



Fluid chemistry of the Baca geothermal field, Valles caldera, New Mexico

Art F. White, Joan M. Delany, Truesdell, Alfred, Janik, Kathy, Goff, Fraser E., and Harrison Crecraft 1984, pp. 257-263. <https://doi.org/10.56577/FFC-35.257>

in:

Rio Grande Rift (Northern New Mexico), Baldrige, W. S.; Dickerson, P. W.; Riecker, R. E.; Zidek, J.; [eds.], New Mexico Geological Society 35th Annual Fall Field Conference Guidebook, 379 p. <https://doi.org/10.56577/FFC-35>

This is one of many related papers that were included in the 1984 NMGS Fall Field Conference Guidebook.

Annual NMGS Fall Field Conference Guidebooks

Every fall since 1950, the New Mexico Geological Society (NMGS) has held an annual [Fall Field Conference](#) that explores some region of New Mexico (or surrounding states). Always well attended, these conferences provide a guidebook to participants. Besides detailed road logs, the guidebooks contain many well written, edited, and peer-reviewed geoscience papers. These books have set the national standard for geologic guidebooks and are an essential geologic reference for anyone working in or around New Mexico.

Free Downloads

NMGS has decided to make peer-reviewed papers from our Fall Field Conference guidebooks available for free download. This is in keeping with our mission of promoting interest, research, and cooperation regarding geology in New Mexico. However, guidebook sales represent a significant proportion of our operating budget. Therefore, only *research papers* are available for download. *Road logs*, *mini-papers*, and other selected content are available only in print for recent guidebooks.

Copyright Information

Publications of the New Mexico Geological Society, printed and electronic, are protected by the copyright laws of the United States. No material from the NMGS website, or printed and electronic publications, may be reprinted or redistributed without NMGS permission. Contact us for permission to reprint portions of any of our publications.

One printed copy of any materials from the NMGS website or our print and electronic publications may be made for individual use without our permission. Teachers and students may make unlimited copies for educational use. Any other use of these materials requires explicit permission.

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

FLUID CHEMISTRY OF THE BACA GEOTHERMAL FIELD, VALLES CALDERA, NEW MEXICO

ART F. WHITE¹, JOAN M. DELANY¹, ALFRED TRUESDELL¹, KATHY JANIK², FRASER GOFF¹, and HARRISON CRECRAFT

¹Lawrence Berkeley Laboratory, Berkeley, California 94720; ²U.S. Geological Survey, Menlo Park, California 94025;

³Los Alamos National Laboratory, Los Alamos, New Mexico 87545; ⁴Union Oil Co. of California, Santa Rosa, California 95406

INTRODUCTION

The Baca geothermal field is located on the western flank of Redondo Peak, a resurgent-dome structure near the center of the Valles caldera in northern New Mexico. The geology of the Valles caldera region is described by Smith and Bailey (1968). The regional hydrology has been presented by Trainer (1974, 1975), Trainer and Lyford (1979), Laughlin (1981), Goff and others (1981), and Goff and Grigsby (1982). Production characteristics of the Baca geothermal field are discussed by Bodvarsson and others (1982) and Union Oil Co. (1982).

To date, 24 geothermal wells have been drilled into the Baca geothermal field in the Sulphur Creek area (Fig. 1) and along the Redondo Creek. The wells at Sulphur Creek penetrated high temperature (>260°C) but low-productivity zones. Wells completed along Redondo Creek, in a large northeast-trending central graben within the caldera, encountered similar high temperatures in a more permeable fracture- and stratigraphically controlled reservoir.

After the initial completion of five commercial wells in the Bandelier Tuff by Union Oil Co. of California (Union), a 50 MWe power plant was proposed in 1977 by the Public Service Co. of New Mexico in cooperation with the U.S. Department of Energy Geothermal Demonstration Power Plant Program. However, drilling of 13 additional wells aimed at completing the required steam capacity resulted in only two production wells. Subsequent attempts to find additional steam in deeper Paleozoic limestones and Precambrian granite, as well as steam derived from hydraulic fracturing in the tuff, failed to adequately increase production and the project was terminated in January 1982.

The fluids tapped by the Union wells represent the deepest and highest-temperature fluids encountered within the Valles caldera. Their chemistry is important in the context of understanding both the overall hydrothermal recharge and discharge system in the caldera and the potential reservoir contributions to thermal springs outside the caldera, which add significantly to surface flow in the Jemez River. In addition, the Valles caldera is a principal target for proposed deep continental drilling into a magma—hydrothermal regime. The geothermal fluids in the Baca reservoir are probably the best available indicators of potential interaction with magma-derived components at greater depth.

Although Union had previously collected geochemical data applicable to their exploration program, final flow tests at a number of the wells during the summer and fall of 1982 represented an excellent opportunity to collect a more comprehensive suite of chemical data. This paper presents preliminary major- and trace-element data and reinterprets some aspects of the regional hydrothermal system. Additional work is underway in interpretation of existing data for other wells, interpretation of isotopic data, and modeling water/rock interaction within and beyond the geothermal reservoir.

GEOCHEMICAL SAMPLING AND RESULTS

Five Baca wells were available in 1982 for chemical sampling (Table 1). Four of the wells, Baca 4, 13, 15, and 24, were classified as commercial based on production rates, and Baca 19 was considered subcommercial. Except for Baca 19, two sets of samples per well were collected during separate flow tests.

The sampling techniques employed were those of Nehring and Truesdell (1977), in which separate liquid water and steam fractions were collected from condensers attached to wellhead separators. The initial 7/23/82 sample from Baca 15 may have been contaminated due to prior injection of waste water from Baca 13. Table 1 lists the sampling conditions of the wells and separators during the flow tests.

TABLE 1. Well and separator characteristics.

Well	Depth T.D. (m)	Production at line pressure (kg/km)	Well head pressure (psia)	Separator pressure (psia)	Water fraction (x*fluid)
Baca 4					
6/11/82	1939	20,000	144	118	0.719
7/02/82			145	124	0.713
Baca 13					
6/04/82	2501	24,000	142	121	0.762
7/01/82			140	122	0.762
Baca 15					
7/23/82	1673	48,000	164	125	0.792
9/08/82			187	125	0.641
Baca 19					
9/08/82	1705	14,000	45	21	0.798
Baca 24					
6/18/82	3233	15,000	152	127	0.811
7/16/82			145	122	0.807

Unstable chemical species that could not be analyzed in the field were taken to the Fenton Hill Laboratory of Los Alamos National Laboratory (LANL) and analyzed soon after collection. The remaining major and trace constituents were analyzed independently at both Lawrence Berkeley Laboratory (LBL) and LANL. The two sets of results showed generally good agreement with charge balances within a maximum of $\pm 4\%$. Table 2 lists a composite of field, Fenton Hill, and LBL chemical analyses.

CALCULATION OF RESERVOIR CHEMISTRY

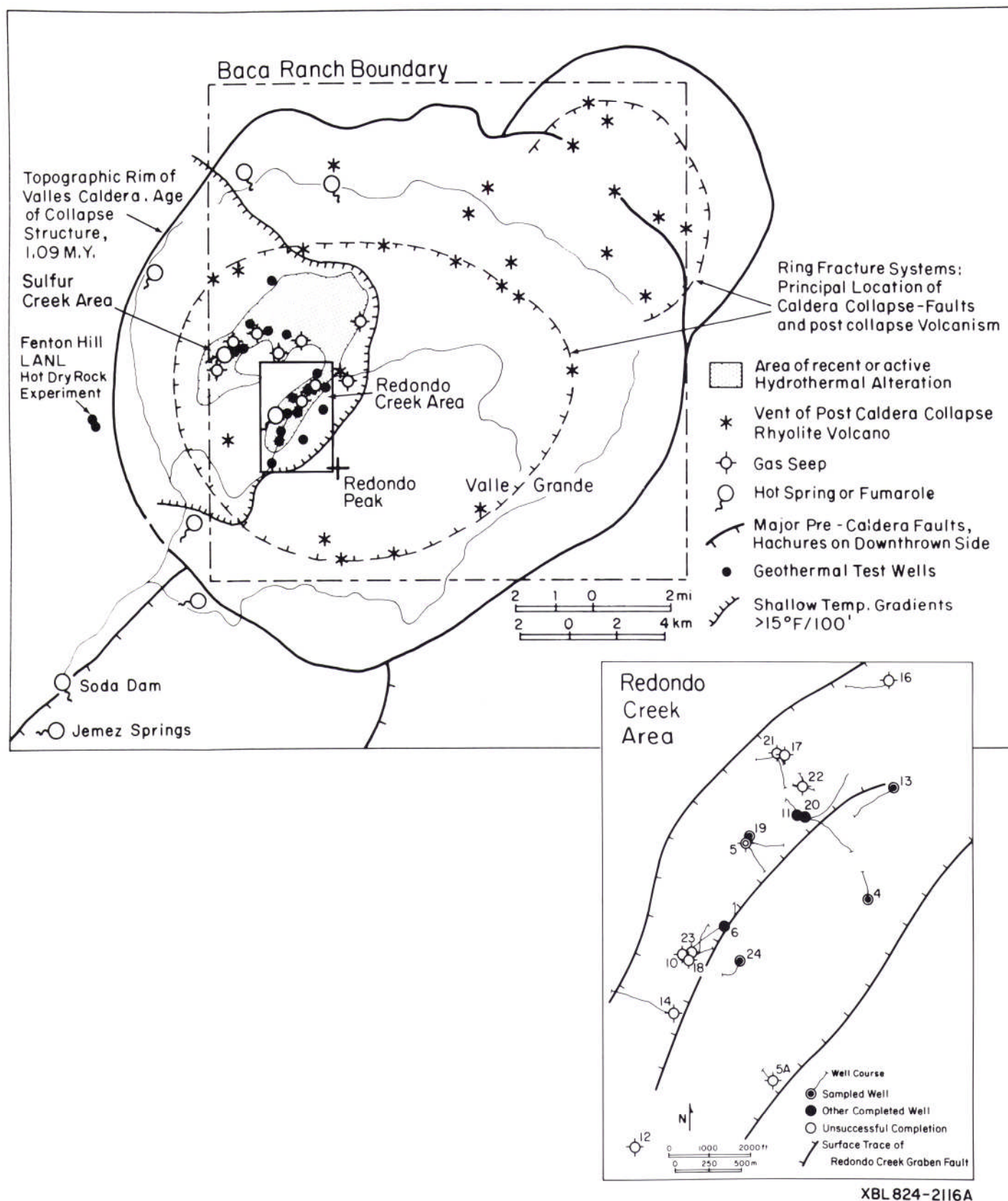
Due to extensive steam flashing in the wellbore during production, chemical concentrations in Table 2 do not represent the chemical composition of the reservoir fluids.

TABLE 2. Chemical analyses of liquid water from the separators (mg l⁻¹).

	Baca 4		Baca 13		Baca 15		Baca 19		Baca 24	
	6/11/82	7/02/82	6/04/82	7/01/82	7/23/82	9/08/82	10/08/82	6/18/82	7/16/82	
pH*	7.28	7.20	7.30	-	7.21	7.12	8.00	-	7.42	
Li	21.1	21.2	22.5	22.7	24.9	24.0	26.6	24.1	24.0	
Na	563	1607	1504	1533	1904	1867	1970	1867	1822	
K	336	336	320	310	391	407	369	281	286	
Mg	0	0	0.049	0	0	0.03	0.02	0	0.02	
Ca	4.9	3.5	4.8	4.4	16.1	19.4	18.7	17.5	24.9	
Al**	0.09	0.09	0.13	0.12	0.14	0.06	0.12	0.16	0.22	
Al ³⁺ **	<.001	<.001	0.003	0.001	0.003	0.002	0.002	<.001	0.006	
R	22	20	22	20	24	27	24	26	28	
Si	376	380	335	333	341	327	294	309	317	
SiO ₂	804	813	717	712	730	689	629	661	678	
NH ₃ **	2.2	2.8	2.0	2.2	-	1.8	1.5	0.9	1.2	
F	6.5	4.8	9.4	6.2	8.6	8.6	8.6	5.0	4.8	
Cl	2770	2750	2499	2650	3328	3766	3356	3082	3046	
Br	5.0	5.7	5.4	6.2	9.8	10.3	10.3	8.3	10.3	
HCO ₃ **	215	190	221	236	89	75	139	89	90	
CO ₃ **	0	0	0	0	0	0	4.8	0	0	
SO ₄	50	50	56	51	47.6	45.6	48.5	50	46.2	
S ²⁻ **	0.35	0.34	0.21	0.22	0.45	0.41	0.23	0.04	0.14	
PO ₄	0.09	0.11	0.12	0.15	0	0	0	0.49	0	
As	1.9	2.6	2.1	3.2	3.5	3.6	4.0	5.0	3.6	
Cr	0.0016	0.0008	<.0001	0.006	0.0036	0.0027	0.0014	0.0006	0.0012	
Cs	-	0.4	0.0015	<.001	0.001	<.001	<.001	<.001	<.001	
Hg	0.0048	<.001	0.006	<.001	0	0	0	0	0	
Mn	0.0039	-	0.0086	-	0.0086	0.0050	0.0050	-	0.018	
Pb	<.01	<.01	<.01	<.01	<.001	<.001	<.01	<.01	<.001	
Se	<.001	<.01	<.001	<.01	-	-	-	<.01	-	
Sr	158	0	184	0	2	2	2	2	35	
Zn	0.012	<.01	0.24	<.01	<.01	<.01	<.01	<.01	<.01	

* measured in field

** measured at Fenton Hill Laboratory (LANL)



XBL 824-2116A

FIGURE 1. Map of the Valles caldera area and locations of the Baca wells and hot springs.

The weight fraction of liquid water, X^* , flashing at the separator pressure (Table 1) was calculated from the relationship

$$H = X^* \times H^*_{\text{liquid}} + (1 - X^*) \times H^*_{\text{steam}} \quad (1)$$

where H is the reservoir enthalpy (J gm^{-1}), and H^*_{liquid} and H^*_{steam} are the enthalpies of liquid water and steam at the separator pressure.

In addition to production from flashing, steam may also originate in the reservoir. Non-volatile chemical species remain in liquid water and volatile species are contained in the coexisting steam phase. The proportions of steam and liquid in the reservoir are related to the reservoir enthalpy by the expression

$$H = X \times H_{\text{liquid}} + (1 - X) \times H_{\text{steam}} \quad (2)$$

in which the liquid water and steam enthalpies are for the temperature and pressure of the reservoir. The reservoir enthalpy can be calculated from equation 1 using the measured separator liquid-water fraction (Table 1) and data for H^*_{liquid} and H^*_{steam} at the separator pressure (Keenan and others, 1969). The liquid fraction in the reservoir was calculated from equation (2) and H_{liquid} and H_{steam} values using reservoir temperatures based on the Na—K—Ca geothermometer (Table 3).

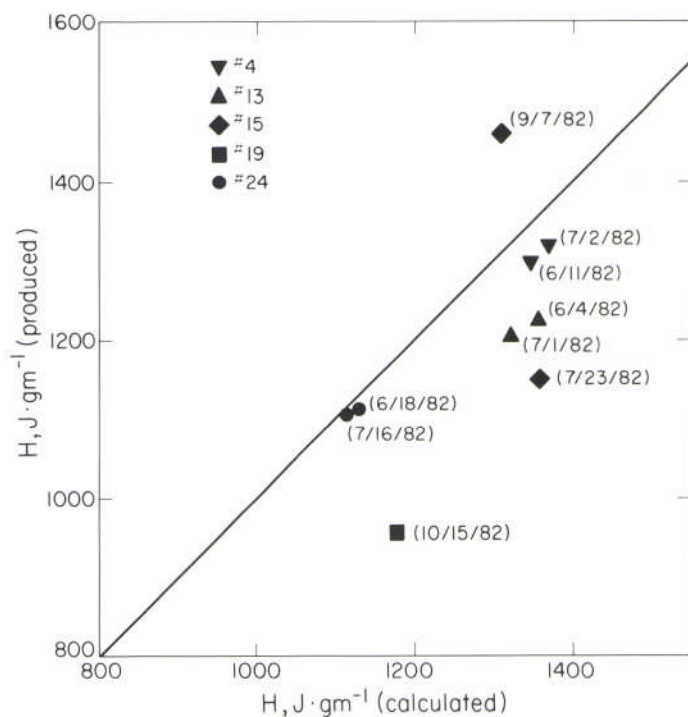
The concentration of a non-volatile chemical species, C , in the liquid-water phase of the reservoir can then be calculated from the relationship

$$C = C^* \times \frac{H^*_{\text{H}_2\text{O}}}{X_{\text{H}_2\text{O}}} \quad (3)$$

where C^* is the concentration in the flashed liquid (Table 2). The relationship assumes no chemical precipitation during flashing and no corrosion in the wellbore.

Bodvarsson and others (1982) concluded that the Baca reservoir contains a single-flow system with hot water at depth and two-phase fluid in the regions of upflow. A comparison is shown in Figure 2 between the produced enthalpies determined from equation 1 and the calculated enthalpies from equation 2 by assuming the wells were fed by liquid water only at the Na—K—Ca-geothermometer temperature of the reservoir. The 9/7/82 sample from Baca 15 plots above the equal enthalpy line, indicating excess steam originating from a two-phase reservoir. All other samples lie either on or below the line, indicating a single-phase hot-water reservoir. The lower than ideal fluid enthalpies for many of the wells are probably due to conductive cooling or steam loss from the wellbore.

Union drilling records and previous flow tests indicate that Baca 4 and 15 had penetrated steam zones in the upper part of the reservoir. The absence of two-phase conditions at Baca 4 during sampling may be due to the effects of final well completion in which these steam



XBL 843-9663

FIGURE 2. Comparison of produced enthalpies and calculated enthalpies assuming single-phase hot water at Na—K—Ca-geothermometer temperatures.

zones were cased off or the effects of thermal equilibration in the wellbore. Earlier flow tests of Baca 15 in 1976 and 1977 produced very high enthalpies ($>2,100 \text{ J gm}^{-1}$), indicating a large steam contribution. Part of this excess steam may have resulted from flashing in the reservoir during these previous long-term flow tests (Bodvarsson and others, 1980). The very low-production enthalpy for Baca 15 on 7/23/82 is probably related to prior injection of fluid from Baca 13. The later 9/7/82 Baca 15 sample is assumed to be more representative of the two-phase nature of the well.

ENTHALPY—CHLORIDE RELATIONSHIPS

Truesdell and Fournier (1976) demonstrated that plots of enthalpy—chloride delineate hydrologic characteristics of geothermal reservoirs and hot springs. In Figure 3, aqueous-reservoir chloride concentrations are determined from the produced enthalpies and calculated liquid-water enthalpies using equations 1-3. The chloride data generally cluster into two groups with low chloride concentrations in Baca 4 and 13 and higher chloride concentrations in Baca 15, 19, and 24. Baca 4 and 13, which are located in the northeastern section of the Redondo Creek graben, also have higher measured and calculated temperatures and larger enthalpies than do the other wells situated to the southwest. Baca 15 and 19 have exhibited intercommunication during flow and interference tests, which explains similar chloride concentrations. No direct interconnection has been demonstrated for the other sampled wells.

The chloride—enthalpy contents of the Baca wells in Figure 3 are bracketed by diagonal lines indicating trends resulting from boiling and steam loss. These straight lines assume a constant steam enthalpy of $2,700 \text{ J gm}^{-1}$ as indicated by intersection with the pure-steam phase in the upper left of the figure. This enthalpy is consistent with the separator temperatures ($\pm 120^\circ\text{C}$), but can be used to describe higher temperature processes because the enthalpy of steam only varies $\pm 4\%$ to the critical point. The lower enthalpy—higher chloride fluids in wells 15, 19, and 24 can be derived from adiabatic cooling and later conductive reheating of fluids with a chloride composition of Baca 4 and 13. Localized boiling requires the separation and loss of steam from

TABLE 3. Geothermometer temperatures ($^\circ\text{C}$).

Location	Sample date	T_{measured}	T_{SiO_2}	$T_{\text{Na-K}}$	$T_{\text{Na-K-Ca}}$	$T_{\text{Na-Li}}$
Baca 4	6/11/82	295	263	288	300	305
	7/02/82	295	264	283	271	301
Baca 13	6/04/82	295	254	286	299	320
	7/01/82	295	254	278	294	319
Baca 15	7/23/82	270	255	281	285	301
	9/08/82	270	251	290	287	298
Baca 19	10/08/82	—	244	267	288	304
Baca 24	6/18/82	247	248	236	258	299
	7/16/82	224	250	242	257	302
Soda Dam	12/01/72	48	102	277	230	310
	1/04/79	48	102	278	226	301
Main Jemez Sp.	11/19/79	35	128	195	194	300
Travertine Mound	1/19/79	72	127	202	196	308
Buddhist Sp.	1/19/79	50	120	205	192	291
Jemez Well "80 ft"	1/19/79	68	118	201	192	296
Jemez Well "500 ft"	1/19/79	60	71	245	192	294

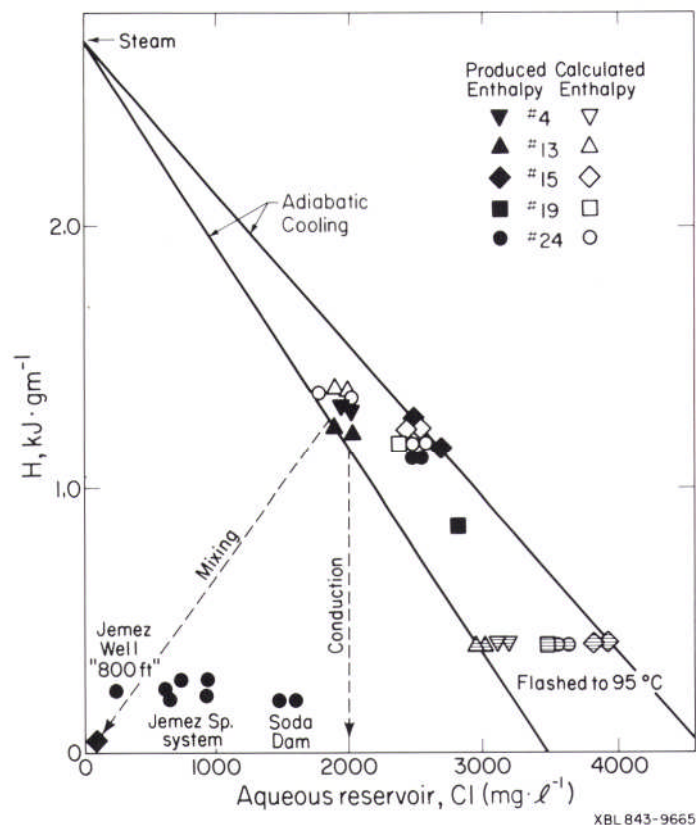


FIGURE 3. Enthalpy-chloride relationships for hot springs and Baca wells.

the reservoir fluid. The upper steam-producing zones in Baca 15 could result from such boiling. Although there are currently no surface manifestations of reservoir steam loss in the area of Redondo Creek, acid-sulfate springs indicative of steam separation do occur at Sulphur Creek.

Chloride—enthalpy data from the Jemez Springs system and Soda Dam (Fig. 4) are also plotted in Figure 3. Previous workers, including Trainer (1974) and Goff and others (1981), have proposed that these hot springs, which discharge from Paleozoic carbonates along fault systems defining the course of the Jemez River, represent a mixture of local meteoric waters and hot waters originating from a geothermal reservoir in the Valles caldera. Both the enthalpies and chloride concentrations of these springs are lower than those of the Baca fluids. The temperatures of the springs range from 70 °C at Travertine Mound at Jemez Springs to 48 °C at Soda Dam (Goff and others, 1981).

Hot-spring chloride—enthalpy relationships can evolve from deeper—hotter geothermal reservoirs such as the Baca system by three mechanisms: (1) adiabatic cooling, (2) conductive cooling, and (3) mixing with cold meteoric water. The chloride compositions plotted at the lower end of the adiabatic cooling trend in Figure 3 represent Baca fluid compositions flashed to atmospheric pressure at 95 °C. Such adiabatic cooling would result in much higher chloride concentrations than are present in the hot springs without extensive mixing with meteoric water.

Changes in chloride concentrations and enthalpies as functions of conductive cooling and mixing with meteoric water are shown in Figure 3, assuming a fluid source comparable to the hottest, most dilute composition of the Baca reservoir. Mixing is assumed to occur with cold meteoric water of the composition of Agua Durme Spring (Goff and Grigsby, 1982). Except for the 500-ft aquifer intersected by the Jemez well (Goff and others, 1981), hot-spring enthalpy—chloride contents fall between the mixing and thermal conduction lines in Figure 3, suggesting both dilution with meteoric water and heat loss to cooler aquifers surrounding the geothermal reservoir. Thermal conduction clearly is more important at Soda Dam than at Jemez Springs.

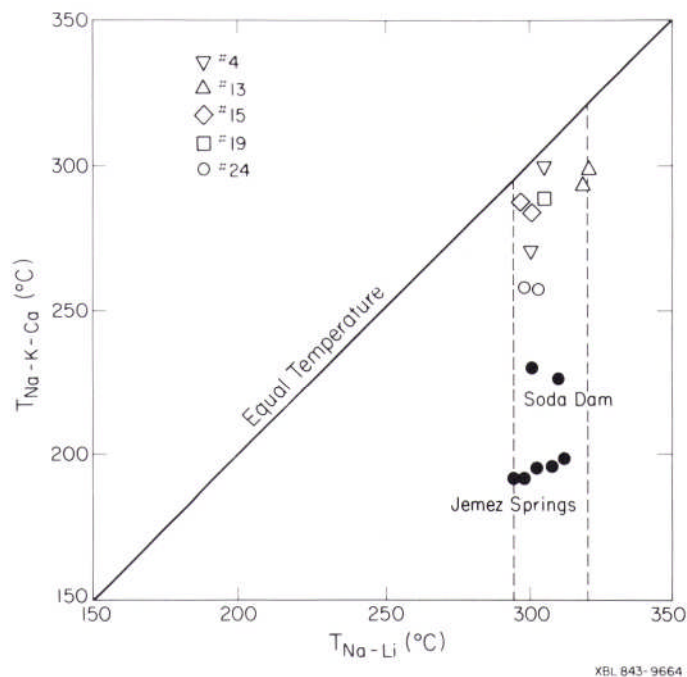


FIGURE 4. Comparison of temperatures of wells and hot springs calculated from Na-K-Ca and Na-Li geothermometers.

CHEMICAL GEOTHERMOMETRY

Chemical geothermometers are widely used to estimate geothermal reservoir temperatures. Four such geothermometers were used to calculate reservoir temperatures for the Baca wells and the hot spring along the Jemez River. The temperature relationship in degrees centigrade are:

$$T_{\text{SiO}_2} = \frac{1535}{0.989 - \log \text{SiO}_2} - 273.15 \quad (4)$$

$$T_{\text{Na-K}} = \frac{855.6}{1.099 + \log(\text{Na} / \text{K})} - 273.15 \quad (5)$$

$$T_{\text{Na-Li}} = \frac{1000}{0.38 + \log(\text{Na} / \text{Li})} - 273.15 \quad (6)$$

$$T_{\text{Na-K-Ca}} = \frac{1647}{\log(\text{Na} / \text{K}) + 0.33 \log(\sqrt{\text{Ca} / \text{Na}})} - 273.15 \quad (7)$$

where all concentrations are in moles l⁻¹.

The silica geothermometer (Truesdell, 1976) is used to calculate reservoir temperatures from discharged surface-silica concentrations assuming adiabatic isoenthalpic cooling in the wellbore. The Na—K (Truesdell, 1976), Na—Li (Fouillac and Michard, 1981), and Na—K—Ca (Fournier and Truesdell, 1973) geothermometer temperatures are calculated from elemental ratios which are essentially independent of the amount of reservoir flashing. As indicated for the Baca data in Table 3, calculated reservoir temperatures increase progressively in order $T_{\text{SiO}_2} < T_{\text{Na-K}} < T_{\text{Na-K-Ca}} < T_{\text{Na-Li}}$.

Baca well 24 shows the closest agreement between all the geothermometer temperatures and the maximum measured downhole temperature.

The T_{SiO_2} estimated for fluids from the other wells is considerably lower than either the measured temperature or other geothermometer temperatures indicating precipitation of quartz during boiling in the wellbore or aquifer. The Na—K and Na—K—Ca geothermometers appear to reflect most closely both maximum measured reservoir temperatures and temperature differences between wells. This correspondence prob-

ably reflects local chemical-equilibrium conditions at different temperature and production zones within the fractured reservoir. The Na—Li temperature estimates are higher and more consistent than the other geothermometer temperatures. As indicated by Figure 4, maximum T_{K-Ca} values approach Na—Li temperatures in some of the wells. As discussed by Fouillac and Michard (1981), lithium is unlikely to re-equilibrate with secondary minerals with decreasing temperature due to its small ionic radius. Therefore, T_{N-L} , probably reflects the maximum temperature achieved during the evolution of the reservoir. The fact that fluids in all the samples have comparable T_{N-L} values indicates a homogeneous, deep-seated heat source.

Comparison of different geothermometer temperature estimates for the hot springs along the Jemez River shows greater differences. The T_{N-L} and $T_{Na-K-Ca}$ temperatures are given in Table 3 as reported by Goff and others (1981), who concluded that silica in the springs either re-equilibrated at a lower temperature or was diluted by meteoric water. Figure 4 shows that although the $T_{Na-K-Ca}$ values of Jemez Springs and Soda Dam are much lower than those of the Baca wells, T_{N-L} values, which are possibly more indicative of maximum reservoir temperatures, are nearly identical for the springs and wells.

Goff and others (1981) suggested that lower Na—K—Ca temperatures are in part due to extensive dissolution of the carbonate aquifer from which the Soda Dam and Jemez Springs discharge. The resulting high calcium concentrations (>300 ppm) relative to the Baca well fluids (<25 ppm) tend to depress T_{N-L} values (equation 7). Therefore, the T_{N-L} estimates are higher (Table 3) and probably more representative of maximum re-equilibration temperatures in the hot-springs system.

MIXING OF GEOTHERMAL WATERS

Some of the best indicators of a mixed geothermal component in hot springs are elemental or isotopic ratios which are unique to the geothermal reservoir and which do not re-equilibrate within the aquifer at lower temperatures. Common elemental ratios which may indicate geothermal origin are B/Cl, Br/Cl, Li/Cl, Cs/Cl, and As/Cl. Both Trainer and Lyford (1979) and Goff and Grigsby (1982) employed such ratios in concluding that waters at Soda Dam and Jemez Springs were derived from mixing of thermal waters of the Valles caldera with cold meteoric water.

Figure 5 shows a plot of boron to chloride concentrations for the Baca well waters and data for hot-spring water analyses from Trainer (1975) and Goff and others (1981, 1982). As indicated, a mixing line, similar to that determined by these workers, passes through the Baca well data. The Baca data are the estimated liquid-water concentrations corrected for wellhead flashing and two-phase reservoir conditions.

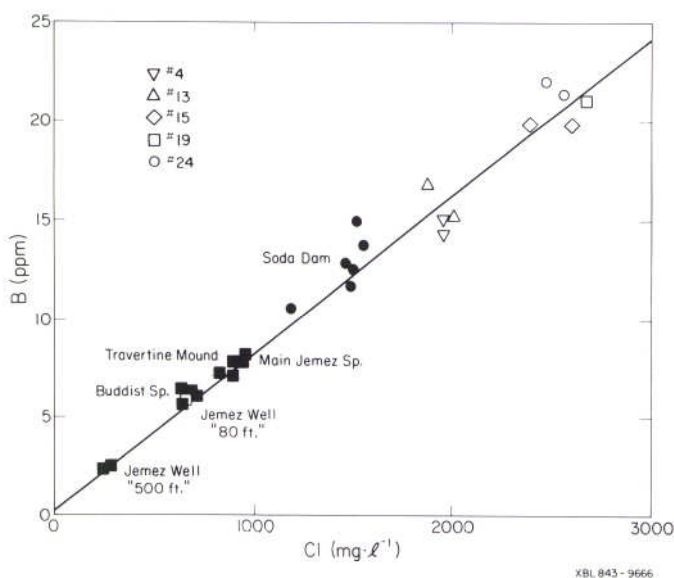


FIGURE 5. Boron and chloride distributions in wells and hot springs.

Based on distribution coefficients for boric acid between the liquid water and steam phases at the separator temperatures used at Baca ($K = 0.01$, Ellis and Mahon, 1977), total reservoir boron is assumed to be contained in the liquid-water fractions.

Two hydrologic processes can produce co-linear concentration charges; boiling which results in concentration increases upward along the line in Figure 5, and mixing with dilute meteoric water which results in decreases downward. Assuming that the highest-temperature wells, Baca 4 and 13, represent the primary hot-water component, boiling of this fluid will result in higher boron and chloride concentrations found in the cooler Baca 15, 19, and 24 wells. Dilution of geothermal fluids in the Valles caldera with meteoric water, as proposed initially by Trainer (1974), will result in the observed hot-spring boron and chloride concentrations. The mixing proportions in Baca 4 and 13 required to produce the spring-water compositions at Soda Dam, Jemez Springs, and the 500-ft aquifer intersected in the Jemez well (Goff and others, 1981) are 80, 50, and 10%, respectively. The proportion of geothermal water relative to meteoric water discharging from the springs would therefore be considerably higher than proposed by previous workers who over-estimated chemical concentrations for the Baca geothermal fluids.

Elemental ratios of non-conservative chemical species can be used to estimate the extent of re-equilibration in a geothermal system. Figures 6a and 6b show respective Na/Cl and K/Cl ratios for the Baca wells and hot springs. Constant Na/Cl and K/Cl ratios for fluids in the wells suggest that differences in sodium, potassium, and chloride concentrations are due to boiling. The major exception is the significant decrease in the K/Cl ratios for Baca 24. This drop, coupled with lower production and geothermometer temperatures, indicates re-equilibration of potassium with reservoir rocks.

Na/Cl and K/Cl ratios for Soda Dam fluids plot close to the mixing line defined by the Baca wells, excluding the potassium values for Baca 24. Mixing lines drawn through the Jemez Springs waters are significantly offset from the Baca—Soda Dam mixing line with higher Na/Cl ratios and significantly lower K/Cl ratios.

DISCUSSION AND CONCLUSIONS

Based on the data presented in this paper and by previous workers, several interesting features of the geothermal system can be inferred.

Comparison of corrected liquid-reservoir compositions with measured temperatures and Na—K—Ca temperature estimates reveals that the fluids with the highest temperatures have the lowest dissolved chemical concentrations. This implies that the lower-temperature, chemically more concentrated fluids intersected in other wells have evolved by boiling. The general agreement between Na—K—Ca and measured temperatures indicates that local chemical equilibrium occurs in different thermal regimes in the reservoir. This is particularly well demonstrated for the low temperatures in Baca 24. The fact that Na—Li temperatures are identical in all the wells suggests that fluids in the reservoir had achieved the same maximum temperatures prior to re-equilibration. The highest calculated Na—K—Ca temperatures approach the Na—Li temperatures, suggesting maximum temperatures in the reservoir have not decreased significantly with time.

The B/Cl ratios show that the chemistry of the hot springs along the Jemez River can be explained by mixing of meteoric water and hot water in the Baca reservoir, as has been proposed by previous workers. Because the dissolved solids in the Baca fluids are lower than previously estimated, the water discharging at the hot springs requires even a greater proportion of thermal water to produce the observed chemistry. The Na—Li temperatures indicate that the fluids from the Baca wells and the hot springs have a common thermal source. These chemical data support the conclusion that the Baca geothermal reservoir is discharging through these springs via a fault system which extends into the Valles caldera.

The chemical re-equilibration data are the only evidence that suggests a more complex discharge pattern and possibly an additional, deeper geothermal reservoir. The Na/Cl and K/Cl ratios for the Soda Dam waters show no re-equilibration from the mixing line defined by the Baca fluids. This is also indicated by the high Na—K-geothermometer

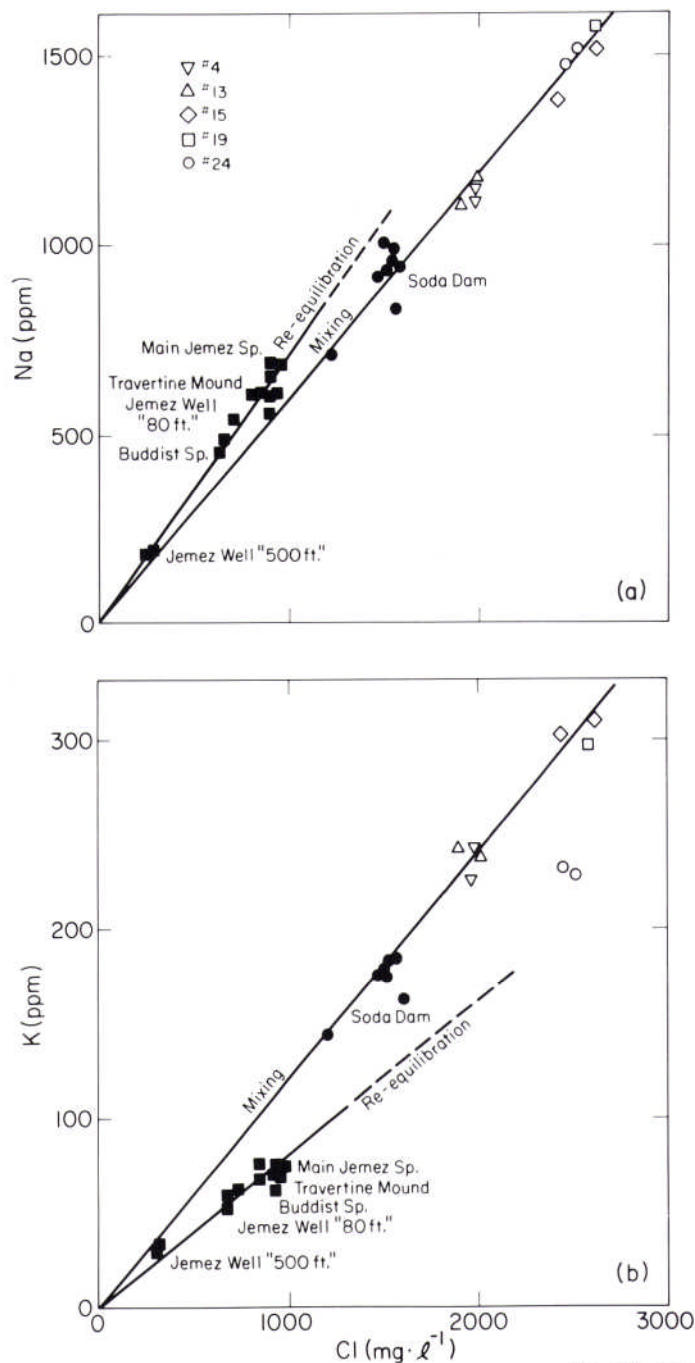


FIGURE 6. Sodium, potassium, and chloride distributions in wells and hot springs.

estimates of temperature for water from Soda Dam, which are in excess of 275°C. These temperatures are hotter than measured and calculated geothermometer temperatures for Baca 19 and 24.

The Jemez Springs waters show strong sodium and potassium re-equilibration at a calculated Na-K temperature of 200°C. Fluids from Baca 24 also show re-equilibration at a Na-K temperature of 240°C. Therefore, the question that must be answered is why thermal waters at Soda Dam failed to re-equilibrate with a cooler aquifer when waters at Jemez Springs and the cooler Baca wells did. The only apparent explanation is that thermal waters discharging at Soda Dam must have been confined in an aquifer or reservoir devoid of sodium- and potassium-silicate phases with which to re-equilibrate. The Paleozoic carbonates which underlie the Bandelier Tuff in the Baca field, and from which the springs at Soda Dam discharge, are the obvious choice.

Reaction with a carbonate aquifer is also indicated by very high calcium and low SiO₂ concentrations at Soda Dam relative to Jemez Springs, and even relative to many meteoric springs in the Valles caldera region.

The Na-K equilibration temperature of 275°C indicates that the thermal waters discharging at Soda Dam must have entered the carbonate rocks at high temperatures from a source containing sodium and potassium silicates. This suggests discharge of the high-temperature reservoir waters, similar to fluids produced by wells 14 and 13 ($T_{ss} = 285^{\circ}\text{C}$), from the Bandelier Tuff into the underlying Paleozoic carbonates. Because concentrations of elements such as Na, K, B, Br, and Li are low in such carbonates, original chemical signatures derived from the overlying tuff would tend to be preserved in the carbonate reservoir, as would the geothermometer temperatures. Deepening of Baca 22 and Baca 12 into the Paleozoic carbonate encountered high temperatures but low permeability. However, high permeabilities have been observed elsewhere in the Paleozoic carbonates at Fenton Hill.

Re-equilibration of the waters at Jemez Springs indicates that these waters have moved through sodium and potassium silicates at lower temperatures ($T_{ss} = 200^{\circ}\text{C}$). These mineral phases could have been contained in lower-temperature zones of the Baca reservoir in the Bandelier Tuff as represented by Baca 24. Because the Jemez Spring waters discharge topographically and stratigraphically below Soda Dam, another possibility is that these waters have re-equilibrated with Precambrian granite which underlies both the Bandelier Tuff and the Paleozoic carbonate. Such granite was encountered at 250 m in the well drilled at Jemez Springs. Reactions with a silicate aquifer, either the Bandelier Tuff or Precambrian granite, is also implied by the higher silica and lower calcium concentrations relative to the Soda Dam waters. In summary, the avenues of transport from a high-temperature source must have been very different for thermal waters discharging at Jemez Spring and Soda Dam.

REFERENCES

- Bodvarsson, G. S., O'Sullivan, M. J., and Tsang, C. F., 1980, The sensitivity of geothermal reservoir behavior to relative permeability parameter: Lawrence Berkeley Laboratory, Report 12040, p. 14.
- , Vonder Harr, S., Wilt, M., and Tsang, C. F., 1982, Preliminary studies of the reservoir capacity and generating potential of the Baca geothermal field, New Mexico: Water Resources Research, v. 18, pp. 1713-1723.
- Ellis, A. J., and Mahon, A. J., 1977, Chemistry of geothermal systems: Academic Press, New York, p. 392.
- Fouillac, C., and Michard, G., 1981, Sodium/lithium ratios in water applied to geothermometry of geothermal reservoirs: Geothermics, v. 10, pp. 55-70.
- Fournier, R. O., and Truesdell, A. H., 1973, An empirical Na—K—Ca geothermometer for natural waters: Geochimica Cosmochimica Acta, v. 37, pp. 1255-1275.
- Goff, F. E., and Grigsby, C. O., 1982, Valles caldera geothermal system, New Mexico, U.S.A.: Journal of Hydrology, v. 56, pp. 119-136.
- , Trujillo, P. O., Jr., Counce, D., and Kron, A., 1981, Geology, water geochemistry and geothermal potential of the Jemez Springs area, Cation de San Diego, New Mexico: Journal of Volcanology and Geothermal Research, v. 10, pp. 227-244.
- , McCormick, T., Trujillo, P. E., Counce, D., and Grigsby, C. O., 1982, Geochemical data for 95 thermal and nonthermal waters of the Valles caldera—Southern Jemez Mountains region, New Mexico: Los Alamos National Laboratory, Report LA-9367-OBES.
- Keenan, J. H., Keyes, F. G., Hill, P. G., and Moore, J. G., 1969, Steam tables (International edition—metric units). Wiley, New York, p. 162.
- Laughlin, A. W., 1981, The geothermal system of the Jemez Mountains, New Mexico, and its exploration; in Ryback, L., and Muffler, L. J. P. (eds.), Geothermal systems: principles and case histories: Wiley, New York, pp. 295-320.
- Nehring, N. L., and Truesdell, A. H., 1977, Collection of chemical, isotope and gas samples from geothermal wells: Proceedings of the Second Workshop on Sampling Geothermal Effluents, EPA-600/7-78-121, pp. 130-140.
- Smith, R. L., and Bailey, R. A., 1968, Resurgent cauldrons; in Coats, R. R., Hay, R. L., and Anderson, C. A. (eds.), Geological Society of America, Memoir Series 116, pp. 613-662.

XBL 843-9662

- Trainer, F. W., 1974, Groundwater in the southwestern part of the Jemez Mountains volcanic region, New Mexico: New Mexico Geological Society, Guidebook 25, pp. 337-345.
- _____, 1975, Mixing of thermal and nonthermal waters in the margin of the Rio Grande rift, Jemez Mountains, New Mexico: New Mexico Geological Society, Guidebook 26, pp. 213-218.
- _____, and Lyford, F. P., 1979, Geothermal hydrology in the Rio Grande rift, north-central New Mexico: New Mexico Geological Society, Guidebook 30, pp. 299-306.
- Truesdell, A. H., 1976, Summary of section III—geochemical techniques in exploration: Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Energy, San Francisco, pp. 1 iii-1 xxix.
- _____, and Fournier, R. O., 1976, Calculation of deep temperatures in geothermal systems from the chemistry of boiling water of mixed origins. Proceedings of the Second United Nations Symposium on Development and Use of Geothermal Energy, San Francisco, pp. 837-844.
- Union Oil Company of California, 1982, Baca Project Geothermal Demonstration Power Plant: Final Report for the U.S. Department of Energy, ET-78F-F-03-1717, p. 385.



The station at Servilleta was a boxcar, looking ready for collapse in 1941 when the 473 made a brief stop with its usual 2-car consist (photo by Bob Richardson).



This concrete basement is the most significant structure remaining at Servilleta. This desolate station, 10 miles south of Tres Piedras, was the transfer point for John Dunn's stage to Taos via the Arroyo Hondo bridge.



The rotting railroad tie in the foreground marks the location of the track at Servilleta. The site of the station is hidden in the sage brush.