



## ***Mixing of thermal and nonthermal waters in the margin of the Rio Grande Rift, Jemez Mountains, New Mexico***

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# MIXING OF THERMAL AND NONTHERMAL WATERS IN THE MARGIN OF THE RIO GRANDE RIFT, JEMEZ MOUNTAINS, NEW MEXICO\*

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## INTRODUCTION

Chemical analyses of ground water from the marginal fault zone of the Rio Grande rift, in the southwestern Jemez Mountains, show that thermal water from depth mixes with local ground water. Mixing of the waters provides evidence of ground-water flow paths in this part of the rift, and general conclusions reached in study of the mixing may be useful in investigations of thermal waters elsewhere.

The geology of the southwestern Jemez Mountains has been described by Wood and Northrop (1946), Ross, Smith, and Bailey (1961), and Smith, Bailey, and Ross (1970). Trainer (1974) summarized the geohydrology and presented representative chemical analyses of ground water. The Jemez Mountains (Fig. 1) comprise a complex pile of late Tertiary and Quaternary volcanic rocks that lies athwart the fault zone at the west margin of the Rio Grande rift. San Diego Canyon has been excavated, in part, in the marginal fault zone. The Jemez River, flowing through the canyon, drains Valles Caldera. Rocks exposed in San Diego Canyon include Precambrian granitic rock, Paleozoic and Mesozoic sedimentary rocks, and Tertiary and Quaternary volcanic rocks and alluvial fill. Water discharged by thermal and cold mineral springs in San Diego Canyon is believed to be derived in part from a hydrothermal reservoir in Valles Caldera and to have flowed out along the fault zone, largely in limestone that overlies the granitic rock. Other hydrothermal features include areas of solfataras and hydrothermal alteration, believed to result from the activity of deep thermal water; and several thermal springs, on the flanks of young volcanoes in the ring-fracture zone of the caldera, that are believed to discharge water which has circulated to only relatively shallow depths.

## ACKNOWLEDGMENTS

The writer gratefully acknowledges the provision of water samples by Los Alamos Scientific Laboratory from its deep test well GT-2 in the Jemez Mountains; discussion of geohydrologic problems with W. D. Purtymun and F. G. West of Los Alamos Scientific Laboratory; and discussion with and assistance from Ivan Barnes, J. K. Kunkler, R. H. Mariner, C. S. Smith, and D. E. White of the U.S. Geological Survey.

## CHEMICAL CHARACTER OF THE GROUND WATER

Analyses summarized by White, Hem, and Waring (1963) characterize compositional groups typical of dilute ground water in several types of rock. Figure 2B illustrates two of these groups: (1) Points near the left vertex of the diagram are

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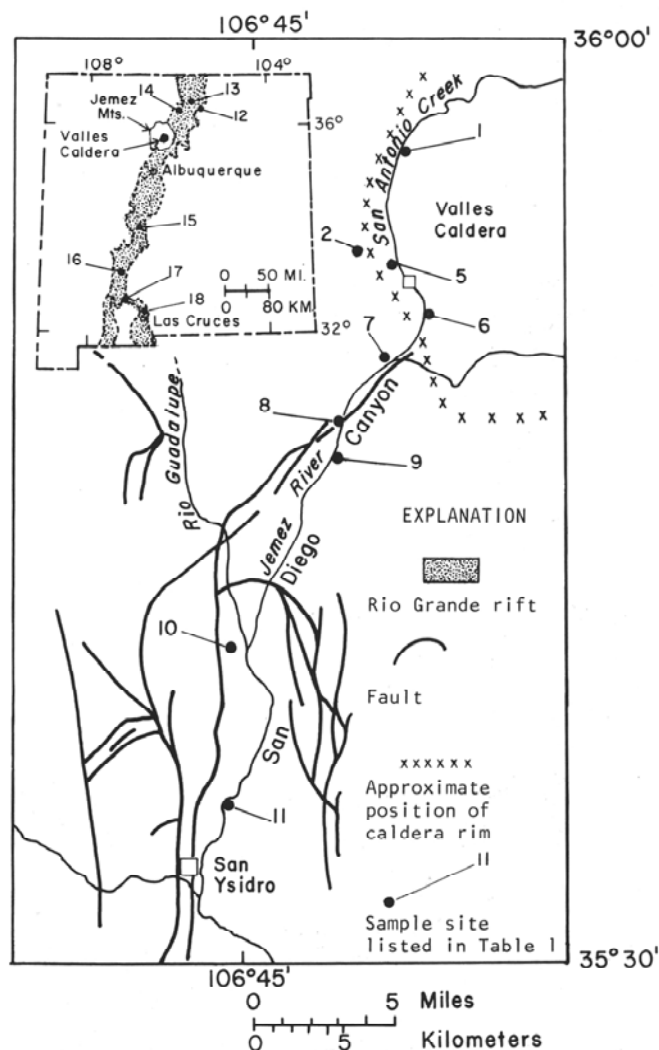


Figure 1. Maps showing locations of water-sampling sites, in Jemez Mountains and elsewhere in Rio Grande rift in New Mexico, relative to structural features.

**Large map:** Sampling sites in southwestern Jemez Mountains. (Sample numbers as in Table 1. Major faults after Wood and Northrop, 1946; and Smith, Bailey, and Ross, 1970.)

**Inset map:** Location of Jemez Mountains, generalized outline of Rio Grande rift in New Mexico (after Chapin, 1971), and sampling sites in the rift outside the Jemez Mountains. (Sample numbers as in Table 1.)

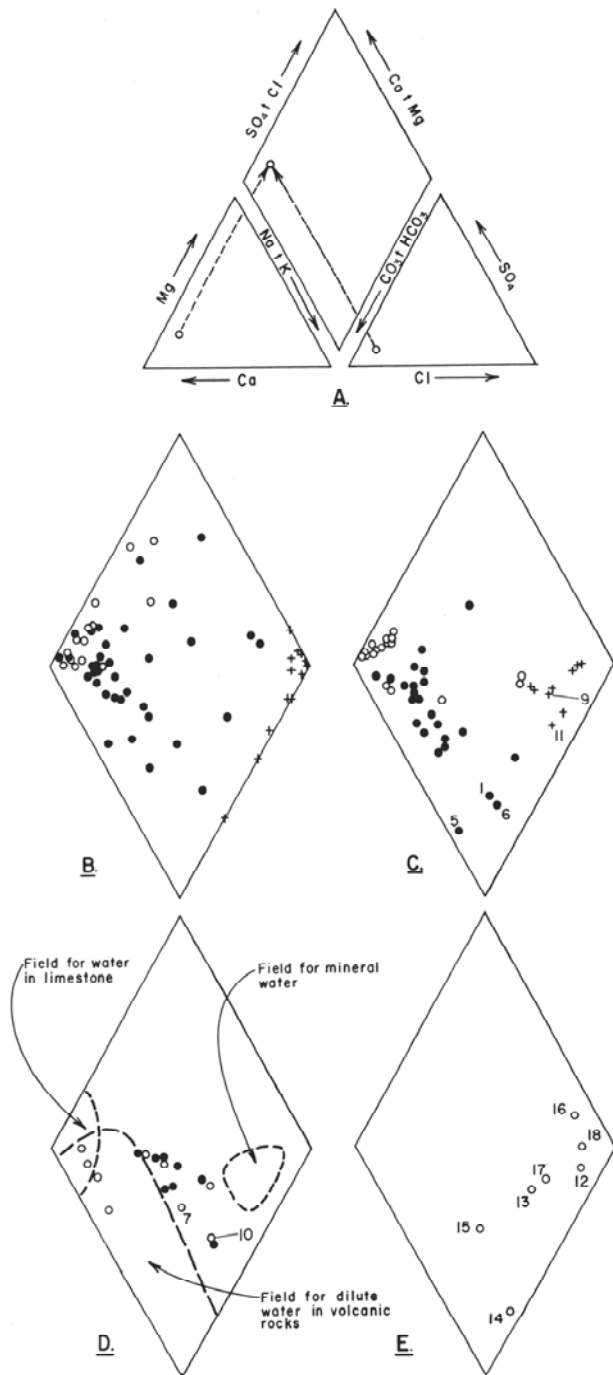


Figure 2. Diagrams illustrating major-ion composition of ground water. Each diagram is the diamond part of the plot shown in the explanatory key.

A. Key to diagram illustrating proportions of major ions in solution in water.

B. Composition of dilute ground water in igneous rocks (solid circles) and in carbonate rocks (open circles); and of thermal water in geyser areas of volcanic environments (crosses). (Data from White, Hem, and Waring, 1963.)

C. Composition of dilute ground water in volcanic rocks in the Jemez Mountains (solid circles) and in carbonate rocks of the Magdalena Group east and southeast of Albuquerque (open circles); and of mineral water in the southwestern Jemez

Mountains (crosses). (Data from southeast of Albuquerque from R. E. Smith, 1957; numbered samples listed in Table 7; other data from files of U.S. Geological Survey.)

D. Composition of mixed waters in southwestern Jemez Mountains, in carbonate rock (open circles) and in alluvium (solid circles). Shaded patterns show approximate distribution fields in Figure 2C; the mineral water, right field, is itself a mixed water. (Numbered samples listed in table 1; other data from files of U.S. Geological Survey.)

E. Composition of selected thermal waters from the Rio Grande rift outside the Jemez Mountains. (Sample numbers as in Table 1.)

representative of water in carbonate rock. The water is of a calcium magnesium bicarbonate composition; points distributed along the upper left side of the diagram represent carbonate-rock water that also contains moderate proportions of sulfate. (2) Points distributed largely near the left vertex and along the lower left side of the diagram are representative of water in igneous rocks. The water is of a calcium sodium bicarbonate composition; calcium is dominant in some samples and sodium in others, a fact that is not surprising when we consider the range in chemical composition of the feldspars. A third group of points, near the right vertex and lower right side in Figure 28, represents waters from a variety of rocks but a single environment; these are thermal waters in geyser areas of volcanic regions. White (1957) has discussed the composition of thermal waters of volcanic origin. White (1957, p. 1646) explained the sodium chloride composition of much of the water by the solution of alkali halides in high-density steam at depth and their accumulation in the hydrothermal fluid because of their low volatility in low-density steam nearer the land surface. With long-continued accumulation the fluid may become a brine containing minor constituents typical of some igneous minerals (for example, arsenic, boron, fluoride, and lithium). (See also Mahon, 1970, p. 1312-1313.)

Figure 2C illustrates the composition of these three types of ground water in samples from the southwestern Jemez Mountains and nearby areas. (1) Points near the left vertex of the diagram represent water in carbonate rocks east of the east marginal fault zone of the Rio Grande rift near Albuquerque (Fig. 1). These carbonate rocks, which are in the Magdalena Group of Pennsylvanian and Permian age, are similar to the Magdalena rocks in the Jemez Mountains. Water analyses from these other areas are used in Figure 2C because samples collected from carbonate rocks in the Jemez Mountains appear to be mixed waters.

(2) Points near the lower left side of the diagram represent cold dilute water in near-surface volcanic rocks in the Jemez Mountains and warm dilute water in volcanic rocks on or near the young volcanoes in Valles Caldera. The composition of these dilute waters corresponds to that of the dilute waters in igneous rocks shown in Figure 28. The warm dilute waters are believed to be examples of a type described by White, Hem, and Waring (1963, p. F55) as thermal waters that are probably entirely meteoric. In the Jemez Mountains this dilute thermal water is more dilute than ground water normally found in the Permian sandstone and shale that underlie the volcanic rocks. Hence the dilute thermal water must have migrated to only relatively shallow depths and gained its heat from young, near-surface volcanic rocks, perhaps near the feeder dikes or pipes where heat flow must be higher than it is in the somewhat

Mountains (crosses). (Data from southeast of Albuquerque from R. E. Smith, 1957; numbered samples listed in Table 7; other data from files of U.S. Geological Survey.)

D. Composition of mixed waters in southwestern Jemez Mountains, in carbonate rock (open circles) and in alluvium (solid circles). Shaded patterns show approximate distribution fields in Figure 2C; the mineral water, right field, is itself a mixed water. (Numbered samples listed in table 1; other data from files of U.S. Geological Survey.)

E. Composition of selected thermal waters from the Rio Grande rift outside the Jemez Mountains. (Sample numbers as in Table 1.)

older ash-flow tuffs that rest on old sedimentary rocks outside the caldera. These thermal waters have not evolved chemically in the way thermal waters in geyser regions (Fig. 2B) appear to have done. Such a chemical distinction between thermal waters of different provenance and history should be useful in geothermal exploration.

(3) Points near the right vertex of the diagram represent mineral waters, largely thermal, from San Diego Canyon. The points are farther from the vertex and lower right side of the diagram than the examples in Figure 2B because the Jemez Water has flowed through carbonate rock and contains somewhat greater proportions of calcium and bicarbonate, and correspondingly lesser proportions of sodium and chloride, than would be expected in water from deep-lying and hot igneous rocks.

The diagrams in Figure 2 show the composition but not the concentration of dissolved solids in the waters. Average concentrations of dissolved solids for the samples shown in Figure 2C are approximately as follows: water in carbonate rocks, 350 mg/l (milligrams per litre); dilute water in volcanic rocks, 200 mg/l; and mineral water, 6,500 mg/l.

## MIXED WATERS

Water in alluvium along the Jemez River is derived principally from dilute ground water in volcanic rocks, but many points representing samples of water from the alluvium (Fig. 2D) fall outside the field typical of dilute water in the volcanic rocks (Fig. 2C). The reason for this atypical composition is clear: this water occurs down-canyon from mineral springs in the canyon floor, and the water is a mixture of local ground water and of mineral water from the springs and probably from faults beneath the alluvium. The points representing this mixed water in Figure 2D lie between the field for dilute water in volcanic rocks and the field for mineral water in San Diego Canyon.

Ground water in carbonate rock in San Diego Canyon has a high concentration of calcium and bicarbonate, but it also contains unexpected proportions of sodium and chloride. Points representing these samples (Fig. 2D) fall outside the field typical of water in carbonate rocks and lie between that field and the field for mineral water. This intermediate position suggests that these waters are also mixed.

Ground-water samples from San Diego Canyon include many that appear, on the basis of major-ion composition, to be mixtures of dilute and mineral waters. Mixing of the thermal and dilute non-thermal ground waters is evidently widespread in this part of the marginal fault zone of the rift.

Further examination of mixing of the waters is desirable. Most of the springs in San Diego Canyon that yield mixed waters have low rates of discharge, and use of a mixing model described by Fournier and Truesdell (1974) is not promising. However, enough data are available to permit investigation of the mixing by calculating the volumes of original mineral water and dilute water required to provide the resultant waters collected at springs and wells in San Diego Canyon. Four constituents—lithium, chloride, bromide, and boron—were used for these calculations, and "standard" concentrations in the original mineral water were assumed on the basis of analyses of water samples from a deep well drilled in the Jemez Mountains by the Los Alamos Scientific Laboratory (LASL) of the University of California. LASL test hole GT-2, a short distance outside Valles Caldera and west of the head of San Diego

Canyon (Fig. 1, Sample Site 2), penetrated water-bearing zones in carbonate rock of the Magdalena Group and in the upper part of the underlying Precambrian granitic rock. Water samples collected during the drilling appear to have been affected by reaction of native water with drilling fluid or grout, but three samples from the granitic rock (Table 1) contain fairly consistent concentrations of the constituents used in this study, and these concentrations are believed to be representative of the native water. The following concentrations of these constituents, in milligrams per litre, were assumed for the calculations: lithium, 20; chloride, 3,000; bromide, 15; and boron, 25. The 3,000-mg/l chloride value was selected because one thermal water outside the caldera (water from "Warm Spring," near San Ysidro; Trainer, 1974, table 1, sample 11), which may have come from Valles Caldera, contains about 3,000 mg/l chloride. The other concentrations were selected arbitrarily from study of data for samples 2, 3 and 4 in Table 1.

Calculations were made by using a simple equation:  $(vol_{min})(conc_{min}) + (vol_{dil})(conc_{dil}) = (vol_{min} + vol_{dil})(conc_{mix})$ , in which *vol* is volume, *conc* is concentration of a selected constituent, and subscripts are *min* for mineral water, *di* for dilute water, and *mix* for mixed water. The dilute water probably enters the ground by infiltration through the bed of Jemez River and San Antonio Creek (Fig. 1). A check analysis of water in Jemez River in San Diego Canyon above the major mineral springs, during base runoff, showed 6 mg/l chloride and 0.1 mg/l each, or less, lithium, bromide, and boron. These concentrations are so small, relative to those in the mineral water, that they can be neglected in an approximate calculation. If, in addition, we assume a unit volume of mineral water, the foregoing equation can be rewritten

$$conc_{min} conc_{mix} + (vol_{dil})(conc_{mix}), \text{ or}$$

$$vol_{dil} \sim \frac{conc_{min} - conc_{mix}}{conc_{mix}}$$

The apparent dilution factors listed in Table 2 were calculated using this relationship and data in Table 1. The computed values are reasonably consistent for each sample site tested. They suggest that sample 8 results from the mixing of one part of original mineral water and about one part of dilute water, and that samples 9 and 11 require about two parts of dilute water. The computed values for sample 7 suggest mixing with about 10 parts of dilute water, and values for sample 10 suggest mixing with a much larger proportion of dilute water, perhaps as much as 60 parts.

The four values computed for each sample are not averaged in the foregoing discussion, and the apparent dilution factor for each sample is treated as an estimate, because of possible differences in the effectiveness of the four constituents as indicators of dilution. For example, errors in analysis for chloride should be much smaller than those in analysis for bromide. Lithium may substitute for sodium in some reactions. The four values determined may therefore not be of comparable precision.

This wide range in mixing proportions is believed to represent considerable differences in the nature of the aquifer: samples such as 8, 9, and 11 are evidently from principal fractures in the main fault zone, whereas the more dilute mixtures

Table 1. Concentration of selected ions, and ion ratios, in thermal waters  
(concentration in milligrams per litre, ratio by weight).  
Locations of sample sites shown by numbers on Figure 1.

Sample Number	1	2	3	4	5	6	7	8	9
Date of Collection	5-16-73	4-3-74	5-3-74	5-14-74	8-14-73	12-1-72	10-24-73	12-1-72	12-2-72
Sodium (Na)	23	---	---	---	170	55	570	990	640
Lithium (Li)	0.04 <sup>1</sup>	25	15	12	0.14	0.69	2.1	13	8.7
Chloride (Cl)	2.3	3,500	2,600	1,800	5.5	12	300	1,500	920
Bromide (Br)	.06	16	14	8.3	.06	.08	1.1	6.9	4.0
Boron (B)	.03 <sup>1</sup>	25	26	15	.64	.07	2.4	12.5	7.4
Li/Na . . .	.0017	---	---	---	.0008	.0126	.0037	.0131	.0136
Br/Cl . . .	.0261	.0046	.0054	.0046	.0109	.0067	.0037	.0046	.0043
B/Cl . . .	.0130	.0071	.0100	.0100	.1164	.0058	.0080	.0083	.0080

Sample Number	10	11	12	13	14	15	16	17	18
Date of Collection	8-21-73	8-30-73	12-3-74	12-3-74	12-3-74	12-4-74	12-4-74	12-4-74	12-4-74
Sodium (Na)	190	1,300	150	130	890	57	740	300	1,100
Lithium (Li)	0.43	6.7	0.25	0.29	3.3	0.06	1.1	0.31	0.1
Chloride (Cl)	49	1,200	92	56	270	16	1,400	170	1,600
Bromide (Br)	.2	5.0	.7	.5	1.4	.5	1.9	.5	2.8
Boron (B)	.38	8.2	.5	.27	1.5	.09	.3	.33	.78
Li/Na . . .	.0023	.0052	.0017	.0022	.0037	.0010	.0015	.0010	.0010
Br/Cl . . .	.0041	.0042	.0076	.0089	.0052	.0312	.0014	.0029	.0018
B/Cl . . .	.0078	.0068	.0054	.0048	.0056	.0056	.0002	.0019	.0005

<sup>1</sup> Sample collected 2-22-74

Name or location, and water-bearing rock:

*JEMEZ MOUNTAINS*

1. San Antonio Hot Spring; Valles Rhyolite.
2. Los Alamos Scientific Laboratory, well GT-2, total depth 3,530 ft; Precambrian granitic rock.
3. Los Alamos Scientific Laboratory, well GT-2, total depth 3,557 ft; Precambrian granitic rock.
4. Los Alamos Scientific Laboratory, well GT-2, total depth 3,727 ft; Precambrian granitic rock.
5. Well near La Cueva; probably Valles Rhyolite.
6. Spence Spring; Valles Rhyolite.
7. U.S. Geological Survey test well, San Diego Canyon; limestone in Magdalena Group.
8. Spring at Soda Dam; limestone in Magdalena Group.
9. Spring at Jemez Springs; probably limestone in Magdalena Group, beneath alluvium.

10. Spring near mouth of Rio Guadalupe; probably limestone in Magdalena Group, but water issues from fractured granite.
11. Indian Spring; probably limestone in Magdalena Group, beneath alluvium.

*Elsewhere in Rio Grande rift zone*

12. Ponce de Leon Hot Spring, Taos County; granodiorite.
13. Manby Hot Spring, Taos County; basalt.
14. Ojo Caliente ("Iron Spring"), Rio Arriba County; basalt (?).
15. Well in Blue Canyon, Socorro County; rhyolite.
16. Spring at Yucca Lodge, Truth or Consequences, Sierra County; limestone in Magdalena Group, beneath alluvium.
17. Derry Warm Spring, Sierra County; limestone.
18. Well at Radium Hot Springs, Dona Ana County; rhyolite.

represented by samples 7 and 10 must be from subsidiary fractures that are less well connected, hydraulically, with the main fault zone. Examination of the map (Fig. 1) in light of this interpretation shows that the marginal fault zone must

provide some conduits through which the mineral water can flow rather directly for considerable distances—sample 11 was collected about 20 mi outside the caldera. Other conduits, perhaps both circuitous and small, permit much greater dispersion and dilution of the mineral water as it mixes with the dilute ground water. The extent of the belt within which mixing occurs is not known in detail because relatively few water samples are available, but on the basis of the fault pattern (Fig. 1) it may be several miles wide at some places along the canyon.

Two lines of evidence are now available with respect to derivation of the thermal water from a reservoir in Valles Caldera. (1) The chemical character of the thermal-spring water in San Diego Canyon, a fault-controlled canyon that heads in the caldera, indicates that part of the water is probably derived from such a reservoir (Trainer, 1974, p. 343). (2) Water found in LASL test well GT-2 is believed to have come from within the caldera because the water contains minor constituents typical of thermal waters in volcanic rocks and because the silica concentration of the water indicates a temperature considerably higher than that of the rock from which the sample was collected. The water sample collected when the hole was 3,557 ft deep contained 170 mg/l SiO<sub>2</sub>. On the assumptions

Table 2. Calculated dilution factors for selected mineral waters in the southwestern Jemez Mountains.

Factor given is quantity of nonthermal ground water believed to have mixed with one part of deep thermal ground water to yield observed water.

See Table 1 for data and text for discussion.

Sample numbers as in Table 1.

Sample Number	7	8	9	10	11
Brief Name	Test well, limestone	Soda Dam	Jemez Springs	Spring, limestone-granite	Indian Spring
Dilution Factor, from:					
Lithium	8.5	0.5	1.3	46	2.0
Chloride	9.0	1.0	2.3	60	1.5
Bromide	12.6	1.2	2.8	74	2.0
Boron	9.4	1.0	2.4	65	2.0

that the silica was derived entirely from quartz and that it had not been increased by the escape of steam, a concentration of 170 mg/l indicates that at equilibrium with quartz the water was at a minimum temperature of about 169 °C (Fournier and Rowe, 1966, Fig. 5, p. 694). On the basis of temperature-gradient and other data from hole GT-2 (Pettit, 1975, p. 18 and Appendix A) the rock temperature at 3,557 ft is computed to have been about 90 °C. The well data show that the water at and above 3,557 ft must be moving principally laterally; under this condition the only likely source of the heat indicated by the higher water temperature is the caldera east of the well (Fig. 1). Surface-geophysical studies (Jiracek, 1975) have revealed a belt of low resistivity in what is probably part of the ring-fracture zone, inside the caldera near well GT-2. This segment of the ring-fracture zone, apparently not occupied by younger igneous rock, is probably a conduit for the flow of hot mineralized water.

Two conclusions are derived from the foregoing discussions of the source and flow pattern of the thermal water. (1) Along some flow paths a dissolved load of volcanic-derived constituents, including several (for example, arsenic, fluoride and perhaps boron) that could affect downstream uses of the water, is carried far from the center of the volcanic region before it is dispersed in other ground water or released to streams. The quantity of this dissolved material and its disposition beyond the Jemez Mountains region, at the surface and in the subsurface, require further study. (2) Dilution of thermal water from Valles Caldera by equal or greater amounts of shallow ground water results in marked decrease in the temperature of the thermal water during its migration, in addition to that due to heat loss by conduction through wall rock, and this consideration suggests that only under very favorable conditions is water hot enough for geothermal-power development through processes now in general use likely to occur outside the caldera.

### THERMAL WATERS ELSEWHERE IN THE RIO GRANDE RIFT

A brief study was made of the chemical composition of selected thermal waters from the Rio Grande rift in New Mexico outside the Jemez Mountains. The major-ion composition of these waters (Fig. 2E) is of interest in light of the foregoing discussion because it suggests that most of them are not in equilibrium with the near-surface rocks. Many investigators have shown that geothermal waters for which adequate isotopic data are available are almost entirely of meteoric origin. If this is true of the thermal waters in the Rio Grande rift, these waters have undergone substantial change in chemical composition since entering the ground. In an area where chemical data are available for the shallow ground water up-gradient from thermal springs, in likely recharge areas for the thermal aquifer, it may be possible to show to what extent the composition of the thermal water differs from that of the shallow ground water, and hence to what degree the thermal water may have evolved under high temperature and pressure. Figure 2E justifies the initial working hypothesis that most of these thermal waters have so evolved, through direct heating or by the addition of steam carrying igneous-derived material.

Several factors may contribute to the dispersion of points in Figure 2E. It would be surprising if some of the waters, all but one of which are discharged from springs at relatively low

altitudes in their respective regions, were not mixtures of thermal water and shallow ground water. Samples 14 and 15 appear, from their proportions of the principal ions, to be most likely to have resulted from such mixing. A second explanation could lie in differences in the degree to which different waters have evolved toward an ideal sodium chloride composition. Third, some waters may simply be ordinary ground water that has been warmed through contact with hot rock in the subsurface. This may be a reasonable explanation for sample 15, which appears to have a dissolved-solids content of a few hundred milligrams per litre (figure not given in available analyses) and relatively low antecedent temperature (estimates are about 77 °C by the SiO<sub>2</sub> geothermometer and 55 °C by the Ca-Na-K geothermometer). It seems much less likely for sample 14, for which the corresponding values are about 1,250 mg/l, 113 °C, and 156 °C, respectively. Another possible explanation for sample 14 is the injection of high-density steam carrying minor constituents typical of volcanic water into dilute ground water. This explanation is consistent with the sodium bicarbonate composition of the water, which is typical of dilute water in igneous rock, and with its intermediate chloride concentration (270 mg/l). Further work could include study of the flow patterns and chemical character of shallow ground water near these thermal springs as a possible aid in resolution of these uncertainties.

Data on selected minor constituents in these thermal waters were compared with corresponding data from waters in the Jemez Mountains. Figure 3 summarizes this comparison using Li/Na, B/Cl, and Br/Cl, three of the ratios of constituents discussed by White, Hem, and Waring (1963). Omitting consideration of the dilute waters, for which White, Hem, and Waring (1963, Table 29, p. F59) found new data, we see that the magnitudes of the ratios shown in Figure 3 are consistent with median ratios for thermal waters. Of the ratios in Figure 3, B/Cl and Br/Cl appear likely to be most useful in distinguishing mineral and dilute waters in the Jemez Mountains.

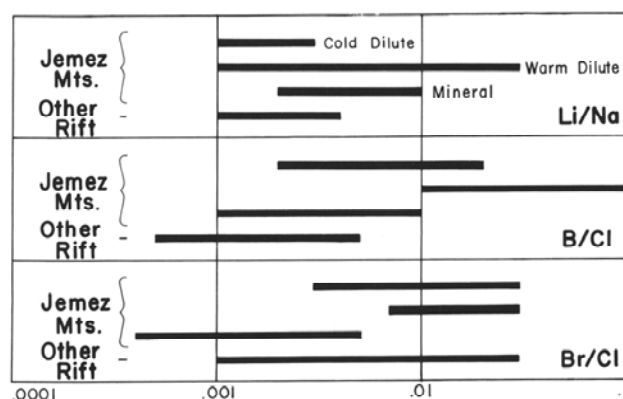


Figure 3. Diagram illustrating ranges of ratios of selected constituents in ground water from the southwestern Jemez Mountains and from seven thermal-water localities elsewhere in the Rio Grande rift in New Mexico.

The Jemez Mountains waters are cold dilute water in volcanic rocks, warm dilute water in volcanic rocks, and mineral water. Waters from elsewhere in the rift are not classified. (Data from Table 1 and, for Jemez Mountains, from files of U.S. Geological Survey. Sample sites from Rio Grande rift outside the Jemez Mountains identified in Table 1.)

Among the thermal waters elsewhere in the rift the range in value for each ratio overlaps the ranges for both dilute and mineral waters in the Jemez Mountains. This feature of the data can be reasonably explained as reflecting a wide range in the nature of mixing among thermal waters in the Rio Grande rift, but it may also be due to a greater diversity of host rocks in the rift generally than in the Jemez Mountains. Integration of minor-constituent studies of water with the hydrologic and hydrochemical investigations mentioned in the preceding paragraph, and with study of the geologic environment in each thermal-spring area, will be needed to evaluate the likely significance of mixing and dilution of the waters. As in the Jemez Mountains, the degree to which mixing of thermal and cold waters has occurred will have an important effect on the value of the thermal-water resource in other parts of the Rio Grande rift.

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