# *Groundwater circulation in the Socorro geothermal area*

Gerado W. Gross and Ralph Wilcox

1983, pp. 311-318. https://doi.org/10.56577/FFC-34.311

*in:*

*Socorro Region II*, Chapin, C. E.; Callender, J. F.; [eds.], New Mexico Geological Society 34 th Annual Fall Field Conference Guidebook, 344 p. https://doi.org/10.56577/FFC-34

*This page is intentionally left blank to maintain order of facing pages.*

# GROUNDWATER CIRCULATION IN THE SOCORRO GEOTHERMAL AREA

GERARDO WOLFGANG GROSS and RALPH WILCOX*
New Mexico Institute of Mining and Technology
Socorro, New Mexico 87801

## INTRODUCTION

Socorro is located near the western edge of Socorro Basin in the Rio Grande valley (fig. 1). Two warm springs supply a substantial part of the municipal water supply. This work was undertaken to determine sources and circulation patterns of the warm water and its relation to the regional groundwater system. This information is needed to predict possible effects of geothermal exploration and development in the area.

Specific questions are the depth of circulation of the warm groundwaters, and their interaction or mixing with geothermal fluids. To address these questions it was necessary to study and compare surface and groundwater of Socorro Mountains and of the Snake Ranch Flats portion of La Jencia Basin, which constitute the recharge areas of Socorro Springs.

## GEOLOGIC SETTING

Uplifted fault blocks of the Socorro Mountains expose a cluster of late Miocene rhyolite domes erupted across the buried northeastern margin of an Oligocene resurgent cauldron. Socorro and Lemitar Mountains separate two structural basins within the Rio Grande rift (fig. 2). Socorro Basin, to the east, is integrated into the Rio Grande drainage system while La Jencia Basin was originally a closed surface-water basin which is in the process of being tapped by through drainage (Nogal Canyon, Socorro Canyon, and La Jencia Creek) to the Rio Grande. Magdalena Mountains, a westward tilted fault block (Precambrian rocks overlain by Paleozoic sedimentary rocks and Tertiary volcanic rocks), form the western rim of La Jencia Basin. Thickness of Miocene-Pleistocene basin fill (Santa Fe Group) in both Socorro and La Jencia basins is unknown, but has been estimated to be on the order of 1200 m (Sanford, 1968).

Three warm springs issue from fractures along the eastern front of the Socorro Mountains where the volcanic complex is faulted against basin fill. A pronounced geothermal anomaly is spatially associated with shallow magma bodies at about 4-5 km depth (Chapin and others, 1978, p. 120).

## PROCEDURE

Precipitation data for the Socorro and Kelly Ranch stations were obtained from the U.S. Weather Service (Climatological Data—New

*Present address: Bureau of Land Management, Albuquerque, New Mexico.

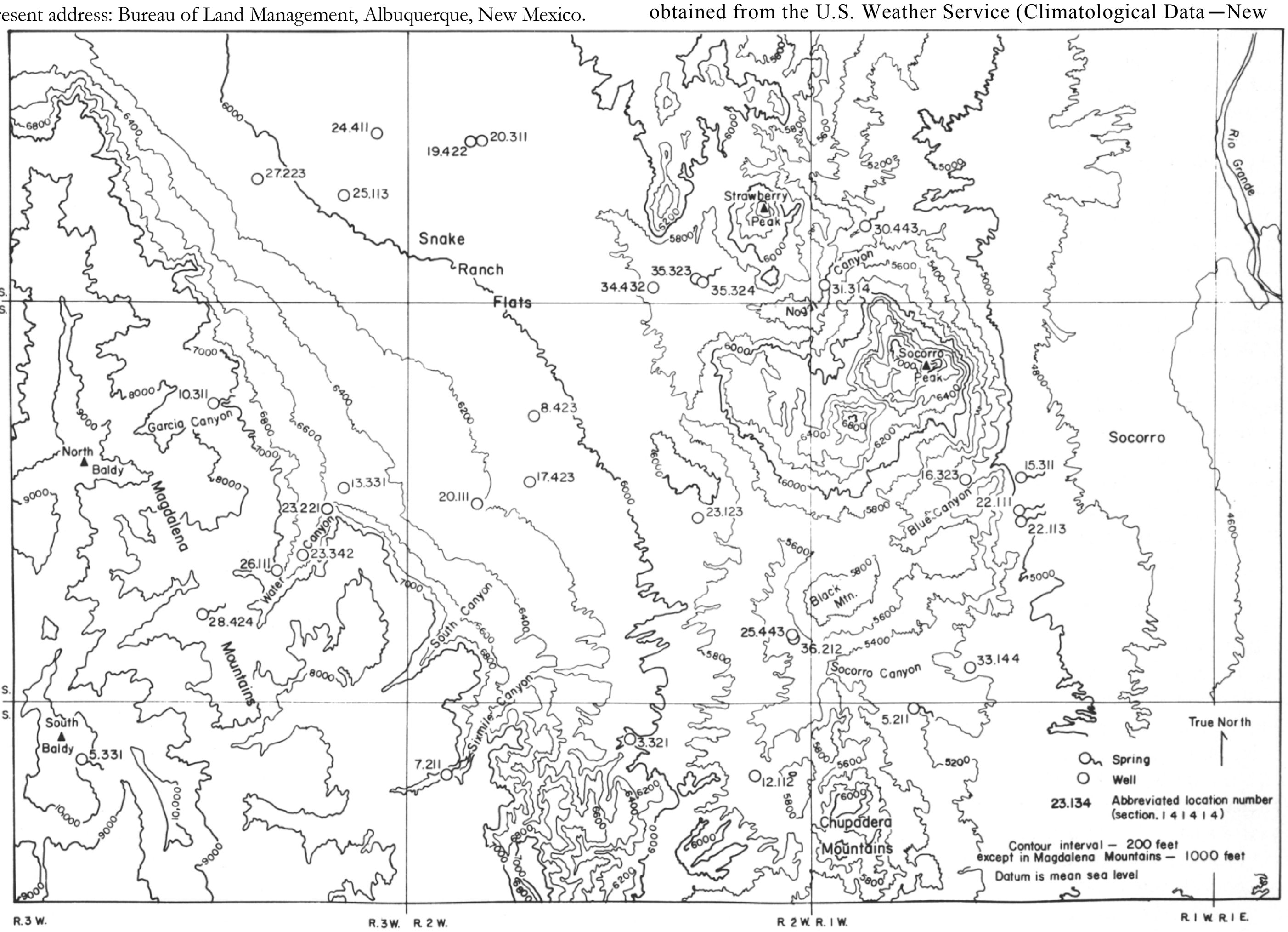


*Figure 1. Physiography and sampling locations.*

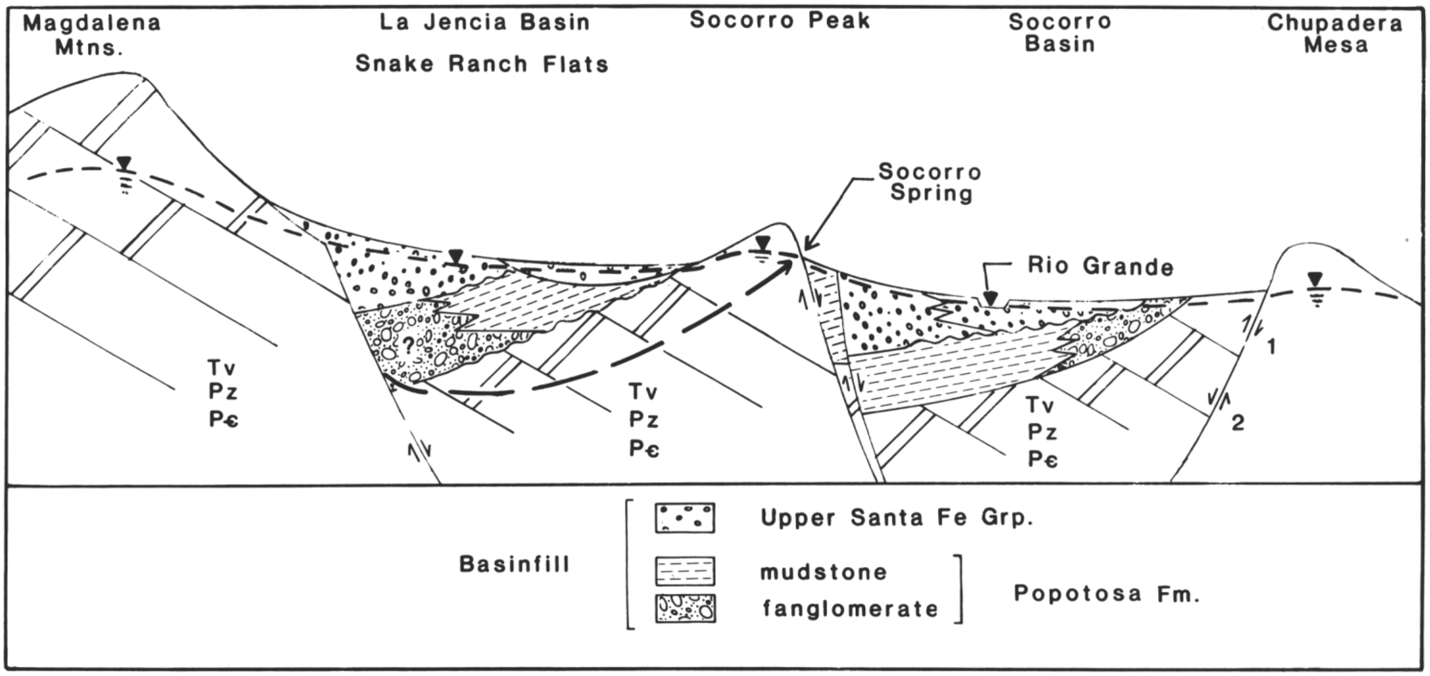


*Figure 2. Schematic cross section through Snake Ranch Flats and Socorro Basin. Shallow and deep ground-water paths suggested by dashed lines. Tv: Tertiary volcanic rocks; Pz: Paleozoic sedimentary rocks; P€ : Precambrian metamorphic rocks.*

Mexico: National Oceanic and Atmospheric Administration, Environmental Data Service, National Climatic Center, Asheville, North Carolina 28801). Springflow rates were furnished by the City of Socorro and SER, Inc., a private consulting firm. Tritium in precipitation at Socorro has been monitored by New Mexico Institute of Mining and Technology since 1957, except for the period September 1968 to June 1971. Tritium determinations for the warm springs were made intermittently in the period 1957-1964. Tritium determinations of spring samples for this study were resumed in 1977 at approximate intervals of 2 months. Springs and wells within the study area were selected for sampling based on previous work by Waldron (1956) and Hall (1963). Tritium and major ions were measured. Chemical data from the literature (Scofield, 1938; Waldron, 1956; Scott and Barker, 1962; Hall, 1963; Summers, 1965, 1976) and from unpublished sources (U.S. Geological Survey Water Resources Division, Albuquerque; City of Socorro Water Department; New Mexico Bureau of Mines and Mineral Resources; Billings, 1974, unpublished report on Socorro's water supply) were included. Where possible, water levels were measured to determine piezometric head distribution over the area. Where wells could not be measured, older data were used (Clark and Summers, 1971). The stable isotopes deuterium and oxygen-18 were measured in 17 samples.

## CHARACTERISTICS OF THERMAL SPRINGS

Both Socorro and Sedillo springs issue from fractures in rhyolite flows interbedded with indurated mudflow and playa deposits assigned to the lower member of the Popotosa Formation. Socorro spring issues into a gallery which has been dug to intercept spring flow. Sedillo spring probably issues from the same joint set. Spring water is of excellent quality and consistently ranges between 32 and 33°C in temperature. Discharge is rather uniform throughout the year. Socorro spring was gauged at 265 to 300 gpm (about 1 m3/min) between July 1977 and February 1978. During the same time, Sedillo spring showed discharges between 95 and 109 gpm (0.4 m3/min).

The thermal springs under discussion, and most of the springs in and adjacent to the Socorro Mountains, are fault-controlled. Impermeable units (such as the Popotosa playa mudstones) have been faulted against permeable rocks (fig. 2).

## WATER TABLE CONTOURS

Figure 3 shows water-table elevations in the study area. The two elliptical contours around Socorro Mountains have been drawn to indicate that there is some local recharge to the springs. The regional gradient is to the northeast. This contrasts with the ground-water gradient in the Rio Grande valley (not shown), which parallels the river course (south). La Jencia Basin ground-water system is tributary to that of the Rio Grande valley.

## GROUND WATER QUALITY

Figure 4 shows the range of water quality types for the study area according to Hall's (1963) classification. Figure 5 shows water chemistry and total dissolved solids represented by pie diagrams. Spring and well water from Magdalena Mountains and Snake Ranch Flats is predominantly of the Ca-HCO, type while sodium predominates in wells and springs of Socorro and Chupadera Mountains. Hall noted that the warm springs (22.111, 22.113, 15.311) and Blue Canyon well (6.323) discharge water of Na-HCO3 type. He suggested that ion exchange must be taking place somewhere within the system west of the location of these samples, as indicated by the dashed line in Figure 5. Springs and wells with sulfate-rich water, such as lower Nogal Canyon spring (30.443), Chupadera spring (5.211), and Gianero windmill (12.112) tap ground water which has probably had prolonged contact with the upper gypsiferous member of the Popotosa Formation.

## ENVIRONMENTAL TRITIUM IN GROUND WATER AND PRECIPITATION

The unstable hydrogen isotope, tritium (31-1), is produced naturally in the earth's stratosphere when atmospheric nitrogen molecules are bombarded by cosmic rays. Tritium is readily incorporated into at- mospheric water vapor and falls to earth in precipitation. Because trit- ium has a half life of 12.3 years, it is only suitable for dating water up to about 50 years old. Prior to 1954, natural tritium levels in at-

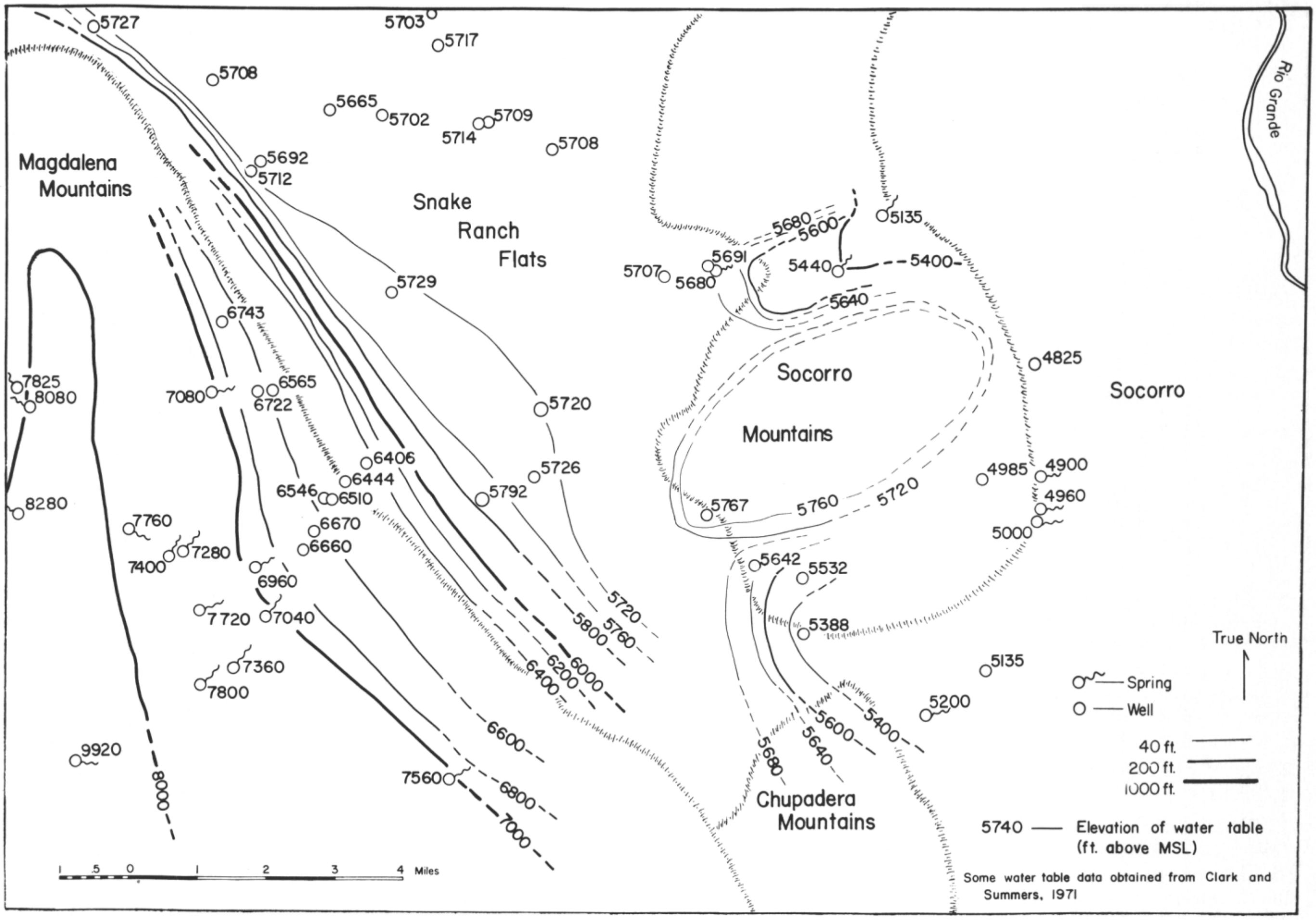


*Figure 3. Water-table contours.*

mospheric moisture were of the order of only 10 tritium units (one TU = one tritium atom per 1018 hydrogen atoms). Atmospheric tritium levels were dramatically increased by atmospheric testing of thermonuclear devices which ended in 1963 (Nuclear Test Ban Treaty) and have been decreasing since.

The increased levels of environmental tritium activity are the basis for a method of tracing natural waters. By correlating activity peaks in precipitation with activity peaks in ground water, residence times and velocities have been determined (Holmes, 1963; Rabinowitz and others, 1977).

Tritium *rainout* is the actual amount of tritium deposited at the ground surface. It is computed as the product of monthly precipitation (p,) and its averaged tritium activity (A,). In Figure 6, monthly rainout values (R,) are normalized with respect to the total annual precipitation of the appropriate year (p)

R, = (A,p,)/P,.

Socorro precipitation exhibits seasonal peaks of tritium activity; the highest values occur in spring and summer, as is typical worldwide. The highest peak was seen in June 1963 (9436 TU). The overall activity has been steadily declining since then. It is now below 100 TU.

Figure 7 shows regional tritium activity distribution in wells and springs. Within the Magdalena Mountains, most of the ground water seems to be quite young, TU values are greater than 40. This is not surprising if one considers that the springs issue from high-mountain ground-water systems in limestone and volcanic rocks; the wells are sunk into the alluvium covering of canyon floors, which is very perme-

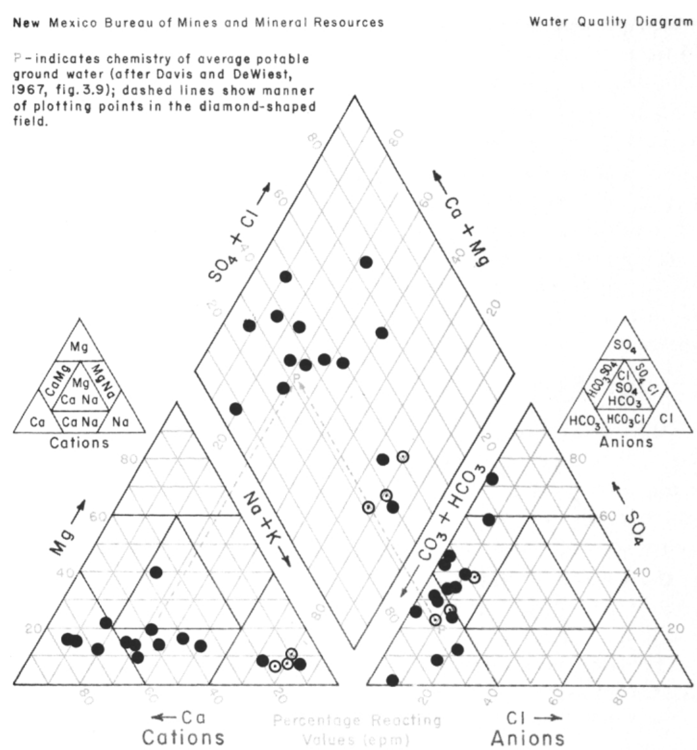


*Figure 4. Water-quality diagram. Open circles: warm water.*

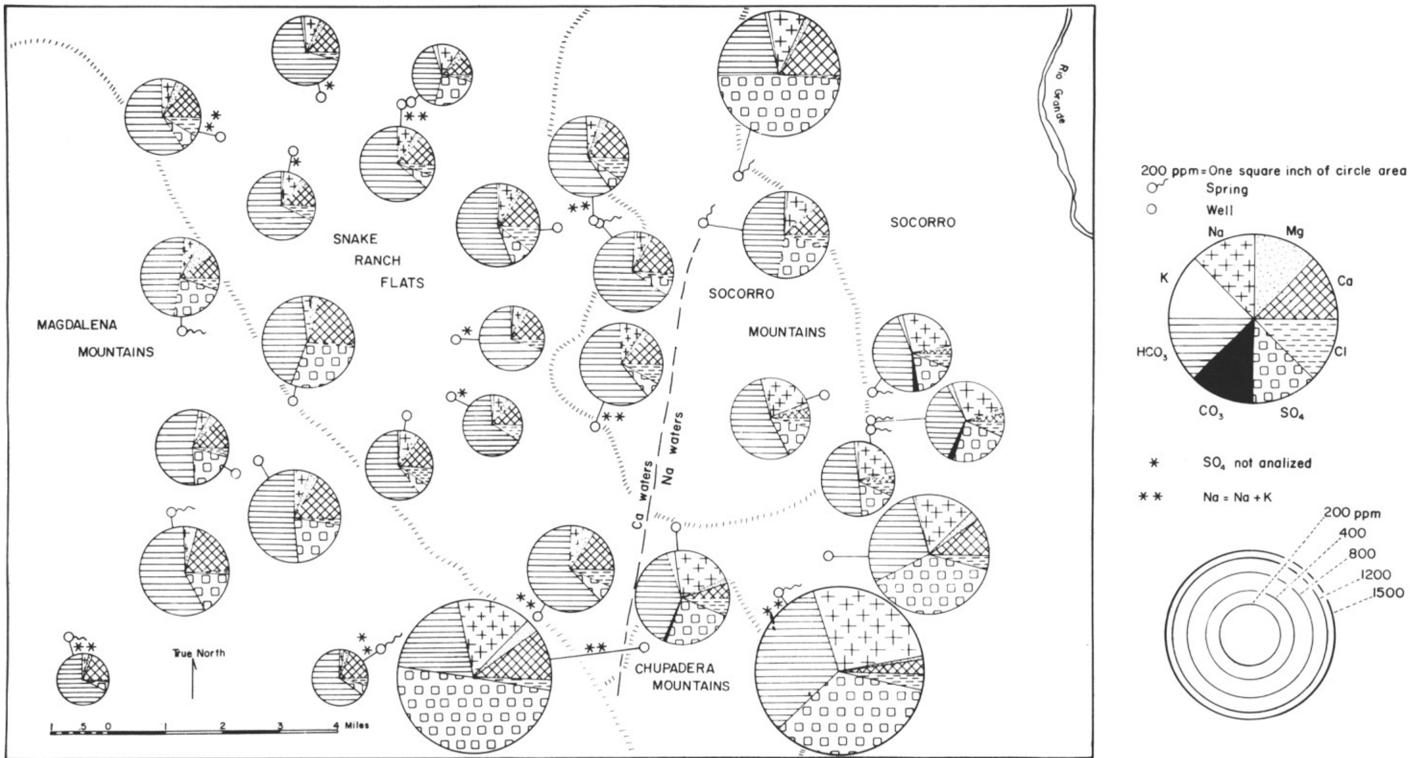


*Figure 5. Water-quality map.*

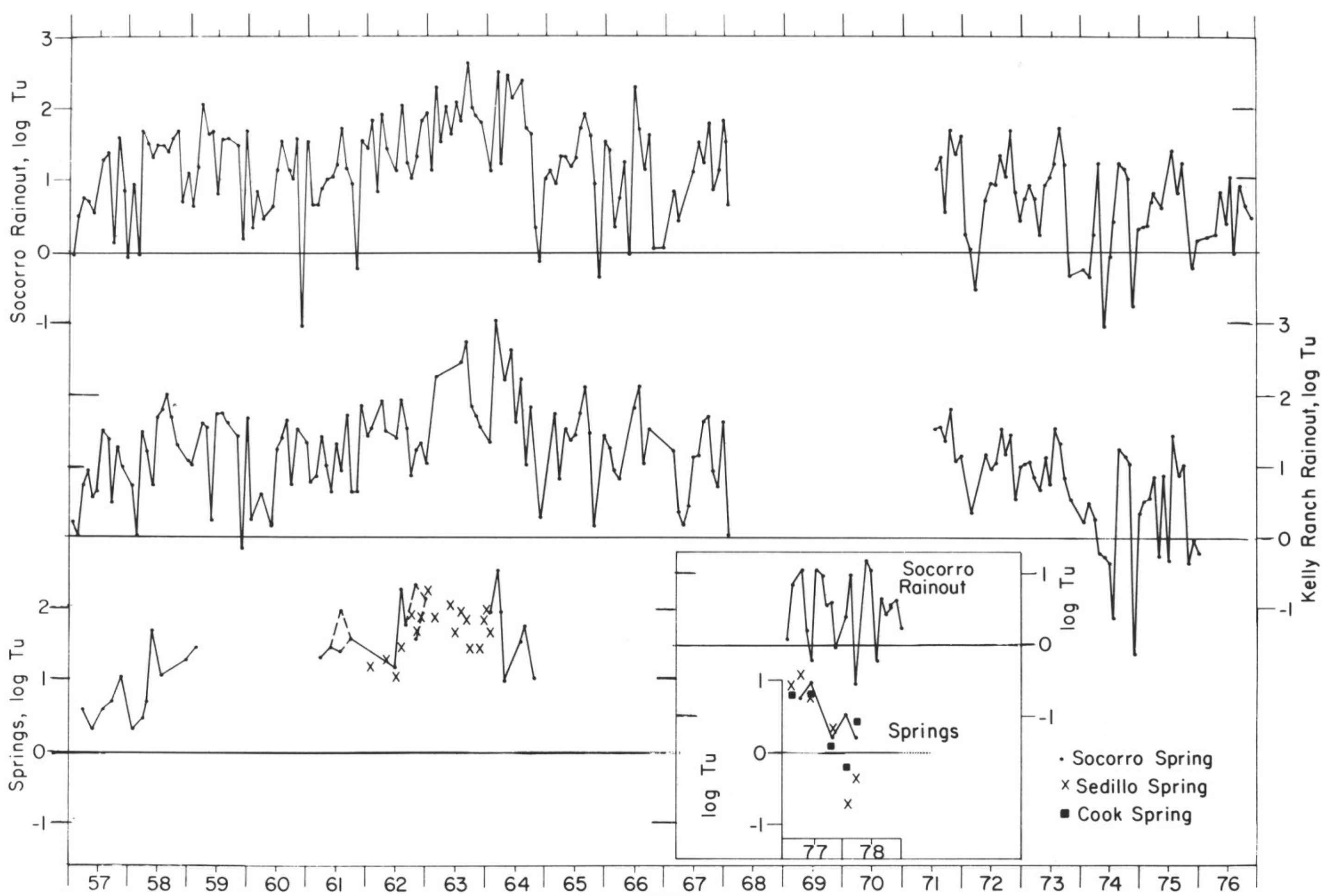


*Figure 6. Normalized tritium rainout and tritium activity in warm springs as a function of time. Note logarithmic scale. Box adds data for 1977–78.*

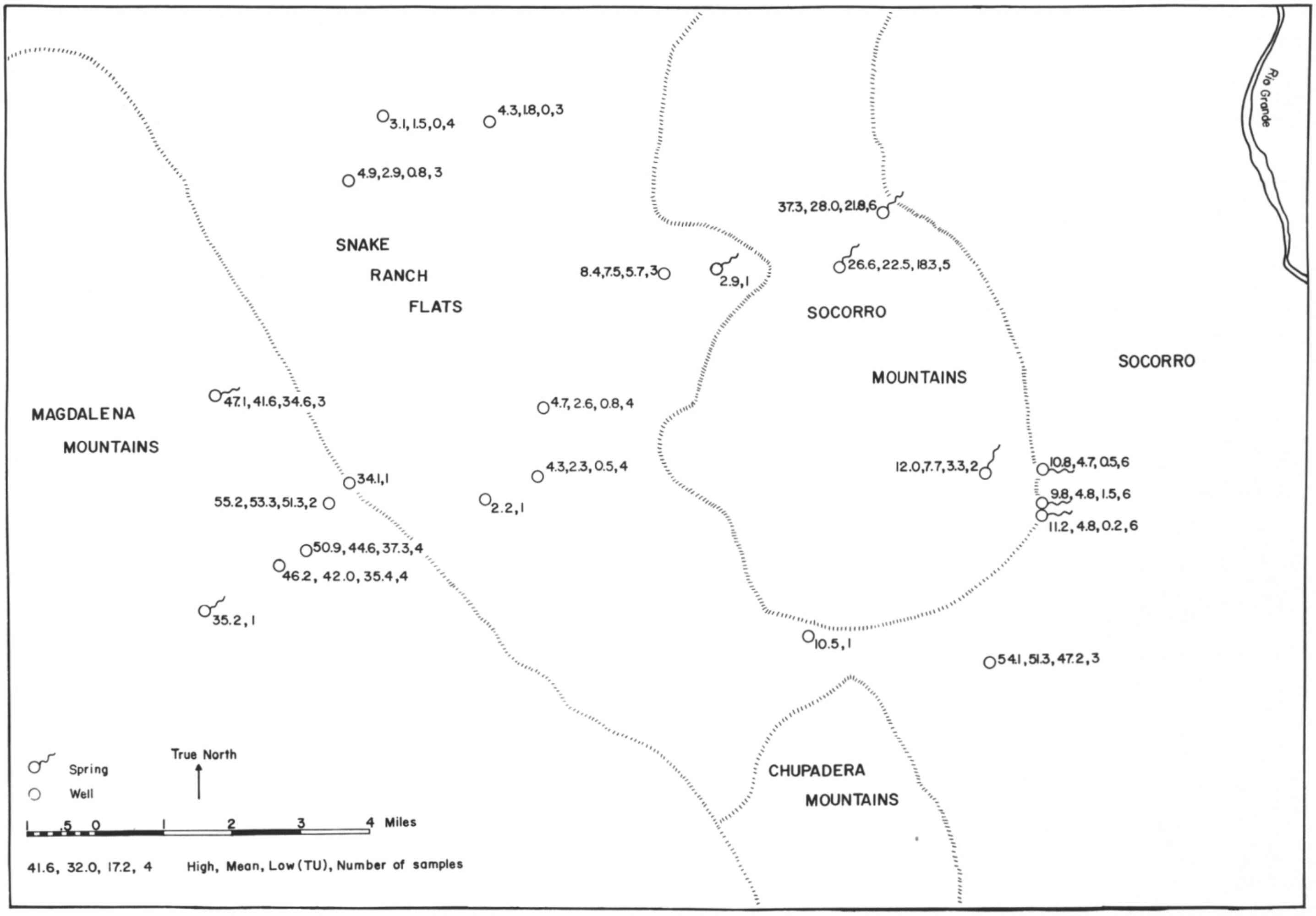


*Figure 7. Distribution of tritium activity in ground water and springs as measured in 1977–78.*

able and shallow, and the water table has a high gradient going down the canyons.

In Snake Ranch Flats, however, the groundwater is old relative to that in the Magdalena Mountains, with TU values generally less than 3. This seems to indicate that the groundwater reservoir in the Flats is quite large, and recharge from the Magdalena Mountains is strongly diluted within this reservoir.

Socorro spring, Sedillo spring, Cook spring, and Blue Canyon well are believed to derive their water from a system of interconnected fractures in Tertiary rhyolites. Water quality is similar, and they show a similar trend of declining tritium activity with time, which parallels that of normalized tritium rainout at Socorro and Kelly Ranch. Clearly, the springwater must contain a fast recharge component of meteoric water but there is at least an order of magnitude difference between average precipitation activity and springwater activity, and this suggests dilution with a slow recharge component or components. The three springs presently have mean values of about 4.8 TU, which is about 2 TU higher than the Snake Ranch Flats system.

## OXYGEN-18 AND DEUTERIUM

Ten samples of thermal-spring and well water were analyzed for their oxygen-18 and deuterium content. The data are exhibited in Table 1 and Figure 8. Five samples from nonthermal springs and wells, and two precipitation samples are given for comparison.

On the standard plot of SD vs. 8180 (fig. 8) the data are close to and slightly to the left of Craig's (1961) meteoric-water line. Typical thermal waters tend to be displaced to the *right* of this line (Faure, 1977, fig. 18.11). This is because isotopic exchange of ground water with the reservoir rocks, which are generally low in hydrogen content, primarily affects the isotopic oxygen composition. On the basis of the limited data presented here, interaction of these samples with reservoir rocks is not appreciable.

## DISCUSSION

### Hydrogeology

In Snake Ranch Flats, permeable gravel and sand deposits which top the basin fill are separated from a deeper sequence of permeable strata by a thick complex of impermeable playa mudstones of the Popotosa Formation (C. E. Chapin, 1981, oral commun.). None of the wells sampled for this study penetrate into the deep permeable strata. We propose that water from both aquifers, which are not connected within the Flats, flows into the volcanic complex of Socorro Mountains where it feeds the springs (fig. 2).

### Ground-Water Quality

As mentioned earlier, the Na-HCO, character of springs and wells in the Socorro Mountain area indicates that ion exchange has taken place within the volcanic complex (Hall, 1963), perhaps aided by above-normal temperatures. Chapin and others (1978, p. 125) found a strong potassium anomaly in the ash-flow tuffs of the Oligocene volcanic complex; the plagioclase feldspars have been metasomatically replaced

*Table 1. Deuterium, oxygen-18, and tritium in thermal and nonthermal waters.*

| Location | Fig. 8 Point # | Sample No. | Date | $\delta O^{18}$ ‰ | $\delta D$ ‰ | T TU |
|---|---|---|---|---|---|---|
| Socorro Spring | | 2320 | 4/14/77 | -10.8 | -61 | 5.9 |
| | | 2348 | 6/22/77 | - 8.1 | -51.7* | 9.8 |
| | | 2423 | 1/19/78 | -10.5 | -62 | 3.5 |
| | | 2428 | 3/14/78 | - 8.4 | -41.7* | 1.5 |
| Sedillo Spring | | 2429 | 3/14/78 | - 8.1 | -49.8* | 0.5 |
| | | 2321 | 4/14/77 | -10.2 | -66 | 11.2 |
| | | 2422 | 1/19/78 | -11.5 | -67 | 0.2 |
| Cook Spring | | 2322 | 4/14/77 | - 8.6 | -51.0* | 10.8 |
| | | 2424 | 1/19/78 | - 8.6 | -50.5* | 0.5 |
| Blue Canyon Well | | 2425 | 2/6/78 | - 8.6 | -56.7* | 3.3 |
| Upper Nogal Spring | (6) | 2421 | 1/19/78 | - 8.6 | -52 | 20.8 |
| Lower Nogal Spring | (7) | 2420 | 1/19/78 | -10.3 | -65 | 21.8 |
| Strozzi Windmill | (1) | 2375 | 3/12/77 | - 6.7 | -37.8 | 0.0 |
| Armijo Windmill | (2) | 2325 | 5/13/77 | - 6.1 | -45.9 | 54.1 |
| Kelly Ranch deep well | (3) | 2381 | 8/19/77 | - 8.2 | -44.4 | 0.0 |
| Socorro Rain | (4) | 2537 | 3/21-22/77 | -12.2 | -76 | 44.5 |
| Socorro Snow | (5) | | 1/19-20/78 | -17.9 | -120 | **-- |

*Analysis by Dr. Gary Landis, Dept. of Geology, University of New Mexico. All others by Geochron Laboratories, Cambridge, Mass.

**Tritium activity was not measured separately from other precipitation for the month (Sample #2479, 40.6 TU)

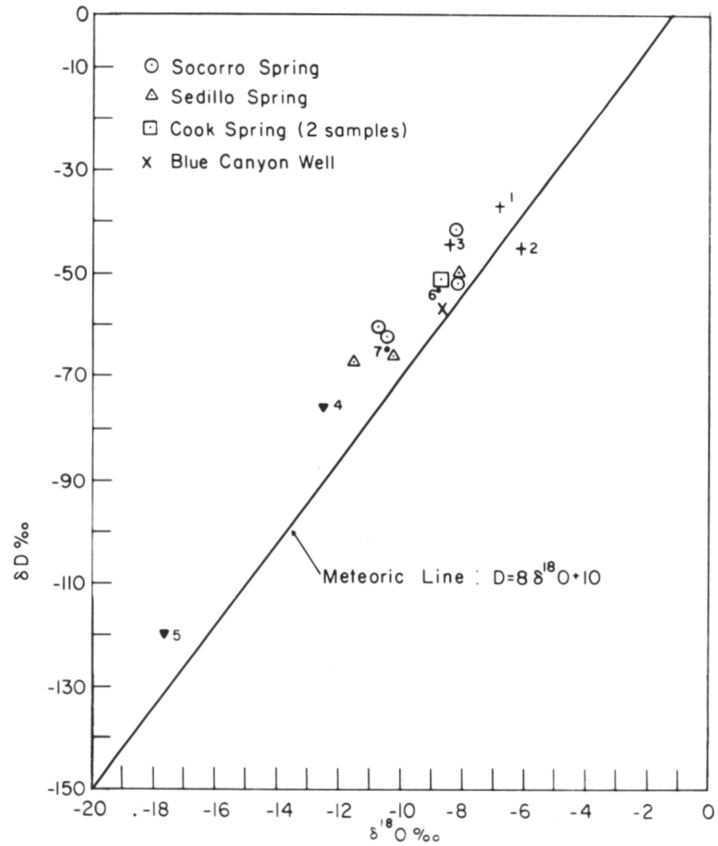


*Figure 8. Deuterium and oxygen-18 in thermal and nonthermal waters. (Numbers refer to nonthermal sampling points specified in Table 1; different sources are labelled by different symbols.)*

by potassium feldspars. Such alteration is typical of geothermal aqueous systems. The mobilized sodium may have been removed by ground water. A similar process may be going on in connection with the present geothermal anomaly. The interaction of ground water with the aquifer matrix has not been intense enough, however, to affect the isotopic makeup of the water with respect to deuterium and oxygen-18. The springs do not have a truly thermal character.

## Tritium Activity, Tritium Rainout, and Recharge

Rabinowitz and others (1977) have shown that tritium *activity* in Socorro precipitation is representative of a broad region including Snake Ranch Flats and Magdalena Mountains. This assertion does not, however, apply to tritium *rainout,* the product of tritium activity and precipitation, and to *recharge,* that fraction of rainout which actually percolates down to the water table. Tritium rainout and recharge, rather than activity alone, are the parameters controlling tritium activity of groundwater and springs.

Kelly Ranch is located at the western edge of Snake Ranch Flats, and precipitation records there may be more indicative of recharge to springs than Socorro precipitation east of the spring locations. Tritium rainout shows similar patterns at both stations but since Socorro precipitation is lower on the average, the peak amplitudes tend to be lower (fig. 6). The magnitude of recharge is unknown but typically it is a few percent of rainfall. Tritium activity peaks in precipitation may not correspond to those in recharge because: (1) a small precipitation event of high activity may contribute less tritium to recharge than a large precipitation event of low or intermediate activity; and (2) recharge is not linear with precipitation (Gross and others, 1976; Rabinowitz and others, 1977). Seasonal contrasts are largely averaged out during percolation.

It will be noticed in Figure 6 that tritium activity in spring water is of the same order as the normalized activity in rainout. This seems to be only in part due to the logarithmic scale. It suggests that normalization of rainout by yearly precipitation (an arbitrary scheme) approximately reflects the dilution ratio of recharge water in the groundwater reservoir.

## Correlation of Tritium Activity in Springs with Precipitation

Holmes (1963) examined three years (1957 to 1959) of tritium data for Socorro spring and Socorro precipitation. He concluded that an August 1958 peak in Socorro spring water correlates with the mid-1954 tritium-activity rise in precipitation, which was caused by the first, or Castle, series of atmospheric nuclear tests (fig. 6). From this result, he concluded that the residence time of Socorro spring water (the time elapsed between precipitation in the recharge area and its reappearance in the spring) is at most four years.

For the reasons discussed, a direct correlation of tritium activity peaks in groundwater with those in precipitation is possible only in special cases. Holmes's correlation of the Socorro spring peak may have been such a special case because the measurements occurred so soon after the rise in atmospheric tritium activity. However, even in this special case, the approach cannot yield quantitative information about mixing (dispersion) of recharge contributions from different sources or recharge following different flowpaths. In the case of the Socorro-spring system three possible recharge contributions are possible: (1) water from the Magdalena Mountains following a deep path (beneath the mudstone complex in the Snake Ranch Flats, fig. 2); (2) water from the Magdalena Mountains following a shallow path (above the mudstone complex) of intermediate travel time; and (3) a fast recharge component consisting of surface runoff from Magdalena Mountains transmitted directly across the Snake Ranch Flats (surface drainage to Nogal Canyon) into the Socorro Mountain volcanic complex, and precipitation on Socorro Mountains themselves. These contributions are mixed at the points of emergence in the springs. In order to investigate recharge quantitatively, it would be necessary to integrate all the tritium rainout contributions over the recharge area and derive from them the effective tritium re- charge as a function of time (Rabinowitz and others, 1977). The ef- fective tritium activity in recharge deduced from this curve could then be correlated stochastically with the spring measurements.

## Alternative Interpretation of Spring Recharge

The correlation proposed by Holmes for the 1958 tritium peak in Socorro spring with the 1954 rise of tritium activity in atmospheric water sets a maximum time frame for tritium activity in the spring (it cannot be older than 4 years), but it does not account for the activity *amplitude* in relation to the amplitude of tritium activity in precipitation. (No measurement of tritium activity in 1954 precipitation at Socorro is available.) In addition to recharge, as discussed above, two main factors determine the amplitude ratio: (1) mixing (dispersion) of the labeled water in the groundwater reservoir (assumed to be unlabeled initially), and (2) radioactive decay. For a residence time of 4 years, radioactive decay would reduce tritium activity to only about 80 percent of its initial value. Subsequent peaks (for example, that of 1962) appear to conform moderately well to the 4-year delay pattern. The greatest problem is to account for the relative amplitudes. For the years in question, atmospheric activity shows very large fluctuations from month to month, and these are averaged out in springflow. The reduction due to this averaging is likely to be larger than that due to radioactive decay. However, if all recharge occurs at the western edge of Snake Ranch Flats and has a residence time of 4 years, then spring water should, after 4 years (that is, starting in 1958), begin to approach the mean tritium activity of precipitation. This is clearly not the case, and it is evident especially from the most recent data because the seasonal fluctuations in atmospheric tritium activity are becoming progressively smaller.

For this reason we offer two alternative interpretations. First, all recharge to the springs originates in the Magdalena Mountains or near the western edge of Snake Ranch Flats. It follows paths of different lengths (travel times) across La Jencia Basin and the Socorro Mountains complex. These streamlines converge in the discharge zone so that they appear mixed in the springs. Tritium activity of spring water therefore represents the diluted activity of the shallowest (shortest) of these streamlines. Residence time of water along this shallow path is of the order of 4 years.

Second, tritium activity of spring water represents the diluted label of local recharge, that is, precipitation that falls on the Socorro Mountain complex and/or surface runoff (following large thunderstorms) that crosses Snake Ranch Flats and is absorbed by the highly fractured and permeable volcanic rocks forming the eastern edge of Snake Ranch Flats. Near the points of discharge, this fast recharge component mixes with water that was recharged at the eastern edge of Magdalena Mountains and took the long path. The shallow or fast recharge component is estimated to be approximately 10 to 20 percent of total springflow. It varies from year to year with local climatic conditions.

Of the two alternative hypotheses, we favor the second one because, where measured, the tritium activity of shallow groundwater in Snake Ranch Flats is lower than the activity of springflow and also because the lithologic structure of southern La Jencia Basin (Snake Ranch Flats) seems to indicate long residence times.

## SUMMARY OF CONCLUSIONS

Recharge to the thermal spring system consists of two main components that follow different paths of different travel times. A regional component is fed by precipitation on the Magdalena Mountains which is transmitted to the fracture system of the springs through permeable strata of the Santa Fe Group (900 to 1200 m thick in La Jencia Basin) and/or fractured volcanic rocks underlying the Santa Fe Group. The residence time of this component is substantially longer than the half-life of tritium (12.3 years).

A local recharge component is fed by precipitation that falls directly on Socorro Mountains and/or is transmitted from the Magdalena Mountains as surface runoff across the Snake Ranch Flats. Its residence time is of the order of 4 years.

These recharge components were differentiated on the basis of their tritium label which yields a mixing ratio of the order of 9:1 for the regional versus the local component.

Cation exchange, sodium replacing calcium in groundwater, takes place across a north-trending line in the Socorro and Chupadera Mountains. It is related to the geothermal anomaly of Socorro Mountains. Deuterium and oxygen-18 determinations in samples of spring and well waters of the geothermal anomaly indicate that these waters are of meteoric origin and have not mixed with deep thermal waters. No hydraulic connection is evident between possible steam or hot water reservoirs of the geothermal anomaly and the ground-water systems studied in this report.

## ACKNOWLEDGMENTS

We are heavily indebted to R. M. Chamberlin and C. E. Chapin (New Mexico Bureau of Mines and Mineral Resources) for much insight into the geology of the area. Led by Professor C. T. Smith and Mr. Richard Griego, sanitarian for the City of Socorro, we were able to visit the springs which are accessible only with difficulty through underground workings. Lynn Brandvold, chemist for the New Mexico Bureau of Mines and Mineral Resources, did the water-quality analyses. Dave Goodrich, Paul Davis, Steve Mizell, Roger Ward, and John Beasley assisted with the collecting of water samples. The City of Socorro allowed sampling of Socorro and Sedillo springs. Our appreciation goes especially to Messrs. James Cole, Director of Utilities, and Richard Griego, Sanitarian, for their support. We also thank the ranchers who gave consent to sample their wells and who supplied well data, notably Joyce Gaines, J. B. Kelly, Allie Strozzi, Tom Kelly, Nathan Hall, and Zeke Armijo.

The manuscript of this report was critically read by C. E. Chapin, R. M. Chamberlin, L. Gelhar, and A. R. Sanford who suggested many improvements. The responsibility for any errors or omissions rests with the authors. This work was partly supported by a grant from the New Mexico Energy Institute at New Mexico State University and the Geophysical Research Center at New Mexico Institute of Mining and Technology. The bulk of the research was performed by Ralph Wilcox in partial fulfillment of the requirements for the M.S. degree at New Mexico Institute of Mining and Technology.

## REFERENCES

Chapin, C. E., Chamberlin, R. M., Osbum, G. R., White, D. W., and Sanford, A. R., 1978, Exploration framework of the Socorro geothermal area: *in* Chapin, C. E. and Elston, W. E., eds., Field guide to selected cauldrons and mining districts of the Datil-Mogollon volcanic field: New Mexico Geological Society Special Publication 7, p. 115-129.

Clark, N. J. and Summers, W. K., 1971, Records of wells and springs in the Socorro and Magdalena areas, Socorro County, New Mexico (1968): New Mexico Bureau of Mines and Mineral Resources Circular 115, 51 p.

Craig, H., 1961, Isotopic variations in meteoric waters: Science, v. 133, p. 1702-1703.

Davis, S. N. and DeWiest, R. J. M., 1966, Hydrogeology: New York, Wiley, 463 p.

Faure, G., 1977, Principles of Isotope Geology: New York, Wiley, 464 p.

Gross, G. W., Hoy, R. N., and Duffy, C. J., 1976, Application of environmental tritium in the measurement of recharge and aquifer parameters in a semi-arid limestone terrain: New Mexico Water Resources Research Institute Report 080, 212 p.

Hall, F. R., 1963, Springs in the vicinity of Socorro, New Mexico: New Mexico Geological Society Guidebook 14, p. 160-179.

Holmes, C. R., 1963, Tritium studies, Socorro Spring: New Mexico Geological Society Guidebook 14, p. 152-154.

Rabinowitz, D. D., Gross, G. W., and Holmes, C. R., 1977, Environmental tritium as a hydrometeorologic tool in the Roswell basin, New Mexico: Journal of Hydrology, v. 32, p. 3-46.

Sanford, A. R., 1968, Gravity survey in central Socorro County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 91, 14 p.

Scofield, C. S., 1938, Quality of ground water in the Rio Grande Basin north of Fort Quitman, Texas: U.S. Geological Survey Water Supply Paper 839, 296 p.

Scott, R. C. and Barker, F. B., 1962, Data on uranium and radium in ground water of the United States 1954 to 1957: U.S. Geological Survey Professional Paper 426, 115 p.

Summers, W. K., 1965, A preliminary report on New Mexico's geothermal energy resources: New Mexico Bureau of Mines and Mineral Resources Circular 80, 41 p.

, 1976, Catalog of thermal waters in New Mexico: New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 4, 80 p.

Waldron, J. F., 1956, Reconnaissance geology and ground water study of a part of Socorro County, New Mexico [Ph.D. thesis]: Palo Alto, Stanford University, 255 p.

*Stope in the Kelly mine, Kelly, New Mexico, ca. 1895. Some idea of the productive thickness of the Silver Pipe limestone bed can be seen in this posed view, probably taken after the mine was closed due to the silver crash. The Kelly was clearly a "great one," producing about 1000 tons per month of direct shipping (and nearly self-fluxing) ore containing 10–12 ounces silver per ton and more than 35 percent lead from at least October 1882 through May 1888. Joseph E. Smith photo, courtesy Ed Smith; New Mexico Bureau of Mines and Mineral Resources collection.*