



## *Geothermal hydrology in the Rio Grande rift, north-central New Mexico*

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# GEOHERMAL HYDROLOGY IN THE RIO GRANDE RIFT, NORTH-CENTRAL NEW MEXICO

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## INTRODUCTION

Although the Rio Grande rift is shown by heat-flow measurements to be the site of a pronounced geothermal anomaly (Reiter and others, 1975), it contains relatively few thermal springs, and only a few of them have been investigated in detail. In north-central New Mexico, the most intensively studied are those in the Jemez Mountains (fig. 1), for which many chemical and other data are available (Table 1). In that region, geologic mapping (Smith and others, 1970; Wood and Northrop, 1946), geophysical surveys (Jiracek and others, 1975), and geothermal exploration and drilling (Dondanville, 1978; Pettit, 1975) facilitate interpretation of the hydrologic data. Elsewhere in the rift in north-central New Mexico (near Taos and near Ojo Caliente (no. 1, fig. 1C), in the San Luis basin north of Santa Fe, and in the Lucero uplift at the western margin of the Albuquerque basin southwest of Albuquerque), considerable information has been provided by mapping and geophysical surveys, but less is known of the geothermal phenomena. This report briefly summarizes the geothermal hydrology of part of the southwestern Jemez Mountains, and examines, against this background, the hydrologic and geothermal data available from the other areas of thermal springs.

## SOUTHWESTERN JEMEZ MOUNTAINS

The Jemez Mountains are made up of a complex pile of Neogene volcanic rocks that lies across the western marginal fault zone of the Rio Grande rift (Smith and others, 1970). Culminating this volcanic pile is a caldera in which deep drilling has shown the presence of a liquid-dominated geothermal reservoir containing water that has a base temperature of more than 260°C (Dondanville, 1978). There is thus no question of the source of heat, nor of the origin of the geothermal fluid that flows out from the caldera, southwestward, through the marginal fault zone. This fluid flow is facilitated by the structure and stratigraphy of the pre-volcanic rocks in and near the marginal fault zone, with cavernous openings in Pennsylvanian limestone of the Magdalena Group providing effective channels that permit subsurface transport of heat and dissolved mineral material away from the caldera. Chemical and isotopic data provide evidence of the mixing with dilute ground water that occurs during movement of the geothermal fluid.

Numerous investigators have described the chemical characteristics of thermal waters in volcanic regions. According to White and others (1963, p. 10-11, 40-43), these waters typically contain high concentrations of SiO<sub>2</sub>, Na, K, Cl, F and such minor constituents as As, B and Li. Major-constituent plots (fig. 2) for several samples from the Jemez Mountains (H6, H14, H32 and H29) illustrate a composition dominated

by Na, K, Cl and F (relatively high concentrations of Ca and HCO<sub>3</sub> reflect flow through carbonate rock in the fault zone); decrease in concentration, in the order in which the springs are listed above, is attributed to dilution of the geothermal component of the water. The linear plots for B:Cl and Br:Cl (fig. 2) for samples A10, All, D6, H6, H14, H17, H29, H32 and N4 also display similarity in composition but a wide range in concentration, and substantiate the dilution.

An earlier study (Trainer, 1975) presented estimates of mixing proportions in this dilution process based on the assumptions that concentrations of Cl, Li, B and Br in a sample from well N4 are typical of the undiluted geothermal water, and that mixing was with water similar to that in the Jemez River above the principal mineral springs. Table 2 summarizes calculated dilution factors for mixed waters at eight sites, five from the earlier study and three first presented here. The calculated values of about two parts dilute water to one part geothermal fluid in springs A10 and All, some 33 km from the caldera, indicate that, under favorable conditions, the mixed water can travel considerable distances without extensive further dilution.

Isotopic data provide a basis for checking the dilution factors in Table 2. Figure 3 is a plot of deuterium (<sup>2</sup>H or D) and oxygen-18 (<sup>18</sup>O) data for selected waters from the Rio Grande rift. Three nonthermal springs in the Jemez Mountains (H2, N10 and P11) were sampled, in addition to several of the thermal waters already cited. The line marked "meteoric waters" is the line found by Craig (1961) and many later workers to represent precipitation, rivers and lakes throughout the world except where the water is subject to high rates of evaporation. It is of particular interest in the present study, as is noted below, that most of the points in Figure 3 lie on or near the meteoric-water line. Conspicuous deviations from the line to the right, as in several of the thermal waters from the Jemez Mountains, may reflect a combination of two phenomena that have been observed in waters in other geothermal areas: a shift in 180 values attributed to exchange of oxygen between fluid and rock, and a shift in both D and 180 attributed to isotopic fractionation during evaporation.

The dilution factors listed in Table 2 are based on the assumption that waters H6, H14 and H17 were derived by dilution from a water similar to N4. We further assume that the isotopic composition of a diluting water is that of the meteoric-water line at its intersection with the line drawn from N4 through one of the three points. For the example of H14, this point of intersection is SD = -83 per mil, 5180 = -11.25

Table 1. — Chemical and isotopic data for selected ground-water samples from the Rio Grande rift, north-central New Mexico. Analyses by U.S. Geological Survey except where noted. Concentrations in milligrams per liter.

Sample Number.....	A10	A11	D6	H2	H6	H14	H17	H29	H32	N4	N10	P11	1	2
Date of Collection..	5-24-73	8-30-73	8-21-73	12-13-74	12-1-72	12-2-72	5-30-74	10-24-73	1-17-73	5-3-74 <sup>4/</sup>	12-2-72	7-20-76	12-3-74	10-6-49
Silica (SiO <sub>2</sub> ).....	13	68	44		50	95 <sup>1/</sup>	96	37	45	170			63	63
Calcium (Ca).....	110	110	32		330	130	160	210	140	7.3				25
Magnesium (Mg).....	18	21	5.7		24	4.8	6.6	59	13	13				8.9
Sodium (Na).....	1400	1300	190		990	640	510	570	390	4800			890	928
Potassium (K).....	63	73	8.2		200	82	63	34	51	180				30
Bicarbonate (HCO <sub>3</sub> )..	1320	1440	366		1578	732	773	1530	761				2073	2160
Carbonate (CO <sub>3</sub> ).....	0	0	0		0	1.5	0	0	0				0	0
Sulfate (SO <sub>4</sub> ).....	470	270	120		52	53	43	290	32	1600				156
Chloride (Cl).....	1400	1200	49		1500	920	700	300	470	2600			270	238
Fluoride (F).....	8.6	4.0	7.6		3.3	4.8	4.4	1.6	4.6	16				16
Boron (B).....	5.8	8.2	0.4		12.5	7.4	7.4	2.4	0.7	26				1.5
Bromide (Br).....	5.0	5.0	.2		6.9	4.0	3.0	1.1	1.0 <sup>2/</sup>	14				1.4
pH (field).....		8.0	8.0		6.1	6.3	6.6	6.5	6.7	7.7				6.6
D (o/oo).....					-80.0 <sup>3/</sup>	-84.8	-82.1	-85.2		-78.9 <sup>5/</sup>	-96.5	-93.2	-107.4	-108.2 <sup>6/</sup>
<sup>18</sup> O (o/oo).....					-12.05	-10.40	-10.52	-11.42		-8.12 <sup>5/</sup>	-13.14	-12.70	-14.56	-14.60 <sup>6/</sup>
Sample Number.....	3 <sup>2/</sup>	4 <sup>2/</sup>	5 <sup>8/</sup>	6	7	8	9 <sup>8/</sup>	10 <sup>8/</sup>	11 <sup>8/</sup>	12 <sup>8/</sup>	13	14	15	
Date of Collection..	4-8-65	4-8-65	7-23-76	2-18-64	12-3-74	12-3-74	7-22-76	7-22-76	7-22-76	7-23-76	5-16-75	4-21-75	5-16-75	
Silica (SiO <sub>2</sub> ).....			32	30	54	58	67	60	50	30	13	30	15	
Calcium (Ca).....	40	80	14	80	11	27	21	27	27	38	410	270	760	
Magnesium (Mg).....	16	29	1.1	15	1.2	5.7	4.6	8.8	6.0	5.6	110	100	420	
Sodium (Na).....	495	102	225	44	150	130	145	26	18	39	520	560	5400	
Potassium (K).....	16	4.7	4.7		4.6	9.2	11	5.1	4.4	3.4	34	12	100	
Bicarbonate (HCO <sub>3</sub> )..	907	274	310	294	79	202	200	160	150	140	117	232	2420	
Carbonate (CO <sub>3</sub> ).....	0	0	0	0	0	0	0	0	0	0	0	0	0	
Sulfate (SO <sub>4</sub> ).....	155	158	96	70	120	130	150	16	6.0	74	1900	1500	3100	
Chloride (Cl).....	149	83	125	30	92	56	58	10	3.0	4	480	380	7300	
Fluoride (F).....	7.5	0.6	10	0.2	18	3.8	2.9	0.5	0.9	0.4	1.3	0.8	0.7	
Boron (B).....			0.4		0.5	0.27	0.25	.06	.06	.06	1.5	.69	4.1	
Bromide (Br).....					.7	.5					0.9	.8	9.0	
pH (field).....			8.2		7.8	6.9	8.0	7.6	7.7	7.5	7.7	7.9	6.7	
D (o/oo).....			-107.1		-93.5	-105.1	-103.7	-100.4	-105.8	-102.0	-57.00	-62.95	-84.65	
<sup>18</sup> O (o/oo).....			-13.90		-13.11	-14.01	-13.90	-13.45	-14.25	-13.65	-8.10	-8.50	-11.10	

1/ Sample collected 1-25-74.

2/ Sample collected 3-8-73.

3/ Isotope analyses by L. A. Adami, S. J. Grigg, and L. D. White, except analyses 13-15, which were by Lillian Merlivat, CEA Department de Recherche et Analyse, Bureau des Isotopes Stables, France.

4/ Depth of well, 1084 m.

5/ Sample collected 4-23-74; depth of well, 1076 m.

6/ Sample collected 12-3-74.

7/ Analyses, New Mexico Public Health Laboratory in Summers, 1976, Table M5.

8/ Analyses by T. S. Presser and W. C. Evans.

per mil. Adding 2.2 parts of this water (dilution factor, Table 2) to one part having the isotopic composition of N4 (SD = -78.9 per mil, 6180 = -8.12 per mil) yields a mixture having the composition SD = -81.72 per mil, <sup>5180</sup> = -10.27 per mil, which is approximately the measured composition for water from spring H14. This point and those computed in similar fashion for H6 and H17, are shown by the symbol x near each of these samples in Figure 3. The close agreement of computed and measured points lends support to the dilution factors in Table 2.

Fournier and Truesdell (1974) described mixing models which permit the estimation of geothermal-reservoir temperature, and of the proportions of hot and cold waters, from the composition and temperature of a mixed water. Application of their model (Fournier and Truesdell, 1974, p. 265-266; Truesdell and Fournier, 1977), to SiO<sub>2</sub> and temperature data from spring H14, yields an estimate of 162°C for the temperature of the original hot water before mixing, and proportions of 41 percent hot water and 59 percent cold water. By comparison, the proportions calculated for spring H14 from the dilution factor in Table 2 are 31 percent hot water and 69 percent cold water. The temperature estimate of 162°C is comparable to an estimate of 169°C, based on the silica geothermometer, for a

sample collected from well N-4 when its total depth was 1,085 m (Trainer, 1975, p. 216-217). Despite the fact that numerous assumptions were necessary in making these estimates, we see even general agreement of estimates as support for the conceptual model of the flow system in the marginal fault zone of the rift in the southwestern Jemez Mountains.

### SAN LUIS BASIN

The San Luis basin contains thick valley-fill deposits with interbedded volcanic rocks (Woodward and others, 1975). In southern Colorado, the thickness of these deposits may be as great as 2.8 km (Emery, 1971, p. 131). Data are not yet available to show whether similar thicknesses are present in New Mexico. Gravimetric data (Cordell, 1976, 1978) suggest that the basin floor about 5 km upstream from the Embudo constriction lies 1,500 m or more below the surface of basement in the constriction, and that much greater depths to basement characterize the trough to the north. In the southern part of the basin, the thickness of Neogene valley fill amounts to a kilometer or more (Kelley, 1956, p. 109). North of Taos and generally west of the Rio Grande, the upper part of the valley

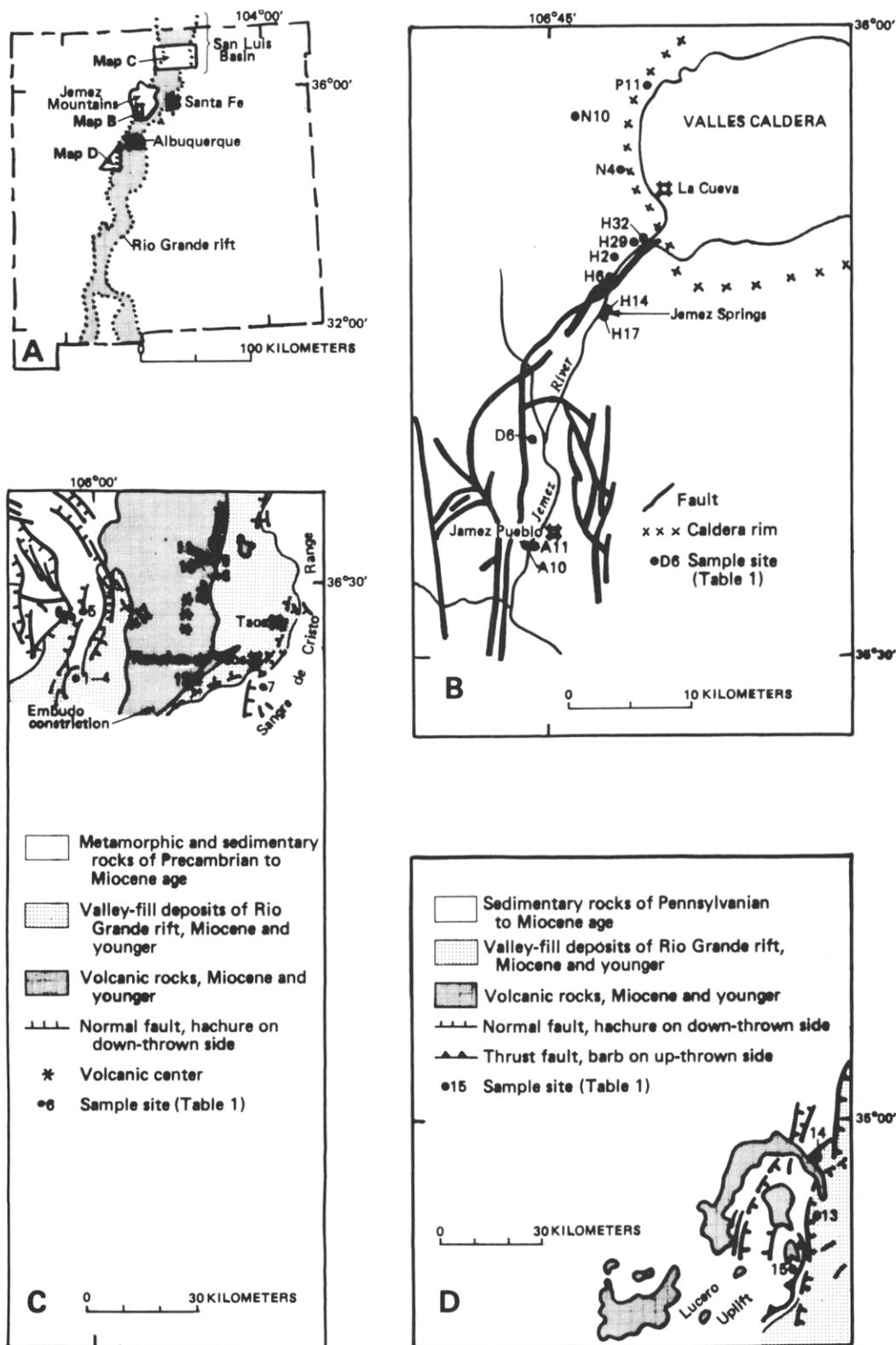


Figure 1. Maps showing locations of water-sampling sites in Rio Grande rift in north-central New Mexico. Sample numbers as in Table 1. (A) Index map. (B) Caldera rim, principal faults, and sampling sites in southwestern Jemez Mountains. Geologic features from Smith and others (1970). (C) Generalized geology and sampling sites, southern part of San Luis basin. Geology from Woodward and others (1975). (D) Generalized geology and sampling sites, Lucero uplift. Geology from Woodward and others (1975).

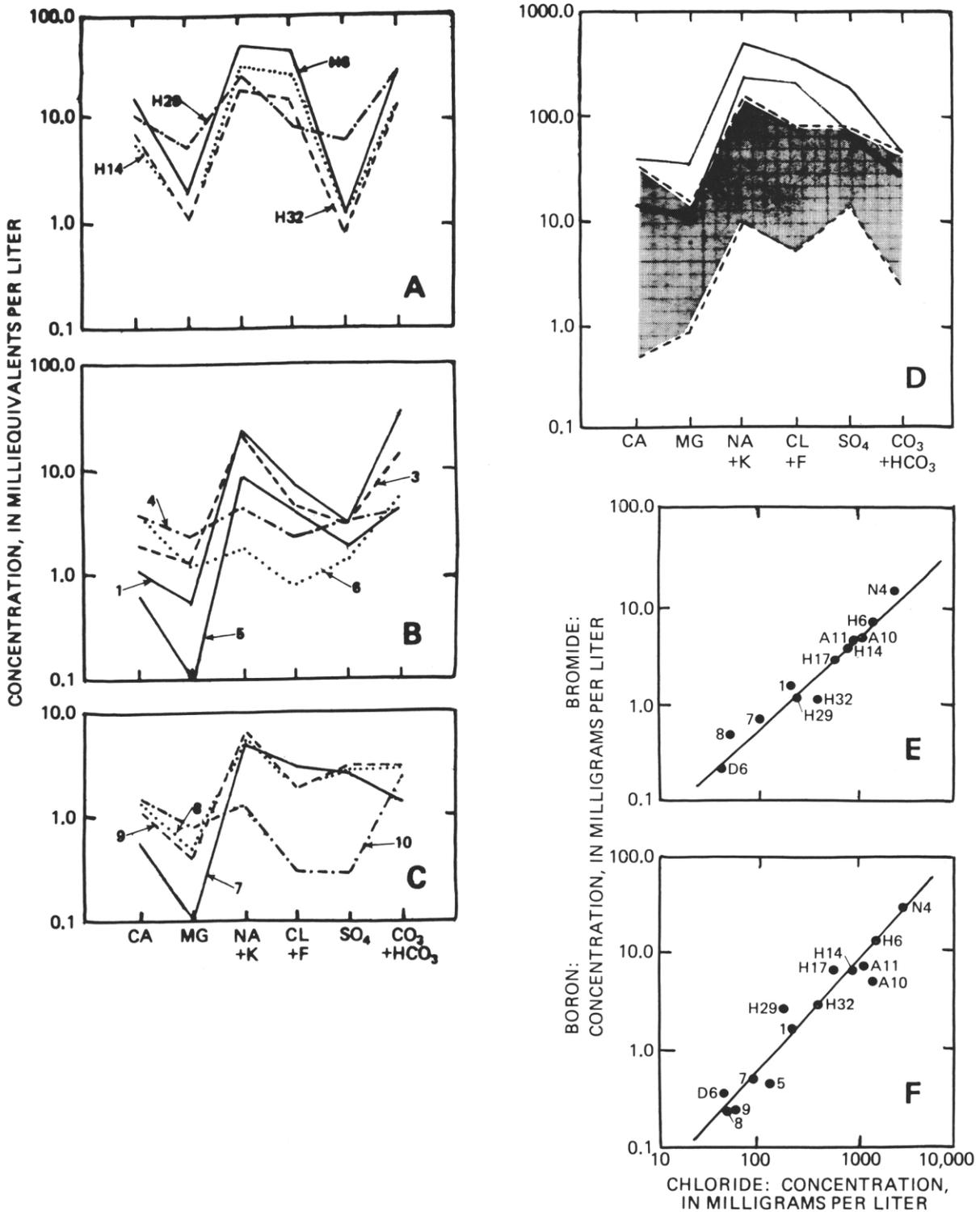


Figure 2. Concentration of major constituents and selected trace constituents in ground-water samples from the Rio Grande rift in north-central New Mexico. Identification of samples is as in Table 1. (A) Major constituents in four mixed thermal waters in the southwestern Jemez Mountains. (B) Major constituents in four mixed thermal waters and one nonthermal water (6) in the Ojo Caliente area, San Luis basin. (C) Major constituents in three mixed thermal waters and one nonthermal water (10) in the Taos area, San Luis basin. (D) Major constituents in mineral water in the rift-margin fault zone in the Lucero uplift (unshaded envelope) and in more dilute mixed waters (shaded envelope). Plots based on data in files of U.S. Geological Survey; analyses 13-15, Table 1, are representative of these waters. (E-F) Plots of Br versus Cl (E) and B versus Cl (F), thermal waters in southwestern Jemez Mountains and San Luis basin.

Table 2. Calculated dilution factors for selected mixed groundwaters in the southwestern Jemez Mountains. Factor given is quantity of nonthermal water believed to have mixed with one part of deep thermal water. Well and spring numbers as in Table 1.

Well or Spring	Dilution Factor	Well or Spring	Dilution Factor
A10	2.1	H14	2.2
A11	1.9	H17	2.8
D6	61	H29	10
H6	0.9	H32	6.0

fill interfingers with and is covered by volcanic rocks (Winograd, 1959); here, the maximum thicknesses of valley fill and volcanic rocks are not known, but well logs show the latter to be at least 550 m.

In the northern part of the basin in New Mexico, ground-water flow in the near-surface parts of both valley fill and volcanic rocks is toward the regional drain provided by the Rio Grande (Winograd, 1959, pl. 2). There is no reason to believe that ground-water flow deeper in the rift is not also toward the river. Hence, it is of particular interest to note that two of three groups of thermal springs in the basin in New Mexico are at the margins of the rift: Ojo Caliente and Ponce de Leon Hot Spring (nos. 1 and 7, respectively, fig. 1). The third group is in the Rio Grande Gorge northwest of Taos.

Thermal water (40°C) discharged from fractured Precambrian crystalline rocks near the south end of the Ojo Caliente prong, at the west end of the Embudo constriction, provides the flow of five developed springs, a number of small springs and seeps, and three wells (Summers, 1976, p. 24-28) (fig. 1). Summers (1976, p. 28) measured a total discharge of 6 L•sec<sup>-1</sup> (liters per second) on December 1, 1965. Several other, smaller thermal springs (Stearns and others, 1937, p. 166) occur along the Caliente fault zone in the Ojo Caliente-La Madera area (Burroughs and Woodward, 1974, p. 15). Extensive, thick deposits of travertine near La Madera (near no. 6, fig. 1) were deposited by water flowing from these springs.

Ponce de Leon Hot Spring (7, fig. 1), 3 km south of Ranchos de Taos, discharges warm (32°C) H<sub>2</sub>S-bearing water from fractures in granitic rock in the eastern marginal fault zone of the rift. Summers (1976, p. 24) measured a total discharge of 15 L•sec<sup>-1</sup>.

Manby Hot Spring (8, fig. 1) and an unnamed spring (9) discharge warm (34-37°C) water from fractures in basalt. Discharge is small (about 2 L•sec<sup>-1</sup> from Manby Hot Spring and about 0.05 L•sec<sup>-1</sup> from the unnamed spring (Summers, 1976, p. 24)).

Mixing-model calculations for springs in these three areas suggest very large proportions of cold water (83 to 93 percent (Table 3)). Limited credence can be placed in the numerical results obtained, for the conditions assumed for the mixing model are unlikely to be met where such a degree of dilution occurred, but the conclusion that dilution has been large is consistent with the chemical and isotopic data. Except for a possible oxygen shift in the sample from Salt Lick Spring (5) near Ojo Caliente, all the points lie on or near the meteoric-water line (fig. 3). B:CI and Br:CI plots (fig. 2) suggest a thermal water similar in these ratios to the waters in the Jemez Mountains. The major-constituent diagrams for the San Luis basin waters (fig. 2) are less distinctive than those for the samples from the Jemez Mountains, but can be explained by the mixture of two components: a concentrated sodium-chlor-

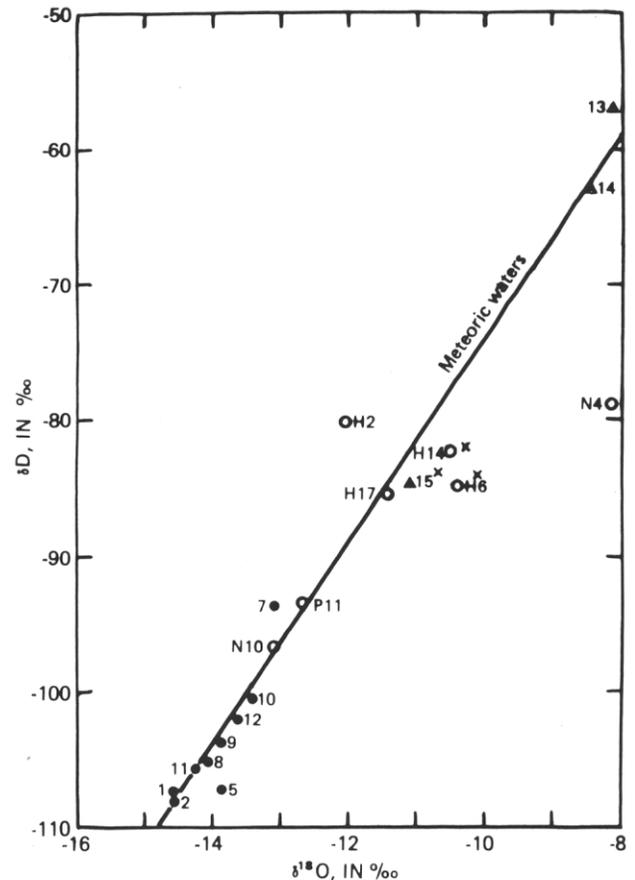


Figure 3. Deuterium and oxygen-18 data for selected groundwaters in the Rio Grande rift in north-central New Mexico. Sample numbers as in Table 1. Symbols: open circle, southwestern Jemez Mountains; solid circle, San Luis basin; triangle, Lucero uplift; x, calculated position of point based on mixing proportions (see text).

ide thermal water and the dilute calcium-sodium-bicarbonate water typical of nonthermal ground water of meteoric origin (White and others, 1963, p. 55). At Ojo Caliente, the bicarbonate content of the water has been accentuated by solution of carbonate rock, and possibly, by reaction of CO<sub>2</sub> with silicate minerals. The characteristics of the three waters, as suggested by the two types of chemical diagrams, are consistent with derivation from a single source or from similar sources.

Fournier and others (1974) summarize the principal assumptions on which the use of chemical geothermometers is based:

1. Temperature-dependent chemical reactions occur at depth.
2. The constituents involved are sufficiently abundant that supply does not limit the reactions.
3. Water-rock equilibrium occurs at the reservoir temperature.
4. Little or no re-equilibrium occurs at lower temperatures as the water flows from the reservoir to the surface.
5. The hot water coming from depth does not mix with cooler shallow ground water.

Assumptions 1 and 3 are thought to be reasonable in the present situation. Assumption 2 appears not to be satisfied with respect to use of the Na-K-Ca geothermometer. The exposed volcanic rocks of the San Luis basin include a large

Table 3. Estimated mixing proportions of thermal waters in San Luis basin in New Mexico, and estimated temperatures of geothermal fluids before mixing.

Sample and Source	Estimated Mixing Proportions (Mixing Model)	Method of Estimation	Estimated Temperature, Hot-Water Fraction (degrees Celsius)	Method of Estimation
(1) Ojo Caliente ("Iron Spring")	Hot water, 17 percent Cold water, 83 percent	Mixing model <sup>1</sup>	113	Solubility of quartz <sup>2</sup>
			85	Solubility of chalcedony <sup>3</sup>
			150	Na-K-Ca geothermometer <sup>4</sup>
			72	Na-K-Ca geothermometer, corrected for Mg <sup>5</sup>
			188	Mixing model
(7) Ponce de Leon Hot Spring	Hot water, 7 percent Cold water, 93 percent	Mixing model <sup>6</sup>	105	Solubility of quartz
			76	Solubility of chalcedony
			127 or 91	Na-K-Ca geothermometer (two forms of equation used)
			225	Mixing model
(8) Manby Hot Spring	Hot water, 7 percent Cold water, 93 percent	Mixing model <sup>6</sup>	109	Solubility of quartz
			80	Solubility of chalcedony
			156 or 93	Na-K-Ca geothermometer
			75	Na-K-Ca geothermometer, corrected for Mg
			238	Mixing model

<sup>1</sup> Assumed cold-water component, water from La Madera municipal well (Dinwiddie and others, 1966, table 11).

<sup>2</sup> Fournier and Rowe, 1966.

<sup>3</sup> Fournier, 1973.

<sup>4</sup> Fournier and Truesdell, 1973.

<sup>5</sup> Fournier and Potter, 1978

<sup>6</sup> Assumed cold-water component, water from spring 28.12.3 (Winograd, 1959, p. 70).

proportion of basaltic or andesitic composition. If these rocks are taken as typical of the subsurface igneous bodies from which the geothermal fluid derives its heat and dissolved constituents, the source may be deficient in Na, and particularly in K, with respect to Ca, for use with the cation thermometer. In the equation for temperature (Fournier and Truesdell, 1973, p. 1264), the effect of bias toward deficiency of K relative to Na, or of deficiency of Na and K relative to Ca, is underestimation of the temperature. In the case of Ojo Caliente, any deficiency of Na and K is accentuated by the ready availability of Ca in carbonate rock. For these reasons, we believe the cation temperatures (Table 3) to be underestimated by unknown amounts.

Assumption 4 is questionable because the relatively low rates of discharge of the springs imply low rates of flow through the rock, with opportunity for conductive cooling and consequent changes in composition through re-equilibration. Assumption 5 clearly is invalid for the San Luis basin. These objections apply particularly to the silica thermometers, which are based on concentration rather than on the constituent ratios used for the cation thermometer. They are taken into account by the mixing-model calculation, which provides an estimate of the concentration of SiO<sub>2</sub> in the unmixed geothermal water by removing the effect of dilution. However, other considerations lend further uncertainty to the temperature estimates.

First, the concentration of dissolved SiO<sub>2</sub> in water in basaltic rock commonly is controlled by the solubility of chalcedony rather than by that of quartz. Hence, the lower temperatures estimated from silica (Table 3) appear to be more realistic than the higher ones. Second, selection of the more appropriate of the two forms of the Na-K-Ca geothermometer is difficult in this instance, but one form (13 = 4/3) yields temperature estimates similar to those provided by chal-

cedony. Finally, correction of the Na-K-Ca estimates for Mg in two samples (Table 3) also suggests lower temperature values. Estimated temperatures for the unmixed hot water thus fall into two groups. Inasmuch as the mixing model assumes derivation of dissolved SiO<sub>2</sub> from quartz, the lower estimated temperatures are probably the more representative for these waters in basaltic rocks. It should be emphasized, of course, that these estimates refer to the last equilibration of water and rock, and thus may not be related directly to the source of heat. Plots in Figure 2 support the interpretation of considerable dilution, but it was probably less than is suggested by the mixing model.

The conclusion that dilution of the thermal waters has occurred, of whatever magnitude, emphasizes the need for better understanding of the ground-water flow system. As was noted above, Ojo Caliente and Ponce de Leon Hot Spring are near the margins of the rift, at relatively high altitudes, rather than at the Rio Grande, the regional drain for ground-water flow. Three factors may help determine the location of these two thermal springs: (1) Structural control favors the occurrence of thermal springs along the major (and perhaps deepest) fault zones in the region. Most if not all of the thermal springs in the Rio Grande rift in New Mexico flow from fractured rock, and as Summers (1965, p. 5-6) notes, most of them are along the border faults, particularly on the west side of the rift. Moreover, so far as we are aware, no one has described a hot spring in the alluvial fill of the rift or has suggested the presence of a geothermal convection system in the valley fill (although relatively high heat flow occurs in at least one locality in the rift, as Reiter and others (1978, p. 86) have shown at Dixon (near no. 12 in Figure 1)). (2) The relatively low density of the thermal water favors its convective rise within the fracture system to discharge at the land surface at levels above that of the regional water table. And finally, (3) the

positions of these springs near the southern (down-valley) ends of masses of faulted rock may facilitate the discharge of rising thermal water. The crystalline and consolidated rocks of the Ojo Caliente prong plunge beneath valley-fill deposits a short distance south of the thermal springs (Kelley, 1954). Ponce de Leon Hot Springs are in a re-entrant of faulted rock that extends southward into less-fractured rock of the Sangre de Cristo Mountains. At both localities, part of the thermal water may discharge at the surface rather than continuing its flow in the subsurface, into valley fill (particularly if the fill has been cemented partly by travertine) at Ojo Caliente, or through less-fractured rock at Ponce de Leon Hot Spring.

The foregoing considerations, taken with the evidence from the Jemez Mountains for the subsurface flow of thermal water, suggest that the sources of these thermal waters may be considerable distances from the springs. Similarly, the thermal springs in the Rio Grande Gorge, if supplied by lateral flow through the fractured and rubbly zones between lava flows, may be separated widely from their sources of heat. If all these springs are so separated, and this interpretation is consistent with the likely dilution and heat loss in the mixed waters, exploration for the sources of heat will be more difficult than if the heat sources were near. If further investigation confirms relatively low temperatures for the unmixed thermal waters, these waters may not be considered a valuable resource for their potential heat.

### LUCERO UPLIFT

Ground waters in the Lucero uplift are relatively highly mineralized and appear to have been derived from several sources. They are more complex mixtures than those described above and scanty data permit only tentative interpretation.

The Lucero uplift (fig. 1) is a westward-tilted fault block whose eastern edge forms part of the boundary between the Rio Grande rift and the older rocks to the west. The stratigraphic section in the eastern part of the uplift includes upper Paleozoic and Mesozoic consolidated sedimentary rocks; Neogene alluvial deposits (the valley fill of the rift and younger alluvium of valley floors); Neogene basaltic lavas; and Quaternary pediment gravels, travertine deposited from spring waters, and landslide deposits (Kelley and Wood, 1946). The travertine is exposed at several stratigraphic positions and represents long-continued spring discharge along several faults at the eastern edge of the Lucero uplift (Callender and Zilinski, 1976, p. 58).

Two ground waters can be distinguished in the eastern part of the Lucero uplift on the basis of chemical character (fig. 2): a mineralized water containing predominant concentrations of Na, Cl and SO<sub>4</sub>, and a less-mineralized water of similar composition. Chemical analyses are given by Titus (1963), U.S. Geological Survey (1976) and Wright (1946). The highly mineralized water is discharged by numerous springs at the eastern margin of the uplift and by a few in water gaps in ridges to the west. Titus (1963, p. 46) concluded that this water comes from the west, principally through the Madera Limestone (Pennsylvanian) (though some of the springs are in other rocks that are connected hydraulically with the limestone in the marginal fault zone). The less-mineralized water occurs in valleys west and north of the upland at the eastern edge of the uplift, and in the rift immediately to the east; with respect to areas west and north of the upland, Titus (1963, p. 48) concluded that this water is provided largely by local precipita-

tion, and that flow through the Permian Abo, Yeso and San Andres formations provides the high content of SO<sub>4</sub> and HCO<sub>3</sub>.

Two new types of evidence support Titus's interpretation. First, flow of a major component of the ground water from the west is consistent with recent studies of hydrodynamics in part of the San Juan Basin, west and northwest of the uplift. Digital modeling of ground-water flow in Jurassic and Cretaceous rocks by Lyford and P. F. Frenzel (written commun., 1978) indicates flow from topographically high areas toward major surface streams such as the San Juan River to the northwest, and the Rio Puerco and the Rio Grande to the southeast. Because of similarities in recharge and discharge areas, respectively, for the several formations, it is reasonable to assume that water in Pennsylvanian and Permian rocks, which are deeper, also flows toward these streams.

Second, isotopic data (fig. 3) are consistent with a relatively high altitude for the recharge area for water from spring 15, which implies that at least a large component of that water may have come from the San Juan Basin; and with derivation of most of the water in samples 13 and 14 from local precipitation.

In one respect, we suggest revision of Titus's interpretation: that one component of both mixed waters is geothermal water which rises toward the surface through the marginal fault zone of the Rio Grande rift. Several of the small springs in the eastern part of the Lucero uplift discharge water at temperatures of 25°C or higher. Considering the very low flow rates of the springs (most less than 1 L•sec<sup>-1</sup>), it is likely that significant heat loss occurred by conduction through the wall rock during flow to the springs. Thus, the observed temperatures, markedly higher than the air temperature when measured in April 1975, suggest the presence of geothermal water.

So far as we are aware, hydrochemical data are not available for water in the Madera Limestone in the central to southeastern part of the San Juan Basin; therefore, hypothetical mixtures of ground water in the Lucero uplift cannot be devised yet using analyses of the San-Juan-Basin water. A hypothetical mixture based on the samples (fig. 2) from the Jemez Mountains and the Lucero uplift (using both major and minor constituents) could consist of a sodium-chloride component from the marginal fault zone and a sodium-chloride-sulfate component, with Ca and HCO<sub>3</sub>, from the San Juan Basin and from the aquifers through which the water flowed to the Lucero uplift. Testing and revision of such hypothetical mixtures will require additional data; even with those data, the use of mixing models and chemical geothermometers may not be practicable because of the complexity of circulation and mixing, and because of the large component of nonthermal, highly mineralized water.

Geophysical investigation (Ander and Huestis, 1978) suggests the presence of an intrusive igneous body at shallow depth (perhaps less than 1 km) beneath the Lucero uplift. Such an intrusion provides a possible source of geothermal heat, an explanation for the uplift of the Lucero area, and a promising target for geothermal exploration.

Drilling done as part of a geothermal investigation could have the important second objective of determining the quantity and quality of ground water which flows into the Rio Grande rift. The extensive deposits of travertine along the eastern edge of the Lucero uplift imply transportation over much of Quaternary time of significant quantities of soluble salts

and of such important minor constituents as boron into the important aquifer in the Rio Grande trough. The magnitude of this dissolved load can be estimated for the surface discharge of the springs, but the magnitude needed for management of the aquifer is the total discharge including that which occurs by subsurface flow into the rift.

## CONCLUSIONS

Good agreement was obtained, in study of the mixing proportions of thermal and nonthermal ground waters in the southwestern Jemez Mountains, among estimates based on selected major and trace dissolved constituents, deuterium and oxygen-18, and silica and water temperature (mixing model). Along at least one conduit in the rift-margin fault zone, the mixed water has flowed more than 30 km without extensive further dilution. Application of the mixing model to study of warm-spring waters in the San Luis basin is of questionable validity because several assumptions on which the model is based are not fulfilled. Estimates using the mixing model indicate intensive dilution of a hot geothermal water, but chemical geothermometers suggest lower initial temperatures. These warm-spring waters may have flowed considerable distances into the subsurface from the sources of heat. Mineral waters in the Lucero uplift are believed to be mixtures of ground water from the San Juan Basin to the west, of geothermal water from the rift-margin fault zone, and of recharge from local precipitation.

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