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Scientific Drilling at Sulphur Springs, Valles Caldera, New Mexico: Core Hole VC 2A

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A scientific core hole has been drilled into the western ring fracture zone of the Valles Caldera, N.Mex. Hole VC-2A, the second scientific core hole in the caldera, was cored through a faulted and brecciated sequence of intracaldera tuffs and volcaniclastic rocks to a depth of 528 m at Sulphur Springs. As of November 1, 1986, the unequilibrated bottom hole temperature was 212°C. The rocks that have been penetrated are intensely altered and contain molybdenite mineralization (MnO_2) that is less than or equal to 1.1 m.y. in age. The active hydrothermal system at Sulphur Springs consists of a thin (5-m) acid condensation zone overlying vapor- and water-dominated zones. The latter two zones are apparently separated by a region of tightly sealed rock.

Objectives

Valles Caldera scientific drillhole 2A (VC-2A) is the second scientific core hole to be drilled into the Valles Caldera as a part of the Continental Scientific Drilling Program (Figure 1). The primary objective of VC-2A was to penetrate the vapor zone beneath the acid sulfate hot spring system of Sulphur Springs, which is located on the western edge of the resurgent dome inside the 1.1-m.y.-old caldera. Secondary objectives were to core through the interface between the vapor zone and hot water–dominated zone, to obtain structural and stratigraphic data on the caldera fill rocks along the boundary between the ring fracture and the resurgent dome, and to determine mechanisms of ore deposition in an active caldera hydrothermal system.

Technology and Safety

Surface conditions at Sulphur Springs suggested that VC-2A would provide a design and drilling challenge for a coring operation using a diamond drill bit. Steel fixtures that have been used in the area, such as culverts, are quickly corroded by surface acid conditions, a fact that did not bode well for the usual drilling rods and hole casings. Furthermore, the presence of hydrogen sulfide and high-temperature fluids at the surface suggested that hydrogen embrittlement of downhole components could be a problem. Thus a number of unique design and operational features were used in the drilling of VC-2A to ensure that it would be usable for a period of at least 5 years. Details of the core hole design and coring operations can be found in the work of *Lysne et al.* [1987]. Three particularly interesting aspects of the operation are discussed below.

Hydrogen sulfide is a component (up to 1500 ppm) of the gases emanating from fumaroles in the Sulphur Springs area. This gas is dangerous to life in concentrations above 300 ppm. Because of the very likely occurrence of hydrogen sulfide in well gasses and drilling fluids, a monitoring system was designed, and personnel were trained in emergency procedures, such as the use of air packs and cardiopulmonary resuscitation. The monitoring system included seven detectors, which were located near the drill rig, at the operations trailers, at living trailers, and in a drainage area provided for flow testing of the well. Information from these detectors was routed to a central panel that automatically activated low (10 ppm) and high (20 ppm) alarms (the Occupational Health and Safety Administration (OSHA) ceiling standard is 20 ppm). Data from all of the sensors were recorded to computer disk at 5-minute intervals throughout the drilling operation.

A core tube loading chamber was designed especially for VC-2A. It consists of a 10-ft (~3-m)–long section of HQ rod (3.5 in drill pipe) with a packer for the wireline at the top and a 4-inch (~10-cm) ball valve at the bottom. Other components were a pressure gage, attachment for the mud line, and the overshot assembly. In operation, the water swivel was removed, and the valve end of the chamber was screwed to the top of the rod string. The valve was opened, allowing the overshot to be lowered into the hole, and the core tube was then withdrawn into the chamber. The valve was closed, and the chamber was removed. Thus the rods were open for a minimum time, and mud could be pumped downhole while core was being recovered. Because of the length restrictions of the loading chamber, it was necessary to use a short (5-ft, or ~1.5-m) core tube throughout the operation. In spite of the increased number of core runs caused by the short tube and the time required to mount and dismount the chamber, the drilling crews recorded three

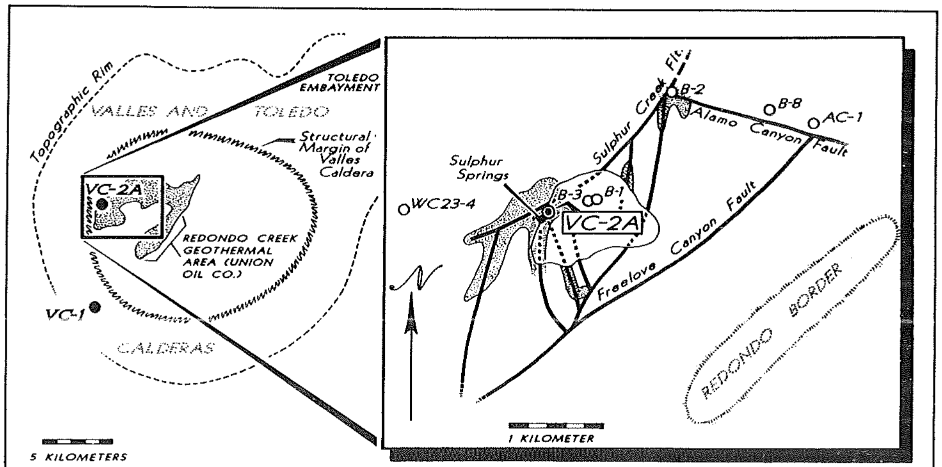

Fig. 1. Location map showing Valles-Toledo calderas, existing CSDP borehole sites (VC-1 and VC-2A), and previous geothermal wells drilled in the Sulphur Springs area and Sulphur Springs fault map [adapted from *Goff et al.*, 1985; *Hulen and Nielson*, 1986*b*]. Stippled pattern shows area of relatively intense argillic alteration. A large landslide complex occurs east of Sulphur Springs.

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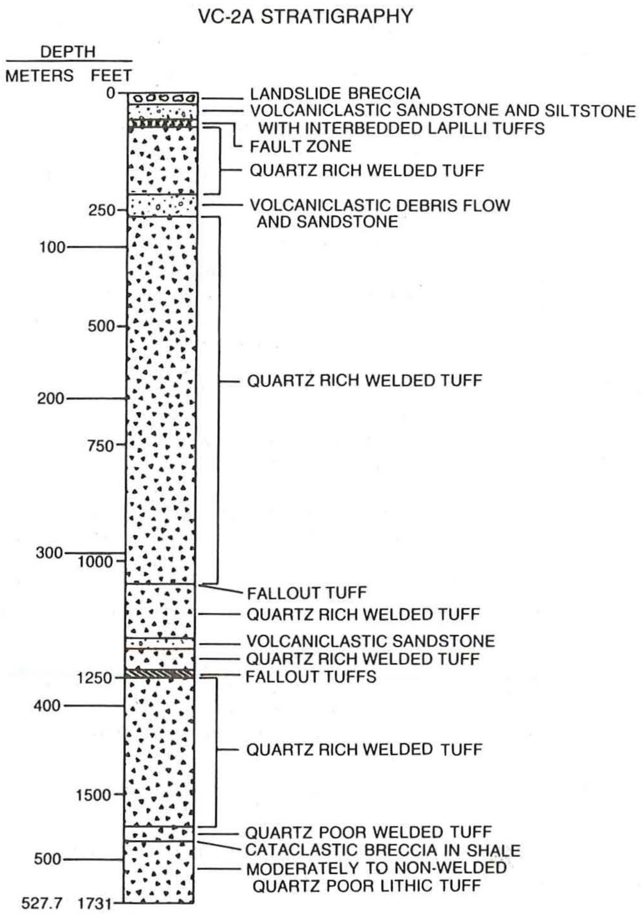

Fig. 2. Stratigraphy of VC-2A.

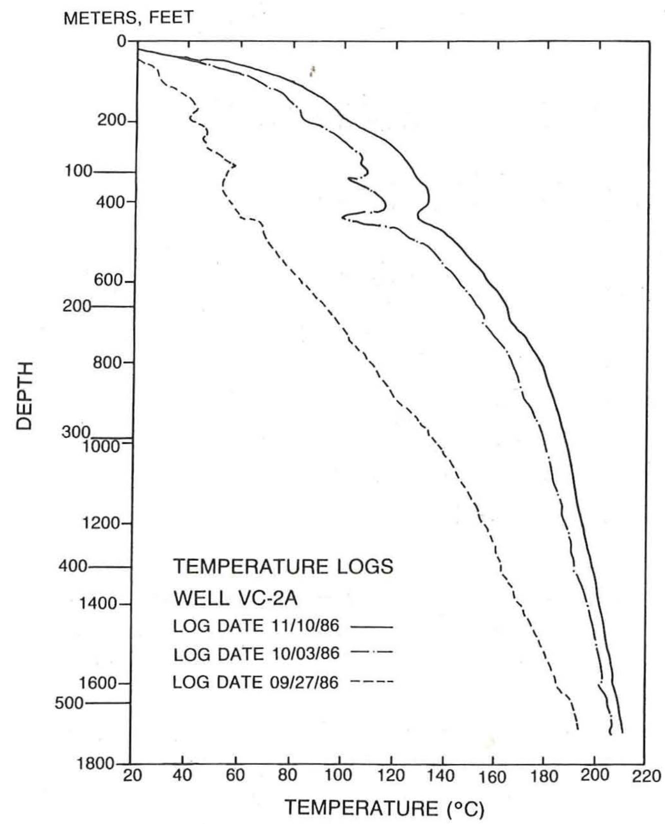

Fig. 3. Temperature logs of VC-2A.

12-hr shifts in which they were able to core ~100 ft (~30 m).

Another important piece of equipment designed for VC-2A was a wireline-retrievable check valve that was set in the core barrel during rod trips in and out of the hole. This valve allowed mud to be pumped through the rods (as well as through the kill line), but it prevented the uncontrolled production of formation fluids. Thus by partially closing the annular preventer, the well could be cooled and well pressure could be maintained while moving the drill string. (Diagrams of the core tube loading chamber and wireline-retrievable check valve may be obtained on request from author Peter Lysne.)

Preliminary Results

VC-2A is a success, with over 98% recovery of HQ core (62 mm in diameter) throughout the entire length of the bore. The core hole was spudded (i.e., started) on September 5, 1986, and was completed in 24 days. Total depth is 527.7 m (1731 ft), and the unequilibrated bottom hole temperature (BHT) was 212°C (410°F) as of November 1, 1986. Although scientific investigations have only begun, it appears that the configuration of the Sulphur Springs hydrothermal system consists of an acid sulfate condensation layer (with $pH < 1.5$) no more than 5 m thick, a vapor zone extending to roughly 240 m depth, a "transitional" layer that extends from ~240 to 500 m, and a hot water–dominated zone at the bottom.

The stratigraphy of VC-2A (Figure 2) is easily correlated with the geologic map of Sulphur Springs developed by *Goff and Gardner* [1980] and with the intracaldera stratigraphy of *Nielson and Hulen* [1984]. About 10 m of altered colluvium and landslide deposits overlie 11.6 m of bedded volcaniclastic sedimentary rocks that are also locally exposed at the surface. From 21.6 to 66.5 m, the core hole penetrates nonwelded to densely welded ignimbrite that correlates with the Upper Tuffs of Nielson and Hulen. This ignimbrite is separated by 15.2 m of debris flow and volcaniclastic sandstone (the "S-2" sandstone of Nielson and Hulen) from a 290-m-thick densely welded ignimbrite that is probably the Upper Bandelier Tuff of *Smith and Bailey* [1966]. Although the "Upper Bandelier" penetrated by VC-2A appears to be thin, it is missing entirely in the WC 23–4 well west of Sulphur Creek Fault, and it thickens progressively to the east into the caldera [*Vuataz and Goff*, 1986, Figure 2). Another volcaniclastic sandstone (the "S-3" sandstone of *Nielson and Hulen* [1984]) occurs from 356 to 362 m and overlies a third densely welded ignimbrite that is presently correlated with the Lower Bandelier Tuff. This unit extends to 478 m and overlies a quartz-poor tuff interval of unknown affiliation that persists to the bottom of the bore.

All of the rock units in VC-2A have undergone moderate to intense hydrothermal alteration that is similar in many aspects to that described by *Hulen and Nielson* [1986*a,b*] in the deep Valles hydrothermal reservoir. The uppermost colluvium and landslide debris are locally altered to kaolinite, with accompanying pyrite, sulfur, and a variety of sulfate minerals deposited in a low-temperature, low-*p*H environment [*Charles et al.*, 1986]. Surprisingly, abundant illite (a characteristic clay mineral in high-temperature liquid-dominated systems) persists to the top of the hole, suggesting that the acid sulfate alteration is superimposed on an older high-temperature alteration assemblage. To a depth of about 150 m, the main secondary phases are quartz, illite, and pyrite in host rocks laced with open fractures lined with prismatic quartz. Molybdenite and fluorite are important minor constituents, and rhodochrosite, chalcopyrite, and sphalerite occur in trace amounts. Molybdenite is strongly concentrated between 25 and 125 m. Below 150 m the rocks are conspicuously grey-green in color, with illite, chlorite, calcite, quartz, pyrite, and scattered fluorite as the obvious secondary minerals. The rocks have been pervasively shattered in a few localized zones below 150 m, but these fractures are commonly sealed with various combinations of illite, chlorite, calcite, and quartz, with local traces of adularia. Because the uppermost altered rocks are intracaldera tuffs, hydrothermal events are less than or equal to 1.1 m.y. old.

Model of Sulphur Springs System

A model of the Sulphur Springs hydrothermal system was presented by *Goff et al.*

[1985], who noted low formation pressures (less than 20 bars) in surrounding geothermal wells to depths of 450 m. Low formation pressures and occurrences of acid sulfate hot springs are typically associated with vapor-dominated geothermal systems [*White et al.*, 1971], but *Goff et al.* [1985] pointed out that the formation pressures and associated temperatures in wells near Sulphur Springs were lower than those recorded in "true" vapor-dominated systems (32 bars at 236°C).

Our preliminary data from VC-2A appear to verify that Sulphur Springs is not a vapor-dominated system of the Geysers or Larderello type. Figure 3 shows a series of temperature logs recorded in the sealed, water-filled liner of VC-2A after completion. Although VC-2A is still recovering, its temperature profiles and BHT of 212°C are not typical of the near-isothermal 236°C conditions documented in dry steam systems. Also, the shut-in pressure of VC-2A between 50 m and 100 m is now about 4.14 bars, considerably lower than the pressures of 32 bars observed in dry steam systems. Therefore, rather than proposing a "true" vapor-dominated system for Sulphur Springs, we attribute the characteristics of this geothermal system to development of a surface acid sulfate condensation zone above a subsurface boiling liquid–dominated reservoir.

The presence of euhedral quartz crystals and a relatively high-temperature secondary mineral assemblage (illite-quartz-molybdenite-fluorite) high in the core hole indicates that a hot water–dominated geothermal reservoir of at least 200°C once occupied the rocks beneath Sulphur Springs at a present depth of only 30 m [*Hulen et al.*, 1987]. Surface outcrops of silica sinter in the general area of Sulphur Springs also suggest that a hot water–dominated reservoir that fed surface hot springs once existed at shallow depths [*Goff et al.*, 1985]. Pure water under hydrostatic pressure at 200°C can only exist as liquid water at depths below approximately 200 m; thus at least 175 m of erosion has occurred at Sulphur Springs since deposition of the molybdenite, if the ore-depositing fluid was not overpressured. The hot water–dominated zone has clearly descended with time to depths below 240 m. It is not known whether the system has merely boiled itself down with time or whether the system has descended due to a lowering water table that was caused by drastic changes in caldera hydrology [*Trainer*, 1984; *Goff and Shevenell*, 1987].

Perhaps the most intriguing zone penetrated by VC-2A is the zone of tightly sealed rock from ~240 to 500 m, in which the fractured tuffs are filled with secondary illite-chlorite-quartz-calcite. Temperature logs reveal very few lost circulation horizons in this region of the core hole, and it may be that this zone is a "cap rock" for the deep hydrothermal system beneath Sulphur Springs. This zone is presently so thick and its fractures so well sealed that there is no sharp interface between vapor and liquid. It is possible that near-surface groundwater percolates down around the margins of the Sulphur Springs system and penetrates locally into the cap rock, where it is boiled off by the high existing temperature (Figure 4). The fractures penetrating through this zone must allow considerable amounts of deep gases (CO_2, H_2S, etc.) but only minor amounts of deep steam to escape to the surface. This may be why, on a plot of δD versus $\delta^{18}O$, Sulphur Springs steam has a negative "isotopic shift" resembling that of vaporization of near-surface groundwater, and why noncondensible gases show an apparent equilibrium at temperatures in excess of 210°C [*Goff et al.*, 1985].

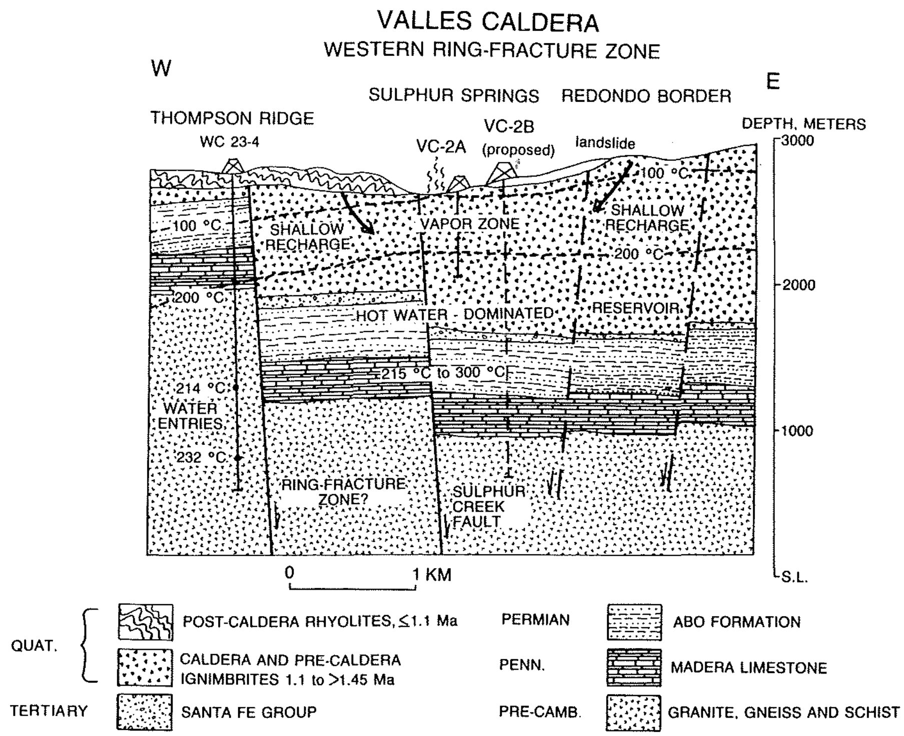

Fig. 4. Model of Sulphur Springs system.

VC-2A will be allowed to equilibrate for about 1 year before additional work is performed in it. During summer 1987, the core hole will be perforated at selected horizons to sample fluids and gases. On the basis of the compositions of fluids from the deep hydrothermal system beneath Redondo Creek to the east [*Truesdell and Janik*, 1986; *Vuataz and Goff*, 1986; *White*, 1986] and from two fluid entries of greater than 210°C in the WC 23–4 well to the west [*Shevenell et al.*, 1987], the deep reservoir beneath Sulphur Springs may be neutral chloride in character, with between 5000 and 18,000 mg/kg total dissolved solids and significant concentrations of Li, B, Br, and As. Molybdenum concentrations in present reservoir fluids range from 30 to 350 ppb.

Continental Scientific Drilling Program at Valles Caldera

The combined depths of core holes VC-1 and VC-2A now give interested researchers access to 1386 m (4545 ft) of continuous core from one of the most famous Quaternary calderas in the world. Included within this core are 529 m of intracaldera ignimbrites and sediments, 332 m of the youngest moat volcanics in the caldera, 491 m of Paleozoic red beds and carbonates, and 34 m of Paleozoic-Precambrian fault gouge and breccia (the latter two sequences are located in the southwestern ring fracture zone; see *Goff et al.* [1986]; also J. B. Hulen and D. L. Nielson (University of Utah Research Institute, Salt Lake City), unpublished data). Results from these two core holes have revealed much about lateral outflow plumes and other geothermal phenomena, the nature and evolution of past hydrothermal systems, ore deposit formation in the caldera environment, moat volcanic petrogenesis, caldera collapse, and development of resurgent domes, as well as basic structure and stratigraphy. Some 50 researchers around the world are working on the core, fluid samples, and geophysical logs from the first two bores. Researchers who wish to obtain samples of core, fluids, and basic data or who have ideas for simple experiments that can be conducted in hot slim holes should contact Fraser Goff and Jamie Gardner (Los Alamos National Observatory, MS D462, Los Alamos, NM 87545), Dennis Nielson and Jeff Hulen (Earth Science Laboratory, University of Utah Research Institute, 391-C Chipeta Way, Salt Lake City, UT 84108), or Peter Lysne (Sandia National Laboratories, Division 6242, Albuquerque, NM 87185). Five additional holes, to a maximum depth of 5.5 km and anticipated temperatures of over 500°C, have been proposed to allow examination of the roots of the hydrothermal system and the crystallized roof of the Bandelier pluton in Valles caldera [*Goff and Nielson*, 1986].

Note Added in Proof

VC-2A was perforated at 490 m, 210°C, on May 1, 1987 (see cover photograph). Flow tests and fluid sampling activities were conducted during early May. Fluid samples show that the 490-m zone contains metal chloride fluids with ~5000 mg/kg total dissolved solids; thus, VC-2A intersected the top of the liquid-dominated reservoir beneath Sulphur

Springs. Vapor zones at higher levels remain to be isolated and sampled.

Acknowledgments

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