GEOTHERMAL POTENTIAL OF VALLES CALDERA, NEW MEXICO

Fraser Goff
Los Alamos National Laboratory
Los Alamos, NM

Valles caldera is a large, Quaternary silicic volcanic complex that contains a hot, but relatively small, liquid-dominated geothermal resource (210º to 300ºC; 20 MWe proven). The portion of the caldera having geothermal significance is now part of the recently created Valles Caldera National Preserve. Past development problems, small size, an uncertain power market, and new public status make future development of the Valles geothermal resource uncertain.

GEOLOGIC AND GEOPHYSICAL SETTING

Valles caldera is a 22-km-diameter resurgent cauldron that formed in the approximate center of the Jemez Mountains volcanic field (JMVF) at about 1.2 Ma (Figures 1 and 2)(Smith and Bailey, 1968). The JMVF consists primarily of calc-alkaline basalt, andesite, dacite, and rhyolite erupted from about 13 Ma to 55 ka (Toyoda, et al., 1995; Goff and Gardner, in press). Volumetrically, two-pyroxene andesite domes and lavas are most abundant (about 1,000 km^3), but volcanism culminated with formation of the Valles and comparably sized Toledo calderas, their high-silica rhyolite igrimbrites (Bandelier Tuffs), and post-caldera rhyolitic products (roughly 600 km^3) (Gardner, et al., 1986). The JMVF lies at the intersection of the Jemez Lineament (JL) and the western margin of the Rio Grande Rift (RGR). The JL is an alignment of volcanic centers formed in Miocene to Holocene time along what is thought to be a reactivated Precambrian structure (Aldrich, 1986). There are no age or compositional progressions along the JL, but by far the largest volume of erupted material occurs in the JMVF. The RGR is an intraplate zone of E-W extension and consists of a series of half-grabens extending from southern Colorado into northern Mexico. The northern RGR first formed about 25 Ma. Pleistocene volcanism associated with the RGR has been predominately basaltic (Riecker, 1979).

Geothermal and scientific drilling from 1959 to 1988 produced enormous amounts of information on the internal stratigraphy, structure, geophysical character, hydrothermal alteration, and hydrothermal fluids within the Valles caldera (Nielson and Hulen, 1984; Goff et al., 1989; Goff and Gardner, 1994). A generalized east-to-west cross section of

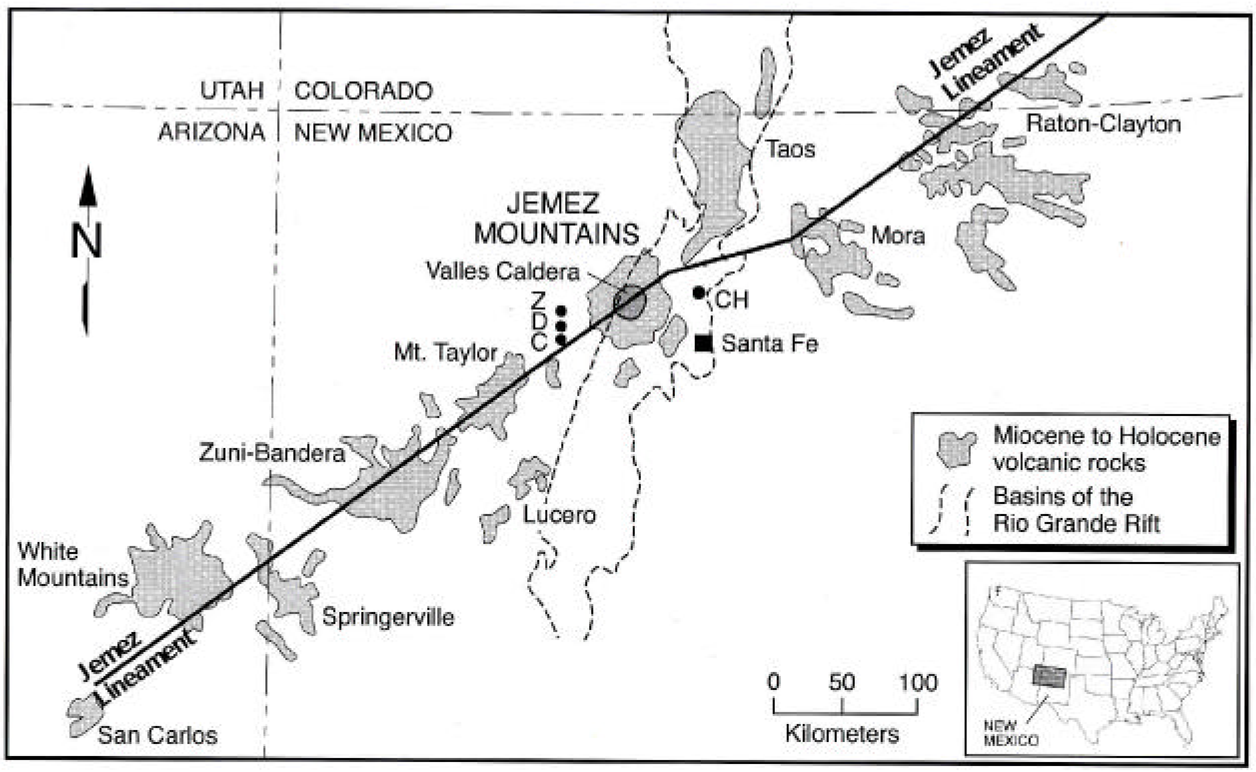

Figure 1. Location map of the Jemez Mountains and Valles Caldera with respect to other volcanic centers of the Jemez Volcanic Lineament and the Rio Grande Rift. Regional thermal sites mentioned in the text are the San Ysidro area to the southwest and the Chimayo area to the east (C= C spring, CH = Chimayo well, D = Double spring, and Z = Zia hot well).

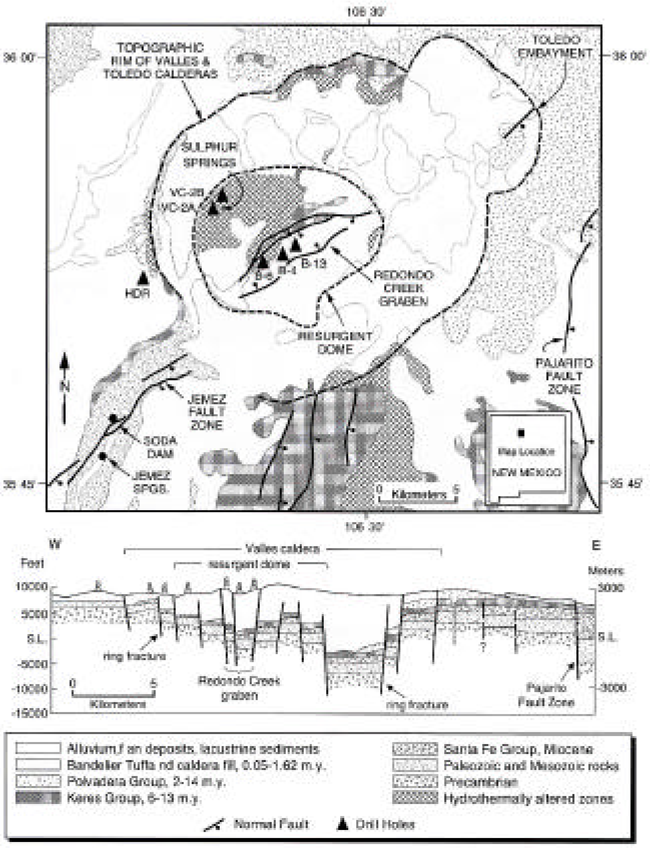

Figure 2. ***Map and E-W cross-section of the Valles Caldera region showing general geology and structure, and the locations of various thermal features and geothermal wells mentioned in the text. Well symbols shown on cross-section denote zone of subsurface stratigraphic control and do not necessarily denote any particular well. Geochronology is from Gardner, et al. (1986), and Goff and Gardner (in press).***

the caldera region (Figure 2) shows typical relations among the major stratigraphic groups of the JMVF and relations to Tertiary basin-fill rocks of the RGR, Paleozoic to Mesozoic rocks of the Colorado Plateau, and Precambrian basement. Drilling and geophysics have revealed that the caldera is structurally asymmetric, being much deeper on the east than on the west (a "trap door" caldera)(Heiken and Goff, 1983). Miocene sedimentary rocks of the RGR thicken eastward toward the axis of the rift. Particularly noteworthy in the structure is the horst beneath the mountains between the eastern caldera ring fracture and the Pajarito fault zone. The Pajarito fault zone bounds the western and deepest part of the RGR. Because of this horst, the caldera depression and the RGR form separate hydrologic basins.

Several geophysical and geochemical studies show that the JMVF is underlain by magma. For example, Valles caldera is aseismic and has multiple, low velocity zones extending into the upper mantle (Steck, et al., 1998). Convective heat flow within the caldera can exceed 5000 mW/m^2; whereas, deep conductive heat flow just outside the caldera is as high as 400 mW/m^2 (Goff, et al., 1989; Morgan et al., 1996). Petrologic models suggest that the youngest post-caldera rhyolites represent a new magma batch separate from the older Bandelier magma chamber (Wolff and Gardner, 1995). Valles intracaldera gases have $^{3/4}$He ratios of <=6 R/R$_a$ (R/R$_a$ = helium ratio of sample gas divided by the helium ratio of air). These values are similar to those of mid-ocean ridge basalt, indicating a mantle/magmatic source for the excess helium-3 (Goff and Gardner, 1994). These combined data indicate that Valles is underlain by a potent magmatic heat source probably replenished by periodic injections of mantle basalt (Goff and Janik, 2002).

GEOTHERMAL SETTING AND CHARACTERISTICS

Hot and/or mineralized fluids discharge from many locations within and outside of the RGR, but few sites contain boiling fluids or release free gas (Summers, 1976). Within a 50-km radius of Valles caldera, gaseous fluids occur in a large cluster of springs and a well to the southwest (San Ysidro area; C, D, and Z) (Figure 1) and in an aquifer along the east margin of the RGR to the east (Chimayo area). The chemistries of these fluids are variable. San Ysidro fluids (25^o to 55^{o}C; CH) (Figure 1) are mineralized due to circulation in late Paleozoic to Mesozoic sedimentary rocks of the San Juan Basin (Vuataz and Goff, 1986). Chimayo fluids are cool (<25^{o}C) and derive their mineralization from circulation in Tertiary basin-fill sediments of the RGR and nearby Paleozoic carbonate rocks on the east margin of the RGR (Cumming, 1997). These regional fluids do not resemble those inside Valles caldera (Summers, 1976).

Valles caldera contains a classic, liquid-dominated reservoir (<=300^{o}C), which is overlain by a low-pressure vapor cap and is recharged by local meteoric water (Dondanville, 1978; Goff, et al., 1985; Goff and Gardner, 1994). The reservoir (210^o to 300^{o}C, 2 to 10 x 10^3 mg/kg chloride) is most extensive in fractured caldera fill tuffs and associated sedimentary rocks located in specific structural zones. A detailed reservoir model and descriptions of the various hot springs have been published previously (Goff and Gardner, 1994, and references therein). Free gas issues at Sulphur Springs and from smaller springs and fumaroles within the resurgent dome of the caldera. Free gas also emerges from several thermal features along the Jemez fault zone (JFZ), southwest of the caldera. The latter hot springs discharge from a hydrothermal outflow plume that flows in the subsurface from the Valles geothermal reservoir down the JFZ (Goff, et al., 1988).

Acid-sulfate springs, mud pots, and fumaroles issue from Sulphur Springs and other canyons within the southwestern resurgent dome of Valles caldera (Figure 2). These areas are characterized by intense argillic to advanced-argillic alteration. Kaolinite, silica, pyrite, sulfur, alunite, gypsum, jarosite, and other complex sulfates are deposited in acid-leached, intracaldera rhyolites and sedimentary deposits (Charles et al., 1986). Two scientific core holes (VC-2a and VC-2b) were drilled in the Sulphur Springs area in 1986 and 1988 to examine the vapor cap and underlying liquid-dominated reservoir (Hulen et al., 1987; Goff and Gardner, 1994). Maximum depth and temperature were 1.76 km and 295^{o}C.

Conventional geothermal wells were drilled in the resurgent dome of Valles caldera from 1959 to 1983 (Baca-1, Baca-4, etc.) to explore and develop the geothermal system (Figure 2). Maximum drilled depth and temperature were 3.2 km and 342ºC in Baca-12 (Nielson and Hulen, 1984). The system proved to be too small in volume for economic development. The geochemistry of Valles spring and well discharges was previously described by Truesdell and Janik (1986) and Goff and Janik (2002), among others.

The hot dry rock concept (HDR) was developed and tested in Precambrian igneous and metamorphic rocks beneath the west margin of the caldera from 1972 to 1998 (Figure 2; Grigsby et al., 1984). During circulation experiments, cold water was pumped down an injection well, forced through artificially fractured reservoir rocks, and extracted from a nearby production well. The cold water dissolved minerals lining the fractured rocks and absorbed CO_2 and other gases while reaching thermal equilibrium (T=160ºC). The depth of circulation was greater than 2.5 km when the project was in operation. Details of this project are summarized in another paper of this volume.

VALLES CALDERA NATIONAL PRESERVE

After two years of negotiations, the White House reached an agreement to buy and permanently protect the 95,000-acre Baca ranch as a national preserve. The ranch and the caldera are roughly coincident in aerial extent. A bill appropriating the money ($101 million) was passed by the U.S. Congress and signed by President Clinton late in 1999. Authorizing legislation, called the Valles Caldera Preservation Act, H.R. 3288/S. 1892, passed the House and Senate and was signed by President Clinton on July 25, 2000.

The newly created Valles Caldera National Preserve is managed by a board of trustees appointed by the President and will be opened to the public within two years. Members of the Valles Caldera Trust hold regular board meetings to share information with the public as they formulate plans for the Preserve. Before the Valles Preserve is opened to the general public, the archeology, geology, animal and plant ecology, grazing potential, and Native American heritage are undergoing intensive investigation and reevaluation. Elk hunting and limited cattle grazing are income-producing activities conducted during 2002. Limited hiking will commence in 2003. For more information on the Preserve, contact www.vallescaldera.gov.

A holdout geothermal interest remains on the Preserve that has not yet been purchased by the federal government. It is presently not known if geothermal development will be a viable income-producing activity for the Valles caldera, considering its new public status.

VALLES (BACA) GEOTHERMAL SYSTEM

The Baca cooperative geothermal demonstration project in Valles caldera began in July 1978 (the Baca name originates from the first, post-1850s owners of the land grant and cattle ranch, roughly coinciding with the caldera boundary). The cooperative project was jointly sponsored by the U.S. Department of Energy (DOE), Union Oil Company (Unocal), and Public Service Company of New Mexico (PSCNM). When the joint project began, Unocal claimed that a 400-megawatt electrical (MWe) resource existed within the caldera, but when the project terminated by mutual agreement in January 1982, Unocal had only proven 20 MWe of resource. Unocal drilled roughly 23 wells and redrills during their lease of the Baca geothermal rights from about 1970 to 1984. After the cooperative agreement was signed, only 2 of 13 wells drilled by Unocal were successful. All the wells were hot but few wells encountered sufficient permeability to be considered production wells. This project, which was supposed to showcase development of liquid-dominated geothermal reservoirs, became extremely frustrating, expensive, and non-productive. PSCNM actually bought two 25 MWe low-pressure steam turbines for use on the initial power plant but when the project terminated, these turbines were sold to the Mexican government for pennies on the dollar (the turbines are now running in the Los Azufres geothermal field, Mexico). The unfortunate history of these efforts is documented in several reports (Kerr, 1982; Goldstein and Tsang, 1984; Mangold and Tsang, 1984).

Although reservoir waters in Valles are 210 to 300ºC and maximum measured temperatures in underlying rocks are 340ºC at roughly 3200 m depth, the fluids are extremely localized. There is little fluid continuity among the successful wells. In addition, reservoir fluids are under pressured because the depth to fluids is <=500 m and the reservoir is overlain by rocks filled with low-pressure vapor. Unocal encountered many drilling problems. In the end, five or six wells were suitable as production wells. Wells displayed highly variable permeability and porosity along their courses. Permeable horizons in one well did not correlate with those in other wells. Inter-connectivity among the wells was extremely bad and bulk reservoir permeability was low. Permeability was restricted to fault zones and short lateral horizons cutting intracaldera Bandelier Tuff and associated rocks, and to zones in precaldera Tertiary volcanic rocks and sediments. Attempts to find permeability in underlying Paleozoic and Precambrian rocks were unsuccessful.

Along with the drilling and development problems, there were legal and economic controversies evolving over the hydrologic relationship of the Valles reservoir to the hot springs in San Diego Canyon, southwest of the caldera (Erickson, 1977; All Indian Pueblo Council, 1979; State of New Mexico, 1980; Balleau, 1984). Basically, Native American groups and resort owners contended that development of the Valles geothermal resource would deplete or terminate water flow from the hot springs and hot aquifers in San Diego Canyon. This issue was never resolved in court because the cooperative geothermal project was terminated. However, results from scientific core holes drilled from 1984 to 1988, and other research studies prove that a hydrothermal outflow plume from the Valles reservoir feeds the hot springs in San Diego Canyon (Goff and Shevenell, 1987; Goff et al., 1988).

CONCLUSIONS

With the above facts in mind, several conclusions can be stated about the Valles geothermal resource:

1. After years of work and considerable expense, only 20MWe of geothermal reservoir capacity is proven in Valles caldera. Geothermal developers occasionally state that Valles contains as much as 1000 MWe of undiscovered power but these claims are unsubstantiated. The shallow heat contained within Valles rocks is immense but extracting large quantities of hot fluids from these rocks has been exceptionally difficult.

2. Finding undiscovered hot fluids in Valles to power more than 20MWe will be difficult. The Redondo Creek graben and fault zone is the only known area within Valles where successful production wells were drilled. Even there, most wells were sub- commercial. Ten more wells were drilled in western sectors of the caldera near Sulphur Springs but no useable production well exists in these supposedly favorable locations.

3. The sustainability of the known 20MWe resource is unknown. Because the Valles geothermal reservoir displays such poor hydraulic conductivity, it is not known if the reservoir will produce sufficient volume of fluids at required pressures to keep a geothermal plant operational for 20 years. This can only be evaluated once flow tests are conducted, the first plant goes online, and long-term well performance is documented.

4. The hydraulic conductivity within the Valles reservoir is extremely poor. Reinjected reservoir fluids from the power plant, whether conventional or binary, could easily wander into zones that are not connected to existing production zones, or could short circuit to production wells along a fault or fracture system. Evaluating the performance of reinjection can only be done after the first plant goes online.

5. Exploitation of the Valles reservoir will have an unknown impact on the hot springs and aquifers in San Diego Canyon (Williams, 1986; Trainer, et al., 2000). Past experience at many other geothermal systems shows that production of reservoir fluids can have dramatic detrimental impacts on surface thermal features (e.g., Hunt and Scott, 1998). The local Pueblos revere the hot springs and some spring waters in the Jemez Springs area are used by resorts and religious institutions for recreational purposes. Unless those groups share in the development scheme, any new geothermal project will probably go to litigation soon after it gets started. As an example, a recent seismic project funded by DOE to be conducted in the Jemez Mountains was delayed by threats of litigation from Native American groups (Baldridge et al., 1997). This project included some *shallow* drilling. It is highly likely that a new Valles geothermal project will face similar obstacles.

6. The original geothermal development plan proposed by Unocal envisioned a transmission line connecting a power plant in the Redondo Creek area to Los Alamos via a typical, surface 115-kV power line. With creation of the Valles Preserve, a transmission line would likely be constructed underground to minimize visual environmental impacts, raising development costs substantially. The path of the line may have to be changed because of new archeological discoveries. This will probably require an amended or new Environmental Impact Statement.

7. The geothermal wells drilled by Unocal are probably not reusable, contrary to what is suggested by some geothermal developers. They were plugged and abandoned to California standards (2000 feet of cement and bentonite plugs, well heads removed, upper 15 feet or so of casing cut off, and then buried). Few rational developers would want to reopen high-temperature wells that have unknown casing problems and that are 20 to 30 years old.

8. Worldwide, the average cost of installed geothermal capacity is roughly \$2M per MWe (Grant, 1996). The local cost of power produced by traditional means in New Mexico is around 1 to 3 cents per kWh. It is highly likely that power produced by geothermal energy in Valles caldera will be considerably more expensive than the above costs. Because of small size and high cost, generating geothermal power in Valles only makes sense if the cost is subsidized.

9. Los Alamos and Sandia National Laboratories are required by DOE to use 7% green energy in their future power mix. Geothermal power would satisfy those requirements. However, there are other sources of green power being developed in the region (Mike Hinrichs, 2001). Thus, geothermal energy is not the sole option of green power for these institutions.

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