrologic systems were considered,
with particular emphasis on the geothermal areas. The extensiveness
of this study provides a reference for almost any isotope hydrology
study.

In New Mexico, only one published study of oxygen 18 and deuterium in groundwater is known to the present authors. Lambert (1978) studied groundwater samples from a portion of the Delaware Basin, just south and southeast of our study area. On the basis of oxygen 18 and deuterium ratios, 3 types of groundwater are present in the Delaware Basin (Lambert, 1978, Figure 3): groundwater of meteoric origin and meteoric isotope makeup; groundwater of meteoric origin modified by evaporation effects, and saltbrines exhibiting the effects of strong isotope exchange with evaporitic bedrock. Most of these samples were from formations of the Artesia Group. Evaporites are much more prominent in the Delaware Basin than in the Roswell Basin.

Objectives of This Study

Three main questions were to be addressed by studying oxygen 18 and deuterium ratios in water samples from the Roswell Basin: (1) is the assumption of precipitation and percolation from the surface of the Principal Intake Area as the dominant source of recharge to the Principal Aquifer substantiated; (2) if precipitation and downward percolation are the principal source of recharge, precipitation over which part of the basin supplies the most recharge; and (3) are there both "fast" and "slow" recharge components in the basin. These questions had previously been addressed on the basis of tritium measurements (Gross et al., 1982). The

results suggested that deep leakage, from aquifers beneath the San Andres Formation, supplied a significant fraction of groundwater recharge to the Basin. The use of stable isotopes was, therefore, to confirm and supplement the results.

A definitive answer to the first question would require pronounced differences in the isotopic signatures of groundwaters from different formations, of water from surface streams crossing the study area, and of precipitation.

For an answer to the second question, precipitation over the warm, semiarid dipslope should be isotopically heavier than that falling in the mountains to the west, and this difference would have to be reflected in the groundwater receiving recharge from this source.

The existence of "fast" and "slow" recharge components would be supported by an isotopic composition of groundwater intermediate between surface flow in the Principal Intake Area and groundwater from the deeper aquifers to the west of the latter.

These relations would be obscured by (1) exchange reactions with aquifer matrix material and (2) mixing of groundwater components of different origin. Appreciable matrix interaction has been ruled out above. Mixing remains to be considered.

EXPERIMENTAL TECHNIQUES

Sampling

Water Samples

Since the water of the Roswell Groundwater Basin is being studied by tritium measurements (Rabinowitz et al., 1977; Gross, et. al., 1976), a water sampling network suitable for the oxygen and hydrogen stable isotopes was already established. It covers all parts of the Basin. During the course of this study, it became apparent, however, that coverage in certain areas, notably in the highest part of the mountain zone, was inadequate. (Suggestions for optimization are included in the section RECOMMENDATIONS FOR FUTURE STUDIES). Furthermore, the water samples were properly stored and catalogued, and data are available on sample site elevation, geologic setting, and so forth. Samples include water from springs, surface drainage, windmills, PVACD water level observation wells, deep and shallow wells located in the producing and recharge zones, and recorded precipitation. Temperature data were also available to complement precipitation data.

Carbonate Samples

The carbonate samples, used to check for isotopic exchange, presented more problems. Drill cuttings would provide excellent samples, and a few were utilized; however, since the area has been declared a closed basin, few new water wells, especially deep ones,

are being drilled; few recent samples were therefore, readily available.

Fortunately, the State Engineer Office in Roswell and the New Mexico Bureau of Mines and Mineral Resources in Socorro have drill cutting 'libraries', and these may be used in the future. Once these offices have completely evaluated the cuttings, only small quantities of each depth interval of the cuttings are kept. Extensive utilization of these samples was postponed until after the completion of this preliminary study, because the determination of the ^{18}O content in a carbonate sample renders the sample unsuitable for future use. The State Engineer Office graciously allowed us to have portions of the cuttings from depth intervals we selected of the PVACD observation wells, and these will be evaluated after this preliminary study, if it is warranted.

The carbonate samples for this study were mainly from roadcuts at various locations in the Basin, with the addition of drill cuttings from one shallow well in the eastern portion of the Basin. The main concern in using samples from roadcuts was that surface exposure would alter the isotopic composition of the samples, resulting in misleading information; however, as discussed under RESULTS, this did not seem to be the case. In all the roadcut samples, care was taken to insure that large blocks of rock material were obtained such that interior portions of the blocks, not in direct contact with the atmosphere, could be chiseled from the blocks.

Isotope Ratios. 'Delta' Notation

Oxygen 18 analyses are made by mass spectrometer. Carbon dioxide derived from the sample is compared with a standard carbon dioxide, which in this study was SMOW (Standard Mean Ocean Water). Carbon dioxide is generated from limestones by reacting them with 100% phosphoric acid at 25°C. This carbon dioxide is analyzed by mass spectrometer to compare the abundance of charged molecules of mass 46 ($^{12}C^{16}O^{18}O$) with the abundance of charged molecules of mass 44 ($^{12}C^{16}O_2$), with correction for those of mass 45 ($^{12}C^{17}O^{18}O$). The results are then converted to per mil differences relative to SMOW:

$$\delta^{18}O = \left[\frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{SMOW}}{(^{18}O/^{16}O)_{SMOW}} \right] \times 10^3 \, ^o/oo \quad .$$

Use of this notation results in values of $\delta^{18}O$ for meteoric water ranging from +10 ^{o}/oo for isotopically heavy samples to -38 ^{o}/oo for isotopically light samples (Craig, 1961a, b).

To analyze for deuterium, the water sample is converted to hydrogen gas by reduction with magnesium or uranium metal at several hundred °C. The gas is analyzed on a mass spectrometer; however, with hydrogen, more difficulties are encountered due to its extremely light, reactive nature. The abundance of H_2^+ ions, mass 2, is compared with the abundance of ions of mass 3. Both HD^+ and T^+ are

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ions of mass 3, therefore, a correction is required to eliminate the influence of the T^+ ions (Kirshenbaum, 1951). The sample ratio is compared with a known standard, and the results are converted to per mil values, as for the oxygen results:

$$\delta D = \left[\frac{(D/H)_{sample} - (D/H)_{SMOW}}{(D/H)_{SMOW}} \right] \times 10^3 \, ^0/oo \, .$$

Use of this notation yields values of δD for meteoric waters ranging from $+60 \, ^0/oo$ for isotopically heavy samples to $-300 \, ^0/oo$ for isotopically light samples (Craig, 1961 b).

RESULTS

All stable isotope determinations are presented in Table A 1;
187 determinations of $\delta^{18}O$ and 76 of δD were made. In addition,
close to 2,700 tritium activity measurements were available to us.
Tritium determinations are shown for many samples for which stable
isotope ratios were measured. In the present report, they are only
discussed to the extent that they aid in the interpretation of
stable isotope results. Detailed discussions of tritium results
will be found elsewhere (Gross et al., 1976; Rabinowitz et al.,
1977; Gross et al., 1979; Gross and Hoy, 1980; Rehfeldt and Gross,
1982). The importance of these stable isotope measurements is not
in the values themselves but in their relationship to each other
and to the geographic and geologic settings of the samples. We
wish to investigate the sources of recharge in relation to the
three geographic zones mentioned in the Introduction, the processes
that incorporate surface water into the groundwater system, ground-
water/surface water interaction and circulation, and the interactions
between groundwater and aquifer matrix. Three associations will be
examined in detail: (1) the relationship between deuterium and
oxygen 18 ratios, (2) the oxygen 18 content of the precipitation
in relation to temperature and amount, and (3) the relationship
between oxygen 18 content of water and limestone. The importance
of each of these associations is discussed in the appropriate
section. Once these relationships have been established, the back-
ground is set for presenting the distribution of oxygen 18 and

deuterium in Basin waters and its interpretation in terms of recharge processes and hydrologic circulation patterns.

Relationship between Oxygen 18 and Deuterium Ratios

Using the assumption of Rayleigh conditions, it may be shown (Dansgaard, 1964) that an essentially linear relationship should exist between the δD and $\delta^{18}O$ values in water samples of atmospheric origin, with a slope of 8.0. Using some 400 meteoric and surface water samples, Craig (1961b) established the straightline relationship $\delta D = 8\delta^{18}O + 10$. This is commonly called the 'meteoric waterline'. The intercept is called the 'deuterium excess'.

In some natural processes, this relationship does not hold true, thus, by plotting the $\delta D-\delta^{18}O$ graph for an area of interest, differences in the behavior of the two isotopes may be investigated. Perhaps the most spectacular example of such contrary behavior is the "oxygen-isotope shift" of geothermal waters. Their deuterium values are in line with those of local meteoric water, however, the oxygen 18 values are shifted to values more positive than those of local precipitation by $5^o/oo$ to $20^o/oo$ in some instances, due to increased reaction with carbonate and silicate rocks at the higher temperatures (Faure, 1977). Since no such effects have been noted in the Roswell Groundwater Basin, this shift should not be observed, but evaporation effects which result in a shift of both oxygen and deuterium ratios, might become apparent because of the warm, dry climate. Based upon theoretical and experimental results

mentioned earlier (Dansgaard, 1964; Craig, 1961b), the oxygen 18 content is more affected than the deuterium content by evaporative processes, such that the slope of the straight-line relationship is decreased to 5 or even 3.

Another fact which may be inferred from a graph of δD vs. $\delta^{18}O$ is whether or not the water in an aquifer is derived solely from meteoric water or whether it has contributions from other sources, such as the controversial 'juvenile' water. Only if the water from wells and springs has an isotopic composition falling on the 'meteoric line' ($\delta D = 8\delta^{18}O + 10$) or some related line, such as an evaporation line, it is assumed to be derived from meteoric origins.

The δD-$\delta^{18}O$ scatter plot for this study is shown in Figure 4. The correspondence with the meteoric line is quite good. A simple linear regression gives the following equation

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

with a correlation coefficient $r = 0.92$ and a standard error of $\pm 10.05°/oo$. For this fit, 6 points near the upper right-hand corner have been omitted because they exhibit obvious evaporation effects and would have unduly flattened the slope and reduced the intercept. (These omitted points are shown in Figure 9 where all the data points are shown differentiated according to source.)
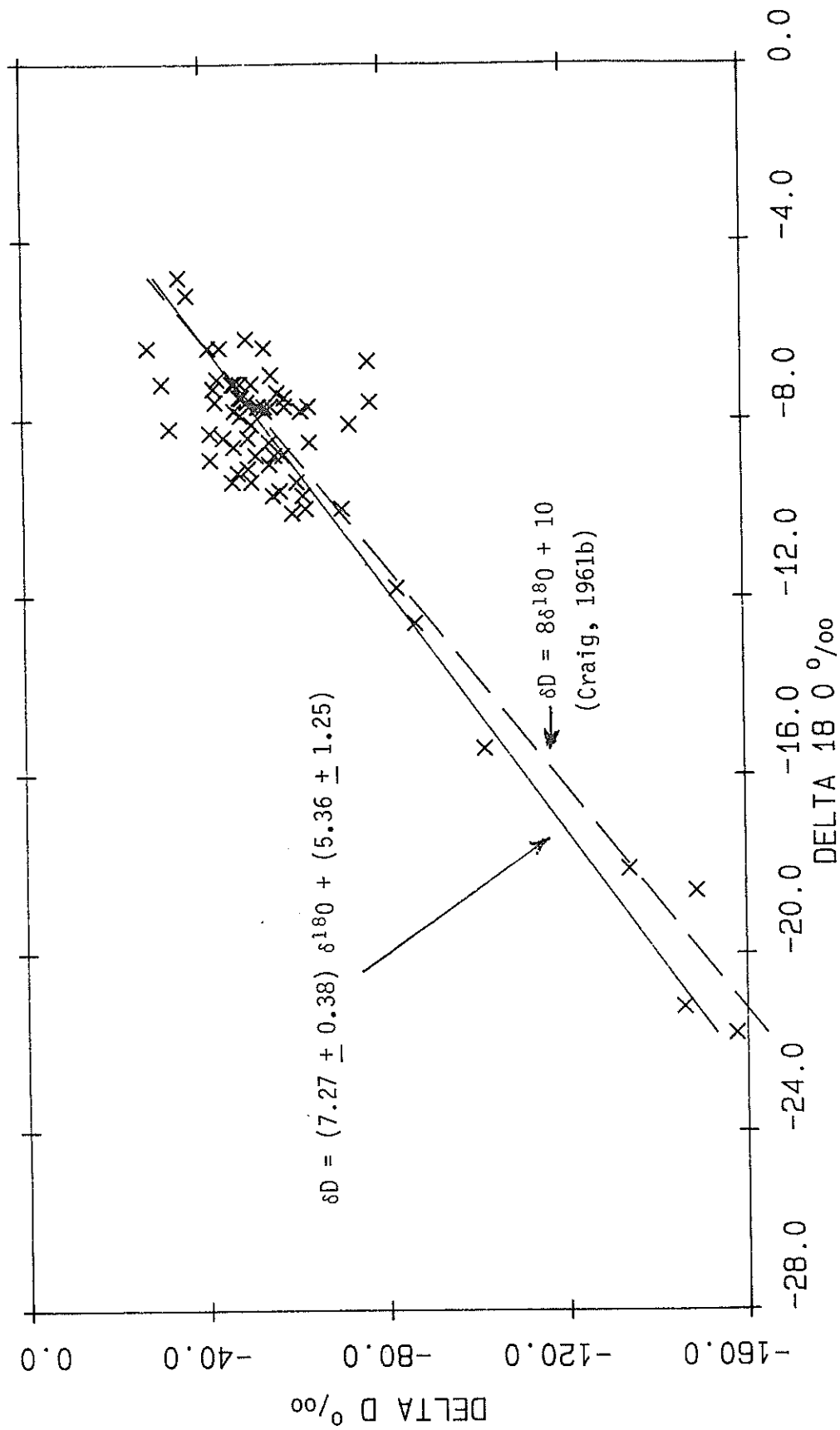
FIGURE 4: $\delta D - \delta^{18}O$ scatter plot and simple least-squares fit.

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

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

The equation fitting the Roswell data should be compared to Craig's (1961a) "meteoric water line", already mentioned, which represents worldwide water samples with an apparent emphasis on more northerly latitudes of temperate and more humid climates

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

The differences between the 2 lines are slight and may not be statistically significant because the bulk of Roswell data fall within a rather narrow range in the northeast quadrant of the graph. The few data points that spread to the lower left (and therefore strongly influence the least-squares fit) are snow samples from Sierra Blanca and 2 samples of winter rain from Elk (cf. Figure 9).

Alternatively, it is possible that this minor departure of the Roswell data from the meteoric line reflects a slight evaporation effect in a predominantly semiarid environment. We will return to the discussion of the deuterium-oxygen 18 relationship when we examine circulation patterns and climatic effects.

Oxygen 18 Content of Precipitation

The $\delta^{18}O$ of precipitation in the basin was measured for two reasons: (a) to determine the relationship between air temperature at the time of precipitation (i.e. the condensation temperature) and $\delta^{18}O$ in the precipitation; and (b) to determine the weighted mean $\delta^{18}O$ of the precipitation, which is assumed to be the recharging water. The first relationship is important for comparing

this basin to other areas and for obtaining data for time periods
when no samples were available. The second relationship is neces-
sary for comparing groundwaters with the assumed source of recharge.

Two NOAA weather reporting stations in the basin provided pre-
cipitation data, precipitation samples, and temperature data.
Weighted mean $\delta^{18}O$ values (with respect to SMOW) were determined
for systematic precipitation samples collected from 1976 to 1978.
The stations were conveniently located, one in the western portion
near Elk, NM. (5,700 ft. a.m.s.l.) and the other in the eastern
portion at Roswell (3,669 ft. a.m.s.l.). This allowed analysis of
data from two of the geographic zones within the basin: the 'pro-
ducing' zone in the Pecos River Valley, and the western edge of
the Principal Intake Area in the foothills of the Sacramento Moun-
tains. Continual precipitation samples were not available from
higher altitudes, but snow samples were collected to measure
isotopic composition of winter precipitation which would influence
the snowmelt composition.

Monthly or bimonthly composite precipitation samples were used
for two reasons: (1) to insure adequate sample size for all the
analyses since precipitation amounts for individual storms vary
from traces to several inches; and (2) to smooth the effects of
varying ^{18}O content among individual storms. Table III shows com-
parisons of smoothed and unsmoothed ^{18}O values. Usually, 500 mill-
iliters of composite sample were prepared with water from all storms
in the time period covered.

TABLE III

Comparison of $\delta^{18}O$ Values in Individual

and Composite Precipitation Samples

Sample Description	Date(s)	$^{o}/oo\ \delta^{18}O$	Time Period	$^{o}/oo\ \delta^{18}O$
Precipitation at Elk, N.M.	1/77 2/77 3/77	-18.1 -7.6 -10.5	1/77 - 3/77	-13.7
	8/8/77 - 8/12/77	-3.4	8/77	-0.9
	10/3/77 & 10/6/77	-5.5	10/77	-7.7
	11/77 12/77 1/78	-10.1 -7.9 -15.5	11/77 - 1/78	-9.7
Precipitation at Roswell, N.M.	8/12/77	-6.0	8/77	-6.6
Fresh snow from overnight precipitation at Alto, N.M.	1/16/79 2/2/79	-13.8 -7.1	--	--

Two temperature values were used, one of which was the average temperature from the whole month and the other of which was an average of the temperature on the days when there was a precipitation event for which we had a sample. This average of event-day temperature probably corresponds more closely to the condensation temperature which is a dominant variable affecting the ^{18}O content of the precipitation.

The temperature and precipitation data from the two stations over a three year time period are compiled in Tables A2 and A3.

A relationship between air temperature and ^{18}O content, such as that described by Dansgaard (1964) was established to determine how these precipitation values compare with those from other locations and to compute ^{18}O values for time periods for which a precipitation sample was not available. To determine the relationship, plots of $\delta^{18}O$ vs. temperature were constructed. At first, the overall monthly temperatures were used, but, since precipitation events are few and far between and temperatures fluctuate considerably in a given time period because of the climatic characteristics of the basin, the average of event-day was compiled. Using the two different temperature sets, the plots of $\delta^{18}O$ vs. temperature values were not markedly different, but when a linear least squares regression was applied, there was some improvement in the 'fit' of the line using the average of event-day values. These plots and their equations are shown in Figures 5,

6, and 7. The Dansgaard line is also shown on these plots for comparison. The differences between the calculated and theoretical lines and the scatter of the data points are readily explainable. The Dansgaard equation is primarily for temperatures on the order of -50°C to 0°C. Above these temperatures, the slope of the line begins to flatten, as shown by theoretical calculations and by a few samples. This is the phenomenon observed in the Roswell Basin. The scatter about the line is due to considering the oxygen 18 content as a function of temperature alone in a simple Rayleigh process. Amount effects, distance from the origin of moisture, and non-equilibrium processes also contribute to the oxygen 18 content as discussed above.

The weighted mean isotope values for each of the stations were computed from the following equation:

$$\delta^{18}O = \frac{1}{P} \sum_{i=1}^{n} P_i \delta_i$$

where: P = total precipitation over the three years

P_i = precipitation during i$\underline{th}$ time period (i.e., month)

n = total number of time periods

δ_i = $\delta^{18}O$ value for the i$\underline{th}$ time period.

The standard deviation for the mean (s_m) at each location was calculated by assuming stratified sampling and using the following equation:

$$s_m = \left\{ \sum \left[\frac{P_i}{P} \right]^2 \frac{s_h^2}{P_i} \right\}^{\frac{1}{2}}$$

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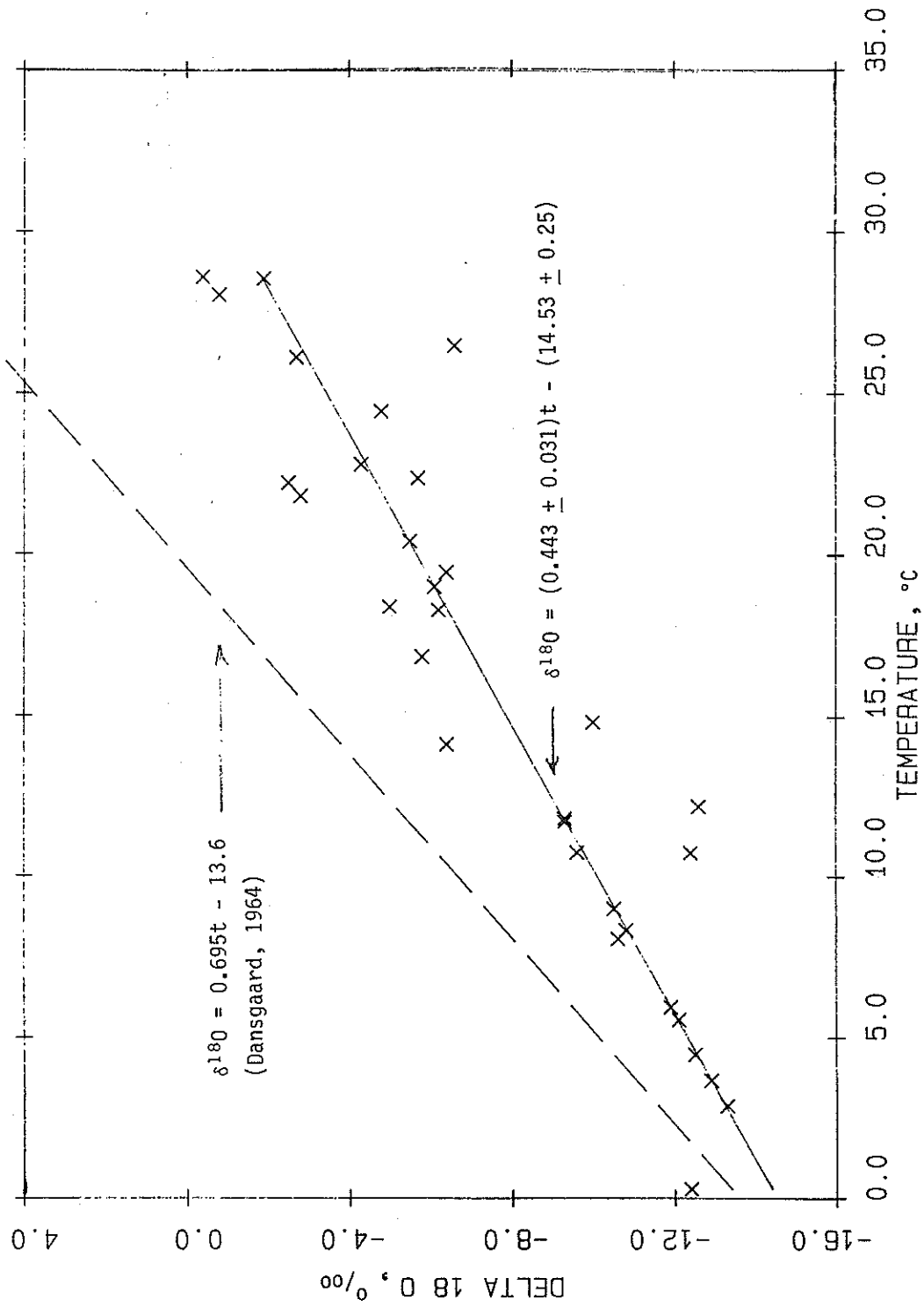
FIGURE 5: $\delta^{18}O$ vs. 'condensation temperature'. Roswell.

$\delta^{18}O = (0.443 \pm 0.031)t - (14.53 \pm 0.25)$

$\delta^{18}O = 0.695t - 13.6$
(Dansgaard, 1964)
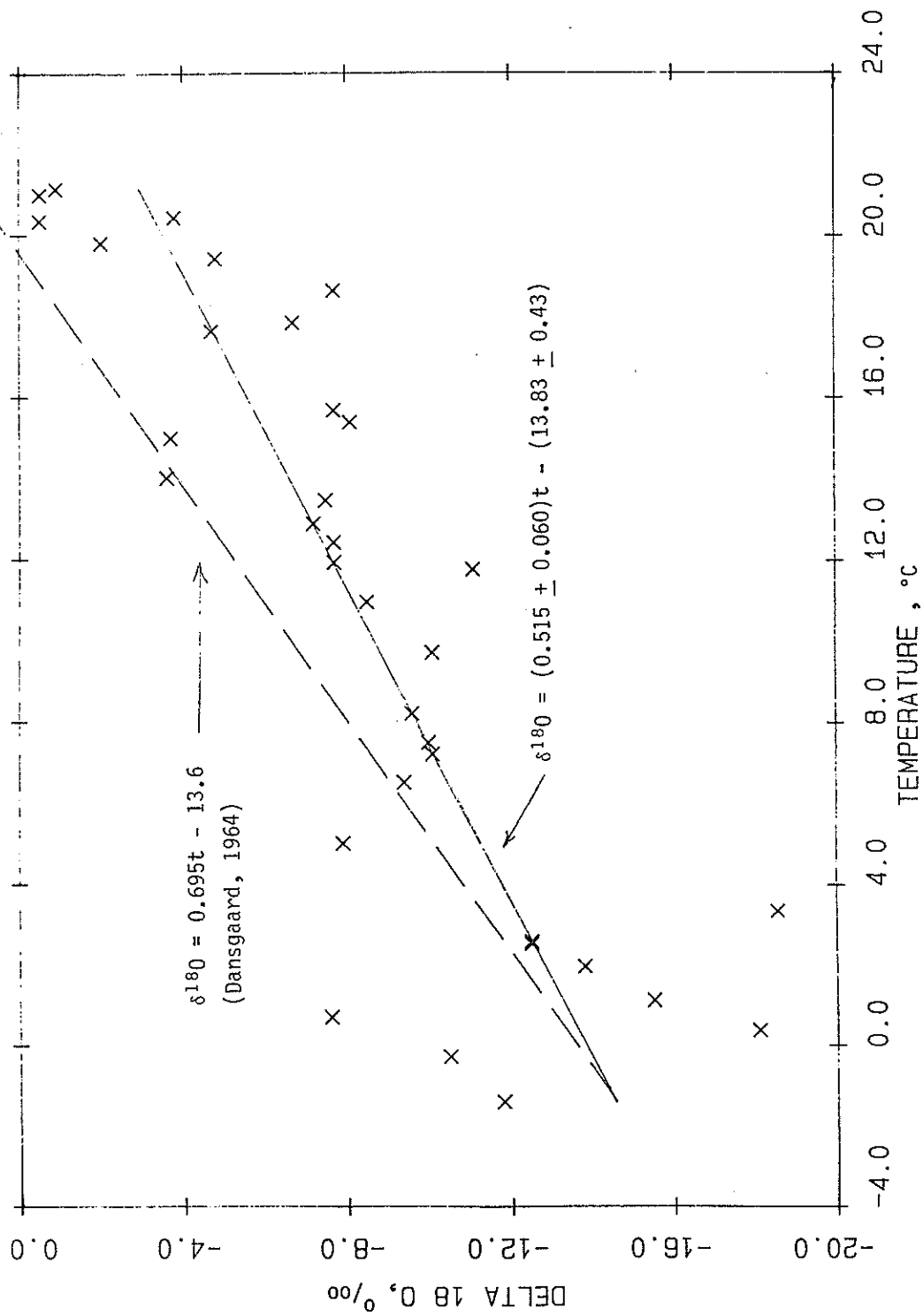
FIGURE 6: $\delta^{18}O$ vs. 'condensation temperature'. Elk.
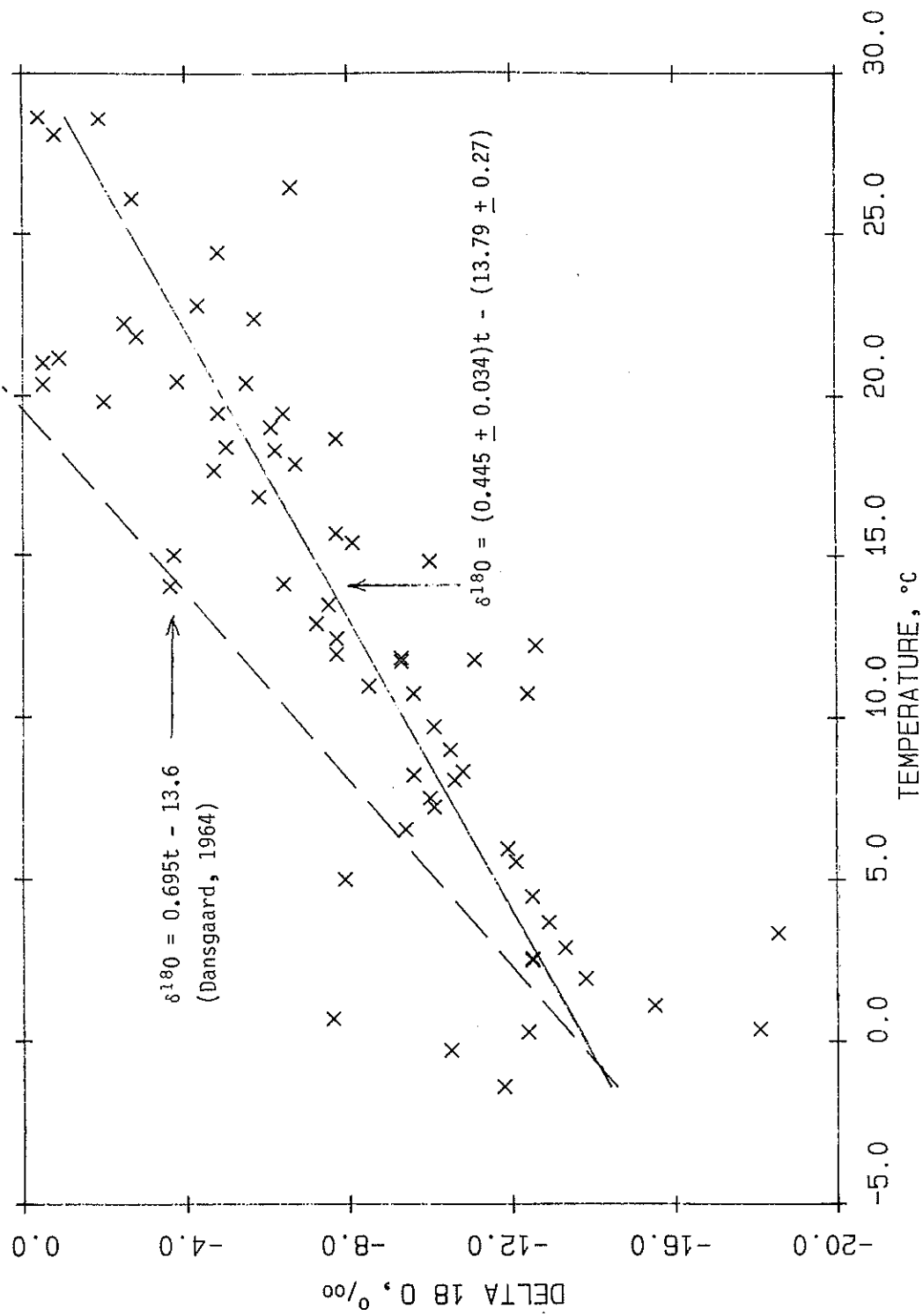
FIGURE 7: $\delta^{18}O$ vs. 'condensation temperature'. Roswell and Elk.

$\delta^{18}O = 0.695t - 13.6$
(Dansgaard, 1964)

$\delta^{18}O = (0.445 \pm 0.034)t - (13.79 \pm 0.27)$

TEMPERATURE, °C

DELTA 18 O, °/oo

where: s_h = the standard deviation within each stratum. For

measured values, this was assumed to be the accuracy

reported by Geochron. For the calculated values,

this was the standard deviation calculated in the

regression program.

The weighted mean results are

Roswell (3669 ft [1119 m] a.m.s.l.). . -6.0 ± 0.3^o/oo

Elk (5700 ft [1738 m] a.m.s.l.). . . . -7.1 ± 0.3^o/oo.

This amounts to an altitude effect of only -0.18^o/oo /100 m,

surprisingly small for a region of such orographic and climatic

diversity. Two geographic factors may contribute to a reduced

altitude effect; they are the gentle regional slope and the low

relief between the two weather stations. The regional slope in

an east-west direction between the longitudes of the stations

(which are about 60 miles [100 km] apart) is only about 34 ft/mi

[~6m/km]. A third factor to keep in mind is that no precipitation

samples were available from the mountain zone proper, which is

still 20-25 miles west of Elk (with elevations of 9,000 ft

[2,750m] up to 11,977 ft [3,650m]). The altitude effect is

expected to be greater there. Other possible factors that could

influence the altitude effect will be discussed in the section on

Circulation Patterns and Climatic Effects.

The range of $\delta^{18}O$ values in the precipitation samples pre-

sented in Tables A2 and A3 is from -18.7^o/oo to -0.2^o/oo. For

comparison, Dansgaard (1964, Table 10) gives a range of $-16^O/oo$ to $0^O/oo$ for Flagstaff, Arizona, and $-19^O/oo$ to $-2^O/oo$ for Chicago, Illinois. Thus, the range and numerical values given in Tables A2 and A3 seem to be fairly typical in comparison with other regions of the central and southwestern United States.

These precipitation samples were not originally collected for the purpose of stable isotope determinations. They came from rain gauges of the weather reporting stations and, although collected into stoppered bottles as soon as possible, they may have undergone some evaporation on occasion. Given the internal consistency of the weighted results shown above, this error is believed to be small.

All but two of the snow samples taken for this survey were from snowpack, not fresh snow. Some samples included the top crust of snow, others did not, and some, such as the sample from St. James Campground, were leftover patches of ice. The isotopically light nature of these samples indicates that, while evaporation may have occurred, it was not sufficient to render melted snow indistinguishable from the lightest rain at Roswell.

Oxygen Isotope Fractionation between Limestone and Water

Six limestone samples were anlayzed for their $\delta^{18}O$ content to determine if the groundwater samples are in isotopic equilibrium with the primary aquifer material. The results of the analyses are shown in Table A4.

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All the values are in the appropriate range of $\delta^{18}O$ values for marine carbonates which range from $+20^{O}/oo$ for Cambrian rocks to $+30^{O}/oo$ for Recent limestones. This progressive increase is attributed to post-depositional recrystallization and oxygen isotope exchange with continental waters which are depleted in ^{18}O compared to sea water (Keith and Weber, 1964). Considering this to be the case, these samples from the Permian San Andres Formation show appropriate ^{18}O values, approximately $+26^{O}/oo$, except for one of them. The one sample shows a value more appropriate for recent limestones, $+32^{O}/oo$. This is probably due to contamination by recent limestone, since this is a surface sample, and improper sample preparation. Fortunately, this contamination only showed in one of the surface samples, and the remaining surface samples compare favorably with the drill cutting sample.

Using these results, the theoretical ^{18}O content of water in equilibrium with the limestone can be calculated with the appropriate isotope fractionation factor. The fractionation factor can be derived as follows:

(1) the isotope exchange reaction between limestone and water is:

$$\frac{1}{3} CaC^{16}O_3 + H_2{}^{18}O \rightleftharpoons \frac{1}{3} CaC^{18}O_3 + H_2{}^{16}O$$
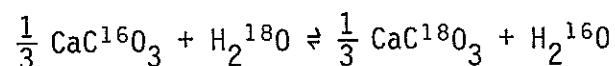
(2) the appropriate equation for the equilibrium constant is:
(Faure, 1977, p. 336)

$$K = \frac{([CaC^{18}O_3] / [CaC^{16}O_3])^{1/3}}{[H_2{}^{18}O] / [H_2{}^{16}O]} \equiv \frac{R_c}{R_w}$$

where: K = isotope fractionation factor.

It can further be shown (Faure, 1977, p. 336) that the equilibrium
fractionation factor for water and limestone is:

$$K = \frac{R_c}{R_w} = \frac{\delta^{18}O_c + 1000}{\delta^{18}O_w + 1000} \, ,$$

where R_c, R_w are the $^{18}O/^{16}O$ ratios for carbonate and water,
respectively.

Clayton (1961) gives the equilibrium fractionation factor as
1.02855 at 25°C. This value is adequate for a rough estimate
because the fractionation factor does not vary much in the expect-
ed range of surface temperatures in the Basin. Since, moreover,
temperature on the average only increases 1°C per 30 meters of
depth (Condie, 1976) it is also acceptable at depths studied in
the Basin (500-1000 ft). Using the high and low $\delta^{18}O$ values
measured in the limestones, the theoretical ^{18}O content of ground-
water in contact with similar limestones may be calculated:

(1) from the low value (25.04°/oo):

$$\delta^{18}O_w = \frac{25.04 + 1000}{1.02855} - 1000 = -3.41°/oo$$

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(2) from the high value $(32.04^o/oo)$:

$$\delta^{18}O_W = \frac{32.04 + 1000}{1.02855} - 1000 = +3.39^o/oo \ .$$

As these results indicate, the $\delta^{18}O$ values of water in equilibrium with San Andres carbonates would be on the order of $-3.0^o/oo$, definitely higher than the actual groundwater $\delta^{18}O$ values to be discussed in the next section.

Distribution of Oxygen 18 in Surface Water

The oxygen 18 values of the surface waters reflect varied contributions to the rivers.

In Table A1, seven samples are from the Rio Hondo and its major tributaries, the Rio Ruidoso and the Rio Bonito. The three highest locations show lighter values in winter than in summer, as would be expected due to precipitation contributions, tempered by contributions from springs and groundwater which would smooth the variations judging from the results of the western springs.

The Rio Hondo at the turnoff to Observation Well #4 rarely flows for more than a month or two during the early spring (except following periods of very high precipitation and flash floods), because of water usage and leakage into the groundwater system. The sample may reflect slightly heavier precipitation causing the flow at this location.

The river waters are isotopically light for the Hondo drainage system, on the order of $-9^O/oo$, in comparison with expected precipitation (using the $-7.1^O/oo$ value of Elk), but they are in line with expected precipitation values at altitudes higher than Elk, and with snowmelt contributions (see Miscellaneous Snow Samples in Table A1).

The next major Pecos tributary south of the Rio Hondo is the Rio Felix. The samples show isotope contents similar to those along the Hondo. One would expect the April sample to be lighter than the July sample rather than vice versa as shown; the groundwater system in this sampling area, the Flying H Ranch, may be an independent system, since all the wells in the area are flowing wells. It contributes substantially to the surface runoff. A comprehensive study of the area would clarify the situation, but for this study it is sufficient to note that the Rio Felix waters are isotopically similar to those of the Rio Hondo.

The last major Pecos tributary in the study area is the Rio Peñasco. The oxygen 18 values are on the order of $-9^O/oo$ to $10^O/oo$ in its upper course, but these values appear more consistent than for either of the other two tributaries. This is probably because of the effluent nature of the stream, with springs contributing greatly to the base flow of the river in its upper reaches. The river sample at Mayhill is essentially a sample of Posey Spring, a large regional spring system just upstream from the sample site.

The importance of these western river measurements is their similarity and isotopically light nature in comparison with the weighted mean values of precipitation. At Elk, $\delta^{18}O$ of Rio Peñasco was $-9^{O}/oo$ (vs. $-7.1^{O}/oo$ for the mean weighted precipitation at this locality). At Observation Well #7, about 25 miles downstream, three samples gave an average of $-8.2^{O}/oo$. The water becomes isotopically heavier downstream, probably due to evaporation and decreased spring contributions.

Only two samples are available for the Pecos River. The extremely light ($-12.6^{O}/oo$) sample at Roswell is considered in error. A more reasonable value is the $-5.5^{O}/oo$ value at Artesia (and perhaps the even heavier values of Boiling Spring), due to evaporation and the heavier oxygen 18 content of precipitation along the Pecos River than in the western mountainous belt.

A significant difference between the Hondo drainage system, which is supplied by Sierra Blanca (11, 977 ft), and the two southern rivers, Felix and Peñasco, are their strikingly different levels of tritium activity, illustrated in Figure 8 (see also Table A1). Hondo water samples consistently register high tritium activities (> 20 TU), similar to precipitation of the same time period. The southern rivers, by contrast, consistently show <10 TU, the effect of mixture of precipitation with 'old' groundwater.

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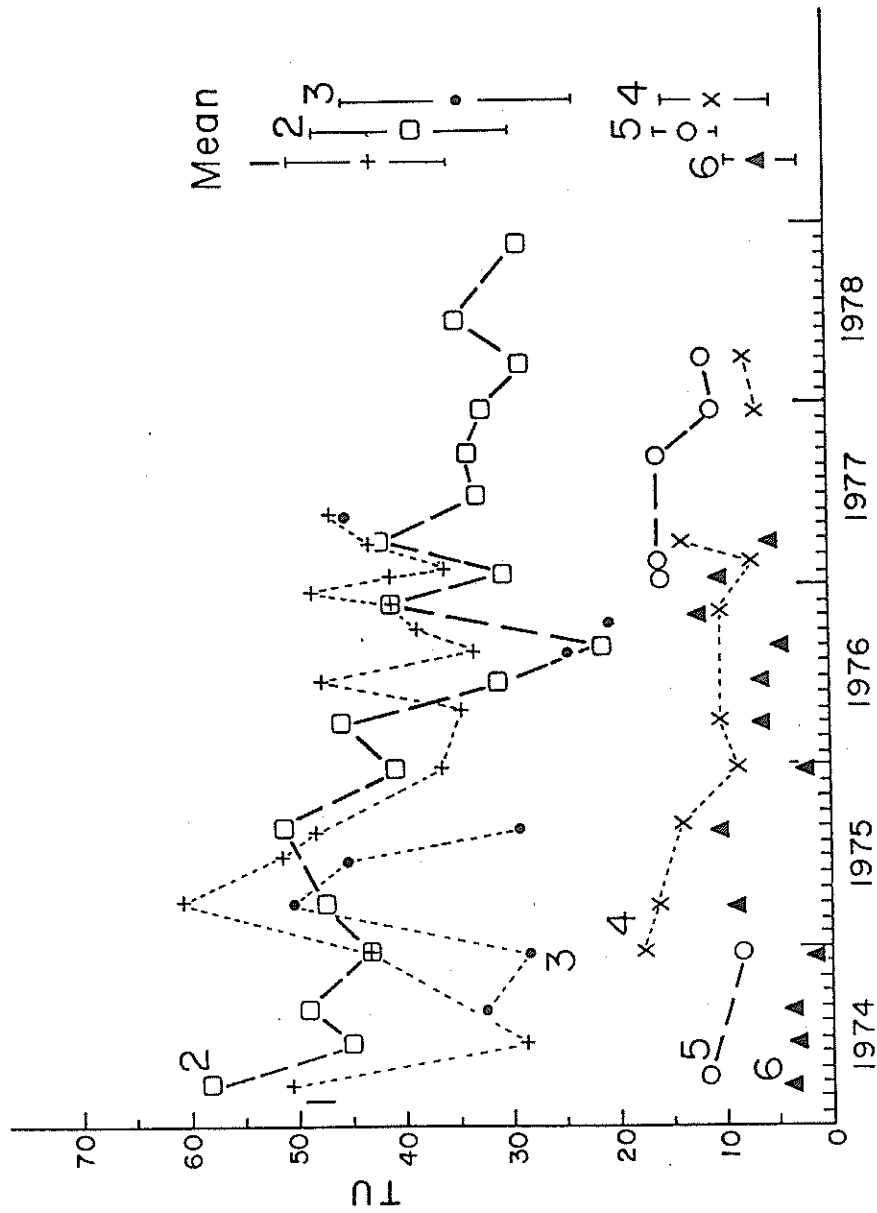
Figure 8: Groupings of natural waters according to tritium activity. Principal Recharge Area. Typical counting standard deviation of individual data points is ± 1 TU. For individual samples, see Gross and Hoy, 1980. 1 = Rio Ruidoso at Hondo; 2 = Observation well 8; 3 = Rio Bonito at Hondo; 4 = Rio Peñasco at Observation well 7; 5 = Observation well 7 (no data for 1975/76 because of cave-in); 6 = Observation well 2.

The situation is especially clear in the upper Rio Felix which receives much of its flow from an artesian aquifer (De Wilde, 1961). Flowing wells, tapping this artesian aquifer, also show generally lower tritium ratios (Gross and Hoy, 1980).

Bitter Lakes is a series of brackish lagunes located to the northeast and east of Roswell between the city and the Pecos River. The δD - $\delta^{18}O$ diagram (Figure 9) indicates that the water is of meteoric origin, typical of contemporary Roswell precipitation, and is undergoing evaporation.

Distribution of Oxygen 18 in Groundwater

In the following discussion, arithmetic means of oxygen 18 determinations will be used to facilitate the presentation of results and to justify certain tentative conclusions or interpretations. Because the sampling program was not systematic in either number of samples taken at specific sampling points, their repetition in time, and their distribution in space, little statistical weight should be attributed to these means, however. In reading and evaluating these results, the preliminary character of this study must always be kept in mind.

Springs

Springs tap groundwater reservoirs and contribute to surface flow. The rivers Felix and Peñasco derive substantial fractions of their runoff from groundwater, much of which enters their

channels in the form of springs. A hydrogeologic study of springs has revealed important features of recharge processes and groundwater circulation patterns in the Basin (Davis et al. 1980).

Waters from only five springs were analyzed for this study. Two of the springs, Paul Spring and Cleve Spring, are located within five miles of each other in the southwestern part of the study area. Trout Farm Spring is located in the northwestern part of the area, and Boiling Spring discharges into the Pecos River in the most southeasternly portion of the study area. Macho Spring, located north of the Capitan Mountains, discharges into the Macho drainage.

There are marked differences in the oxygen 18 values among the springs. The two springs in the southwest show oxygen 18 values on the order of -6.0^o/oo to -8.6^o/oo with a mean of -6.8^o/oo. It was expected that both these springs would show similar values due to their proximity and similar geologic setting. The systems feeding these springs are considered small perched systems near the Yeso/San Andres contact which should reflect local precipitation, and perhaps are a little heavier due to evaporation during infiltration. They are typical of many spring systems in the mountain zone. The weighted mean precipitation for the Elk weather station, which is just across the Rio Peñasco from Paul Spring, is -7.1^o/oo, in the range of the spring values.

A detailed study of the geology, spring flow, and tritium ratios of Paul Spring (Gross et al., 1979) indicates that its system is complicated with contributions to the spring water from 'young' and 'old' components. The younger component is precipitation which penetrates rapidly through the San Andres limestones. The older component is precipitation which travels more slowly through the less permeable Yeso Formation. As outcrops of both geologic units occur in this area, local precipitation would be the recharging water to both units. Snowmelt probably contributes more to the Yeso, as the meltwater usually has more time to infiltrate than the intense thundershowers of summer and fall, perhaps resulting in isotopically lighter water in the Yeso than in the San Andres. Tritium measurements seem to indicate events of younger water displacing older water. This "piston" effect was interpreted as flushing of the system following recharge espisodes, perhaps associated with intense localized rainfall events. (Mixing and dispersion will complicate this process.)

Trout Farm Spring in the northwest is also described as a perched system (Davis et al., 1980); however, it shows isotopically lighter water than the two springs above mentioned, approximately -8.2^o/oo. As the spring is in a similar geographic position as Paul and Cleve Springs, near the western edge of the long regional dipslope, local precipitation should have the same range of isotopic composition as at Elk. Although previously classified

as a perched system, it seems to be more extensive than either of
the above two springs, the discharge is larger, Yeso outcrops are
more extensive in this part of the Basin, and it may have a larger
component of snow melt from Sierra Blanca in its recharge. Any or
all of these factors may be reflected in the lighter oxygen 18
values.

Macho Spring had the lightest $\delta^{18}O$ value measured for any
spring. This may reflect its relation to the regional artesian
groundwater system (Davis et al., 1980, p. 31). It derives its
discharge from deep percolation which comes from the Capitan
Mountain massif, (10,179 ft a.m.s.l.) an intrusive stock or
laccolith (Kelley, 1971, p. 42).

The importance of these western spring measurements is their
apparent correspondence to local precipitation and overall un-
iformity in time.

Boiling Spring in the southeast is isotopically very heavy,
-2°/oo to -3.4^o/oo, in comparison with most oxygen 18 measurements
in the Basin. There are two possible explanations. The more
probable explanation is mixture with river water and evaporation
due to restricted circulation in the small 'cove' in which the
spring is located (see Figure 9). At Artesia, approximately
twenty miles upstream from the spring, the river water measured
-5°/oo. The other possibility is that the spring may issue water
which has resided in the San Andres long enough to exchange

oxygen isotopes with the limestone or has originated from an even deeper source than the San Andres. This possibility is considered in light of the fact that Boiling Spring is one of the few springs still flowing into the Pecos River, although this may be due to lack of intense agricultural development near the spring. High tritium activity suggests that the first alternative is more likely.

Wells

The most interesting results in the basin are those from the well samples. In the recharge area, seven observation wells, two windmills, and six domestic, stock, or irrigation wells were sampled for this investigation. In the major water usage area, along the Pecos River, 18 "deep" wells (producing from the Principal or Deep Aquifer) and five "shallow" wells (producing from the Alluvial or Shallow Aquifer) are listed in Table A1.

Observation Wells of the Intake Area

They are a special class of Principal Intake Area wells, removed from points of major groundwater exploitation. The dominant aquifers are the Glorieta Sandstone and the Yeso Formation. Water levels have been recorded continuously since about 1954, and periodic tritium determinations have been done since 1974 (Gross et al., 1976; Gross and Hoy, 1980). Duffy et al. (1978) found that water levels in two of these wells (07 and 08)

responded rapidly to runoff events in the nearby rivers Peñasco and Hondo, respectively. The remaining five wells, located in the interfluvial highlands of the San Andres dipslope, show mainly slow, long-term changes in water levels. Tritium determinations (Table A1) show that 08 reflects direct recharge of Hondo stream water ($\geq$29 TU). 07 also is controlled by direct recharge from the Peñasco but since the Peñasco runoff has a large groundwater component, the TU values are lower (10-16 TU). As illustrated in Figure 8 and discussed earlier, tritium ratios of these two observation wells fall squarely within the range of tritium activities of their respective recharge sources. Samples from the other observation wells are lower still in tritium, suggesting an absence of direct recharge. These relationships are not clearly reflected in the $\delta^{18}O$ values. The grand mean of all observation wells is -8.1°/oo. This compares to -8.6°/oo for the other Intake Area wells (see below). The difference may be fortuitous or it may reflect some evaporation along the casing in the static (that is, no artificial flow induced by pumping) observation wells. In any case, these values seem to fall in the range characterizing recharge from the mountain zone. 02, 03, and 07 are slightly higher (-7.4°/oo to -7.5°/oo). In the case of 07, this may either reflect evaporation of the river water during the recharge process, or it may be attributed to the generally slightly heavier character of groundwater in the southern part of the basin, as will

be discussed below. Either explanation leaves out 02 and 03(-7.5^O/oo). These two wells are located in the interfluvial highland to the north of Rio Hondo, but still belong to its drainage basin. They straddle the Border Hill structural zone (Figure 2). There is a danger to overinterpret these statistically insufficient data (only 1 or 2 data points from each well).

Production Wells of the Intake Area

The production wells in the Principal Intake Area may be grouped into three categories: those within the drainage of the Rio Hondo, one well in the drainage of Arroyo del Macho (Tom Corn), and two within the drainage of Rio Peñasco (Hope municipal well, and McAshan windmill). This is the order of increasing $\delta^{18}O$ values.

The wells along the Rio Hondo are isotopically light ($\delta^{18}O$ = -8.9^O/oo to -9.4^O/oo), and are in the same range as the river water or slightly lighter. The Tom Corn well (in the Macho drainage) was slightly heavier than the Hondo wells (-8.6^O/oo to -8.7^O/oo). Hope municipal well and McAshan windmill, along the Rio Peñasco, are isotopically still heavier, -7.2^O/oo and are also heavier than the Peñasco river water.

The isotope composition of wells in the Roswell area may reflect the high-altitude runoff which disappears into the San Andres and lower formations along the course of the Rio Hondo.

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Generally speaking, recharge to the northern wells (Arroyo del Macho and Rio Hondo drainage systems) seems to include more contributions from higher altitudes than recharge to wells near the Peñasco. The Rio Hondo drainage includes Sierra Blanca (11,977 ft a.m.s.l.), highest peak in the Sacramento Mountains, in its source area. Arroyo del Macho drains the northeast side of the Capitan Mountains (10,179 ft a.m.s.l.). The Peñasco drainage basin includes vast highlands of somewhat lower elevation. As investigated elsewhere (Rehfeldt and Gross, 1982), deep leakage (from underlying aquifers, notably the Yeso Formation) supplies a significant fraction of the groundwater, and the isotopic composition of this source is presumably determined by the elevation of its outcrops along the Sacramento-Sierra Blanca-Capitan mountain front.

Principal Aquifer Wells in the Confined Zone

East and south of Roswell, where the Principal Aquifer is in close hydraulic connection with the alluvial aquifer immediately overlying it (the Artesia having largely been eroded away), the signals are mixed.

Three saltwater wells east of Roswell (Elk #1, Conservancy, and Roswell Saltwater Treatment Plant) range from $\delta^{18}O = -7.6^0/oo$ to $-8.9^0/oo$. $\delta^{18}O$ values of the flowing irrigation wells of the Clardy group southeast of Roswell range from $-4^0/oo$ to $-8.8^0/oo$, with a mean of $-7.1^0/oo$. Allison RA 1102 south of Roswell showed

-9.3^o/oo to -9.5^o/oo, while another Allison well close by (RA 1015/1012) gave values of -7.8^o/oo to -8.2^o/oo. All of these wells are in the Rio Hondo drainage basin. No alluvial aquifer wells were sampled in this area.

The deuterium and oxygen 18 results of the three saltwater wells (Figure 9) indicate a purely meteoric origin. No exchange reactions with the aquifer matrix seem to have taken place.

Of the above mentioned wells, the three saltwater wells are located on Havenor's (1968, Plate 1) Roswell tectonic block, a structural high with respect to the Orchard Park block to the south-east, on which the remainder of the wells are located. We do not suggest that our isotope data reflect these structural relation-ships. Rather we suggest that the pattern of somewhat higher and lower $\delta^{18}O$ values in this area reflects the superposition of localized recharge during the irrigation season (leakage from the alluvial aquifer including irrigation returns) upon the isotopic-ally lighter water of the Principal Aquifer which originates from the high-mountain zone to the west. Leakage through defective casings or mixing, in pumping wells, of water from the two aquifers can also cause fluctuation of $\delta^{18}O$ values in this area.

In the Hagerman-Artesia section of the Basin under study, (i.e. all wells listed after Allison in Table A1), Principal Aquifer wells show a rather homogeneous $\delta^{18}O$ between -7°/oo and -8°/oo. One exception is Pollard with -9.0^o/oo to -9.4^o/oo. Pollard well

is located close to Havenor's (1968, Plate 1) K M Fault. It is within the Rio Felix drainage basin, as are three Principal Aquifer wells north of this location (Villa Solano, Hagerman, Jake Johnson). Principal Aquifer wells in and south of Artesia belong to the Rio Peñasco drainage basin and show a similar range (i.e. between -7°/oo and -8°/oo), with two exceptions: the Gates well shows a spread of $\delta^{18}O$ values from -5.4^o/oo to -8.6^o/oo (with a mean of -6.5^o/oo). This is probably the result of mixture with Alluvial Aquifer water in variable proportions. The Alluvial Aquifer is not cased off. The deep Vandiver well, in which the Alluvial Aquifer is cased off, ranges from -8.4^o/oo to 9.2^o/oo. It derives its production exclusively from the San Andres.

Alluvial Aquifer Wells

The Alluvial Aquifer wells in the Hagerman-Artesia section show a wider spread of $\delta^{18}O$ values and are, on the average, isotopically heavier (from -3.6^o/oo to -8.6^o/oo with a mean of -7.0^o/oo or -7.3^o/oo). This is the result of evaporation which especially affects irrigation returns (see, e.g., the hand dug windmill well with $\delta^{18}O = -3.6^o$/oo) and of direct recharge to the Alluvial Aquifer at the lowest elevations in the basin. In this southern section of the basin, the Principal and Alluvial Aquifers are hydraulically isolated from each other, but leakage along well casings and mixing within wells nominally pumping from the Principal Aquifer may mask the true isotopic composition of Principal

Aquifer water in this section of the basin. For comparison, the mean for all Principal Aquifer wells was -7.6^o/oo. This is only lowered to -7.7^o/oo if the three highest values, ($> -6.0^o$/oo), attributed to leakage or mixing, are excluded.

In summary, then, our oxygen 18 data seem to indicate that: Principal Aquifer water is rather homogeneous and relatively light, possibly slightly lighter in the north (Roswell) where water is derived from the highest elevations (Sierra Blanca, Rio Hondo drainage basin) than in the south (Felix and Peñasco drainages). The alluvial aquifer is isotopically heavier, in accordance with its recharge at lower elevations and contamination with irrigation returns. These relations are masked where hydraulic connections have been established through wells.

Tritium Results

To judge by the tritium results, the Principal Aquifer wells contain predominantly 'old' (slow recharge component) water. Higher tritium values have been observed, however (Rabinowitz et al., 1977). These indicate a mixture of a 'fast' component, which is mainly attributed to recharge by surface streams in the Principal Intake Area and leakage from the Alluvial Aquifer during the pumping season. Springs and wells in the mountain zone (Davis et al., 1980; Wasiolek and Gross, in preparation) show similar mixing effects. On the basis of tritium determinations, mixing ratios were computed

that estimate the fast recharge contributions at less than 50% of total recharge (Gross et al., 1979; Rehfeldt and Gross, 1982; Wasiolek and Gross, in preparation).

The Artesia area wells have never displayed the tritium peaks observed in the Roswell area. This has been attributed to a lower transmissivity in the southern part of the basin (Rabinowitz et al., 1977).

Circulation Patterns and Related Effects

We now return to the δD vs. $\delta^{18}O$ relation, shown in Figure 9. Minor evaporation effects are noticeable in the departure from the meteoric line of some precipitation, as well as of spring and surface samples in the northeast quadrant of the graph. Precipitation is fairly well spread out over the whole usual range of Craig's meteoric line, with snow being isotopically lightest (southwest quadrant), as expected. This reflects the orographic and climatic diversity of this extensive basin. Groundwater samples (including springs) fall, however, into a relatively narrow range, roughly: (δD = -30°/oo to -80°/oo and $\delta^{18}O$ = -5°/oo to -10°/oo). This range is comparable to that measured by Lambert (1978) in the Delaware Basin. It indicates a meteoric origin unmodified by aquifer matrix interactions.

Because the groundwater data are crowded in such a narrow range ostensibly falling within the isotopic composition of precipitation at lower to intermediate elevations in the basin, it could
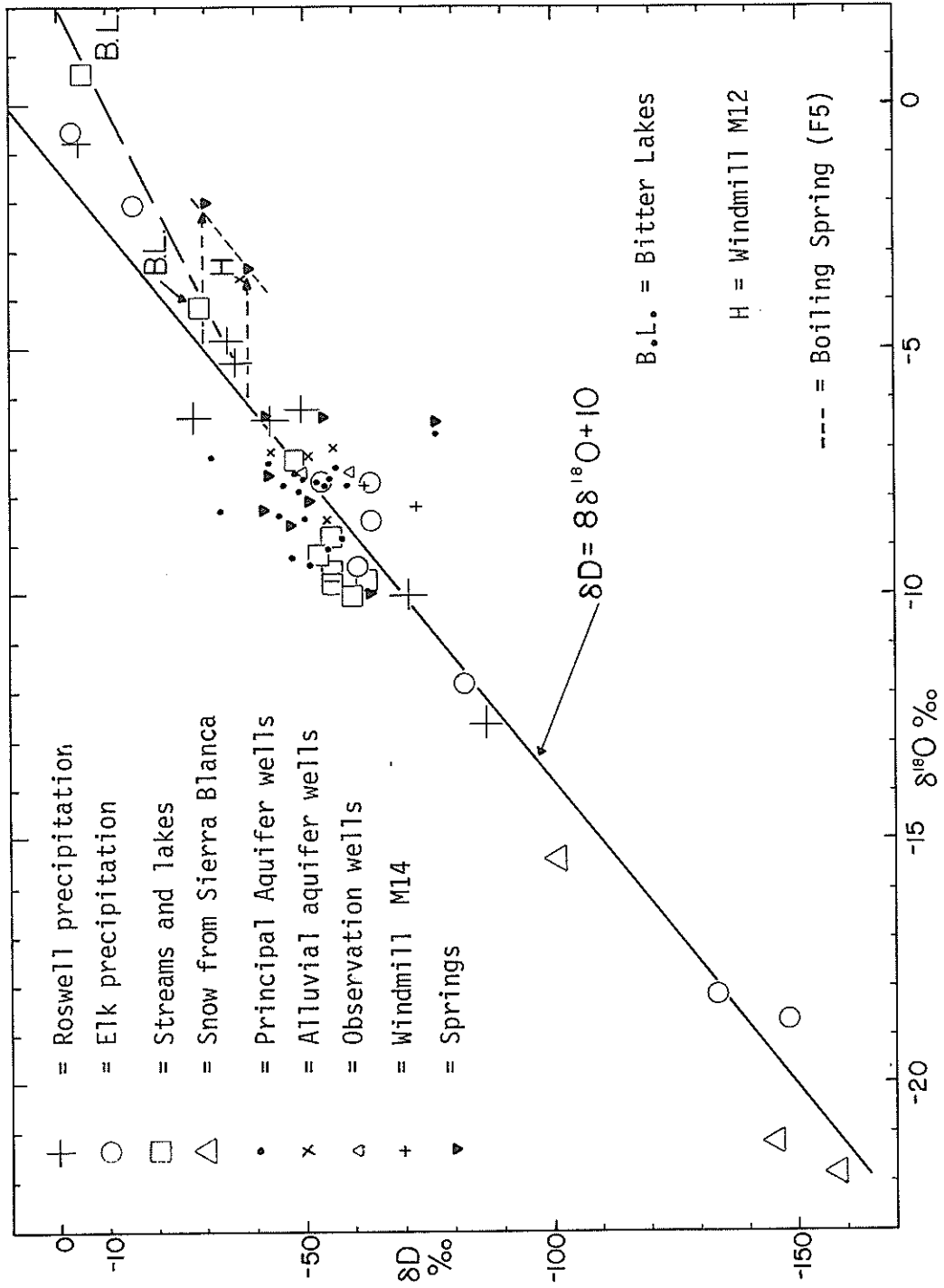
Figure 9: $\delta^{18}O$ for basin waters. Standard deviation for individual data points $\pm 0.2^{\circ}/oo$ for $\delta^{18}O$, and $\pm 1.5^{\circ}/oo$ for δD.

See Table A1 for numerical values.

be argued that, in fact, these data support the classical concept of groundwater recharge predominantly originating by summer precipitation and runoff in the Principal Intake Area. This conclusion is at variance with the tritium data (Figure 8, see also Gross et al., 1976), as well as with other hydrologic evidence (e.g.: Gross et al., 1976; Duffy et al., 1978; Gross and Hoy, 1980; Rehfeldt and Gross, 1982). Moreover, the Elk weather station is located outside of and higher than the Principal Intake Area, yet summer and fall precipitation at this locality considerably overlap with Roswell (where winter precipitation is very infrequent). As we have seen, the mean oxygen 18 content at Elk is somewhat lighter than at Roswell. For all these reasons we feel justified in looking to alternative ways of explaining the isotopic composition of groundwater in the basin. A brief outline follows.

A homogeneous δD-$\delta^{18}O$ distribution in groundwater, such as observed in the present case, is usually considered evidence of thorough mixing in the aquifer (Conrad et al., 1978) or of a very localized recharge source (Gallo, 1978). In our case, mixing is reasonable because the flowpaths are long. There are other factors that promote mixing. In years of ample moisture at the higher elevations, rivers flow farther east and contribute recharge over a larger area. In dry years, smaller surface flows are incorporated further to the west and must percolate through more limestone to reach the discharge zone. The southern rivers (Felix and

Peñasco) "shunt" groundwater from the western mountain belt into the Principal Intake Area where it is reabsorbed into the ground-water system of the Principal Aquifer. Upward leakage from deeper aquifers (which also get their water from the western mountains) enters the Principal Aquifer from beneath, and this process is furthered by the large drawdowns produced in the agricultural belt during the pumping season.

Two meteorological factors may also contribute to 'mixing' by reducing geographic and seasonal effects: (1) In this semiarid continental environment, the altitude effect may be weakened by the large and rapid temperature fluctuations that occur at all elevations as a result of atmospheric disturbances. (2) Moisture to the region is supplied from two sources, the Gulf of Mexico and the Pacific, although the former predominates in summer (Rabino-witz et al., 1977).

These suggestions are offered to account for the apparently homogeneous stable isotope makeup of groundwaters in the Basin. The concept of recharge by 'deep' leakage is illustrated in Figure 10.
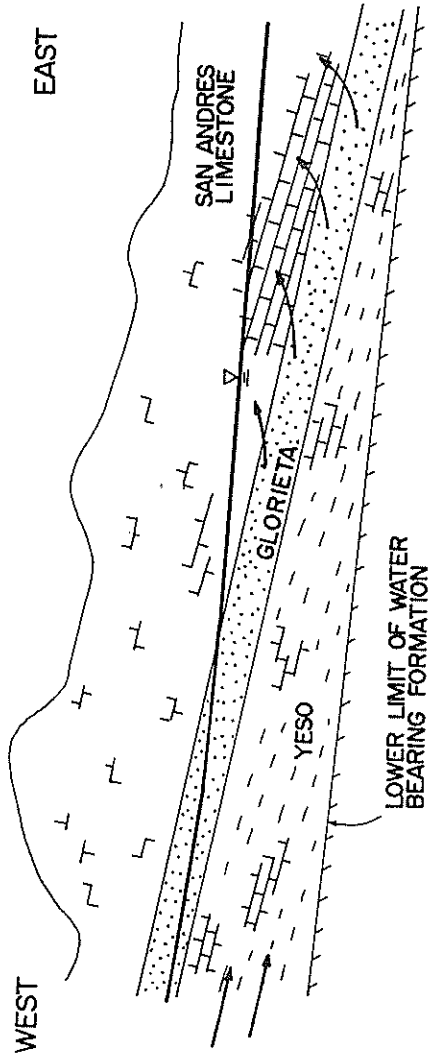
Figure 10: Diagram illustrating the concept of recharge to the Principal Aquifer in the San Andres Formation by upward leakage from underlying formations.

SUMMARY AND CONCLUSIONS

The purpose of this study was to distinguish recharge components in the Roswell Groundwater Basin using the stable isotopes of oxygen and hydrogen. Different components would, in principle, be distinguishable by their original isotopic compositions and possible history effects. Since the isotopic makeup of precipitation varies with geography, especially with elevation, we tried to find out whether such differences are noticeable in the Basin and whether they are reflected in surface and groundwater. For this purpose, the basin was divided into three parallel zones, the valley, the dipslope, and the mountains.

Precipitation data were analyzed to answer four questions: (1) What are the general ranges of isotopic composition? (2) What is the relationship between oxygen 18 and deuterium ratios in the basin? (3) What is the relationship between oxygen 18 content and condensation temperature? (4) Is this relationship reflected in a dependence on geographic zone or elevation?

(1) The range of $\delta^{18}O$ values ($-18.7^o/oo$ to $-0.2^o/oo$) was comparable to those measured in other regions of the central and southwestern U.S.

(2) The relation between deuterium and oxygen 18 ratios in the basin is similar to Craig's (1961) meteoric line. A slightly flatter slope (7.2 vs. 8) is probably due to evaporation effects

during precipitation. The smaller hydrogen excess (5.5^o/oo vs. 10°/oo) is believed to be statistically insignificant because of sampling deficiencies.

(3) A systematic relation was found to exist between condensation temperature and oxygen 18 content of precipitation. This relation is somewhat weaker than that established by Dansgaard for more northerly latitudes.

(4) Similarly, the dependence of oxygen 18 on elevation, though systematic, is somewhat weaker than in more temperate climate.

Next, it was necessary to ascertain whether surface and groundwater had undergone significant evaporation during surface storage, runoff or percolation. Such effects were observed in only a few specific cases that have been discussed.

The limestone analyses and appropriate calculations indicate that no appreciable isotope exchange has occurred between groundwater and aquifer matrix. Apparently, groundwater does not reside in the system long enough for such reactions, as verified by tritium results. Even the deepest recharge sources may be too shallow for significant exchange reactions with bedrock to have taken place. Nothing like the highly atypical saltbrines reported by Lambert (1978) from the Carlsbad area, indicative of intense isotopic exchange between water and evaporite bedrock, seems to exist in the Roswell Basin. Groundwaters in the Roswell Basin, therefore, represent present climatic conditions.

With the two major history effects (evaporation and wallrock interaction) evaluated, it is assumed that, in general, the isotopic composition of the recharge is not significantly altered during infiltration through the groundwater system, except by mixing and dispersion, as indicated in tritium studies (Gross et al., 1976), and verified by the stable isotope values.

Whereas the δD and $\delta^{18}O$ values of precipitation range over the whole usual range of the meteoric line (Figure 9), groundwater samples are remarkably homogeneous and narrowly clustered. This is tentatively attributed to thorough mixing over long flowpaths, large temperature fluctuations that overshadow orographic temperature effects, and the existence of two moisture sources (Gulf of Mexico and Gulf of California) for precipitation in this Basin. Complex hydraulic connections between aquifers and variable recharge through stream channels further contribute to mixing. A separation of recharge sources on the basis of stable isotope seems to require more detailed and better distributed determinations in both space and time. This will also mean much greater numbers of samples in this very large Basin.

The clearest differentiation of recharge sources (inclusive of the computation of mixing ratios) is still made on the basis of tritium, as discussed elsewhere.

RECOMMENDATIONS FOR FUTURE WORK

In the course of this study, numerous possibilities for
future directions have become apparent.

Systematic sampling should be continued to resolve ambig-
uities of the interpretation and improve the data base where
deficiencies have become apparent. For example, how significant
is the observed difference in mean oxygen 18 weight between north-
ern and southern groundwaters, and between the latter and the
rivers Felix and Peñasco? Renewed sampling in space and time
should be systematic and be guided by statistical principles.

Precipitation from the extreme western portion of the basin,
to complement the Roswell and Elk weather data, would improve the
profile of isotope input in water across the Basin. While the
miscellaneous snow samples provided some information, more quantita-
tive and continuous data would be helpful and could possibly be
obtained at Ruidoso or Cloudcroft. Similarly, groundwater from
the mountain zone needs to be investigated more systematically.

The sampling of groundwater at more locations would improve
the profile of groundwater isotope variations. Four locations
of interest for which water samples are readily available are:
(1) shallow wells in the Roswell area, (2) wells of more ap-
propriate construction in the Artesia area, (3) wells far
from the major drainage systems, and (4) Macho Spring at the
head of the Arroyo del Macho. This location is in an area

of great interest, northwest of the present study area. It is
the northward continuation of the regional bedrock slope, drained
to the southeast towards Roswell by the Arroyo del Macho. A study
of the groundwater contributions from this area would be most infor-
mative, but much of the area is relatively inaccessible.

A fact mentioned, but not dealt with in this paper, is the
air circulation pattern in the area and its possible effects on
the isotopic composition of precipitation. Both the Gulf of Mexico
and the Pacific Ocean serve as sources of moisture, which probably
accounts for the lack of a rain shadow effect by the Sacramento
Mountains. It was assumed that there are no major differences in
isotopic composition between the two sources but it might be
possible to distinguish summer and winter precipitation on the
basis of moisture sources.

Understanding water circulation in the basin was the primary
purpose of the study, and it became apparent that many underground
solution features are related to surface drainages, as might be
expected in karstic terrain. A detailed study of the terrain
would be most profitable, and aerial and Landsat photographs of
the area are available. Time of circulation, evidenced by the
'fast' and 'slow' recharge components, is also quite important,
and greater resolution of residence time would be helpful.

In some isotopic studies, a positive correlation between
salinity and isotope content of water has been noted (Faure, 1977,

Ch. 18). A wide range of salinities is observed in the Roswell Basin, and such a study in the basin could prove interesting. Evaporation is usually the basis for the correlation, and, while evaporation has not been proven significant in this preliminary study, a more detailed study would be necessary. Also related to salinity, the isotopic composition of the brines encroaching from the northeast could provide information on the rate of encroachment and the sources of the brines. This might also lead to information on the presence or absence of water in the pre-Yeso formations.

In line with studying the waters in the pre-Yeso formations, more geologic information would be necessary for interpretation. In terms of interaquifer leakage and a 'slow' recharge component, it seems imperative to understand the hydrologic behavior of these lower formations.

The list of possibilities becomes self-generating at this point, but the above suggestions seem the most feasible and would contribute the most to understanding of the Roswell area and the general applications of isotope hydrology to the solution of problems in this basin.

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APPENDIX:

SUPPORTING DATA
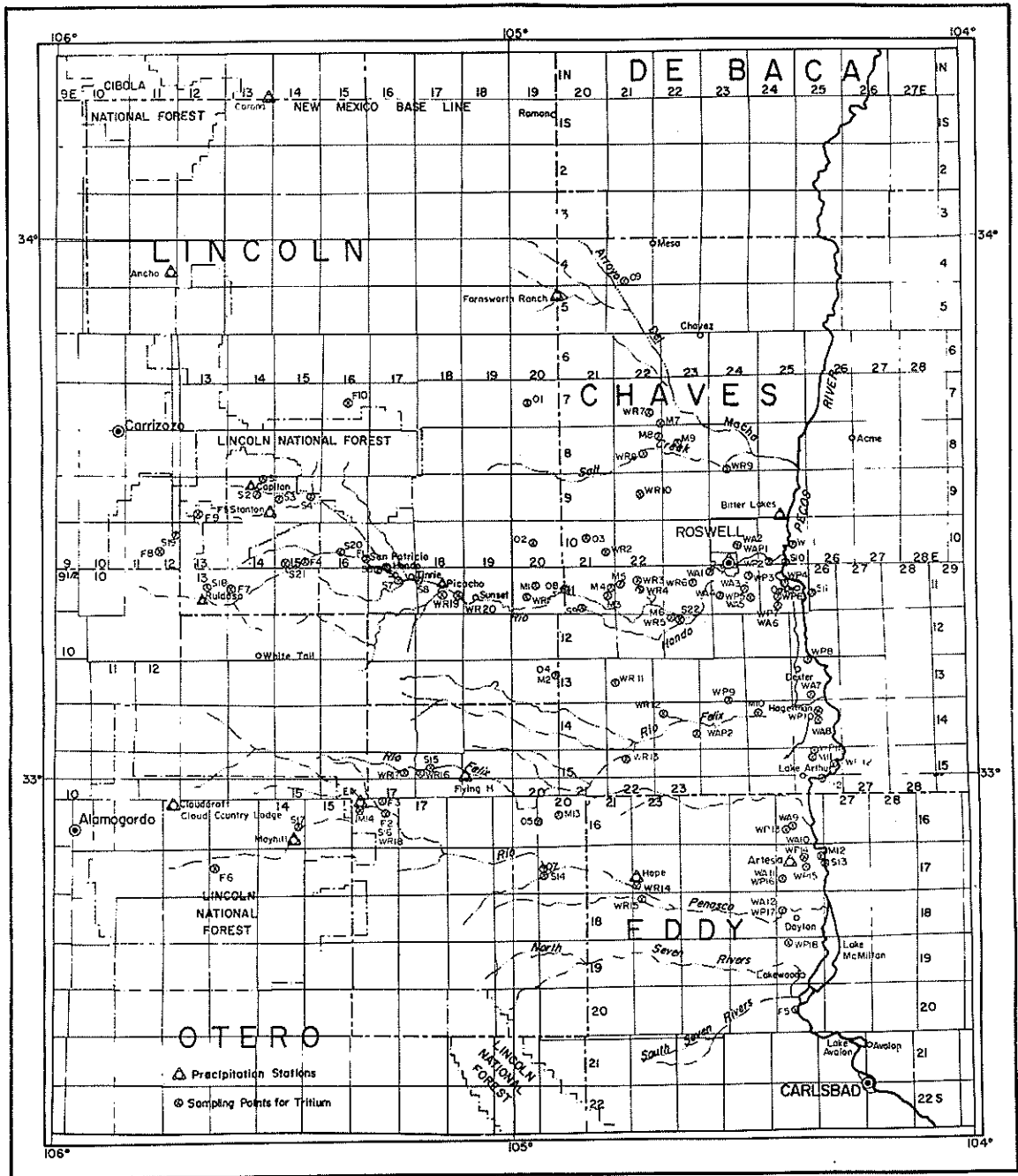
Figure A1: Sampling points for tritium and for stable isotopes. This map shows all sampling points, including many that were not used for this report.

Table A1

Roswell Groundwater Basin
Oxygen 18, Deuterium, and Tritium Analyses of Water Samples

Sources and Precision

Oxygen 18:   Estimated precision. . . . .$\pm$ 0.2 o/oo
                    Estimated accuaracy. . . . .$\pm$ 0.1 o/oo
                    Analyzed by Geochron Laboratories

Deuterium: Samples marked * were analyzed by
                    Geochron with a typical precision of $\pm$ 2.0 o/oo
                    All others by DR. G. P. Landis and
                    H. R. Northrop (Stable Isotope
                    Laboratory, Dept. of Geology,
                    University of New Mexico) with
                    precision of. . . . . $\pm$ 1.5 o/oo

                    $\delta^{18}O$ and δD results are given as
                    deviations with respect to SMOW.

Tritium: All samples analyzed by the
                    Tritium Laboratory, New Mexico
                    Institute of Mining and Technology.
                    Precision is given with each result.

Sampling locations are shown on the general sampling map of Fig. A1.

Table A1

Roswell Groundwater Basin
Oxygen 18, Deuterium, and Tritium Analyses of Water Samples

Type of samples	Map #	Sample Location	Sample #	Date Collected	$\delta^{18}O$ $^o/_{oo}$	δD $^o/_{oo}$	Tritium (T.U.)
Springs	F1	10.17.29.4143 (Trout Farm Spring)	2800 1264f	3/19/78 11/16/78	-8.3 -8.1	-41.8 -51.1	6.9+0.7
	F3	16.16.02.323 (Cleve's Spring)	2368 2539	5/5/77 1/14/78	-6.2 -7.4		6.4+0.8 3.6+0.6
		Mean of Cleve's Spring			-6.8		
	F2	16.16.11.342 (Paul Spring)	2370 2397 2398 2394 2404 2406 2408 1439f	5/5/77 7/15/77 8/17/77 9/16/77 11/20/77 1/14/78 3/11/78 6/3/79	-6.0 -6.5 -7.6 -6.4 -6.3 -6.4 -6.3 -8.6	-43* -54* -41.5 -47.1	3.5+0.7 1.5+0.9 12.1+0.9 5.4+0.8 1.4+0.7 0.9+0.7 2.0+0.8
		Mean of Paul Spring			-6.8	-46.4	
	F5	20.26.27.100 (Boiling Spring)	2435 2563	9/17/77 4/1/78	-3.4 -2.0	-38.5 -30.0	39.1+1.6 34.6+1.6
	F10	7.16.7.43 (Macho Spring)	1414f	4/14/79	-10.0	-63.0	
Surface Water	S4	9.15.14.240 (Rio Bonito @ Baca Campground)	2565 2566	6/25/78 11/16/78	-8.9 -10.1	-60.0	21.5+1.4 47.7+2.0
	S21	10.15.33.333 (Rio Ruidoso @ Fox Cave)	2564 2568	6/23/78 12/1/78	-9.3 -9.7	-62.4	46.6+1.6 50.0+2.1
	S8	11.18.16.000 (Rio Hondo @ R.O. Anderson Well)	2513 2569	6/23/78 12/1/78	-7.3 -10.1		15.9+0.7 41.3+1.6
	S9	11.21.29.400 (Rio Hondo @ turnoff to Obsv. Well #4)	2567	11/18/78	-8.8	-56.2	38.9+1.7
	S10	10.25.34.334 (Pecos R. @ Roswell)	2562	4/1/78	-12.6		40.7+2.0

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Roswell Groundwater Basin
Oxygen 18, Deuterium, and Tritium Analyses of Water Samples

Type of samples	Map #	Sample Location	Sample #	Date Collected	$\delta^{18}O$ $^o/oo$	δD $^o/oo$	Tritium (T.U.)
Surface Water (continued)	S13	17.27.08.200 (Pecos R. @ Artesia)	2581	4/1/78	-5.5		36.0+1.3
	S15	15.18.16.000 (Rio Felix @ Flying H)	2580 2582	7/15/77 4/2/78	-10.4 -8.0		4.4+0.8 6.7+0.7
	S17	16.14.24.000 (Rio Peñasco @ Mayhill)	2533 2584	4/2/78 7/7/78	-9.7 -9.6	-55.8 -57.3	7.1+0.9
	S16	16.16.11.240 (Rio Peñasco @ Mulcock's)	2532 2585	4/2/78 7/7/78	-9.0 -9.0		3.2+0.7 4.9+0.8
	S14	17.20.18.434 (Rio Peñasco @ Obsv. Well #7)	2524 2531 2586	12/17/77 4/2/78 7/7/78	-8.2 -7.2 -9.1	-48.6 -50.3	6.2+0.7 7.9+0.9 0.1+0.8
	S23	Bitter Lakes	1281f 1410f	11/19/78 4/03/79	-4.1 +0.6	-29.5 -6.0	
Windmills	M13	16.20.16.241 (McAshan Windmill)	2544	4/2/78	-7.2		5.6+0.8
	M14	16.16.08.121 (Bates Windmill)	1188f 1225f	4/2/78 7/7/78	-7.8 -8.1	-62.1 -72.8	
Observation Wells	O1	7.20.16.333 (P.V.A.C.D. #1)	2583 2587	6/24/78 11/17/78	-9.3 -8.9		5.3+0.9 0.2+1.2
				Mean O1	-9.1		
	O2	10.20.16.444 (P.V.A.C.D. #2)	1266f	11/16/78	-7.5	-58.5	
	O3	10.21.16.222	1267f	11/17/78	-7.5	-48.9	
	O4	13.20.13.222 (P.V.A.C.D. #4)	1212f 1277f	6/25/78 11/18/78	-8.0 -8.9		1.2+0.5 3.7+0.6
				Mean O4	-8.5		

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Table A1

Roswell Groundwater Basin
Oxygen 18, Deuterium, and Tritium Analyses of Water Samples

Type of samples	Map #	Sample Location	Sample #	Date Collected	$\delta^{18}O$ °/oo	δD °/oo	Tritium (T.U.)
Observation Wells (continued)	O7	17.20.18.434 (P.V.A.C.D. #7)	2534	9/17/77	−6.9		16.0+1.1
			2538	12/17/77	−6.8		11.1∓0.9
			2530	4/2/78	−8.6		9.8∓0.9
				Mean O7	−7.4		
	O8	11.21.18.333 (P.V.A.C.D. #8)	766f	3/26/77	−7.3		42.1+1.6
			839f	6/26/77	−7.5		33.0∓1.3
			974f	9/18/77	−9.0		34.0∓1.5
			1059f	12/18/77	−8.6		32.4∓1.3
			1130f	3/19/78	−8.3		28.7∓1.1
			2518	6/25/78	−8.9		34.9∓1.5
			1278f	11/18/78	−7.5		29.0∓1.3
				Mean O8	−8.2		
	O9	4.21.33.111 (P.V.A.C.D. #9)	1205f	6/24/78	−8.9		3.0+0.6
			1274f	11/18/78	−8.2		4.0∓0.7
				Mean O9	−8.6		
		Mean of All Observation Wells			−8.1		
Intake Area Wells	WR19	11.18.15.313 (R.O. Anderson) domestic and stock	2514	6/23/78	−9.3		25.5+0.9
	WR3	11.22.09.321 (Woods Well) domestic and stock	2510	12/18/77	−9.4	−46.7	4.2+0.5
			2517	6/25/78	−8.9	−41.8	5.0∓0.8
	WR5	12.23.06.441 (Patterson 'Big Cat') irrigation	2516	6/24/78 (pumping 391 gpm)	−9.3		2.7+0.5
	WR5	12.23.05.313 (Patterson 'House Well') domestic	2515	6/24/78	−9.2		15.9+0.7
	WR7	7.22.26.131 (Tom Corn Well) stock	2525	3/18/77	−8.6		4.9+0.7
			1268Bf	11/17/78	−8.7		4.2∓0.6

Roswell Groundwater Basin
Oxygen 18, Deuterium, and Tritium Analyses of Water Samples

Type of samples	Map #	Sample Location	Sample #	Date Collected	$\delta^{18}O$ $^{o}/_{oo}$	δD $^{o}/_{oo}$	Tritium (T.U.)
Intake Area Wells (continued)	WR14	17.23.30.120 (Hope Municipal Well)	2535 2543	5/12/77 1/78	−7.2 −7.2	−47.3 −46.8	9.1+0.7 3.6+0.6
		Mean of All Intake Area Wells			−8.6	−45.7	
Principal Aquifer Wells	WP1	10.25.22.324 (Elk #1) Flowing, closed, not in use	1785 1280f	3/26/75 11/18/78	−8.8 −7.6	−52.0 −50.1	1.0+1.1
	WP2	10.25.32.333 (Conservancy Well) Flowing, closed, not in use	1926 2801	8/27/75 4/03/79	−8.9 −7.7	−55.4	5.5+0.8 10.4+0.9
	WP2	10.25.33.144 (Roswell Saline Water Treatment Plant Well)	2116	6/04/76	−7.7	−52.5	7.0+0.8
	WP4	11.25.23.111 (Clardy RA 62) irrigation	2103	10/02/76 (pumping 850 gpm)	−7.6		2.3+0.5
	WP4	11.25.15.343 (Clardy RA 1102) irrigation	2102 1068f	10/02/76 (pumping 2000 gpm) 12/19/77 (flowing slightly)	−6.4 −7.4		7.8+0.6
	WP4	11.25.15.334 (Clardy RA 61) irrigation	2055 2119 2101 2597 2520 2757 2881 2526 2602 2610	3/28/76 6/4/76 (pumping 1500 gpm) 10/2/76 (flowing 450 gpm) 1/5/77 3/25/77 6/25/77 (pumping 1700 gpm) 9/17/77 (pumping 1750 gpm) 4/1/78 (pumping 1600 gpm) 7/8/78 (pumping 2000 gpm) 11/18/78 (flowing slightly)	−4.0 −6.5 −7.2 −7.2 −8.4 −7.2 −7.0 −8.8 −7.4 −7.6	−44.8 −58*	3.1+0.9 9.7+0.6 6.5+0.5 9.4+0.9 6.9+0.9 9.2+0.7 8.1+0.7 4.2+0.6 5.6+0.7
		Mean of Clardy			−7.1		

Table A1

Roswell Groundwater Basin
Oxygen 18, Deuterium, and Tritium Analyses of Water Samples

Type of samples	Map #	Sample Location	Sample #	Date Collected	$\delta^{18}O$ °/oo	δD °/oo	Tritium (T.U.)
	WP5	11.24.25.341 (Allison RA 1015/1012-S-Comb-B) irrigation	2519	3/25/77	-8.2	-32.7	5.5+0.9
			2527	4/1/78 (pumping 1150 gpm)	-7.8	-47.2	1.1+0.7
	WP5	11.24.26.224 (Allison RA 1102) irrigation	2507	9/17/77 (pumping 1850 gpm)	-9.3		6.8+0.8
			2511	4/1/78 (pumping 1800 gpm)	-9.5		2.6+0.7
	WP9	13.24.34.441 (Villa Solsano)	1160f	4/1/78	-7.2	-31.1	
			1308f	12/2/78	-7.7	-52.7	
	WP10	14.26.10.222 (Hagerman Municipal Well)	1161f	4/1/78	-7.4	-56.9	
			1307f	12/2/78	-7.8	-54.1	
	WP11	15.26.04.141 (Jake Johnson Farm)	1309f	12/2/78	-7.7	-58.5	
	WP12	15.26.13.121 (Pollard Well)	2506	9/17/77	-9.4	-51*	4.1+0.8
			2512	4/1/78 (pumping 978 gpm)	-9.0	-55*	1.9+0.6
	WP14	17.26.10.333 (Gates RA 307) irrigation	1958	8/28/75	-5.0		9.6+0.4
			2128	6/4/76 (pumping 800 gpm)	-6.3		4.2+0.3
			2199	8/11/76 (pumping 500 gpm)	-6.7		9.7+1.0
			2598	3/25/77	-7.0		7.9+0.7
			2605	7/1/77	-6.1		7.1+0.5
			2607	9/17/77	-7.4		6.9+0.7
			2608	4/1/78	-6.7	-77*	4.9+0.6
		(2598-2608: flowmeter not indicating)					
		Mean of Gates			-6.5		
	WP14	17.26.10.433 (Sullivan (Pennington) Farms)	1167f	4/1/78 (pumping 400 gpm)	-7.3	-42.6	
			1379f	4/1/79 (pumping 830 gpm)	-7.9	-48.6	
	WP15	17.26.14.211 (Sharp RA 895)	2536	9/17/77 (pumping 652 gpm)	-7.5		3.8+0.8
			2542	4/1/73 (pumping 455 gpm)	-7.6		2.7+0.8

Principal Aquifer Wells (continued) (row label at left, vertical)

Roswell Groundwater Basin
Oxygen 18, Deuterium, and Tritium Analyses of Water Samples

Type of samples	Map #	Sample Location	Sample #	Date Collected	$\delta^{18}O$ $^{o}/oo$	δD $^{o}/oo$	Tritium (T.U.)
Principal Aquifer Wells (continued)	WP16	17.26.29.111 (Menefee deep Well, RA 1925)	2780	7/1/77 (pumping 1000 gpm)	−7.5	−48.4	16.4+0.8
	WP17	18.26.18.41124 (Vandiver RA 1167/A)	2521	8/17/77	−9.2	−48.0	2.6+0.7
			2529	4/1/78 (pumping 3260 gpm (?))	−8.4	−50.3	0.5+0.7
		Mean of All Principal Aquifer Wells			−7.6	−50.8	
		Removing 3 Low ^{18}O Values (> −6.0)			−7.7		
Alluvium Aquifer Wells	WA10	17.26.20.333 (Gates RA 1331)	1959	8/28/75	−6.1		7.2+0.5
			2129	6/4/76 (pumping 900 gpm)	−7.7		3.8+0.6
			2200	8/11/76 (pumping 500 gpm)	−7.0		9.5+1.1
			2604	3/25/77	−5.4		6.6+0.7
			2606	7/1/77	−7.6		6.3+0.7
			2522	9/17/77	−7.6		8.1+0.9
			2528	4/1/78	−8.6		2.7+0.7
		(2604-2528: flowmeter not indicating)					
		Mean of Gates			−7.1		
	WA11	17.26.30.211 (D. Menefee RA 1826-AS)	2781	7/1/77	−7.2	−51.1	6.8+0.7
			1171f	4/1/78 (pumping 235 gpm)	−7.0	−55.5	
		11.24.11.33334 (T. White RA 4239-S5)	1406f	4/3/79 (pumping 540 gpm)	−7.1	−43.5	
		11.24.28.413 (RA 1335-B)	1407f	4/3/79 (pumping 1100 gpm)	−8.5	−55.1	
	M12	17.26.12.142 (Hand-dug Windmill)	1164f	4/1/78	−3.6	−38.3	
		Mean of All Alluvium Aquifer Wells			−7.0	−48.7	
		Without hand-dug windmill			−7.3	−51.3	

Table A1

Roswell Groundwater Basin
Oxygen 18, Deuterium, and Tritium Analyses of Water Samples

Type of samples	Map #	Sample Location	Sample #	Date Collected	$\delta^{18}O$ °/oo	δD °/oo	Tritium (T.U.)
Miscellaneous Snow Samples		Sierra Blanca Ski Area					
		Near top of gondola (11,400 ft)	2612	2/3/79		−134*	26.7+1.1
		Top of Moonshine Gulch	2611	2/3/79	−17.0		28.9+1.3
		Ski area base . . .	1350f	2/3/79		−145*	
		Sierra Blanca Rd. 0.8 miles above Oak Grove Campground	2255	10/28/76	−12.6		29.8+0.9
		Oak Grove Campground .	2256	10/28/76	−12.0		30.3+1.0
		Sierra Blanca Rd., turnoff to Oak Grove Campground. . . .	2614	2/3/79	−16.8		32.5+1.4
		Sierra Blanca Rd., turnoff to Mon Jeau Lookout.	2615	2/3/79		−133*	32.4+0.9
		Intersection of NM 48 & Sierra Blanca Rd. .	2257	10/28/76	−14.5		11.8+1.1
		Bonito Lake	2558	1/16/79	−21.2	−146.1	34.1+1.4
		Swiss Chalet Inn @	2551	1/16/79	−13.8		24.4+1.0
		Alto, N.M. . . .	2616	2/2/79	−7.1		29.4+0.9
		Apache Summit . . .	2550	1/15/79	−22.0		25.8+1.3
		National Park Snow Play Area	2546	1/14/79	−21.8	−157.6	24.7+1.3
		Cloudcroft Ski Area base.	2547	1/14/79	−18.5		26.5+0.9
		St. James Campground .	2548	1/14/79	−15.4	−102.1	18.7+1.2
		16.16.08.121 (Bates Windmill)	2258	10/29/76	−13.0		23.8+1.2
		15.18.18.000 (Flying H Ranch)	2268	10/29/76	−13.0		21.9+1.3
Precipitation		Roswell	2628	3/76	−9.6		55.3+2.0
		Weather Bureau	2704	4/76	−10.0	−71*	32.4+1.4
		(3669′ a.m.s.l.)	2629	6/76	−4.3		62.2+1.6
			2242	7/76 & 8/76	−4.8	−35.0	
			2454	9/76 & 10/76	−6.2	−50*	36.5+1.7
			762f	2/77	−3.8		
			2638	3/77 & 4/77	−6.4	−44.1	76.7+1.6
			2639	5/77	−5.7		74.1+2.4
			CRD4	6/77	−0.4		
			2557	7/77	−0.8	−5*	75.3+2.5
			2637	8/77	−6.6		49.8+1.4
			2523	8/12/77	−6.0		28.7+0.9
			CRD5	9/77	−2.7		
			2571	10/77	−6.4	−28*	51.8+1.7

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Table A1

Roswell Groundwater Basin
Oxygen 18, Deuterium, and Tritium Analyses of Water Samples

Type of samples	Map #	Sample Location	Sample #	Date Collected	$\delta^{18}O$ $^o/_{oo}$	δD $^o/_{oo}$	Tritium (T.U.)
			2541	1/78	−12.4		46.7+1.1
			1151f (in 2559)	2/78	−10.6		73.9+2.2
			1152f (in 2559)	3/78	−12.6	−87*	
			2693	5/78	−5.0		71.7+1.8
			2694	6/78	−2.8		34.9∓0.9
			2695	9/78	−6.4		29.2∓1.0
		P.V.A.C.D.	1290f	8/78	−2.5		
			2696	9/78	−5.2	−36.8	23.4+0.9
			2697	10/78	−12.4		24.4∓0.9
		Mr. Charles Mulcock's ELK, N.M. (5,700′ a.m.s.l.)	CR67	4/76	−8.5	−64*	
			CR68	5/76	−11.1		
			2174	6/76	−4.7		58.2+1.9
			CRD1	7/76	−7.7		
			2186	8/76	−2.0	−15.5	27.9+1.4
			CRD2	9/76	−7.5		
			2263	10/76	−11.8	−83*	37.3+1.4
			2357	11/76	−11.5		30.7∓1.1
			CRD3 (in 2362)	1/77	−18.1	−134*	
			705f (in 2362)	2/77	−7.6		
			728f (in 2362)	3/77	−10.5		
			2362	1/77 − 3/77	−13.7		45.3+2.1
			2369	4/77	−9.4	−61.1	42.9∓1.5
			2373	5/77	−3.7		55.0∓1.9
			2395	6/77	−3.6		76.3∓1.5
			2400	7/77	−0.5	−4*	44.5∓1.5
			2392	8/77	−0.9		
			933 (in 2392)	8/8/77-8/12/77	−3.4		26.5+1.5
			2393	9/77	−6.7		31.1+1.3
			1011f (in 2402)	10/3&10/6/77	−5.5		
			2402	10/77	−7.7	−54*	20.7+0.9
			1111f (in 2409)	11/77	−10.1		
			1112f (in 2409)	12/77	−7.9		
			1113f (in 2409)	1/78	−15.5		

Type of samples: Precipitation (continued)

Roswell Groundwater Basin
Oxygen 18, Deuterium, and Tritium Analyses of Water Samples

Type of samples	Map #	Sample Location	Sample #	Date Collected	$\delta^{18}O$ $^o/_{oo}$	δD $^o/_{oo}$	Tritium (T.U.)
Precipitation (continued)			2409	11/77 – 1/78	-9.7		29.0+1.4
			1114f (in 2560)	2/78	-13.8		
			2540	3/78	-18.6	-149*	149.3+2.2
			1229 (in 2560)	5/78	-8.1		91.7+2.6
			1230	6/78	-4.8		
			CR110	7/78	-0.5		
			CR108	8/78	-3.8		
			CR109	9/78	-7.7	-63.8	

TABLE A2. Climatological Data* and $\delta^{18}O$ in Precipitation at Roswell

	1976 Precip. (inches)	1976 Temperature** (°C)	1976 $\delta^{18}O$ (°/oo)	1977 Precip. (inches)	1977 Temperature (°C)	1977 $\delta^{18}O$ (°/oo)	1978 Precip. (inches)	1978 Temperature (°C)	1978 $\delta^{18}O$ (°/oo)
January	0.12	4.67 NS***	-12.5	0.07	3.67 NS	-12.9	0.50	2.22 0.28	-12.4
February	0.22	11.83 NS	-9.3	0.36	9.00 NS	-10.5	0.48	6.44 8.06	-10.6
March	0.24	12.28 10.74	-9.6				0.39	13.11 12.22	-12.6
April	0.79	17.61 14.82	-10.0	1.52	14.00 14.11	-6.4	0.02	19.00 NS	-6.1
May	0.82	20.39 NS	-5.5	2.43	22.94 22.36	-5.7	1.81	21.94 18.37	-5.0
June	1.55	26.28 22.78	-4.3	0.25	27.56 28.61	-0.4	4.31	26.28 21.81	-2.8
July }	3.99	26.34 24.42	-4.8	0.46	29.00 28.06	-0.8	0.52	28.56 NS	-1.9
August }				4.45	28.33 26.46	-6.6	3.49	25.56 22.22	-2.5
September }	2.98	17.61 18.27	-6.2	0.29	25.78 26.11	-2.7	3.58	20.72 16.82	-5.8
October }				0.52	17.83 19.44	-6.4	1.47	15.72 10.74	-12.4
November	0.41	5.94 NS	-11.9	0.48	11.72 NS	-9.3	1.25	5.55 NS	-12.1
December	0.00	4.06 --	--	0.02	8.33 NS	-10.8	0.43	2.89 NS	-13.3

Weighted Mean $\delta^{18}O$ = – 6.0±0.3 °/oo

*   From NOAA: Local Climatological Data, and Don Barton of the Roswell Weather Bureau (personal communication).

**   Left column: Monthly average. Right column: average on days for which precipitation sample available.

*** NS = No Sample. $\delta^{18}O$ was calculated from the relation: $\delta^{18}O$ = 0.44 t -14.54 (Figure 5), and left-column temperature.

TABLE A3.   Climatological Data* and $\delta^{18}O$ in Precipitation at Elk

	1976				1977				1978			
	Precip. (inches)	Temperature (°C)		$\delta^{18}O$ (°/oo)	Precip. (inches)	Temperature (°C)		$\delta^{18}O$ (°/oo)	Precip. (inches)	Temperature (°C)		$\delta^{18}O$ (°/oo)
January	0.29	2.56	NS***	-12.5	0.76	1.89	0.37	-18.1	0.84	2.22	1.11	-15.5
February	0.64	7.50	NS	-10.0	0.29	5.33	0.69	-7.6	0.36	2.50	1.94	-13.8
March	0.18	7.22	NS	-10.1	0.15	5.67	-0.28	-10.5	0.50	8.00	3.33	-18.6
April	0.58	11.61	10.97	-8.5	1.49	10.78	6.53	-9.4	0.47	11.94	NS	-7.7
May	2.01	14.17	11.78	-11.1	1.12	15.00	15.00	-3.7	1.88	15.78	15.39	-8.1
June	1.22	19.28	17.64	-4.7	1.38	20.56	14.03	-3.6	2.06	21.22	19.44	-4.8
July	3.50	19.22	18.64	-7.7	1.57	21.22	21.00	-0.5	1.56	21.89	20.35	-0.5
August	1.01	19.83	19.81	-2.0	2.33	21.72	21.15	-0.9	4.65	20.44	20.44	-3.8
September	2.14	15.39	13.47	-7.5	1.43	19.33	17.85	-6.7	7.06	16.22	12.43	-7.7
October	1.37	9.06	-1.39	-11.8	0.65	13.28	15.69	-7.7	2.45	12.89	NS	-7.2
November	1.03	NO	NO****	-11.5	0.62	7.44	9.72	-10.1	2.54	8.22	NS	-9.6
December	0.00	-1.06	--	--	0.09	6.61	5.00	-7.9	0.88	2.50	NS	-12.5

Weighted Mean $\delta^{18}O = -7.1\pm0.3$ °/oo

*   From NOAA: Local Climatological Data

** Left column: monthly average. Right column: average for days on which precipitation sample available

*** No sample. $\delta^{18}O$ was calculated from the relation: $\delta^{18}O = 0.52\, t - 13.83$ (Figure 6), and left-column temperature

**** No data (point not used).

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TABLE A4

Oxygen 18 Analyses of Limestone Samples

(San Andres Formation)

Sample Location	Type of Sample	$\delta^{18}O$ ($^{O}/oo$)[1]
1$\underline{st}$ large limestone outcrop on NM 13 west of US 285, very weathered in appearance	road cut	+25.76
16.20.21.000	"	+32.04
16.16.05.111 (a) white with crystals of calcite < 0.5mm	"	+27.85
(b) dark grey		+26.77
Turnoff to Carr Gap Road near Elk, N.M. Yeso(?)	"	+25.04
11.25.09.411113 (J.P. White RA 1510S6)	drill cuttings[2] (limestone gravel, 150' to 160')	+25.18

[1]By Geochron Laboratories

[2]These are probably from the Artesia Group, but are still Permian in age and may represent gravel weathered form the San Andres.