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The Valles caldera hydrothermal system, past and present, New Mexico, USA*

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Abstract. The 20-km-diameter Valles caldera formed 1.14 Ma and has had continued post-caldera rhyolitic eruptions until 0.13 Ma. Hot springs and fumaroles are surface manifestations of a hydrothermal reservoir (210° to 300°C; 2 to 10 x 10^3 mg/kg Cl) that is most voluminous in fractured, caldera-fill tuffs and associated sedimentary rocks located in specific structural zones. Fluids are composed of deeply circulating water of meteoric origin that have a mean residence time in the reservoir of 3 - 10 k.y. Host rocks show intense isotopic interaction with hydrothermal fluids. The only component of clear magmatic origin is anomalous ^{3}He. Alteration assemblages are controlled by temperature, permeability, fluid composition, and depth. A generalized configuration (top to bottom) consists of argillic, phyllic, propylitic and calc-silicate assemblages. Typical alteration minerals in phyllic and propylitic zones are quartz, calcite, illite, chlorite, epidote, and pyrite, whereas common vein minerals consist of the above minerals plus fluorite, adularia, and wairakite. Argentiferrous pyrite, pyrargyrite, molybdenite, sphalerite, galena, chalcopyrite, arsenopyrite, stibnite, barite, and tetradymite (?) have been found at various levels of the Valles system. Fluid inclusion studies show that these mineral assemblages formed from dilute liquid water at temperatures ranging from 175° to 310°, depending on location in the system. Fluid inclusion studies also show that the top of the hydrothermal system has cooled dramatically since initial formation and that the top of the liquid-dominated zone has descended, leaving behind a low-pressure vapor cap. Dating of spring deposits and core samples of vein minerals and altered host rocks by K-Ar, U-Th, U-U, and paleomagnetic methods indicates that the hydrothermal system was created about 1.0 Ma and has been continuously active to present. However, these dates in combination with other evidence suggest that the vapor zone formed about 0.5 Ma after breaching of the southwest caldera wall, draining of widespread intra-caldera lakes, and lowering of hydraulic head on the hydrothermal reservoir. Although petrologic and geophysical evidence indicate that residual pots of melt still reside in the pluton beneath the caldera, the size of the hydrothermal system has shrunk since initial formation. Thus, Valles caldera contains a mature hydrothermal system that remains very hot and that displays a fascinating evolution.

Introduction.

Calderas are collapse features resulting from the largest, most explosive volcanic eruptions documented in the Earth's geologic record, and they represent the surface expressions of shallow, subsurface plutons that can exceed 10 x 10^3 km^3 in volume (Smith, 1979). The vast heat content and high subsurface temperatures associated with shallow, crystallizing magma create convecting systems of hot groundwaters in overlying rocks. These hot convecting fluids commonly form surface hot springs and fumaroles. Hot waters leach soluble elements from fresh volcanic rocks and older rocks. Magmatic volatiles from depth may be absorbed by overlying reservoirs of convecting fluids. As a result, hydrothermal minerals are deposited in favorable structures and horizons within the hydrothermal system. Many of the world's precious- and base-metal ore deposits are mined from the eroded remnants of ancient calderas (Bethke and Rye, 1979), whereas geothermal energy is commonly tapped from superheated groundwaters circulating in younger ones (Steiner, 1977). The youngest calderas create substantial volcanic hazards because they produce explosive pyroclastic eruptions as well as less violent domes and flows (Rosi and Sbrana, 1987).

The Valles caldera in northern New Mexico (Fig. 1) has become well known in recent years as the "type" resurgent caldera (Smith and Bailey, 1968) and as a host for a

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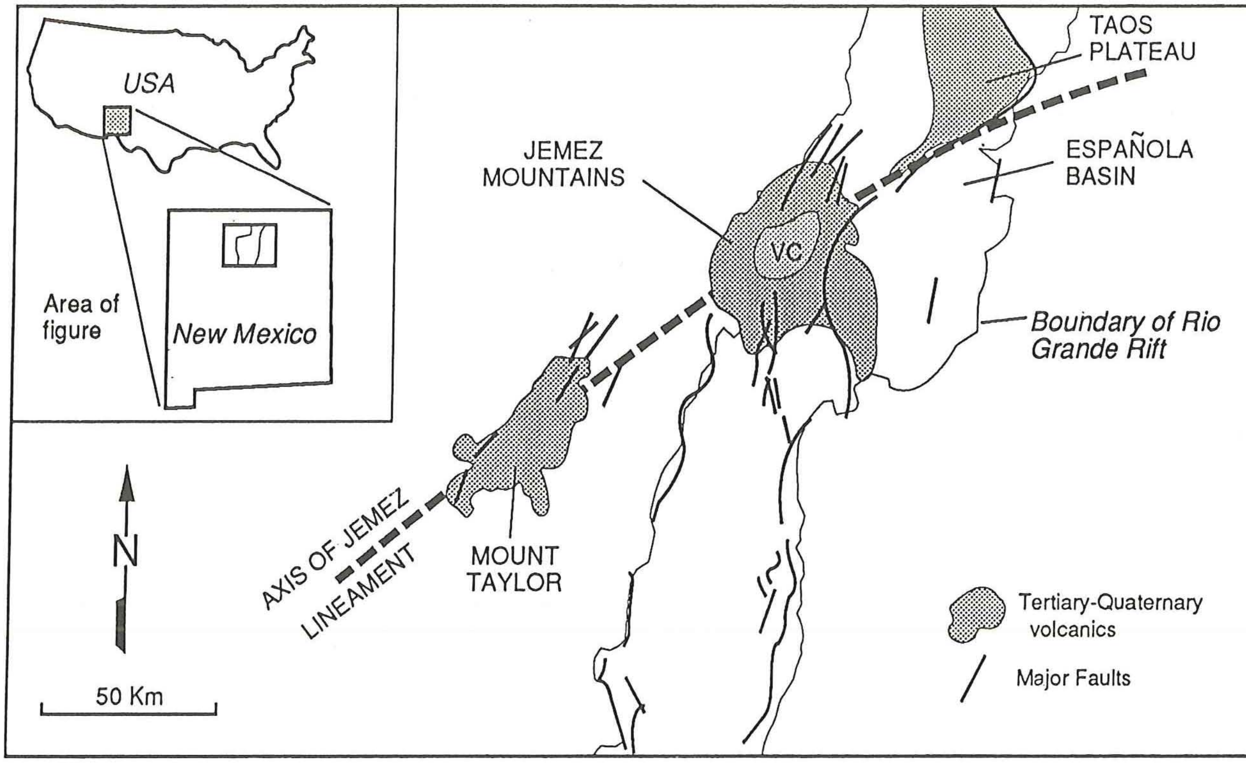


Fig. 1: Location map of the Valles caldera region showing regional features (modified from Self et al., 1986).

high-temperature (≤300°C) geothermal system (Dondanville, 1978; Nielson and Hulen, 1985). However, the caldera is but the youngest major episode of the long-lived Jemez volcanic field (>13 Ma to 0.13 Ma). Older volcanic rocks host gold deposits that were mined at the turn of the century (Lindgren et al., 1910) and an enormous variety of ignimbrites, domes, flows, and associated sedimentary rocks are easily observed for studies of volcanic phenomena (Smith et al., 1970).

Valles caldera has been discussed as a high-priority site for the investigation of fundamental processes in magmatism, hydrothermal systems, and ore deposit mechanisms from the earliest planning phases of the U.S. Continental Scientific Drilling Program (CSDP)[Shoemaker, 1974; U.S. Geodynamics Committee, 1979; Continental Scientific Drilling Committee, 1984 a, b]. As a result, a considerable amount of research has been focused on Valles caldera and the Jemez volcanic field since 1980 (Goff and Gardner, 1988; Goff et al., 1989; Heiken et al., 1990). A major highlight of this research has been the findings resulting from investigations on the fluids and cores from three scientific holes drilled in 1984, 1986, and 1988 (Goff et al., 1986, 1987; Nielson et al., 1988; Gardner et al., 1989; Hulen et al., 1989). The object of this paper is to briefly summarize results from the three scientific holes, to present some significant data on the character of the Valles hydrothermal system, and to propose a model of that system, past and present.

Geologic Overview

The Jemez volcanic field contains a diverse suite of basaltic through rhyolitic rocks that were erupted from >13 to 0.13 Ma, although the field is best known for the Valles caldera (1.14 Ma) and the Bandelier Tuff (Smith and Bailey, 1966; Gardner et al., 1986; Self et al., 1986; Spell et al., 1990). The volcanic field overlies the western edge of the Rio Grande Rift (RGR) at the intersection of the rift with the Jemez volcanic lineament (JVL). The lineament is defined by a chain of Miocene to Quaternary volcanic centers stretching from southeast Colorado across New Mexico to central Arizona (Mayo, 1958; Aldrich, 1986). The largest volume and diversity of volcanic rocks along the JVL have been erupted in the Jemez Mountains. Tertiary basin-fill rocks of the Española and Santo Domingo Basins of the RGR underlie the volcanic rocks on the eastern side of the volcanic field, whereas Paleozoic to Mesozoic sedimentary rocks and Precambrian crystalline rocks of the Colorado Plateau underlie volcanic rocks on the west.

Valles caldera is the youngest of several Quaternary calderas that have formed in the Jemez volcanic field since 1.75 Ma (Self et al., 1986; Heiken et al., 1990; Spell et al., 1990). Collapse of the Valles caldera during eruption of the Tshirege Member, Bandelier Tuff produced a circular depression about 22 km in diameter. About 300 km^3 of high-silica rhyolite magma was vented to form the ignimbrite plateaus that flank the Jemez Mountains and to fill the caldera depression (Smith and Bailey, 1968; Nielson and Hulen, 1984). Structural resurgence of a circular dome in the approximate center of the caldera occurred about 0.1 m.y. after caldera formation (Smith and Bailey, 1968). Resurgence was accompanied by small-volume eruptions of rhyolite lavas. A ring of "moat" rhyolite eruptions forming domes, flows, and pyroclastic deposits followed from about 1.05 to 0.13 Ma. Depth to the top of the pluton (Bandelier magma chamber) is estimated at about 5.0 km. Eruption temperature of the Tshirege Member tuffs ranged from 850° to 700°C (Warshaw and Smith, 1988). The subsurface "floor" of Valles caldera is very asymmetric due to superposition of caldera collapse structures on earlier structures associated with the RGR. Depth to "basement" increases eastwards from about 760 m on the west, to 3100 m in the center of the resurgent dome, to 4500 m on the east (Goff and Grigsby, 1982). A summary of geophysical investigations in the caldera is given in Goff et al. (1989).

CSDP Holes.

Approximately forty intermediate to deep wells have been drilled into the Valles caldera and its margins since 1960 primarily to exploit geothermal resources (Laughlin, 1981; Heiken and Goff, 1983; Nielson and Hulen, 1984; Goff et al., 1989; Fig. 2). As a result, the known stratigraphic section of the Valles caldera exceeds 7 km and includes about 1830 m of Quaternary caldera fill,

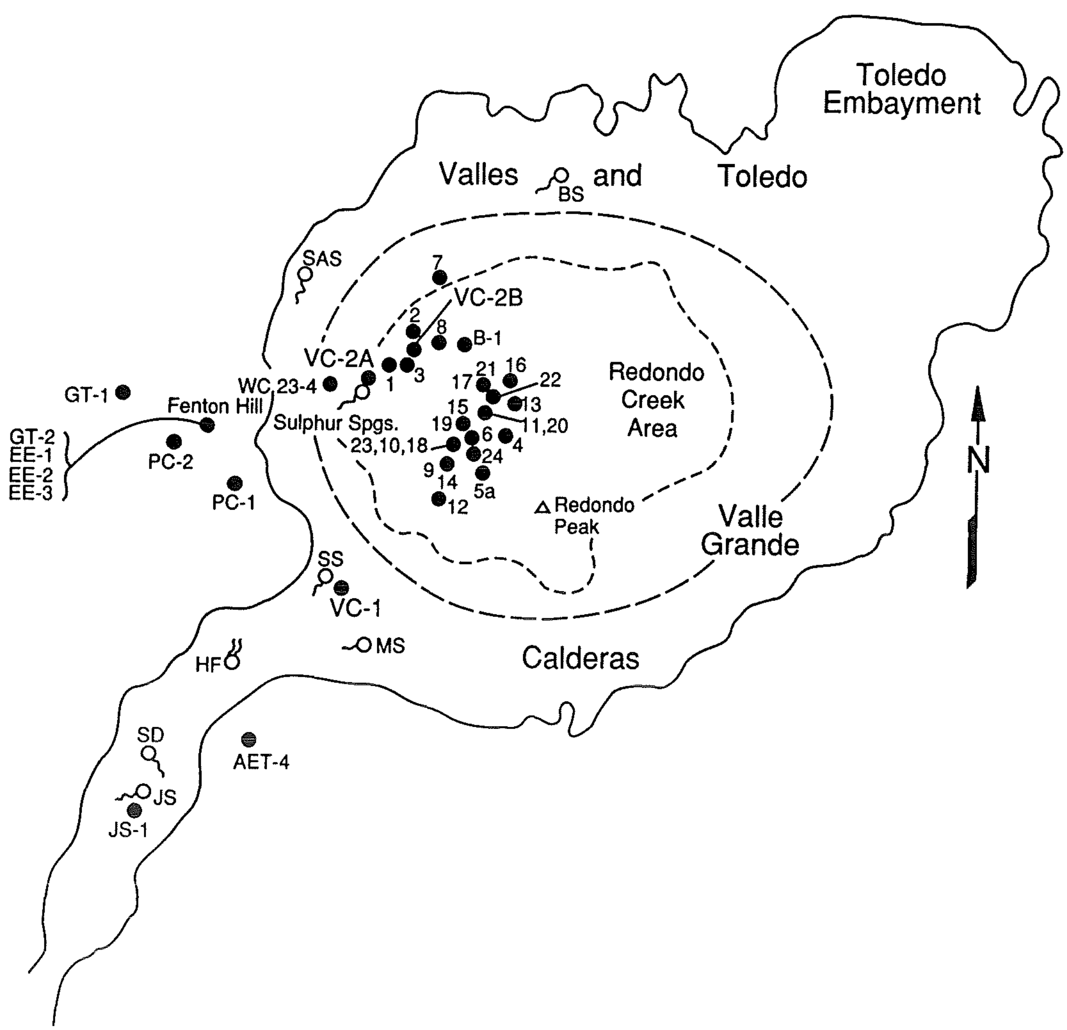


Fig. 2: Map of Valles caldera region showing locations of hot spring areas and geothermal wells. Hot springs: BS = Bathhouse Spring; SAS = San Antonio Hot Spring; SS = Spence Hot Spring; MS = McCauley Spring; SD = Soda Dam; JS = Jemez Springs; HF = Hummingbird Fumarole. All wells with numbers only have "Baca" prefix. B-1 = Westates - Bond #1 well. Long dashed line marks the approximate position of the ring-fracture zone and vent sites for post-caldera rhyolites. Short dashed line marks boundary of resurgent dome.

370 m of Pliocene to Miocene pre-caldera volcanic and rift-filling sedimentary rocks, 800 m of Paleozoic redbeds and carbonates, and over 4000 m of Precambrian crystalline rocks. Excellent discussions of stratigraphy, structure, alteration, and mineralization in the Redondo Creek portion of the Valles geothermal system can be found in Nielson and Hulen, 1984; 1985; and in Hulen and Nielson, 1986. Three scientific core holes have been drilled since 1984 and the objectives of these holes were greatly aided by the subsurface knowledge gained from the earlier wells.

Valles Caldera #1: VC-1 was drilled in August to September of 1984 in the southwest moat of Valles caldera near the intersection of the ring-fracture zone with the pre-caldera Jemez fault zone (Fig. 2). The major objective of VC-1 was to intersect the postulated hydrothermal outflow plume of the caldera at a point approximately midway between the source geothermal reservoir and derivative hot springs in San Diego Canyon. Secondary objectives were to core through the youngest volcanic eruption in the caldera (Banco Bonito obsidian flow), to obtain structural and stratigraphic information in the southwest moat, and to obtain possible information on past and present hydrothermal activity. Engineering objectives were to achieve a depth of at least 600 m, and a temperature of 150°C while obtaining nearly continuous core.

VC-1 achieved all objectives and exceeded all expectations (Goff et al., 1986). Final depth is 856 m and bottom hole temperature is 184°C with >95% core recovery (Fig. 3a) (Rowley et al., 1987). The hydrothermal plume was intersected at depths ≥480 m (Goff et al., 1988). The Banco Bonito obsidian is

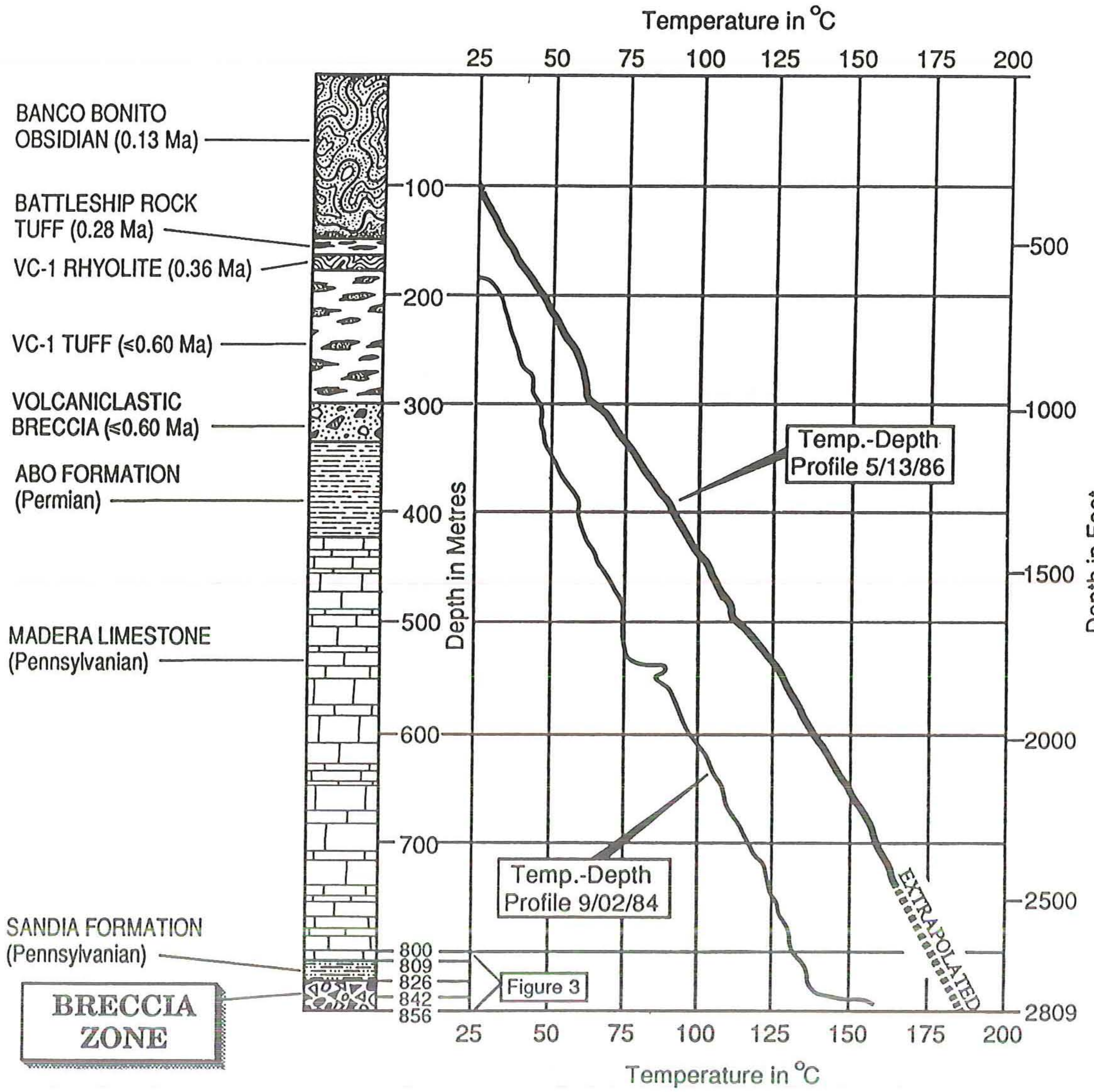
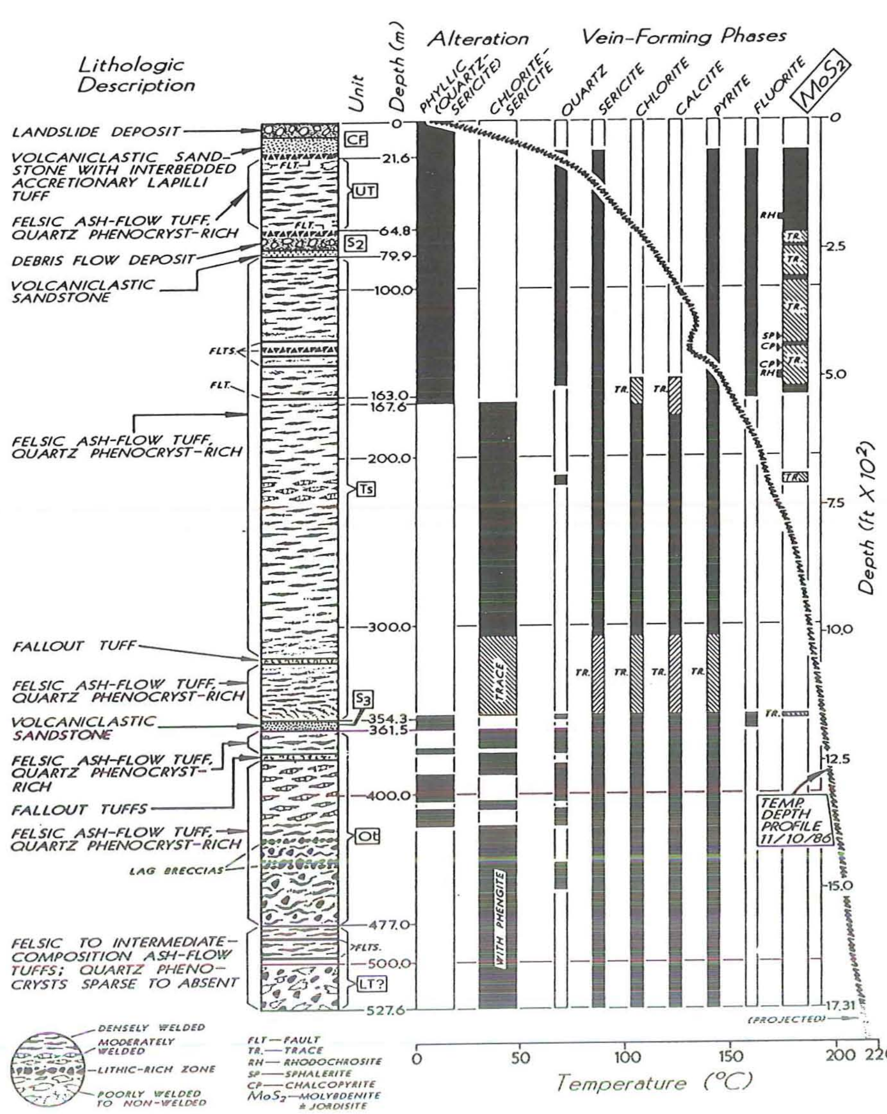


Fig. 3a: Stratigraphy and temperature logs for core hole VC-1 drilled in the southwest moat of Valles caldera, New Mexico. "Fig. 3" refers to the detailed diagram of the complex, mineralized breccia zone discussed by Hulen and Nielson (1988). Last temperature log is extrapolated due to a plug at about 750 m. Locations of specific mineralized zones are shown in Goff et al. (1986) and Keith (1988).

considerably thicker in the southwest moat than expected (~150 m) implying that the flow fills a paleocanyon. In fact, all post-caldera moat deposits are considerably thicker than expected at this location (~335 m) implying several episodes of rapid canyon cutting and backfilling since approximately 0.7 Ma. Paleozoic rocks and Precambrian breccias show several periods of faulting, hydrothermal disruption, and mineralization (Hulen et al., 1988; Nielson et al., 1988). Apparently, maximum temperatures in the hydrothermal plume at 400 to 856 m were once 300°C at about 1 Ma (Geissman, 1988) although salinites were approximately the same as found in the hydrothermal system today (Sasada, 1988). Minerals identified include molybdenite, sphalerite, galena,.chalcopyrite, and arsenopyrite mixed with gangue minerals quartz, calcite, pyrite, and others. Alteration style is propylitic to phyllic. Valles caldera #2a: VC-2A was drilled in September, 1986 in the Sulphur Springs acid-sulfate, hot spring area located near the intersection of the ring-fracture zone with the western margin of the resurgent dome. The major objective of VC-2A was to penetrate the "interface" between the vapor cap and the underlying liquid-dominated (neutral-chloride) reservoir of the Sulphur Springs sub-system of the Valles geothermal system. Secondary objectives were to obtain information on hydrothermal/ore deposit processes and structural and stratigraphic information (as before). Engineering goals were to obtain a depth of 500 m and temperatures of 200°C with high core recovery.

In spite of the acid conditions and constant concern with H_2S control, VC-2A also exceeded all expectations (Goff et al., 1987; Musgrave et al., 1989). Final depth is 528 m at 212°C with ~98% core recovery (Fig. 3b). The top of the Sulphur Springs system consists of an acid condensation zone only 5 m thick overlying a vapor-zone that is about 240 m thick. Surprisingly, there is no sharp interface between vapor- and liquid-dominated zones. Rather, the two zones are separated from each other by a



3b: Generalized lithologic, structural, alteration, and vein-mineralization log for core hole VC-2A, Sulphur Springs, Valles caldera, New Mexico (modified from Hulen et al., 1987).

245 m thick region of brecciated but tightly sealed caldera-fill rocks. A rubble horizon at 490 m that showed lost circulation was stimulated and found to contain typical neutral-chloride fluids that were slightly more concentrated than fluids produced in the Redondo Creek sub-system of the Valles geothermal system (Meeker and Goff, 1988).

The biggest discovery in VC-2A was penetration of molybdenite mineralization in hydrothermally-brecciated, quartz-sericitized tuff at only 25 to 125 m depth (Hulen et al., 1987; Nielson et al., 1988). MoS_2 locally runs 0.56 wt-% and the "moly" is associated with quartz, fluorite, illite, sphalerite, chalcopyrite, and rhodochrosite. Fluid inclusion work indicates temperatures of deposition at 200 to 240°C from fluids whose salinites are again similar to present hydrothermal fluids. Because the above mineral assemblage was deposited from liquid water but resides in an interval of the system where fractures are now filled with low pressure vapor, the top of the liquid-dominated reservoir has descended since formation of the molybdenite deposit. Dating of hydrothermal illite in this deposit indicates that the vapor zone is ≤0.66 Ma (WoldeGabriel and Goff, 1989).

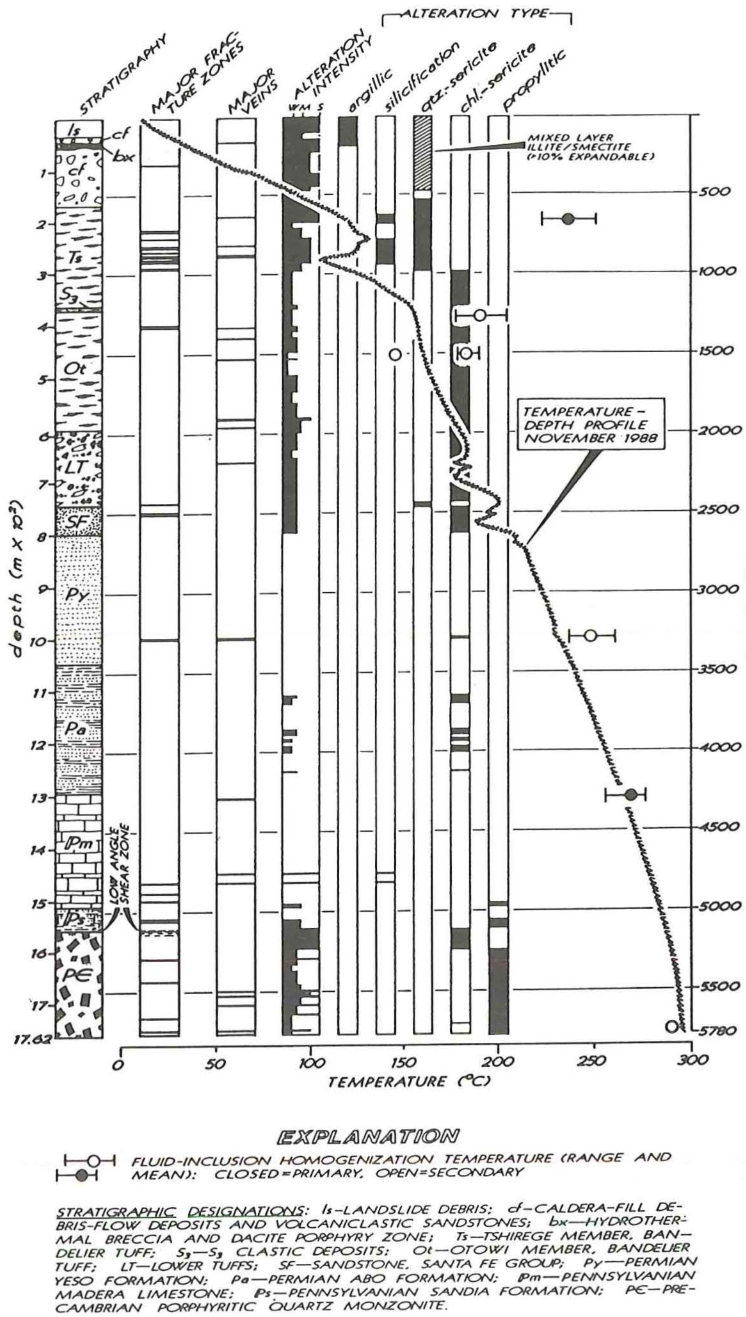
Valles Caldera #2b: VC-2B was drilled from July to October of 1988 approximately 1/2 km east of Sulphur Springs. A companion hole to VC-2A, the major objective of VC-2B was to penetrate the roots of the Sulphur Springs hydrothermal system and to bottom in Precambrian rocks beneath the floor of the caldera. To accomplish this task, VC-2B utilized a much larger diamond core rig than had been used on the two previous holes. Secondary objectives were to obtain yet more information on hydrothermal/ore processes and on stratigraphic and structural relations in the western resurgent dome area. Engineering objectives were to reach a depth of 1750 m and a temperature of approximately 300°C with good core recovery.

VC-2B is another complete success (Gardner et al., 1989; Hulen et al., 1989; Lysne and Jacobson, 1990). Final depth is 1762 m at 295°C with >99% core recovery making VC-2B the deepest, hottest, continuously cored hole in North America (Fig. 3c). Although research in this hole is still continuing, it appears that the liquid-dominated zone of the Sulphur Springs sub-system consists of stacked hydrothermal aquifers that generally show slightly increasing salinity with depth. Brecciation and mineralization in the Paleozoic section is relatively scarce. Most fluid circulation occurs in the caldera fill sequence, the immediately underlying sandstones of the Miocene Santa Fe Group, and the Precambrian quartz monzonite at the bottom of the hole. Fluid inclusion work indicates that the rocks at the top of the well have cooled substantially and that liquid-dominated conditions have changed to present vapor-dominated conditions. The bottom of the well has only cooled 5 to 10°C relative to earlier temperatures, but some inclusions are three to four times more saline than present hydrothermal fluids (Musgrave and Norman, in press). Dates on hydrothermal illites from all horizons show a distinct hydrothermal pulse ≤1 Ma., but do not rule out that older (≤8 Ma) alteration events are still preserved in pre-caldera rocks. These older events would presumably be associated with older volcanic episodes in the Jemez volcanic field (WoldeGabriel and Goff, in press).

Characteristics of the Valles System

Fluid Chemistry: The Valles caldera possesses a diverse suite of thermal waters (Table 1) that are typical of those existing at many high-temperature geothermal systems around the world (Goff and Grigsby, 1982; Henley and Ellis, 1983; Trainer, 1984). Acid-sulfate waters with associated mud pots and fumaroles discharge in the central and western resurgent dome areas, particularly at Sulphur Springs (Goff et al., 1985). These acidic springs result from the condensation of steam mixed with near-surface groundwaters, oxidation of H_2S, and bacterial reactions, to form natural sulfuric acid. Thermal meteoric waters occur at isolated spots throughout the western ring-fracture zone of the caldera. They appear to be mostly dilute groundwaters heated by the relatively high subsurface temperatures present at shallow depths. Deep reservoir waters are encountered by wells in the Redondo Creek and Sulphur Springs areas, beneath the acid-sulfate/vapor zone that caps the liquid-dominated part of the hydrothermal system. They are neutral-chloride in character, with anomalous concentrations of As, B, Br, Cs, Li, Rb, and other trace elements usually enhanced in deep reservoir fluids. Hot springs derived, in part, from deep reservoir waters are encountered outside the southwest caldera margin in San Diego Canyon (along the Jemez fault zone) and in wells drilled in the flanking plateaus. They appear to be mixtures of reservoir waters and different types of cooler groundwaters (Goff et al., 1981; 1988; Vuataz and Goff, 1986). Yet another type of thermal water is encountered in Precambrian basement rocks at the Fenton Hill hot dry rock site and at the WC23-4 well in the ring-fracture zone just west of Sulphur Springs (Grigsby et al., 1984; Meeker et al., 1988). These waters are more concentrated than reservoir waters and their origin is still not resolved (pore-fluid brine? magmatic emanations?). The fluid from the Precambrian zone at the bottom of VC-2B shows a link between reservoir fluids in caldera-fill rocks and the less voluminous Precambrian fluids mentioned above but research on this topic is still continuing.

Vuataz and Goff (1986) presented stable-isotope and tritium data on over 100 thermal and non-thermal waters in the Valles caldera region. They concluded that recharge to the geothermal reservoir comes from meteoric precipitation and slow infiltration of cool groundwater to depth, particularly from the basins of the northern and eastern caldera moat. They also concluded that derivative thermal waters in San Diego Canyon and beneath the



3c: Generalized lithologic, structural, alteration, and vein-mineralization log for core hole VC-2B, Sulphur Springs, Valles caldera, New Mexico (from Hulen et al., 1989).

southwestern plateaus were mixtures of reservoir waters and various cooler groundwaters (Fig. 4). Tritium data could only bracket the mean age of the reservoir water between 60 and 10,000 years. By applying appropriate analytical solutions to equations governing both piston-flow and homogeneously-mixed reservoirs, Shevenell (1990) has calculated a mean residence time of roughly 3000 to 10,000 years for reservoir waters using additional tritium data.

A strontium-isotope study of Valles caldera rocks and hydrothermal fluids shows an extremely good correlation between the rocks and co-existing fluids (Vuataz et al., 1988). Both total Sr and the $^{87}Sr/^{86}Sr$ of the deep reservoirwaters respond quickly to changes of rock type and mixing with cooler waters outside the caldera (Table 2). Inside the caldera, hydrothermal fluids in the Sulphur Springs subsystem are more enriched in $^{87}Sr/^{86}Sr$ than waters in the Redondo Creek area showing that the former are partially circulating in Precambrian and Paleozoic rocks whereas the latter are circulating primarily in Quaternary caldera-fill rocks. Because the caldera floor is progressively down-faulted to greater depths in an eastward direction across the caldera (Goff and Grigsby, 1982; Heiken and Goff, 1983), the thickness of caldera-fill

TABLE 1 - Selected geochemical data for hot springs and geothermal wells, Valles caldera, New Mexico (values in mg/kg except where noted.) Locations shown in Fig. 2; data from Goff et al. (1985), Goff et al. (1988), Grigsby et al. (1984), Shevenell et al. (1987), White (1986) and Goff et al. (1990).[a] Acid-sulfate springs occur at Sulphur Springs (Fig. 2). [b]VC-2A data are average of five analyses (from Goff et al., 1989). Tritium data are not necessarily from samples collected on dates shown.

	Hot springs						Geothermal wells							
	Acid-sulfate springs[a]		Thermal meteoric springs		Derivative hot springs		Pore fluid(?) Precambrain rocks		Sulphur Springs		Redondo Creek		Outflow plume	
	Women's Bathhouse Spring	Footbath Spring	Spence Hot Spring	San Antonio Hot Spring	Soda Dam Spring	Main Jemez Spring	EE-3 Fenton Hill	WC23-4 Thompson Ridge	VC-2A[b]	VC-2B	Baca-13	Baca-15	VC-1	JS-1
Sample	S-6-80	S-4-80	VA-120	VA-128	VA-140	VA-216	V56	VA-116	--	VC2B-90	BA-1	BA-8	VA-209	VA-15
Date	9/80	9/80	1/83	3/83	2/1/84	10/4/85	5/3/83	1/4/83	8/27/87	1/17/90	6/4/82	9/8/82	9/5/85	1/79
Depth,m							>3000	1921	490	1750	>1000	>1000	483.2	152
Temperature, °C	90	33	42.3	41.3	46.8	73.7	>200	233	210	295	278	267	111	60.5
pH (field)	1.40	1.10	7.60	7.88	6.71	6.90	6.67	7.10	6.20	4.74	7.30	7.12	7.06	6.69
SiO_2	168	214	66	74	47	91	156	450	315	882	546	441	74	24
Ca	131	56	5.9	3	342	137	140	46.0	5.9	78.5	3.35	12.4	49	120
Mg	50.0	26.5	1.6	0.5	21.9	5.1	9.8	0.45	0.14	0.76	0.04	0.02	17.8	9.31
Sr	0.14	0.10	0.08	0.06	2.84	0.64	--	1.98	0.76	1.22	0.14	0.13	1.33	0.40
Na	18.9	10.8	50	23	960	638	4830	5890	1842	2350	1146	1196	883	185
K	72	94	1.4	1.8	160	68	730	1020	308	700	244	261	85	29.9
Li	0.17	0.10	0.58	0.06	13.8	8.90	106	68.0	26.5	32.8	17.0	15.0	8.00	2.27
Rb	0.1	--	<0.1	--	1.8	0.7	--	--	4.3	11.5	2.7	3.1	0.4	--
HCO_3	0	0	140	57.3	1488	745	1100	382	273	105	168	48	942	479
SO_4	6400	7900	17.1	9.5	34	40.8	51	95	55	7.8	42	29	56.8	38.0
Cl	<1	<1	8.2	7.0	1480	917	10500	9960	2943	4150	1897	2093	964	243
F	5.2	10.6	0.76	0.79	3.33	4.99	2.3	13.8	5.68	5.67	7.2	5.5	3.94	3.30
Br	<0.4	<0.4	0.10	<0.02	4.60	2.40	71	27.0	5.9	13.6	5.3	5.9	2.80	--
B	0.2	0.2	0.12	<0.01	12.1	7.34	272	96.2	25.6	29.6	17.0	17.0	8.55	2.20
As	0.04	--	0.05	--	1.5	0.7	18.3	7.8	1.92	<0.1?	1.6	2.3	<0.1?	--
δD,‰	-60.8	-82.1	-86.5	-91.6	-84.9	-81.9	--	-71.5	-74.4	-85.2	-86.0	-84.0	-88.0	-85.9
$\delta^{18}O$,‰	-8.45	-20.4	-12.25	-12.7	-10.56	-10.46	--	-5.05	-7.1	-7.5	-10.0	-8.7	-11.35	-11.8
^3H, T.U.	19	13	0.20	0.85	1.29	1.20	--	--	0.47	0.77	0.61	0.18	0.66	1.75

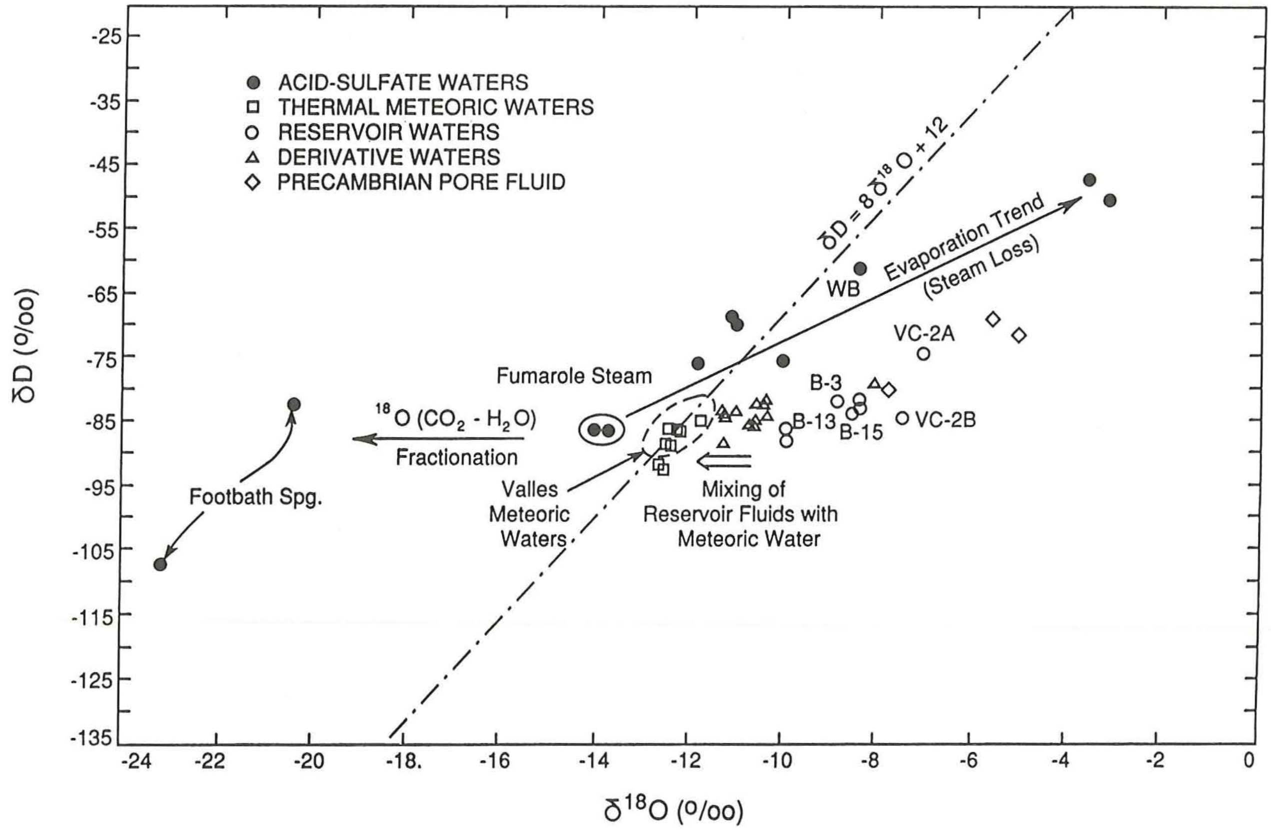


Fig. 4: Plot of δD versus $\delta^{18}O$ for all thermal water types in the Valles caldera region (data from Vuataz and Goff, 1986; Goff et al., 1988; Goff et al., 1989; Musgrave et al., 1989; and unpub.)

and, therefore, the thickness of the producible reservoir increases west to east. Thus, the influence of rock type on strontium-isotopes in the hydrothermal fluids is linked to configuration of the geothermal system in both vertical and horizontal directions.

Magmatic Components: Carbon isotope investigations by several researchers show that Valles hydrothermal fluids have $\delta^{13}C$-CO_2 values ranging from -3 to -5‰. Because there is a 250 m thick section of Paleozoic carbonate rocks underlying the caldera and because the fresh carbonate rocks have $\delta^{13}C$-CO_3 of -3 to -5‰, magmatic carbon is not distinctive geochemically in the Valles system and total reservoir carbon is dominated by carbon originating in Paleozoic rocks (Goff et al., 1985; Truesdell and Janik, 1986; Goff and Shevenell, 1987).

A ^{36}Cl investigation of a limited number of hydrothermal fluids (Phillips et al., 1984) concluded that reservoir chloride was in secular equilibrium with tuffaceous reservoir rocks (half-life of $^{36}Cl = 3 \times 10^5$ years). In addition, "fresh" tuffs equivalent to those filling the caldera depression may contain as much as 2800 ppm Cl (Gardner et al., Table 2, 1986), thus it is not necessary to call upon magmatic chloride as a source for the chloride in reservoir fluids (1500 to 3000 mg/kg Cl, Table 1). Sources of chloride in Precambrian fluids have not been investigated.

Only a few analyses have been made on the ^{34}S-H_2S of Valles fluids (McKibben and Eldridge, 1991; F. Goff, unpub. data) and the values range between -2 to +2‰. Possibly, the sulfur is of magmatic origin. By using the SHRIMP ion microprobe, McKibben and Eldridge have discovered radical sulfur isotope zonation (>22‰) in pyrites in the shallow, phyllic zone of CSDP core hole VC-2A. These zonations are linked to (epithermal?) enhancements of gold in the upper 240 m of the well and, thus, to formation of the vapor cap of the hydrothermal system.

The best evidence for a magmatic component in Valles hydrothermal fluids comes from the ^3He content of noble gases (Smith and Kennedy, 1985; B. M. Kennedy unpub., 1990). In a lateral sense, Table 3 shows that hot springs in the region contain higher $^R/R_A$ as their point of discharge moves closer to the caldera. Zia Hot Well and "C" Spring, for example, are mineral waters associated with the San Juan Basin about 40 km southwest of Valles caldera. The $^R/R_A$ values of these springs are considerably less than values at Sulphur Springs inside the caldera. Also, it can be seen that $^R/R_A$ is slightly greater for deep fluids in the Sulphur Springs sub-system than in the Redondo Creek

TABLE 2 - Comparison beteen measured strontium isotope ratios of geothermal waters and reservoir rocks, Valles caldera, New Mexico; data from Vuataz et al (1988) and Goff et al (1989), except VC-2B (unpub.).

Source	Type[a]	Temp. (°C)	Depth (m)	$(^{87}Sr/^{86}Sr)_m$	Associated Rock[b]
Hot Springs					
Women's Bathhouse Spg.	AS	90	--	0.71061	Bandelier Tuff (0.7110)
Spence Hot Spg.	TM	43	--	0.70845	Bandeler Tuff (0.7110) and Banco Bonito Obsidian (0.70471)
Soda Dam Spg.	D	47	--	0.72193	Altered Paleozoic Limestone (0.7261; 0.7161)
Main Jemez Spg.	D	74	--	0.72174	Altered Plaeozoic Limetone (0.7161) and Shale (0.7214)
Wells					
VC-1	D	111	483	0.71522	Altered Paleozoic Limestone (0.7161) and Calcite Vein (0.7164)
Baca-13	NC	278	>1000	0.70842	} Bandelier Tuff (0.7110) and Pre-caldera Andesite (0.7047)
Baca-15	NC	267	>1000	0.70941	}
VC-2A[c]	NC	210	490	0.71867	Bandelier Tuff (0.7110)
VC-2B	NC	295	1750	0.73690	Precambrian Granodiorite (0.7249) and Gneiss (0.8163)

a AS = acid-sulfate water; TM = thermal meteoric water; NC = neutral-chloride reservoir water; D = derivative water from neutral-chloride reservoir; see Vuataz and Goff (1986) for complete definitions.

b Rock types for which strontium isotope data exist; comprehensive strontium isotope measurements have not been performed on the core or cuttings from the wells except VC-1 and the Fenton Hill (hot dry rock) wells (see Vuataz et al, 1988).

c The poor correspondence between water and rock for this sample implies that the water has partially circulated in deeper rocks having enriched $(^{87}Sr/^{86}Sr)_m$.

TABLE 3 - Helium isotope ratios of geothermal fluids in the Valles caldera region, New Mexico; data for Redondo Creek from Smith and Kennedy (1985); other data from B.M. Kennedy (unpub.).

Source	Temp. (°C)	Distance from Caldera (km)	Depth (m)	R/R_A
Hot Springs				
Zia Hot Well	54	40	--	0.23
"C" Spring	19	37	--	0.32
Main Jemez Spring	74	12	--	1.27
Soda Dam Spring	47	10	--	0.84
Footbath Spring	35	0	--	5.01
Women's Bathhouse Spring	95	0	--	5.98
Redondo Creek Reservoir				
Baca-4	295	--	>1000	3.86
Baca-13	278	--	>1000	4.75
Baca-15	267	--	>1000	4.14
Baca-24	260	--	>1000	3.93
Sulphur Springs Reservoir				
VC-2A (n = 4)	210	--	490	4.2 to 5.0
VC-2B (n=6)	295	--	1750	4.8 to 5.4

a R/R_A means the ratio of $^3He/^4He$ in sample divided by the $^3He/^4He$ in air.

subsystem to the east. In a vertical sense, hydrothermal fluids from the shallow part of the liquid-dominated reservoir at Sulphur Springs contain slightly lower $^R/R_A$ than fluids from the Precambrian horizon at the bottom of VC-2B. This can only mean that the source of high ^3He is not from leaching of tuffaceous caldera-fill rocks by reservoir fluids. Instead, the excess ^3He must originate from a magmatic source beneath the Precambrian "floor" of the caldera.

Isotopic Variations in Host Rocks: Isotopic variations of deuterium and oxygen-18 in host rocks can be compared in Table 4. Caldera-fill rocks are composed primarily of the Tshirege and Otowi Members of the Bandelier Tuff and compositionally similar tuffs and associated sedimentary rocks. Fresh Bandelier Tuff from samples collected outside the caldera has variable δD caused probably by weathering and hydration but has systematic $\delta^{18}O$ of about +8 to +11‰. Altered tuffs in the caldera fill have δD values very similar to the values of present-day meteoric water and underlying hydrothermal fluids, especially those in more voluminous production horizons. The $\delta^{18}O$ values of altered rocks are depleted compared to their fresh equivalents. These characteristics show strong interactions between the host rocks and hydrothermal fluids of meteoric origin as has been noted at extinct calderas of other regions (Criss and Taylor, 1983; Larson and Taylor, 1986).

The vertical isotopic changes in caldera-fill rocks can be reviewed in Fig. 5 where silicate rocks are shown by dots and carbonate rocks by X's. Although alteration is pronounced in tuffaceous rocks of the caldera-fill that contain a high proportion of volcanic glass, $\delta^{18}O$ depletion of Santa Fe Group sandstones is apparently less severe. These sands still display considerable primary porosity and permeability indicating that quartz (major primary mineral) is being leached and that isotope values reflect the original $\delta^{18}O$ of sedimentary quartz grains (mostly of igneous origin). The $\delta^{18}O$ of Precambrian quartz monzonite (-4 to +4‰) reflects the severe alteration that locally appears in this unit. The δD values of the quartz monzonite (~-90‰) show interaction with hydrothermal fluids of meteoric origin.

Carbonate rocks also show the effects of alteration. As mentioned before, "fresh" Paleozoic limestone has $\delta^{13}C$-CO_3 of -3 to -5‰ and $\delta^{18}O$-CO_3 of about +24‰ (Goff et al., 1985). However, the $\delta^{13}C$ of the carbonate rocks beneath the caldera are somewhat depleted to values of -8 to -4‰ in $\delta^{13}C$ and significantly depleted in $\delta^{18}O$. Similar depletions were noted in 38 samples of carbonate rock from VC-1 drilled just outside the caldera depression within the hydrothermal outflow plume (Goff et al., 1986).

It is not necessary, of course, to rely on isotope data to see the effects of widespread hydrothermal alteration in both intra-caldera and pre-caldera rocks (Goff and Gardner, 1980; Charles et al., 1986; Hulen and Nielson, 1986; 1988; Hulen et al., 1987; Keith, 1988; Neilson et al., 1988; WoldeGabriel, 1990). Generally speaking, alteration style changes top to bottom from advanced argillic to argillic to phyllic to propylitic to calc-silicate depending primarily on the pH of the fluids, the temperature of the fluids, the depth or position in the system, the amount of fracturing, and volume of fluid in contact with rock. Hydrothermal breccias are common in all parts of the system (Hulen et al., 1987; Hulen and Nielson, 1988).

TABLE 4 - Summary of deuterium and oxygen-18 values of fresh Bandelier Tuff, altered tuff, reservoir fluids, and present meteoric water, Valles caldera, New Mexico; data unpublished except where noted.

Rock Type	δD (‰)	$\delta^{18}O$ (‰)
"Fresh" Bandelier Tuff		
Ashfall pumice (n=2)	-150 to -53	+10.7 ± 0.1
Whole rock tuff (n=5)		+8.2 ± 0.9
Quartz (n=3)	--	+7.3 ± 0.5
Sanidine (n=4)	--	+7.4 ± 0.3
Altered tuff, VC-2A		
Whole rock core (n=11)	-95 ± 20	+4.8 ± 1.0
Altered tuff, VC-2B		
Whole rock core (n=8)	-87 ± 6	+3.7 ± 0.5
Altered tuff, B-4 and B-7[a]		
Cuttings (n=6)	-95 ± 4	+1.7 ± 0.9
Reservoir Fluids[b]	-90 to -70	-10 to -5
Present Meteoric Water[b]	-90 to -82	-13 to -11

a Data from Lambert and Epstein, 1980; B-4 and B-7 mean Baca-4 and Baca-7 wells, respectively.

b Data from Vuataz and Goff (1986) and other references listed in Table 1.

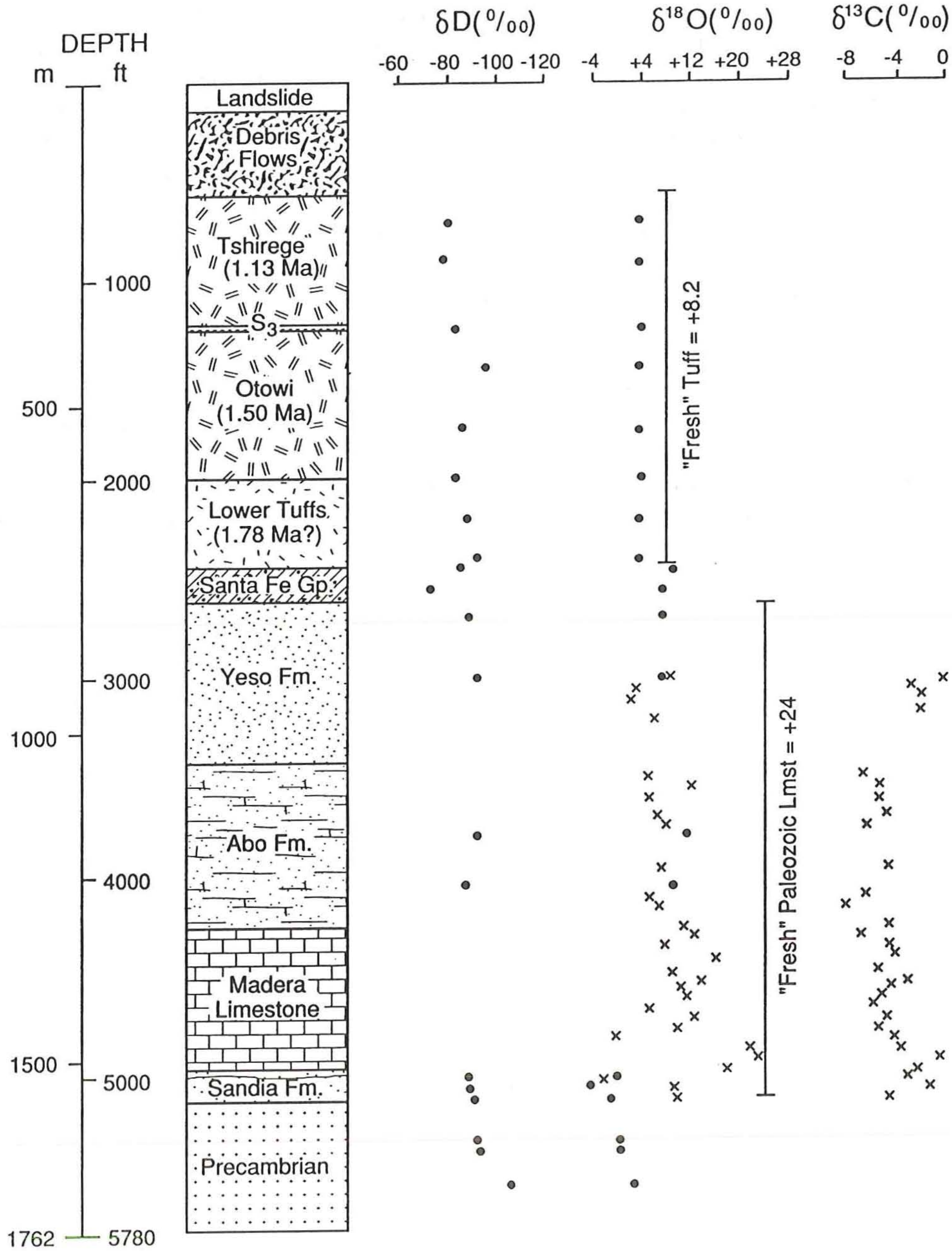


Fig. 5: Plot of deuterium, oxygen-18, and carbon-13 values of whole rock samples versus depth and stratigraphy, VC-2B, Valles caldera, New Mexico. Dots are "silicate" rocks (tuffs, sandstones, shales, quartz monzonite) and x's are "carbonate" rocks. The $\delta^{18}O$ values of average "fresh" Bandelier Tuff and average "fresh" Madera Limestone can be compared to individual samples to detect pervasive interaction of rock with meteoric water in a high-temperature environment.

Veins occur throughout the system but are most common in Quaternary caldera-fill and Precambrian crystalline rocks or near fault zones (Hulen et al., 1989). A list of the common alteration, vein, and ore minerals identified in the deeper, high-temperature zones in the liquid-dominated portion of the Valles system is given in Table 5. For a discussion of the advanced-argillic and argillic minerals occurring in near-surface, acid-sulfate hot spring areas see Charles et al. (1986).

Configuration of System(s)

The general configuration of the Valles caldera hydrothermal system can be studied in Fig. 6 (Goff et al., 1988; 1989). The hydrogeochemistry of thermal and non-thermal waters in combination with surface geology and the wealth of available geologic and geophysical data in the 40 odd wells drilled inside and outside the caldera place relatively tight constraints on this model (see also

Faust et al., 1984). Meteoric precipitation recharges the hydrothermal system, which equilibrates at depths of 2 - 3 km and temperatures approaching 300°C in caldera-fill tuffs and pre-caldera sedimentary and volcanic rocks. Thermal waters rise convectively to depths of roughly 500 to 600 m before flowing laterally to the southwest toward the caldera wall. A vapor zone that contains steam, CO_2, H_2S, and other volatile components has formed above a liquid-dominated zone whose top is at a temperature of approximately 200°C. Acid springs, mud pots, and fumaroles occur in a surface condensation zone only a few meters thick. The lateral flow system crosses the southwestern caldera wall above Precambrian basement through the Jemez fault zone and semipermeable Paleozoic strata. Mixing of reservoir water and other groundwaters occurs along the lateral flow path to form the derivative fluids that issue as hot springs or flow in subsurface aquifers southwest of the caldera.

The model in Fig. 6 is relatively simple in concept and resembles general models of volcanically driven hydrothermal systems presented by Henly and Ellis (1983). Differences between the models occur primarily in structural setting and direction of lateral flow due to differences in tectonics and hydrogeology (see also Goff et al., 1988). We know, however, that the hydrothermal system is more complex when examined in detail. Smith and Kennedy (1985) and Truesdell and Janik (1986) demonstrated that the Redondo Creek subsystem contains two somewhat discrete reservoir fluids with subtle differences in chemical and isotopic composition.

A more detailed model of the Sulfur Springs subsystem is shown in Fig. 7. In this model, it can be seen that a set of superimposed or "stacked" reservoirs is restricted to highly-fractured, tuffaceous, caldera-fill rocks and pre-caldera volcanic and sedimentary rocks of Quaternary to Tertiary age. Hydrothermal fluids at deeper levels appear

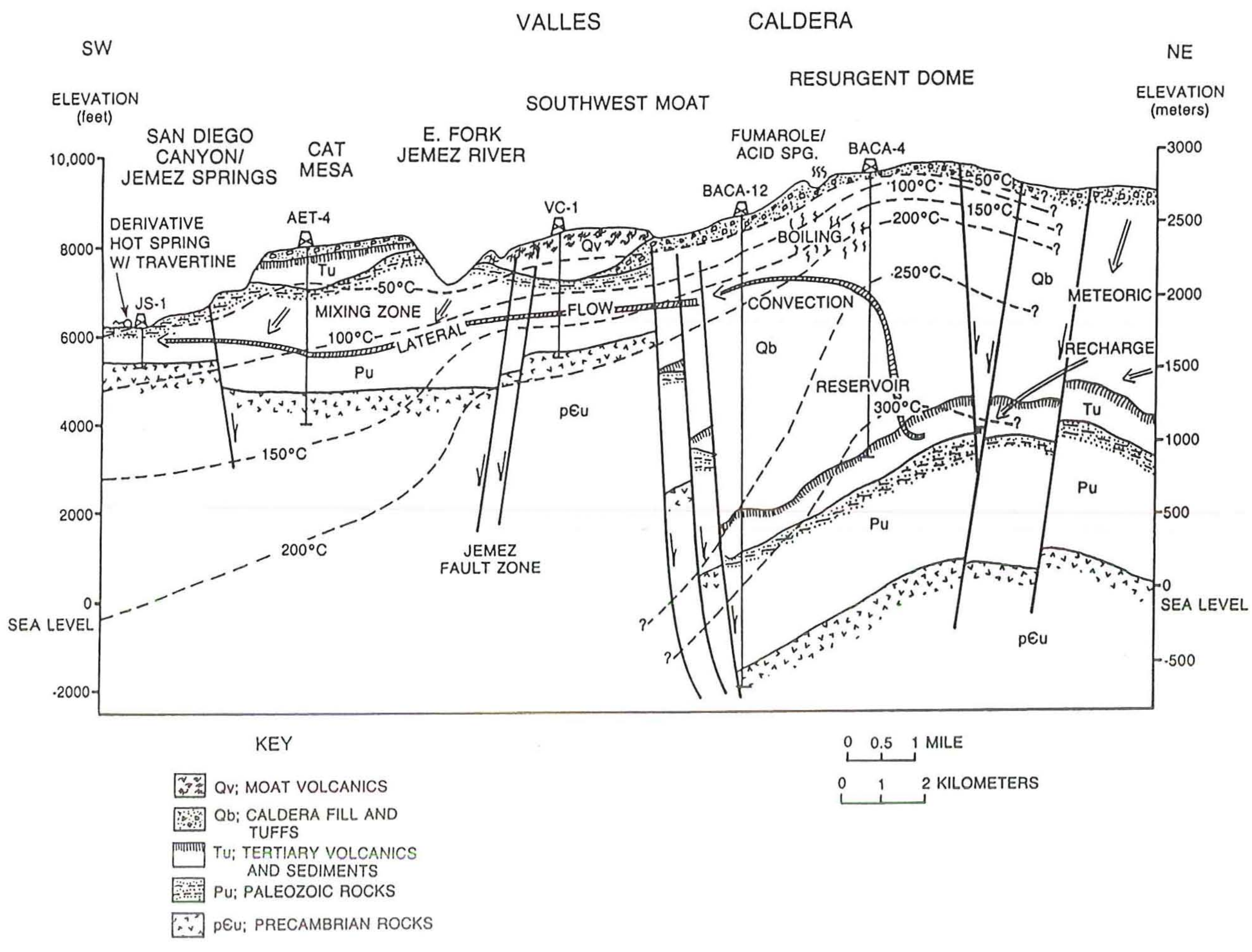


Fig. 6: Cross-section of southwest margin, Valles caldera showing general configuration of the active hydrothermal system (modified from Goff et al., 1988). Surface geology, wellbore data, geophysics and fluid geochemistry provide tight constraints on this model.

TABLE 5 - Lists of secondary/vein and ore minerals identified to date in the phyllic, propyllitic, and calc-silicate alteration zones of the Valles caldera hydrothermal system; data from Hulen and Nielson (1986; 1988), Keith (1988), Hulen et al (1987; 1989), and unpublished.

Secondary/Vein	Ore
Quartz	Molybdenite
Calcite	Sphalerite
Illite	Chalcopyrite
Chlorite	Galena
Adularia	Barite
Epidote	Rhodochrosite
Wairakite	Pyrargyrite
Anhydrite	Stibnite
Fluorite	Arsenopyrite
Hematite	Tetradymite (?)
Actinolite	
Diopside	
Pyrite	

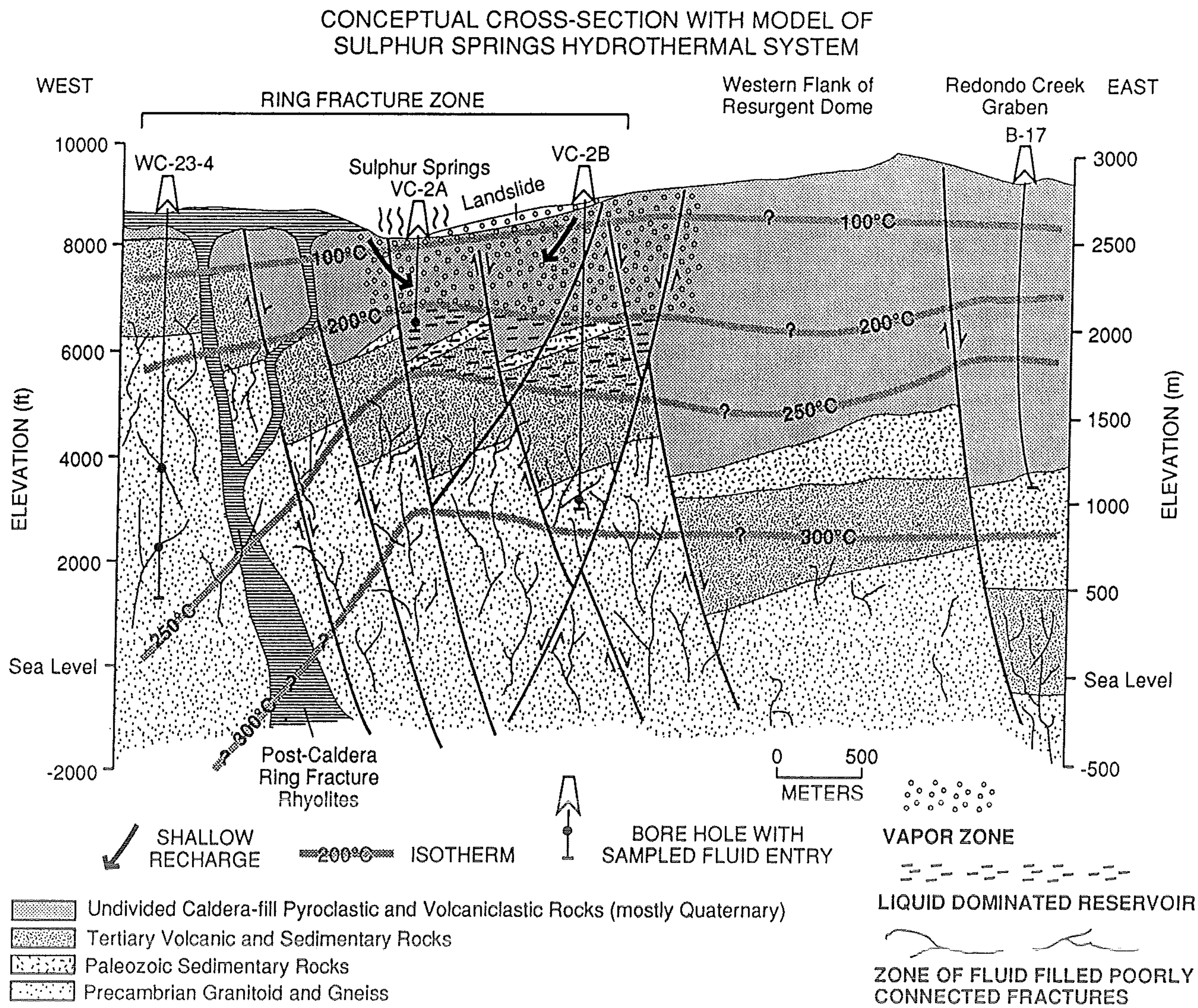


Fig. 7: Cross-section of Sulphur Springs sub-system, Valles hydrothermal system showing detailed configuration of a major upflow zone in the caldera (from Gardner et al., 1989).

to be restricted to sets of poorly-connected, fluid-filled fractures (Gardner et al., 1989). This condition appears to be particularly true for the Paleozoic section. In general, as depth increases, fluid temperatures and salinities increase. Although the hydrothermal system is overwhelmingly dominated by meteoric water, deep reservoir waters contain elevated $^3He/^4He$ that can only be coming from the crystallizing pluton beneath the caldera.

Evolution of System(s)

Hydrothermal alteration occurs in pre-caldera volcanic rocks throughout the central and southeastern Valles caldera region. Based on surface mapping and crosscutting relations between veins and intrusive rocks, Wronkowicz et al. (1984) and Gardner et al. (1986) concluded that the gold-bearing quartz veins and hydrothermally altered rocks of the Cochiti mining district in the southeast Jemez Mountains were formed about 6 Ma. Recent K-Ar dates by WoldeGabriel and Goff (1989) on hydrothermal illites pinpoint this event at 6.5 to 5.6 Ma. The latter authors have used stable isotope evidence to argue that the epithermal deposit was formed from a hydrothermal system composed predominantly of meteoric water. Wronkowicz et al. (1984) have demonstrated from fluid-inclusion studies that the Cochiti veins were formed at temperatures of about 195 to 375°C and that the fluids had salinities of about 0 to 4.9 wt-% NaCl (equivalent).

Gardner et al. (1986) also suggested that other hydrothermal events occurred in the time frame of 10 to 7 Ma in mafic to intermediate rocks of the southern Jemez volcanic field. K-Ar dates on hydrothermal illites from altered volcanic rocks from the northern and western caldera wall and from Paleozoic rocks in VC-1 indicate different episodes of hydrothermal activity throughout a period lasting from ≥13 Ma to 1.5 Ma (Ghazi and Wampler, 1987; WoldeGabriel, 1990). While the absolute ages of most of these events are not verified, a widespread event at about 8 Ma appears certain (WoldeGabriel, 1990). Some fluid inclusions in VC-1 core from Paleozoic and Precambrian rocks have cooler homogenization temperatures and higher salinities than those identified as part of the Valles hydrothermal event, thus, pre-Valles age hydrothermal activity was widespread (Sasada, 1988).

Much more is known about the evolution of the hydrothermal system created after formation of Valles caldera (Table 6). Goff and Shevenell (1987) applied U-Th disequilibrium and U-U dating techniques to the present and ancient travertine deposits at Soda Dam hot springs to show that the hydrothermal system was initiated at about 1 Ma. Ghazi and Wampler (1987) obtained a K-Ar age of 1.0 ± 0.1 Ma on hydrothermal illite from Paleozoic limestone at about 500 m depth in core hole VC-1. A similar age was obtained by WoldeGabriel (1990) by the same methods. Geissman (1988) obtained a reverse magnetic polarity of unique magnetic character on hydrothermally altered Paleozoic rocks in VC-1 and concluded that high-temperature (300°C) fluids permeated the rocks ≥0.98 Ma. WoldeGabriel and Goff (1989) dated hydrothermal illite throughout the VC-2A core by K-Ar and obtained ages of 0.83 to 0.66 Ma. WoldeGabriel and Goff (in press) obtained ages of ≤1 Ma from Quaternary caldera-fill rocks and from altered andesite pebbles incorporated into the Permian Abo Formation in VC-2B by similar methods, although other dates in the pre-caldera rocks of this hole have ages as old as 8 Ma. Clearly, caldera formation and post-caldera rhyolitic eruptions have provided sufficient heat to continuously drive the Valles hydrothermal system from 1.14 Ma to present (Table 6).

Lateral flow has been an essential characteristic of the hydrothermal system during the last 1 Ma. Dates on the travertine deposits of Soda Dam (Goff and Shevenell, 1987) and U-Th dates on calcite veins in VC-1 core (Sturchio and Binz, 1988) indicate that the hydrothermal fluids have continuously flowed out of the caldera along the Jemez fault zone throughout this period.

Goff and Shevenell(1987) suggested that the vapor cap of the hydrothermal system began to form about 0.5 Ma. This age corresponds to cessation of travertine deposition at the oldest travertine deposit at Soda Dam and coincides with the age of breaching of the southwest caldera wall and draining of intracaldera lakes (Doell et al., 1969; Nielson and Hulen, 1984). The thick moat-filling sequence penetrated by VC-1 is <0.7 Ma by paleomagnetic methods (Geissman, 1988) and ≤0.6 Ma by K-Ar indicating that a deep canyon occurred in the southwest moat during this critical time period. Such a deep canyon could have been cut during catastrophic draining of intracaldera lakes. In addition, the "moly" deposit in VC-2A formed at 0.66 Ma implying that the vapor zone is less than that age (WoldeGabriel and Goff, 1989). It has been postulated that draining of intracaldera lakes and resulting loss of hydraulic head on the hydrothermal system caused the maximum elevation of hydrothermal fluids in the geothermal reservoir to drop (Trainer, 1984).

Fluid inclusion studies in the VC-2A and VC-2B cores (Sasada and Goff, 1988; Musgrave et al., 1989) verify that the boiling point curve is presently much lower than it once was in the past (Fig. 8) and that the change occurred rather suddenly. Rapid erosion or sudden draining of the intracaldera lakes could have caused this shift in the position of the boiling point curve. If the vapor zone formed as a result of hese sudden changes in caldera hydrology, this explanation is drastically different than the model proposed by White et al. (1971) for the formation of vapor-dominated systems at other geothermal sites. A series of diagrams summarizing the evolution of the Valles hydrothermal system is shown in Fig. 9.

Conclusions

The Valles hydrothermal system is configured like most volcanic-hydrothermal systems the world over. The basic hydrologic elements consist of local meteoric

TABLE 6 - Geochronology of volcanic, hydrothermal and geomorphic events associated with Valles caldera, New Mexico (modified from Goff et al, 1989).

	Event	Age	Method	Reference
1.	Eruption of Tshirege Member, Bandelier Tuff; formation of Valles caldera	1.13 Ma	K/Ar; Ar/Ar	Doell et al, 1968; Izett et al, 1981; Spell et al, 1990
2.	Uplift of resurgent dome; eruption of early rhyolites	~1.0 Ma	Inference	Smith and Bailey, 1968
3.	Eruption of northern arc of postcaldera moat rhyolites.	1.04-0.45 Ma	K/Ar	Doell et al, 1968
4.	Initial formation of Valles hydrothermal system and voluminous travertine deposit at Soda Dam.	~1.0 Ma	U/U	Goff and Shevenell, 1987
		1.0 Ma	K/Ar	Ghazi and Wampler, 1987
		>0.97 Ma	Paleomag.	Geissman, 1988
5.	Formation of Sulphur Springs subsystem of Valles hydrothermal system.	≤1.09 Ma	K/Ar	WoldeGabriel and Goff, 1989; in press
6.	Formation of Sulphur Springs molybdenite deposit.	≥0.66 Ma	K/Ar	WoldeGabriel and Goff, 1989
7.	Breaching of SW caldera wall; deep erosion of SW caldera moat zone	~0.5 Ma	Inference	Doell et al, 1968; Nielson and Hulen, 1984
		~0.5 Ma	K/Ar	Hulen and Nielson, 1988
8.	Cessation of voluminous travertine deposition at Soda Dam.	0.48 Ma	U/U	Goff and Shevenell, 1987
9.	Initial formation of vapor zone above liquid-dominated hydrothermal system.	≤0.5 Ma	Inference	Goff and Shevenell, 1987
10.	Eruption of southern cluster of postcaldera moat rhyolites.	0.49-0.13 Ma	K/Ar; FT; U/Th	Doell et al, 1968; Marvin and Dobson, 1979; Gardner et al, 1986; Self et al, 1988
11.	Partial filling of SW caldera breach.	≤0.65 Ma	Paleomag.	Geissman, 1988
		<0.5 Ma	K/Ar	Hulen and Nielson, 1988
12.	Formation of hydrothermal calcite veins along Jemez fault zone beneath SW caldera moat.	>400-95 Ka	U/Th	Sturchio and Binz, 1988
13.	Late hydrothermal fluorite vug in Sulphur Springs subsystem.	~150 Ka?	U/Th	N. Sturchio, unpub. data
14.	Second period of travertine deposition at Soda Dam.	110-60 Ka	U/Th	Goff and Shevenell, 1987
15.	Last pulse of thermal activity at Fenton Hill.	40-10 Ka	Transient analysis	Harrison et al, 1986
16.	Final period of travertine deposition at Soda Dam.	5 Ka-present	U/Th	Goff and Shevenell, 1987

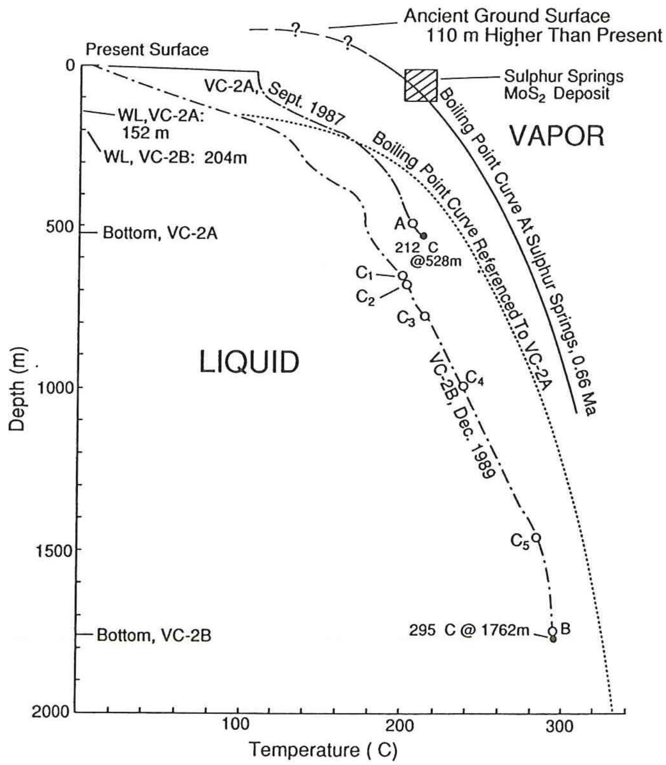


Fig 8: Plot of depth versus temperature for core holes VC-2A and VC-2B, Valles caldera, New Mexico. Log for VC-2A was obtained after several flow tests, thus the upper part of curve reflects steam above the water column. The boiling point to depth is referenced to the water level (WL) in VC-2A. Points A and B refer to the positions of fluid horizons that have been flow tested to date (see analyses in Table 1). Points C1 to C5 represent horizons that have been recently perforated and for which flow tests have just begun. Present Sulphur Springs system has a vapor cap in upper 150 m. Reservoir beneath is liquid-dominated. A boiling point curve representing the past Sulphur Springs system is shown based on fluid inclusion measurements and the mineral assemblage in the "moly deposit". This past curve implies that the top of the liquid-dominated reservoir was once much higher, and that either rapid erosion or draining of lakes changed the local hydrology. This change in hydrology occurred ≤ 0.66 Ma and probably at 0.5 Ma.

recharge, equilibration at temperatures approaching 300°C, convective upflow along faults and fractures, and lateral flow along structures that cut the southwestern caldera wall (Jemez fault zone). A vapor zone and acid-sulfate condensation zone originate from subsurface boiling (~200°C) above a liquid-dominated reservoir inside the caldera. However, there is no sharp interface between vapor- and liquid-dominated zones. The lateral flow system produces a tongue of mixed reservoir water and cooler groundwaters in Paleozoic rocks around the southwest caldera margin. Magmatic/mantle components in the hydrothermal system are difficult to identify but include excess ^3He and possibly, sulfur.

Episodic hydrothermal events have occurred in the Jemez volcanic field for at least the last 8 Ma (e.g., Cochiti gold-silver district at 6.5-5.6 Ma). The Valles hydrothermal system has been continuously active for the last 1 m.y., but the vapor zone first formed about 0.5 Ma. Creation of the vapor zone is linked to breaching of the southwestern caldera wall by the ancestral Jemez River, draining of intracaldera lakes, and resulting loss of hydraulic head on the liquid-dominated hydrothermal reservoir.

Hydrothermal alteration and ore mineralization in Valles caldera resemble those found at many fossil calderas hosting economic ore deposits. Host rocks of most ages and compositions have been drastically altered by reaction with hot, meteoric waters. Alteration style ranges from advanced argillic to anhydrous calc-silicate, depending on depth, location, and other factors. Secondary mineral assemblages and fluid-inclusion studies indicate temperatures of formation and salinities that are either similar or only slightly hotter and more concentrated than those presently occurring in the system today, although a relatively complex evolutionary history can be unraveled. Sub-ore grade molybdenite (up to 0.56 wt% MoS_2) is the primary ore mineral found so far, but Cu, Pb, Zn, Mn, Ag, As, Sb, and Te (?) minerals have also been identified.

Students of magma-hydrothermal systems should recognize that the Valles system is cooling down, losing wide-spread permeability, shrinking in size, and becoming more localized since it was initially formed (Goff and Shevenell, 1987, p. 301). Post-caldera eruptions of rhyolite have replenished heat in the upper 2 to 3 km of the caldera as recently as 0.13 Ma, but none of these eruptions compare in size and heat content, or in ability to create fracture networks, to the caldera-forming event at 1.14 Ma. Simple thermal models applied by Kolstad and McGetchin (1978) to Valles caldera and by Smith and Shaw (1975) to other Quaternary magmatic systems imply that crystallization of the Valles pluton is nearly complete. A few petrologic and geophysical studies indicate that small pots of magma or partial melt still exist at depths 6 to 9 km in the pluton beneath the caldera (Suhr, 1981; Ankeny et al., 1986; Self et al. 1988; Roberts et al., 1991). Thus, the Valles magma-hydrothermal system should be viewed as a relatively mature system, although it remains very hot and incredibly fascinating to study.

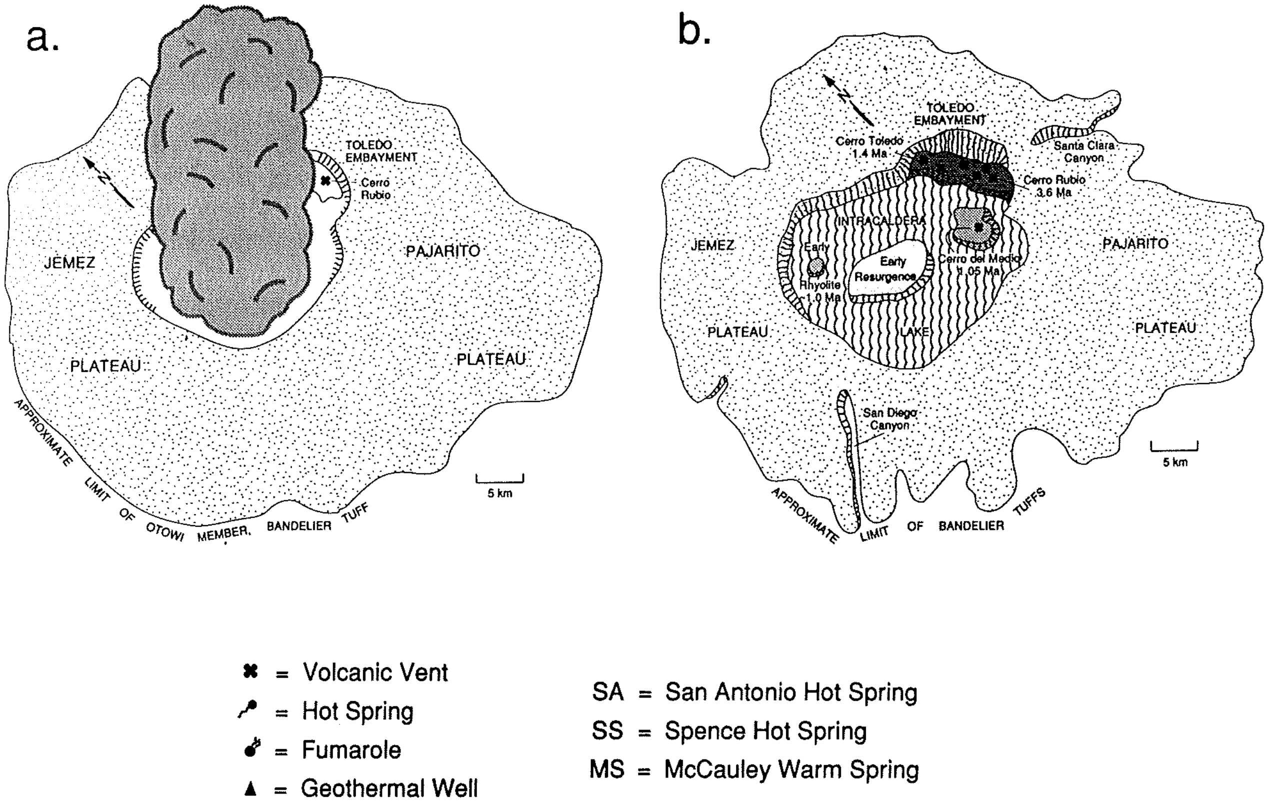
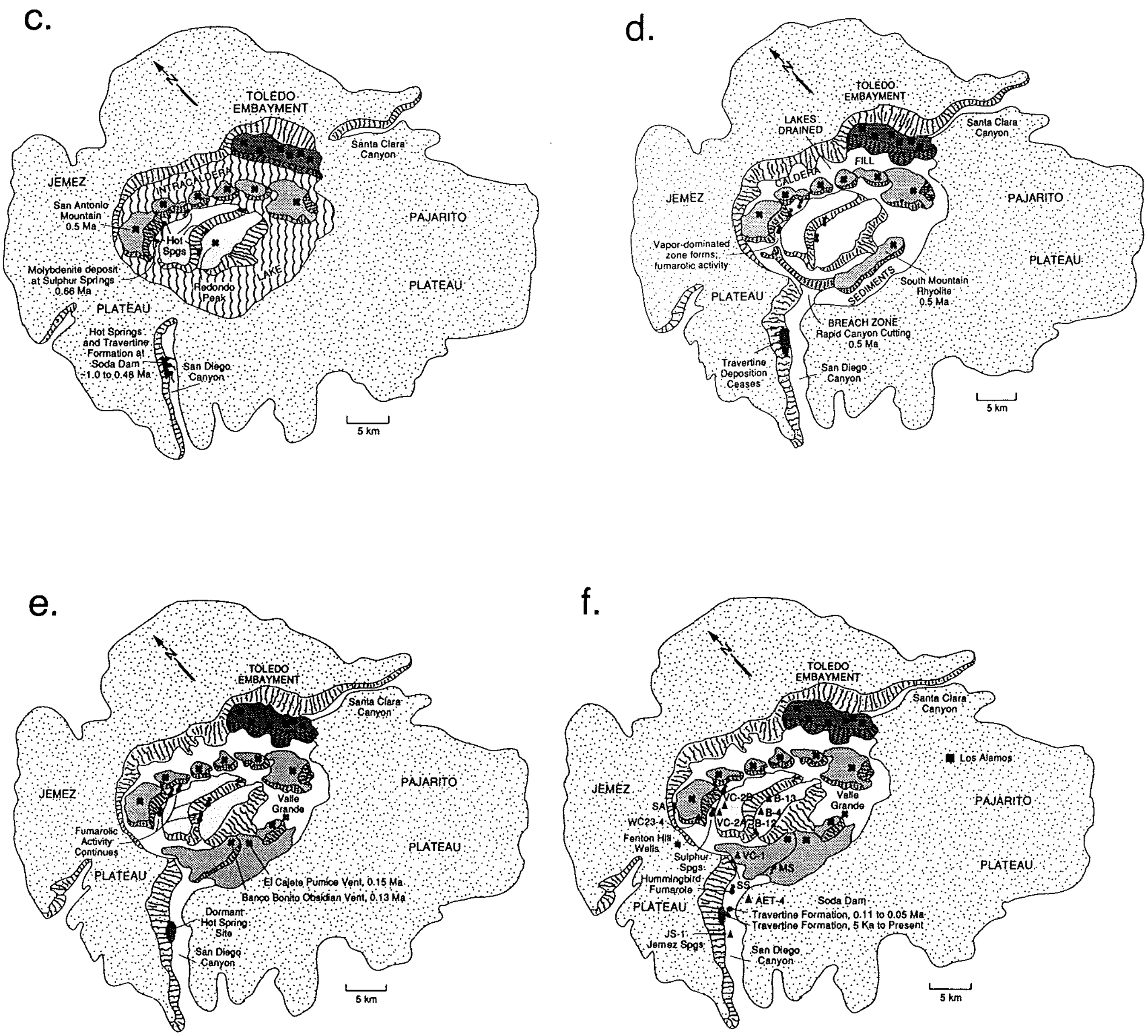


Fig. 9: Diagrams showing the evolution of the Valles caldera hydrothermal system and post-caldera events. 9a: First catastrophic event; formation of Valles caldera (1.14 Ma) and obliteration of Toledo caldera (1.50 Ma)(the earlier caldera resulted in deposition of the Otowi Member of Bandelier Tuff); partial destruction of the Toledo embayment (Heiken et al., 1986; Stix et al., 1988). 9b: Period from 1.14 to about 1.0 Ma; first intracaldera lake(s); initial growth of resurgent dome and eruption of early post-caldera rhyolites; first moat rhyolite at Cerro del Medio; rapid erosion in San Diego Canyon (Smith and Bailey, 1968; Goff and Shevenell, 1987). 9c: Period from about 1.0 to 0.5 Ma; resurgence complete; continued eruption of northern moat rhyolites; initiation of large-scale, intracaldera hydrothermal circulation; hot spring activity inside and outside caldera; travertine formation in San Diego canyon; molybdenite deposition beneath Sulphur Springs. 9d: Second catastropic event; southwest caldera wall breached (about 0.5 Ma); caldera lakes drain; deep canyon cutting in upper San Diego Canyon and southwest moat; liquid-dominated hydrothermal system descends; vapor-dominated system forms; travertine deposition in San Diego canyon ceases. 9e: Period from about 0.5 to 0.13 Ma; southern cluster of moat rhyolites is erupted and partially fills southwest breach; fumarolic activity continues in resurgent dome area; hot spring activity in San Diego canyon is dormant. 9f: Period from 0.13 Ma to present; two more periods of travertine deposition and hot spring activity in San Diego canyon; liquid-dominated reservoir becomes localized beneath the Redondo Creek and Sulphur Springs areas of the resurgent dome.

Fig. 9 (cont'd.)


c.
TOLEDO EMBAYMENT
Santa Clara Canyon
JEMEZ
INTRACALDERA
San Antonio Mountain 0.5 Ma
Hot Spgs
PAJARITO
Molybdenite deposit at Sulphur Springs 0.66 Ma
Redondo Peak
LAKE
PLATEAU
PLATEAU
Hot Springs and Travertine Formation at Soda Dam 1.0 to 0.48 Ma
San Diego Canyon
5 km
d.
TOLEDO EMBAYMENT
LAKES DRAINED
Santa Clara Canyon
CALDERA
FILL
JEMEZ
PAJARITO
Vapor-dominated zone forms; fumarolic activity
PLATEAU
SEDIMENTS
South Mountain Rhyolite 0.5 Ma
PLATEAU
BREACH ZONE Rapid Canyon Cutting 0.5 Ma
Travertine Deposition Ceases
San Diego Canyon
5 km
e.
TOLEDO EMBAYMENT
Santa Clara Canyon
PAJARITO
JEMEZ
Valle Grande
Fumarolic Activity Continues
PLATEAU
PLATEAU
El Cajete Pumice Vent, 0.15 Ma
Banco Bonito Obsidian Vent, 0.13 Ma
Dormant Hot Spring Site
San Diego Canyon
5 km
f.
TOLEDO EMBAYMENT
Santa Clara Canyon
Los Alamos
JEMEZ
SA
VC-2B
B-13
B-4
B-12
VC-2A
Valle Grande
PAJARITO
WC23-4
Fenton Hill Wells
VC-1
MS
PLATEAU
Sulphur Spgs
Hummingbird Fumarole
SS
AET-4
Soda Dam
PLATEAU
Travertine Formation, 0.11 to 0.05 Ma
Travertine Formation, 5 Ka to Present
JS-1
Jemez Spgs
San Diego Canyon
5 km

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