



## ***Thermal mineral springs in Canon de San Diego as a window into Valles caldera, New Mexico***

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# THERMAL MINERAL SPRINGS IN CANON DE SAN DIEGO AS A WINDOW INTO VALLES CALDERA, NEW MEXICO

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## INTRODUCTION

Two groups of mineral springs are among the best-known surficial thermal features in the Jemez Mountains. Detailed chemical data for the spring waters were first collected in 1912. Despite accumulation of considerable information since then, the springs remain puzzling features. The objective of this report is a re-examination of the springs as a basis for inference of geohydrologic conditions up-canyon, toward and into Valles caldera.

The complex pile of volcanic rock that forms the Jemez Mountains straddles the western marginal fault zone of the Rio Grande rift (Fig. 1). Pre-volcanic rocks—Precambrian crystalline rocks and Paleozoic and Mesozoic sedimentary rocks outside the rift, and Tertiary and Quaternary valley-fill deposits within it—are covered in most of the Jemez Mountains. Volcanism began in late Tertiary time and culminated, about 1.4 and 1.0 m.y. ago, in explosive eruptions that led to the successive formation of two calderas and two extensive tuff sheets. The subsequent history of the younger (Valles) caldera included formation of a resurgent structural dome and of a series of rhyolite domes in the ring-fracture zone (Smith and Bailey, 1968); fumarolic and hot-spring activity that has occurred during at least part of the post-caldera period continues at present.

Part of the main aquifer in Valles caldera is known to be a hot-water geothermal reservoir beneath the resurgent dome. Vapor-dominated conditions are present locally. The reservoir rocks are fractured tuff, sedimentary and crystalline rocks, and semi-consolidated valley-fill sediments. The geothermal water, dominated by Na and Cl, contains about 2,500 mg/L Cl. Temperatures are on the order of 260°C and higher

(Dondanville, 1978; Kerr, 1982). Recharge of the reservoir is believed to be by infiltration of meteoric water along fractures. Subsurface discharge from the reservoir is also controlled by fractures, and is largely through limestone beneath Canon de San Diego, the canyon which carries surface drainage from the caldera.

The two groups of thermal mineral springs are at Soda Dam and Jemez Springs (Fig. 1) in the canyon, about 5.8 and 7.5 km, respectively, outside the rim of the caldera. Summers (1976) described the history and the geographic setting of the springs and presented representative chemical data. Goff and Kron (1980) have recently mapped the geology near the springs and logged a geothermal well at Jemez Springs. At Soda Dam the springs flow from fractured rock where a fault contact between sedimentary and crystalline rocks is exposed in the canyon floor. Jemez Springs issue from alluvium, but alignment of the springs indicates control by faults in the underlying bedrock. Observations to date have shown large, consistent, and puzzling differences between the two spring waters.

## THE MINERAL WATERS

The waters at Soda Dam and Jemez Springs have Na and Cl as principal ions, high concentrations of Ca and HCO<sub>3</sub>, and minor constituents that include B, Br, and Li (Table 1 and Fig. 2). The ratios Li/Na and B/Cl are in the ranges described by White (1957, pp. 1669, 1671) as typical of thermal waters in volcanic terranes. The Soda Dam water is nearly twice as mineralized as that at Jemez Springs, but the latter water is markedly hotter—75°C as against 50°C. Both groups of springs emit H<sub>2</sub>S fumes.

Results of numerous studies show that the chemical character of these waters is unlikely to have formed under near-surface conditions. White and others (1963, p. F42) considered the water at Jemez Springs typical of thermal water from non-geyser areas associated with volcanism; Woltz (1972, pp. 42, 45-47) concluded from study of selected constituents that these waters, among others in the region, contain contributions from magmatic sources. After the discovery of subsurface geothermal conditions in Valles caldera in the 1960's during drilling for oil, the caldera was widely discussed as a possible source of the heat and mineral constituents in the spring waters. Dondanville (1971, p. 15) noted the similarity between geothermal fluid and the mineral water in Canon de San Diego, although the relationship of the sample he cited to fluid in the main part of the reservoir as it has later become known has not been established. Trainer (1974) concluded that ion ratios in the spring waters are consistent with derivation from Valles caldera and (1975) suggested that mixing of geothermal and dilute ground waters could explain the mineral-spring waters. Trainer and Lyford (1979) and Goff and others (1981) used chloride-variation diagrams to show possible relationships between water types. Goff and others (1981, fig. 6) were the first to include data from the geothermal reservoir in their plots, and their diagrams provide the most convincing argument published to date for a caldera provenance for the mineral waters. New data from the reservoir (White and others, this volume; and BACA 4, Table 1 and Figs. 2, 3) make the case for a caldera source for the mineral waters even more convincing.

The mixing hypothesis assumes that geothermal fluids flow out of the caldera through the subsurface and mix with dilute ground water along discrete flow paths. So long as the dilute component of the mixture provides little or none of the diagnostic constituents, the ratios of those

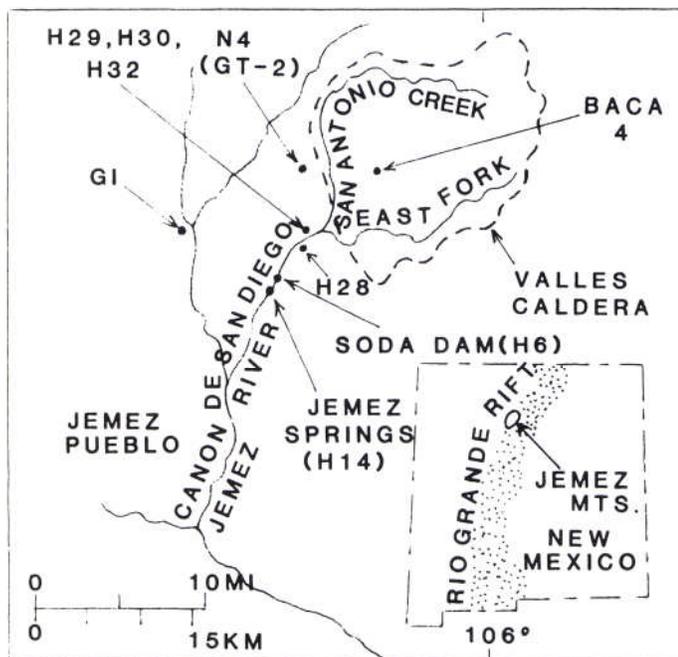


FIGURE 1. Map showing locations of features described; inset shows location of Jemez Mountains relative to Rio Grande rift.

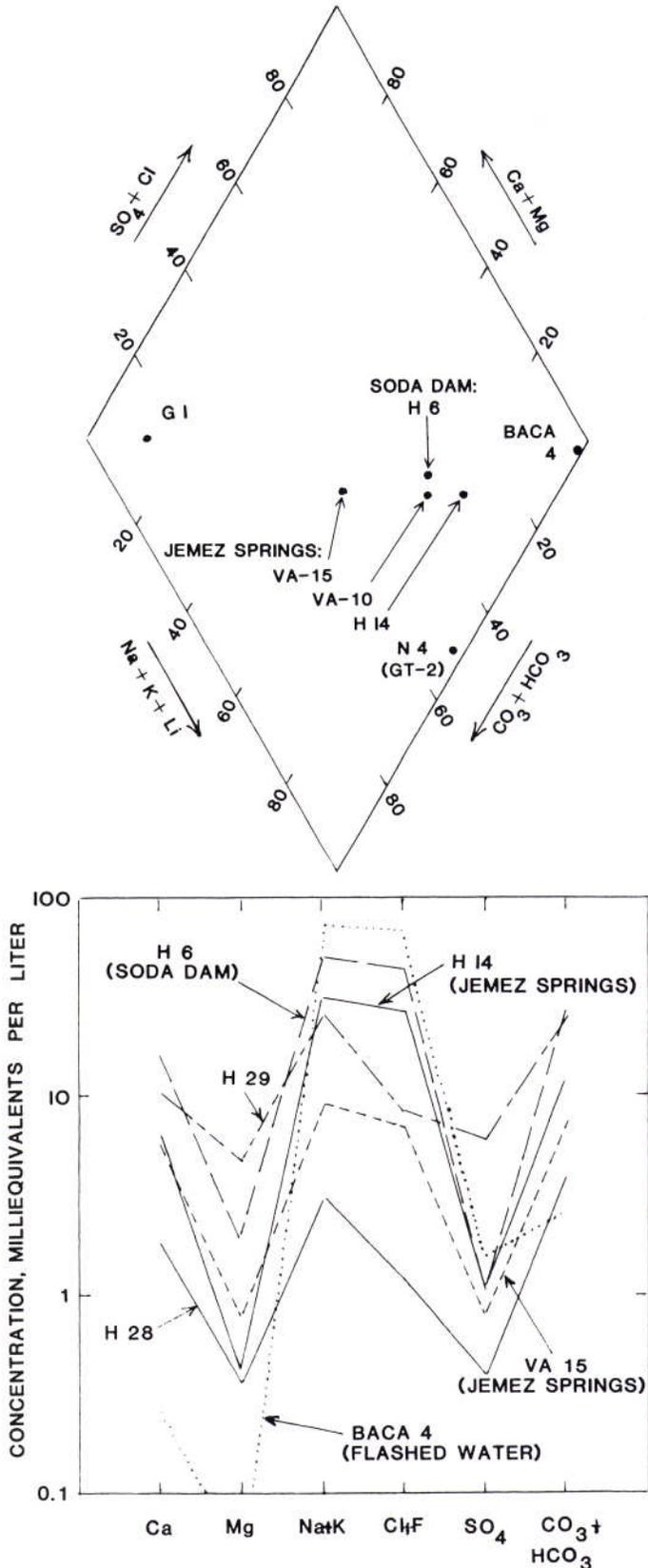


FIGURE 2. Chemical diagrams for waters. *Diamond field of Hill-Piper diagram* shows composition of geothermal and dilute waters, and of mixed waters at Soda Dam (H 6) and Jemez Springs (H 14, H 17, VA-15); analyses in Table 1 except VA-15 ("500-foot aquifer") from Goff and others (1981), and H 17 (78-foot well in Jemez Springs) from Trainer (1978). See Figure 1 for locations. *Schoeller (semilogarithmic) diagram* shows composition of waters and concentration of major constituents.

the linear relationship in the variation diagram (Fig. 3). The inferred course of change in composition is illustrated by the diamond diagram in Figure 2. Geothermal water from near the right (Na—Cl) vertex, on mixing with water in limestone (similar to G 1, near the CaCO<sub>3</sub> vertex) and with water from tuff or granitic rock (points for which fall near the southwest edge of the diamond), attains a composition similar to that of H 6 (Soda Dam), or of H 14 or VA-10 (Jemez Springs). Goff and others (1981, fig. 6) further illustrated a mixing line for samples from several springs at Jemez Springs which is represented in the diamond diagram by the shift from H 14 and VA-10 to VA-15. This further mixing appears to have occurred in the limestone near the springs, through dilution of mineral water by limestone water similar to G 1. (Data for VA-10 and VA-15, not given in Table 1, are from Goff and others, 1981, p. 234.) Even with all these changes, however, the NaCl composition of the geothermal water is preserved (see logarithmic plots in Figure 2).

The original mixing calculations were made with a simple mass-balance equation, assuming the geothermal water to be like sample N 4 (Table I) from well GT-2 of the Los Alamos National Laboratory (Fig. 1); samples from the caldera were not then available. Recalculated mixing proportions based on average concentrations of Cl, Li, and B in analyses of geothermal fluid (White and others, this volume; and BACA 4, Table 1), taken as the parent water, are presented in Table 1.

A second plot by Goff and others (1981, fig. 4), based on stable-isotope data, reinforces the interpretation of mixing. Their isotopic line is replotted in Figure 4 as the continuous line through H 14 and H 15.

The isotopic data can be used to test the dilution factors in Table 1. Trainer and Lyford (1979) did this by assuming the parent geothermal fluid for the mineral water to be like sample N 4. In terms of Figure 4 the method is based on the argument that water H 6 has an isotopic composition determined by the combination of fractions having the isotopic compositions of N 4 and of the intercept on the meteoric-water line of the dashed line through N 4 and H 6. These fractions, from Table I, are 1.0 part from N 4 and either 0.4 part or 0.8 part meteoric water (depending on whether data for flashed geothermal water or for water plus steam are used in calculation of the dilution factor).

Figure 4 shows the results of this test. The dilution factor based on flashed water gives a closer approximation of the observed value than

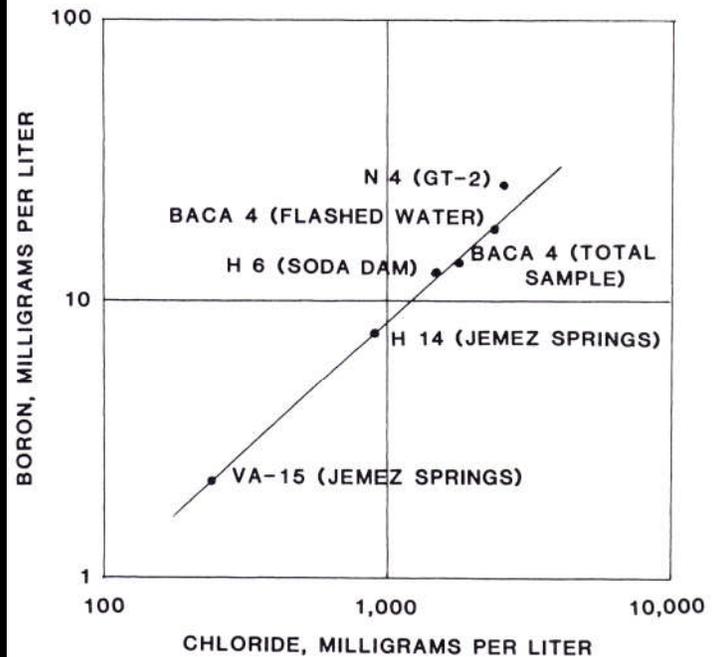


FIGURE 3. Covariation diagram for boron and chloride. Analyses in Table 1 except VA-15 (Goff and others, 1981).

constituents remain constant over a wide range of concentrations; hence

TABLE 1. Chemical analyses, isotopic data, and calculated dilution factors for selected ground-water samples collected in and near Cañon de San Diego<sup>0</sup>. Concentration of constituents in milligrams per liter, specific conductance in micromhos per centimeter at 25°C, isotopes in per mil. Lesser dilution factor calculated from total sample of geothermal fluid, greater factor from flashed liquid; see text for discussion. Indicator constituents for dilution factor: Cl, 2,800 and 2,200 mg/L; Li, 23 and 18 mg/L; B, 23 and 28 mg/L. See Figure 1 for locations of sampled wells and springs.

Sample Number.....	Well BACA 4 <sup>1</sup>		N 4 (GT-2)	G 1	H 6	H 14	H 28	H 29	H 30	H 32
	(water)	(steam)								
Date of collection.	8-22-73		5-3-74	10-30-73	12-1-72	12-2-72	7-18-74	10-24-73	3-21-73	1-17-73
Silica (SiO <sub>2</sub> ).....	760	0.3	170	16	50	95 <sup>3</sup>	87	37	37	45
Calcium (Ca).....	5	.6	7.3	100	330	130	38	210	130	140
Magnesium (Mg).....	0.6	.4	13	11	24	4.8	4.4	59	25	13
Sodium (Na).....	1,500	1	4,800	14	990	640	70	570	100	390
Potassium (K).....	300	.4	180	5.8	200	82	5.5	34	11	51
Lithium (Li).....	22		15	0.06	13	8.7	0.56	2.1	0.69	3.6 <sup>4</sup>
Bicarbonate (HCO <sub>3</sub> ).....	196	6	6,770	376	1,578	732	254	1,611	660	761
Carbonate (CO <sub>3</sub> ).....	0	0	0	0	0	1.5	0	0	0	0
Sulfate (SO <sub>4</sub> ).....	74	3	1,600	21	52	53	18	250	32	32
Chloride (Cl).....	2,500	1	2,600	1.3	1,500	920	40	300	61	470
Fluoride (F).....	7.1	.0	16	.3	3.3	4.8	1.4	1.6	1.0	4.6
Boron (B).....	18		26	.06	12.5	7.4	.37	2.4	.51	3.3
Dissolved solids...	5,080	10	9,380	365	3,740	3,500	393	2,260	728	1,520
Specific con- ductance.....	8,000	50	14,200	640	6,160	3,930	540	3,200	1,100	2,200
pH.....	6.8	4.5	7.7	7.3	6.1	6.3	7.3	6.5	6.8	6.7
D.....			-78.9 <sup>2</sup>		-84.8	-82.1				
<sup>18</sup> O.....			- 8.12 <sup>2</sup>		-10.40	-10.52				
Dilution factor, from chloride....					0.5, 0.9	1.4, 2.0	54,69	6.3, 8.3	35, 45	3.7, 5.0
from lithium....					.4 .8	1.1, 1.6	29,37	7.6, 10	25, 32	4.0, 5.4
from boron.....					.4 .8	1.4, 2.1	44,56	6.5, 8.6	35, 45	25, 32
average.....					.4 .8	1.3, 1.9	42,54	7, 9	32, 41	11, 14

<sup>0</sup> Analyses by U.S. Geological Survey.  
<sup>1</sup> 25 percent of total flow flashed to stream.  
<sup>2</sup> Sample collected 4-23-74.  
<sup>3</sup> Sample collected 1-25-74.  
<sup>4</sup> Sample collected 3-4-74.

does the factor based on geothermal water plus steam. Interestingly, and perhaps significantly, the original calculation in which the dilution factor was based on data from well N 4 produced a still better fit. These observations suggest that the fluid that flows out of the reservoir is of composition and concentration broadly similar to the samples now available from the reservoir but modified by boiling. The dilution factors in Table 1 appear to be of the correct general magnitudes.

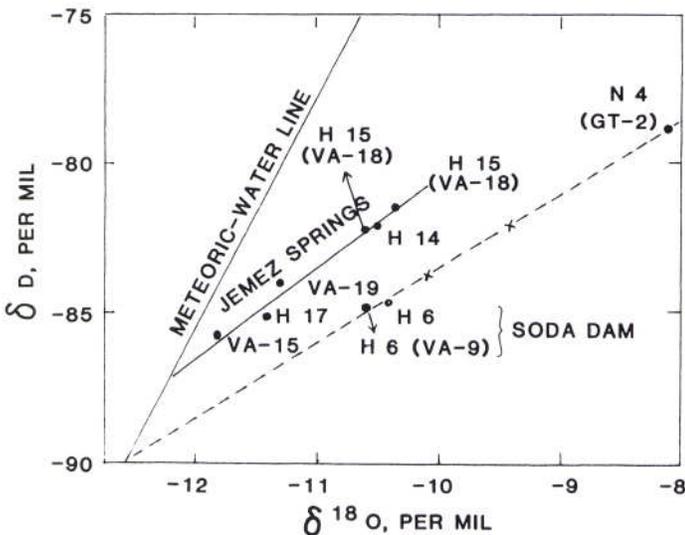


FIGURE 4. Plot of deuterium-oxygen-18 values for thermal mineral waters at Soda Dam, Jemez Springs, and well N 4 (GT-2); data in Table 1 except VA samples (Goff and others, 1981) and H 17 (Trainer, 1978). Also shown (x) are constructed positions of isotopic values for Soda Dam sample (H 6), calculated from calculated mixing proportions for water H 6 (Table 1) and from D, <sup>18</sup>O data for N 4 and for intercept of dashed line on meteoric-water line. See text for discussion.

Composition of the mineral waters has remained rather stable over time, but concentration of constituents has fluctuated. Figure 5A illustrates fluctuation in Cl and HCO<sub>3</sub> in one spring at Jemez Springs over a period of nearly a year. This record is too short and too fragmentary to suggest more than an orderly change in concentration.

In a second approach all available analyses for Cl were tabulated by month of sampling to determine whether fluctuations in concentration of Cl could be found within the year. Thirty-four analyses were available from springs H 14 and H 17 (VA-10 in Figure 2) at Jemez Springs, 58 analyses for Soda Dam. Two disadvantages were recognized in this procedure: (1) only one analysis was available for each of several months (none for one month at Soda Dam), and (2) if change in concentration occurred as a result of some seasonal effect, changes in timing of the seasons from one year to another could lead to poor definition of the change in concentration. In an attempt to address these two difficulties, the data were summarized as median values for successive two-month periods (December—January, January—February, etc.) to obtain 12 values for the year. Sizes of the two-month samples ranged from three to 10 analyses for Jemez Springs and from three to 18 analyses for Soda Dam. The two-month running median values are shown in Figure 5B.

Periods of relatively high concentration in the plots in Figure 5B, as in November—January, can be explained as representing times of higher discharge from the geothermal reservoir, lesser dilution of the thermal-mineral water, or both; and periods of low concentration, as in late spring (at Soda Dam) and in early autumn, can be explained as times of low flow from the reservoir, greater dilution, or both. Our knowledge of the geothermal reservoir is inadequate to support informed speculation about fluctuation in discharge; but fluctuation in head is typical of shallow aquifers, and the following discussion is based on the assumption that the troughs in the Cl hydrographs represent annual episodes of ground-water recharge, increase in ground-water head, and increase in the flow of dilute water into the conduits that contain the thermal-mineral water.

The principal "event" which leads to recharge of shallow aquifers in this region is melting of the snow cover during February—June (but

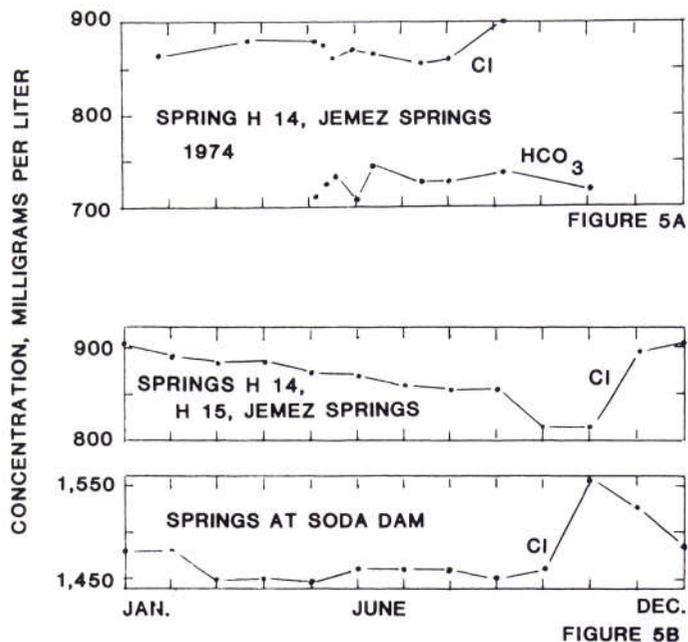


FIGURE 5. Chemical plots for mineral waters at Soda Dam and Jemez Springs. **A**, Concentration of Cl and HCO<sub>3</sub>, spring H 14, Jemez Springs, 1974; data from Trainer (1978). **B**, Summary hydrographs of Cl concentration, Jemez Springs (H 14, H 15) and Soda Dam, based on two-month running median values for all available data. Data from Goff and Sayer (1980); Goff and others (1981); Purtymun and others (1974, 1975, 1976, 1978a, 1978b, 1981); Summers (1976); Trainer (1978); and files of the U.S. Geological Survey.

during a shorter period within that range, in a particular year). Given its presence in both hydrographs, the low concentration of Cl in the autumn is reasonably correlated with recharge and dilution following melting of the snow cover. A lesser pulse of ground-water recharge and dilution may occur during the late-summer thundershower season, and the writer correlates the spring trough at Soda Dam with the episode of rain.

The suggested correlations indicate lag times of five to six months which represent, in this hypothesis, the time required for mass transport of diluted mineral water from the sites of mixing to the springs. The geohydrologic setting of aquifer recharge is considered in a later section of this report, but comments concerning residence time of the shallow ground water and lag time for flow in the conduits should be added here.

Tritium data provide a basis for examination of likely residence time. The concentration of tritium in precipitation had not been determined before fusion testing during 1952-63 produced large quantities of artificial tritium that mask the natural concentration in the atmosphere. Thatcher (1962, p. 48) concluded that in the continental-interior region of the United States this natural concentration was about 8-10 TU (tritium units, 1 atom <sup>3</sup>H-1 in 10<sup>10</sup> atoms H). Because tritium has a half-life of 12.26 years, it can be used to investigate the residence time of ground water where that time is short enough for measurable tritium to remain, but long enough to predate artificial tritium.

In 1973 the mineral water at Jemez Springs (spring H 14) contained 6.4±0.6 TU, and that at Soda Dam (H 6) 4.0±0.4 TU (Trainer, 1978, p. 127). These values are thought to be of the correct relative magnitude because Jemez Springs water contains the larger component of dilute (presumably young) water.

Samples from deep wells in Valles caldera contained less than 1 TU in 1982 (A. F. White, pers. comm. 1984). If the Jemez Springs mineral water is assumed to contain 1.0 volume of geothermal water and 1.6 volumes of dilute water, and if the geothermal water is assumed to have contained no measurable tritium by the time it reached the mixing sites, then by calculation the tritium content of the dilute-water component was about 10 TU in 1973. By working back in time using the half-life

of 12.26 years we find that the dilute water could have contained about 20 TU in 1960 and 40 TU in 1948. The 40-TU estimate is invalid if atmospheric concentration was on the order of 10 TU before fusion testing. The 20-TU estimate is credible if the water entered the ground early in the period of testing, before atmospheric tritium levels had reached more than about three times the prior natural level. Hence, the dilute-water component of the Jemez Springs water is thought to have entered the ground in 1952 or 1953, giving a residence time for the shallow ground water of about 20 years. According to the interpretation presented in this report, water from the shallow aquifer entered a geothermal-water conduit, near the end of the 20-year residence time, and mixed with the thermal-mineral water.

Similar calculation yields a 9-TU value for the dilute-water component of the Soda Dam mineral water. Considering the degree of uncertainty inherent in the dilution factors used in the calculations, this value does not differ from that calculated for the Jemez Springs water.

Lag time between mixing of waters and discharge from the springs is inferred to be five to six months. So far as interpretation of the hydrographs can show, this lag time could as well be another period, one or more years longer than five to six months (that is, 17-18 months, or 29-30 months, for example). Later discussion notes that the limestone conduits under Cation de San Diego probably are cavernous, and in such a setting the half-year flow time is believed to be more realistic than longer estimates.

Differences in the plots for Jemez Springs and Soda Dam in Figure 5B may be apparent rather than real. However, three types of evidence already mentioned are consistent with the conclusion that the two groups of springs drain conduit systems that are isolated from one another. These are: (1) the consistent differences in concentration of dissolved solids in the two spring waters; (2) the interrelations of D and  $\mu$ ; and (3) the inverse relationship between mineralization and water temperature. If the conduit systems are isolated, the differences in Figure 5B may be real.

## SPRING DISCHARGE

Measurement of Cl and water discharged by the groups of mineral springs is another approach to characterization of the conduit systems. Figure 6 summarizes these measurements in terms of Cl load in the Jemez River. The lowest hydrograph is for the river at a gaging station of the U.S. Geological Survey just outside the rim of Valles caldera. There Cl load is adequately explained by contributions from precipitation and from small mixed-water springs in upper Cation de San Diego (data in Trainer, 1978). Because very little Cl is added to Jemez River between the gaging station and Soda Dam, this hydrograph can be taken as background against which to judge Cl discharge of the mineral springs. The hydrographs are arranged from bottom to top in downstream order; the numerical difference between the lower pair of graphs is Cl discharge of the Soda Dam springs, and the difference between the upper pair is Cl discharge of Jemez Springs. The mineral springs discharge quantities of Cl substantially above background.

The most striking aspect of these hydrographs is their peakedness. Peaks in all the curves occur during streamflow peaks, notably during the melt-water flood in spring. This observation is expectable at the gaging station but surprising with respect to the mineral springs. Reference to the Cl curve in Figure 5A shows that these conspicuous peaks are not due in an appreciable way to change in Cl concentration in the mineral water.

Increase in Cl discharge of the springs during surface-water floods is accompanied by corresponding increase in springflow (not shown in Figure 6; data given in Trainer, 1978). The rapid transmission of head change in the mineral-water system necessary to explain such an increase in springflow is believed to have been by means of pressure waves in confined conduits, which account for the near-synchronism of cause and effect. Three explanations for such pressure waves can be considered: (1) changes of head in the reservoir, (2) repetitive external loading and unloading of the conduits by flood water in the canyon, and (3) fluctuations of head in the conduits, transmitted to them by diluting water at sites of mixing.

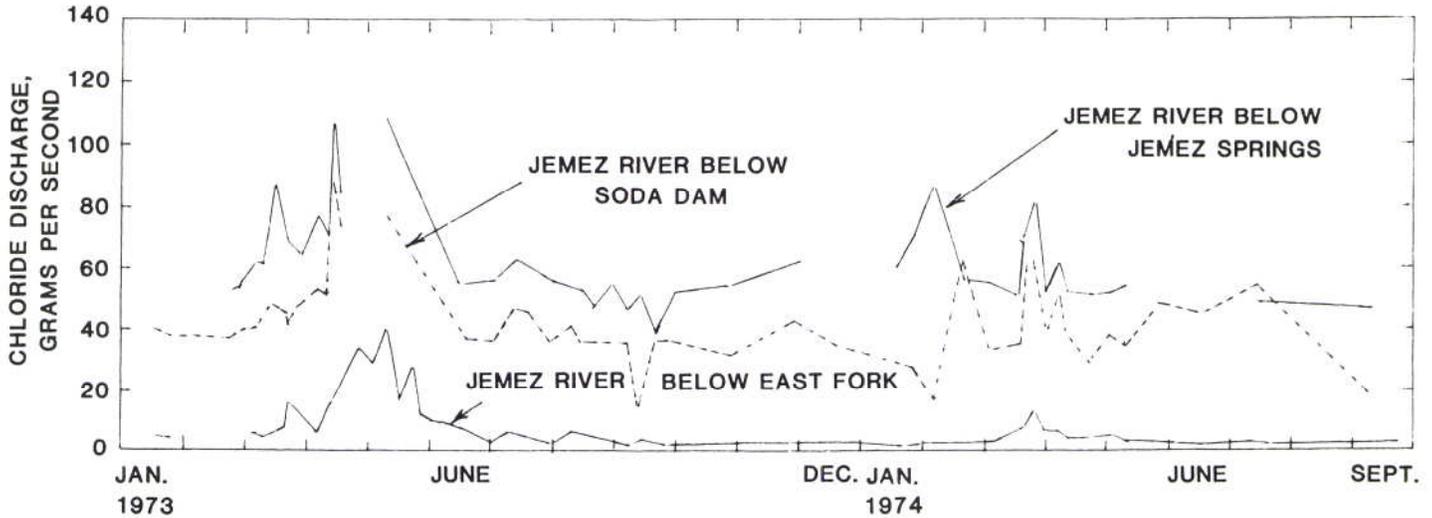


FIGURE 6. Chloride discharge at three stations on the Jemez River, 1973-74. See text for discussion.

The first hypothesis would explain increase in geothermal reservoir head and flood wave in the stream as due to the same episode of snow melt or to the same rain storm(s). Near-synchronism of flood wave and springflow peak would require almost instantaneous recharging of the reservoir. By any reasonable estimate the time required for water to percolate from the land surface to the reservoir would be many years. The tritium concentrations of less than 1 TU in deep water in Valles caldera suggest a travel time of 30 years or more.

Repetitive loading and unloading of confined aquifers by effects at the land surface is a widely recognized phenomenon capable of causing pressure waves that are practically synchronous with the loading and unloading. Such a process would accelerate the discharge of water already in the conduits near the springs but would not affect its dissolved load. Hence it does not account for even the small fluctuations in water chemistry noted earlier. Moreover, the most conspicuous transient loading effects in near-surface confined aquifers are caused by rather heavy and very localized loads such as railroad trains. In the local instance, loading is unlikely to amount to more than a meter or two of water on the canyon floor, believed to be more than 300 m above the confined conduit. For these reasons loading is thought to provide only part of the explanation of the springflow peaks, if that.

The third hypothesis, which explains the pressure pulse through temporary increase in head transmitted to the conduits at the sites of mixing, is believed to provide an adequate explanation for the observations. As noted in the last section, recharge is thought to occur where shallow aquifers receive infiltration from the stream, so that substantial increases in both recharge and ground-water head are highly seasonal.

In summary, near-coincidence of peaks in streamflow and springflow is seen as a transient pressure effect caused by pulses of recharge to the conduits. The fluctuations in water chemistry described earlier, on the other hand, are transport phenomena whose effect is seen months after the causative pulses of recharge and dilution.

Geothermal water discharged by the mineral springs at Soda Dam and Jemez Springs is one component of the fluid discharged from the caldera and traveling down Cation de San Diego. Discharge of geothermal fluid down the upper canyon is believed to be almost entirely by flow in subsurface conduits. Beginning at Soda Dam, two additional flow components come into play: surface-water transport, and transport in ground water flowing through the canyon-floor alluvium. Geothermal water and solutes enter the river chiefly by springflow into the stream, largely at Soda Dam, Jemez Springs, and Jemez Pueblo (Fig. 1). Two mineral springs at the Pueblo show that conduit flow continues at least that far down the canyon, some 32 km outside the caldera as measured along major faults (Trainer, 1975). Some conduit flow very likely continues past the sites of leakage and discharges mineral water into the valley-fill aquifer in the Rio Grande rift. Geothermal water and solutes

reach the alluvium by discharge directly from the bedrock and by infiltration from losing reaches of the river. Flow through the alluvium near Soda Dam and Jemez Springs is limited by the small cross section of the deposit in the narrow canyon floor. At Jemez Pueblo, where the canyon floor is wider and the alluvium may be thicker, ground water flowing through the alluvium must account for a significant part of the geothermal water and solutes being transported down Callon de San Diego at any time.

The magnitude of that transport cannot be estimated from observations at the mineral springs alone because those observations do not cover the other modes of transport. The chief significance of the observations at Soda Dam and Jemez Springs, for the present discussion, lies in what they show of conduit flow. In brief, the annual hydrograph of either Cl or water discharge consists of two members: *peak flow* during a pronounced surface flood, with decay to a longer episode of *low flow*.

In 1973-74 low flow fluctuated within a relatively narrow range, peak flow was substantially greater, and total peak flow was considerably greater during the large flood of 1973 than during the small one of 1974. Median flow of the group at Soda Dam was 23 liters per second (Lps), or 365 gallons per minute (gpm); at Jemez Springs it was 21 Lps (333 gpm). However, more than half the measurements for each group of springs was made during low flow, and the median values therefore represent that flow regime. Average values include the effects of extreme values that may be in error, but have the advantage of representing the entire flow cycle. Average discharge for the entire period of record in 1973-74 was 25 Lps (397 gpm) at Soda Dam and 23 Lps (365 gpm) at Jemez Springs. Estimates of the long-term geothermal component of the spring discharge would require a longer period of record so that the magnitudes of discharge in the two flow regimes could be established more precisely.

#### GEOHYDROLOGIC SETTING AND THE CONDUIT SYSTEMS

The area surrounding the mineral springs, relatively well known as a result of geologic mapping by Wood and Northrop (1946), Smith and others (1970), and Goff and Kron (1980), lies within the complex, southwest-trending Jemez fault zone. The main fault, as it is now known, branches northeast of Soda Dam. The southern strand passes down-canyon beneath the village of Jemez Springs. The northern strand bifurcates to enclose a small horst of granitic rock at Soda Dam, southwest of which the branches merge into a single strand that passes through the mesa to the west. The tuff sheets on the mesa, cut by the near-vertical normal fault, are offset about 45 m. Thus the fault has been

active for at least part of the time since formation of the caldera, estimated by Doell and others (1968, p. 211) to be about 1 m.y. Paleozoic rocks in the canyon are offset about 230 m across the fault, indicating a pre-caldera history of deformation (Goff and others, 1981, p. 231). According to Slemmons (1975, p. 10) the fault does not offset a young rhyolite flow, farther up the canyon, that is thought to be younger than 0.1 m.y. (Smith and Bailey, 1968, p. 641).

The springs at Soda Dam issue from the north side of the horst, where limestone is in fault contact with the granitic rock. These springs are at the lowest altitude at which the fault is exposed in the canyon. The modern dam is a linear travertine mound built along a line of springs across the canyon floor. Older, inactive spring deposits lie on higher ground to the northeast and southwest. They mantle the horst hill to a level nearly 215 m above the active springs; the highest travertine on the hill is cut by the horst-bounding fault (Goff and Kron, 1980). Still older travertine on the canyon walls is at levels as high as 300 m above the modern springs (Bailey and Smith, 1978, p. 186). These observations imply a considerable age for the springs at Soda Dam, or for earlier mineral springs there if discharge has not been continuous. Moreover, the vertical separation of old and modern travertines indicates a substantial change in hydraulic-head relationships in the mineral-spring system. Even if part of this separation were due to faulting, a large part of it appears to postdate the deformation and to be due to deepening of the canyon. Migration of the spring outlets to successively lower levels must have been accompanied by steepening of hydraulic gradient in the conduit system, with consequent increase in discharge, or, to the extent that supply of water to the reservoir was insufficient to maintain increased draft, by decline in reservoir pressure. M. L. Sorey (written comm. 1982) has suggested that lowering of the outlet at Soda Dam may have contributed to development of vapor-dominated conditions in the reservoir through such a decrease in pressure.

The Jemez Springs locality marks the downstream limit of limestone exposures in the canyon, beyond which the limestone is covered by younger sandstone and shale. The springs issue from alluvium in and near the Jemez River. Linear areal distribution of the springs and the fact that the outlets maintain their positions despite annual flooding suggest fault control.

Goff and others (1981) summarized and discussed geohydrologic information obtained from a test well drilled at Jemez Springs; the information includes driller's log, additional geologic and hydrologic data, and chemical and isotopic analyses of water samples. The hole penetrated about 70 ft (22 m) of gravel, 700 ft (215 m) of sedimentary rock, chiefly limestone, and 60 ft (18 m) of gneiss. Water was found at several levels in the gravel, and confined thermal water was found in an "80-foot aquifer" at the contact of alluvium and limestone and in a "500-foot aquifer" in fractured shale within the limestone. No major aquifer was found at the top of, or in, the crystalline rock.

Goff and others (1981, p. 235) concluded that the samples from springs H 14 and H 15 (which are the principal springs and are thought by several investigators to be those in this group most representative of the source water) are from the 80-foot aquifer. This conclusion is consistent with temperature data from the well and from nearby springs. Maximum water temperatures recorded during drilling were 68°C in the 80-foot aquifer and 60.5°C in the 500-foot aquifer. (The first of these values may be in error on the low side and the second on the high side; Goff and his colleagues concluded that the 80-foot and 500-foot aquifers had not been successfully isolated during sampling, because of problems of well construction, and that the shallower sample contained water from both levels.) In comparison, as noted earlier, the maximum temperature measured at the surface outlets (H 14) is 75°C. The writer believes the anomalous thermal gradient in the well to reflect a ground-water flow pattern developed locally in the fractured and solution-eroded limestone and in the alluvium (in which some strata have probably been selectively cemented by calcite). Major conduits in the limestone are most reasonably explained as steeply dipping, solution-widened fractures in the fault zone, but flow to individual springs is probably largely along a combination of vertical fractures and near-horizontal bedding-plane openings in the limestone and along porous layers in the gravel. In such a situation local

hydraulic and thermal fields tend to be layered horizontally, and thermal anomalies such as that observed in the well can develop.

Flow through the gravel also provides opportunity for dilution of mineral water near the springs. Such dilution would explain the mixing line defined by the Jemez Springs samples as a local phenomenon. The waters of the two principal springs may also have been affected by local mixing, but data to test this possibility are lacking.

No direct information on the nature of the conduit systems is available; except for a single geophysical study, only inference can be used to postulate the character of the conduits. Using direct-current resistivity data from a surface survey, Pearson and Goff (1981) interpreted an electrically conductive zone beneath the village of Jemez Springs as a thermal aquifer. This zone, at a depth of 24 m and in alluvium just above bedrock, appears to be equivalent to the 80-foot aquifer in the test hole. Pearson and Goff traced this conductive zone for several kilometers up and down the canyon from Jemez Springs but found resistivity to increase with increasing distance from the village. The writer believes the thermal water in the 80-foot aquifer to have been isolated from water at shallower levels in the gravel, and hence probably to have been derived from a bedrock conduit, basing these inferences on the relatively high temperature of the spring water and on its low content of tritium. Both lines of evidence argue lack of interconnection with shallow aquifers, which are likely to have received recharge from the surface recently.

Because of the general absence of primary porosity in the limestone, fractures must form the continuous and hydraulically effective conduit systems implied by the data summarized in earlier sections. The areal pattern of faults, taken with the three observed occurrences of mineral water (the two groups of springs, and well GT-2) in limestone, suggests that fault zones modified by dissolution of wall rock provide a reasonable explanation for the conduits.

Given the enormous quantity of limestone that has been removed from the conduit systems (obvious at Soda Dam, inferred from the dissolved load at Jemez Springs), the conduits are likely to be far larger and more conductive than is required to transport the relatively modest quantities of water discharged by the springs. From this reasoning and from the inference, already described, of rapid pressure transients and slow mass transport, the conduits are believed to contain large quantities of confined water in transient storage, with fluctuations in discharge being governed by fluctuation in prevailing head.

One consequence of slow transport and large conduit volume (large wall area) is high conductive heat loss from fluid to wall rock. The Soda Dam conduit system must be significantly larger than the Jemez Springs system, inasmuch as the springs at Soda Dam discharge far more Ca, Mg, and HCO<sub>3</sub>, than those at Jemez Springs in a roughly comparable volume of water. Greater heat loss in the conduits is thought to explain the lower temperature of the Soda Dam water. This general reasoning suggests that very hot water is not likely to be found beneath Cat'ion de San Diego very far outside the caldera.

Fumaroles just outside the rim of Valles caldera reveal the presence of water at or above the boiling temperature (about 93°C at that altitude) beneath the canyon there. The area of fumaroles extends along the axis of the canyon floor for about a kilometer, its course marked by patches of alteration of soil and rock. 1-1S is emitted at one locality. The linear distribution of fumaroles suggests that the hot-water conduit is an unmapped strand of the Jemez fault.

This area near the caldera rim is of unusual geohydrologic interest because data from three springs and three shallow wells show the presence of six near-surface perched aquifers within an area of less than 0.5 km; one well taps alluvium, and two wells and three springs (including wells H 29 and H 30 and spring H 32, Table 1) are in limestone. Samples from H 29, H 30, and H 32 are mixtures of geothermal and dilute waters; H 29 also contains ELS and therefore must have received fumarolic vapor. Tritium analyses for H 32 before and after the snowmelt flood of 1973 revealed  $18.8 \pm 2.1$  TU and 75.0 4.0 TU, respectively (Trainer, 1978, p. 127). The aquifer drained by spring H 32 evidently received recharge during the flood, and, because the aquifer is situated beside the river (and probably beneath it, farther

upstream), flood water is thought to have moved directly into the limestone at some point near the spring.

These observations bear on the problem of how and where mixing of geothermal and dilute fluids may occur. The reservoir in Valles caldera and its outflow conduits just outside the caldera appear to be the regional aquifer in this part of the Jemez Mountains; other known aquifers are perched above the main zone of saturation. In such a situation, flow from a perched aquifer to the main aquifer can occur where two conditions are met: (1) the perched aquifer received recharge in excess of its storage capacity and loses water by leakage through its confining bed or through spillover; and (2) the rock that confines the geothermal conduit (which locally is the regional aquifer) is sufficiently fractured locally to permit flow into or out of the conduit. Under these circumstances a recharge mound is maintained above the conduit by percolation from the perched aquifer. Where the head in the mound exceeds the head in the conduit, water flows in and dilutes the stream of geothermal water. Where the conduit head is greater, geothermal water leaks out into the mound and creates a mixed water in the country rock. The latter process has evidently occurred near the caldera rim, where several variants of mixed water have been found in the limestone (H 29, H 30, H 32, Table 1). This general area may also contain sites of flow into the conduit inasmuch as the presence of fumaroles shows the conduit to be imperfectly confined here.

Upper Canon de San Diego is thought to be a favorable general site for mixing because perched aquifers are present in the limestone, the rocks appear to be sufficiently fractured to facilitate rapid flow, and the river is a continuous but fluctuating source of recharge. The ring-fracture zone in the caldera may also satisfy the conditions required. The ring fracture seems, from areal geological relations, to be occupied by intrusives over much of its extent (Smith and others, 1970). However, geophysical data suggest that this zone contains water in an area in the southwestern part of the caldera (Jiracek and others, 1975). That area is beneath or near San Antonio Creek, one of the headwaters of the Jemez River, and thus from the consideration of a potential source of recharge it appears a favorable site for the mixing of waters.

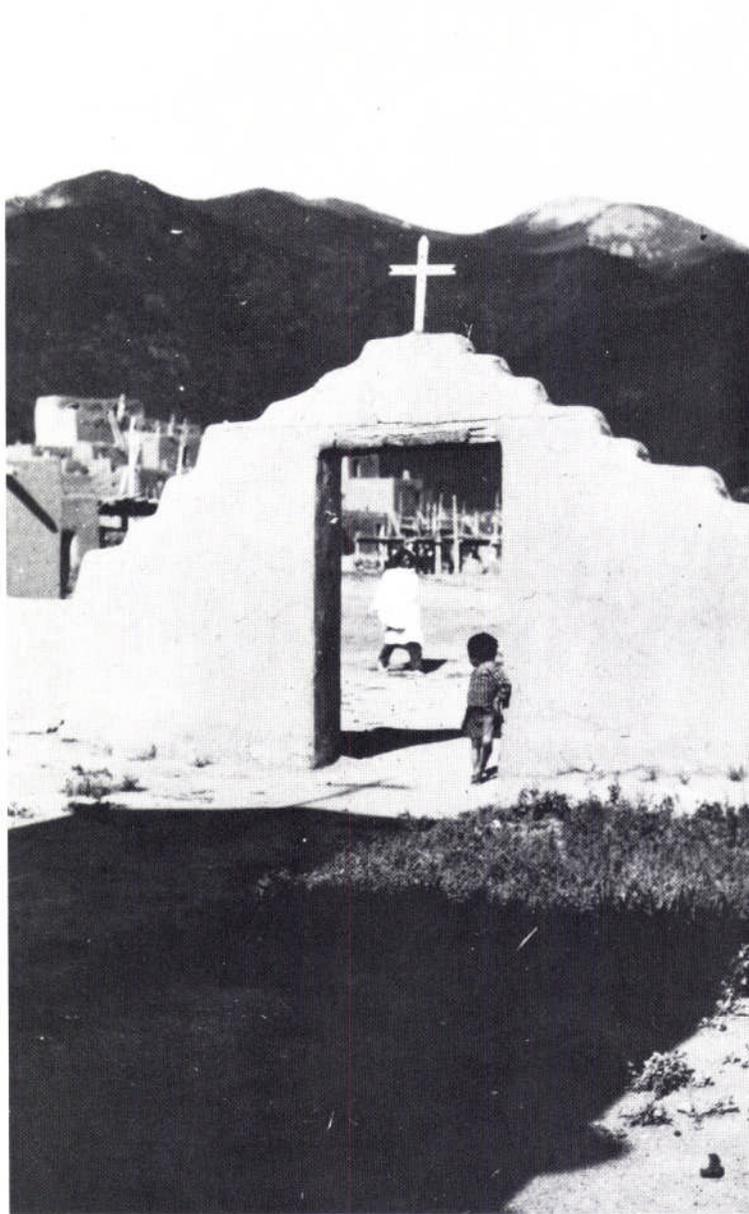
Isolation of the two systems of conduits from one another, as required by the conceptual model developed in this report, is difficult to explain on the basis of the pattern of faults as it is now known. Future mapping may resolve this difficulty despite the obstacle of large covered areas. Bifurcation of the Soda Dam conduit, with subsequent mixing of water along only one branch to form the Jemez Springs water, may give an alternative explanation more consistent with the known structural setting.

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Taos Pueblo, ca 1920. Photo by Burt Harwood.