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LALP 93-82

Continental Scientific Drilling Program: Valles Caldera, New Mexico

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U.S. Continental Scientific Drilling Program
Valles Caldera, Northern New Mexico

Abstract

The U.S. Continental Scientific Drilling Program attempts to develop a better understanding of the geologic and hydrologic mechanisms within the continental crust, under the auspices of an interagency group comprising the U.S. Department of Energy, the National Science Foundation, and the U.S. Geological Survey. Ten years of research and drilling in the Valles caldera of northern New Mexico has provided a new understanding of volcanism and geothermal systems within a large caldera. Situated at the intersection of the Río Grande rift and the Jemez volcanic lineament, the Valles caldera and Toledo calderas were formed during two massive eruptions 1.1 and 1.5 Ma that vented approximately 300 to 400 km^3 of high-silica rhyolitic tephra.

The research at the Valles/Toledo caldera has provided more than 3000 m of corehole samples, which are stored in a repository in Grand Junction, Colorado, and are accessible to the public. This research has also helped support theories of mineral deposition within hydrothermal systems—hot water circulating through breccias, leaching elements from the rocks, and later depositing veins of economically valuable materials.

Introduction

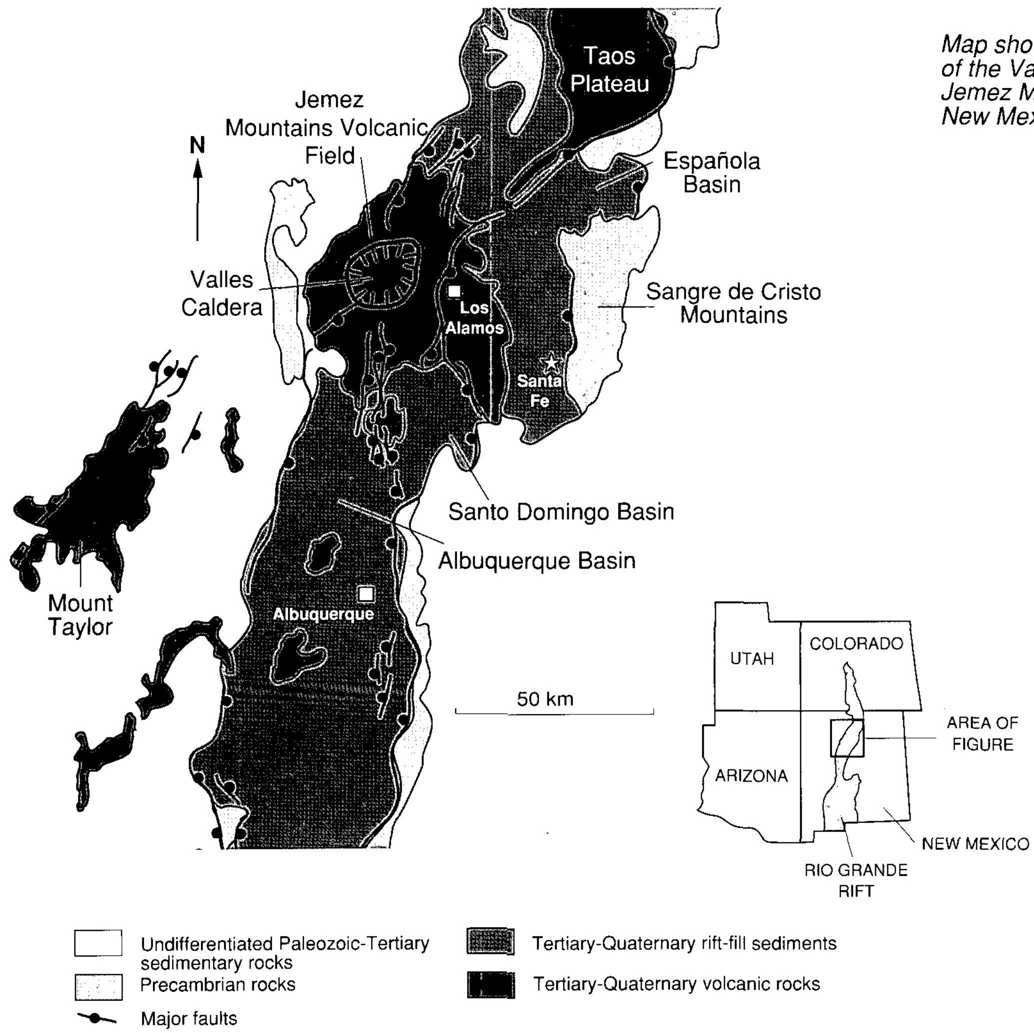
In an attempt to better understand the dynamic geological and hydrothermal systems within the North American continent, the multidisciplinary U.S. Continental Scientific Drilling Program (CSDP) was proposed in the early 1970s. When compared to similar scientific drilling programs examining the geological structures beneath the sea floor, scientific drilling of the continents is still in its infancy.

The U.S. Department of Energy (DOE), the National Science Foundation, and the U.S. Geological Survey form the interagency group responsible for the CSDP within the U.S. The Department of Energy has focused its efforts on the thermal state of the Earth's crust, and to this end they have sponsored scientific coreholes in the Valles caldera of northern New Mexico.

The policy objectives and scientific goals of the U.S. CSDP are oriented toward an improved understanding of the Earth's continental crust. This research involves, among other things, studies of volcanic and hydrologic processes, hydrocarbon and ore formation, and the mechanisms that control earthquakes. The application of this information yields social benefits as well as economic and technological advantages that can be used to solve major national problems such as the reduction of the hazardous effects of earthquakes and volcanic eruptions, enhance U.S. industrial competitiveness in related drilling technologies, provide opportunities for training in science and engineering, to develop methods for isolating radioactive and other hazardous wastes, and evaluate adequate alternative sources of energy and mineral resources (Interagency Coordinating Group for CSDP, report to Congress, 1991).

Geologic overview

The Valles caldera and its coincident predecessor the Toledo caldera, now mostly buried, lie within the Jemez volcanic field that overlies the western edge of the Río Grande Rift at the intersection of the rift with the Jemez volcanic lineament (Heiken *et al.*, 1990). The lineament consists of a chain of Miocene to Quaternary volcanic centers running from eastern Colorado through New Mexico to central Arizona. Two eruptions, dated at 1.5 and 1.1 Ma, deposited approximately 300 to 400 km^3 of ash and pumice (the Bandelier Tuff) and created the 22-km-diam Toledo and Valles calderas (Heiken *et al.*, 1986). Although known best



Map showing the location of the Valles caldera in the Jemez Mountains of northern New Mexico.

for the Valles caldera and the Bandelier Tuff, the volcanic field also contains a diverse suite of basaltic to rhyolitic rocks that were erupted from more than 13 Ma to 0.13 Ma (Goff *et al.*, 1992). These are divided into three groups: the Keres, the Polvadera, and the Tewa (oldest to youngest) (Gardner *et al.*, 1986).

In the same way that the Valles caldera represents a "typical" resurgent caldera, it can also be considered a typical example of a volcanically driven hydrothermal system because it contains a magmatic heat source, convecting hydrothermal fluids, and an outflow plume of hot water.

The three research coreholes in the Valles caldera of the Jemez volcanic field have helped to answer questions about explosive volcanism, active hydrothermal systems, and mineralization.

The Calderas

Calderas form when the crust overlying reservoirs of molten rock near the Earth's surface collapses during large volcanic eruptions that drain the magma chambers below. The largest caldera in the Jemez volcanic field is 22 km in diameter (when measured at the topographic rim).

Large bodies of molten or partly molten rock lying 2 to 7 km below a caldera rim may take several million years to cool from their original temperatures of approximately 900°C to the ambient temperatures of the surrounding rocks. Such conditions provide outstanding long-term heat sources and play an important role in mineral deposition.

The Valles caldera, the youngest of several Quaternary calderas that have formed in the Jemez volcanic field over the last 1.75 Ma, represents an active analog to many "fossil" systems that are mined for precious and base ores (Hulen *et al.*, 1987). Drilling in the Valles caldera offers an opportunity to observe the processes that are depositing ores of silver, copper, zinc, lead, and molybdenum.

CSDP coreholes

Surveys of the geology, volcanism, and hydrology of the Jemez Mountains began in the early 1920s. Since 1960, 40 intermediate-to-deep wells have been drilled into the Valles caldera and the surrounding margins, primarily to exploit geothermal resources (Goff *et al.*, 1992). Collectively, these wells have penetrated 1950 m of Quaternary caldera fill, 300 m of Tertiary precaldera and volcanic and sedimentary rocks, more than 800 m of Paleozoic sedimentary rocks, and 3700 m of Precambrian basement (Heiken *et al.*, 1990).

Drilling in the Valles/Toledo caldera has yielded over 3000 m of corehole samples, which are stored in a repository in Grand Junction, Colorado, and are accessible to the research community.

Corehole VC-1

Corehole VC-1 is located on the southwestern edge of the Valles caldera complex, comprising the 1.12-Ma Valles caldera, its spatially coincident predecessor, the 1.45-Ma Toledo caldera, and possibly small precursor calderas formed at the same site between 3.6 and 1.45 Ma (Hulen and Nielson, 1988).

Completed in September 1984, corehole VC-1 penetrates Cenozoic volcanic rocks from the surface to 333 m, and penetrates the Permian Abo Formation, Pennsylvanian Madera Limestone, and Sandia Formation to the bottom at 856 m.

The main objective for this corehole was to intersect the postulated hydrothermal outflow plume of the caldera midway between its origin in the Valles geothermal reservoir and the hot springs in San Diego Canyon (Goff *et al.*, 1992). The Jemez fault zone, a major crustal flaw since perhaps Pennsylvanian time, not only controls the location of the apical graben of the Valles caldera's resurgent dome, but also focuses the southwesterly flowing hydrothermal plume from the caldera's active geothermal systems (Hulen and Nielson, 1988; Goff *et al.*, 1989).

Located just southwest of the intersection of the Valles caldera's structural margin and the subsurface projection of the Jemez fault zone, VC-1 reached a final depth of 856 m and a bottomhole temperature of 184°C. More than 95% of the core was recovered. The corehole intersected the hydrothermal plume at a depth of no less than 480 m (Goff *et al.*, 1992).

The VC-1 hydrothermal breccias host abundant fluid inclusions, many of which were trapped during brecciation. Homogenization temperatures and corresponding freezing-point depression for these inclusions, when combined with alteration mineralogy and paragenesis as well as the inferred geologic history at the VC-1 site, have allowed researchers to create a model of hydrothermal brecciation that should be broadly applicable in similar settings worldwide (Hulen and Nielson, 1988). Both geothermal and precious-

Core Samples

Cores from the scientific coreholes in the Valles caldera are stored in a US DOE facility at Grand Junction, Colorado.

Inquiries about core samples should be addressed to:

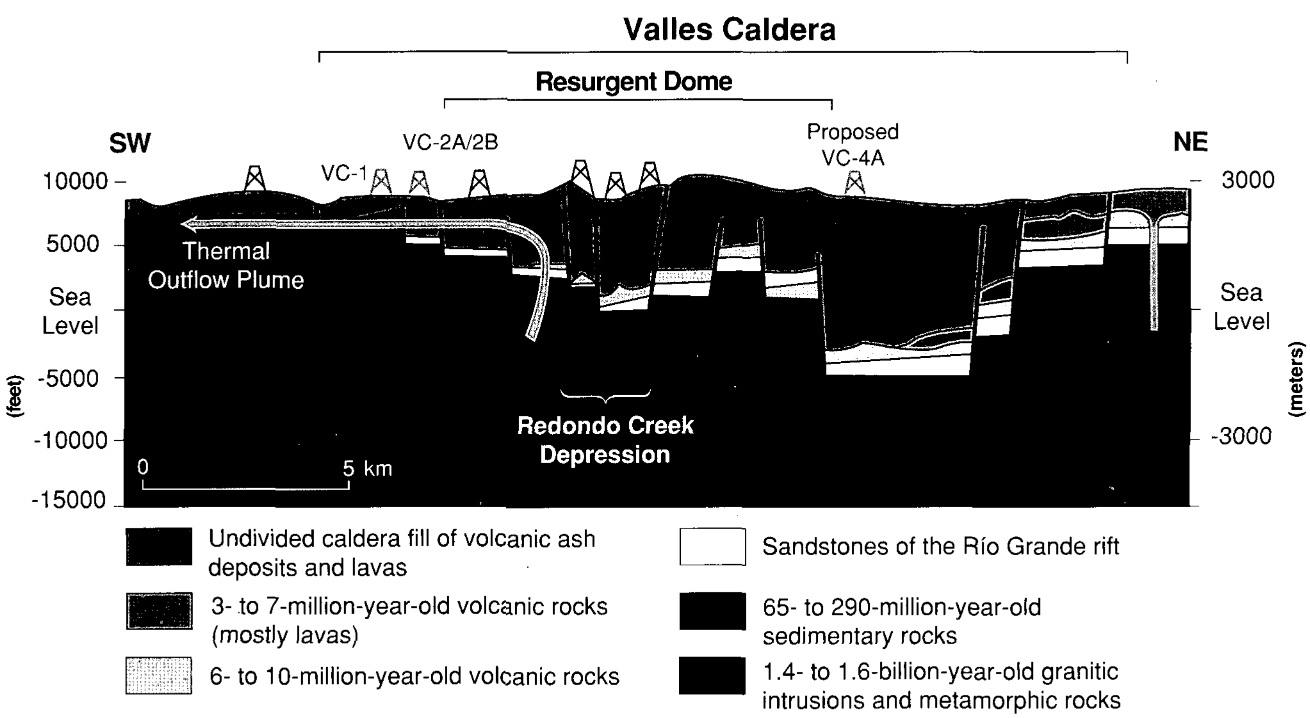
Attn: R.D. Dayvault
Core Curator
Chem-Nuclear Geotech
Grand Junction Operations
P.O. Box 14000
Grand Junction, CO 81502
(303) 248-6000

metal exploration and development therefore should benefit from a clearer understanding of the physical processes governing natural hydraulic rock rupture.

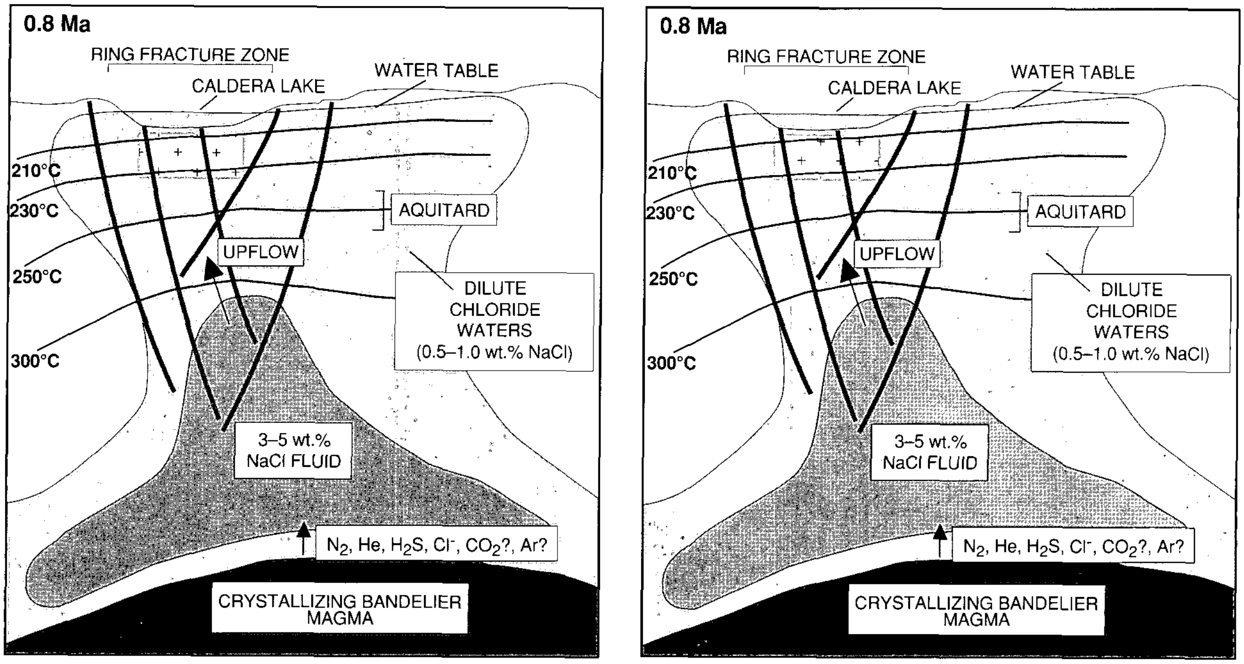
Corehole VC-2A

Drilled in the Sulphur Springs area along the western ring fracture zone of the caldera, corehole VC-2A reached a depth of 528 m and had a bottomhole temperature of 212°C. The corehole, started September 5, 1986, penetrated sediments fractured and faulted by both tectonic and hydrothermal activity. The sediments consisted of intracaldera volcanic ash and volcaniclastic sediments; fracturing was most pervasive in the upper 600 m.

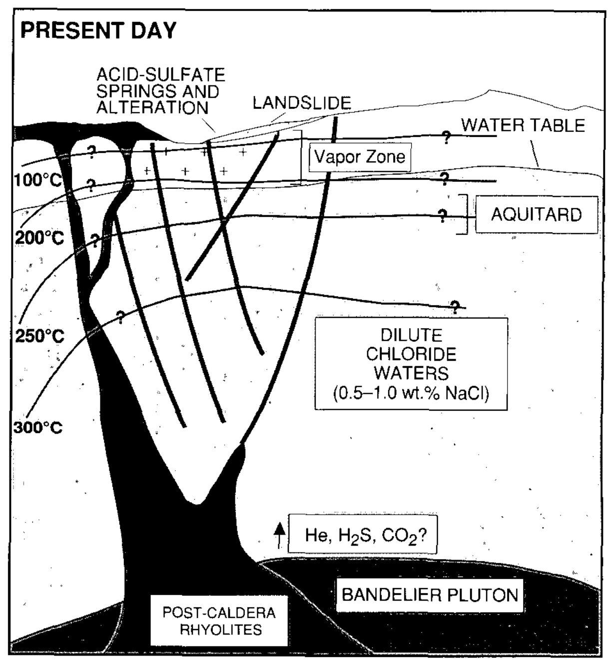
Corehole VC-2A's primary objective was to penetrate the zone between the vapor cap and underlying liquid-dominated reservoir of the Sulphur Springs hydrothermal system within the Valles geothermal system (Goff *et al.*, 1992). Fluid inclusion data from VC-2A and VC-2B show that the temperature and composition of fluids before 0.5 Ma differ from today's fluids (Musgrave and Norman, in press). Before 0.5 Ma, the Sulphur Springs hydrothermal system's upper 1000 m contained fluids of 0.5 to 1 equivalent weight per cent (eq. wt. %) NaCl salinity and temperatures of less than 250°C. Below 1000 m, the fluid salinity was between 2 and 5 eq. wt. % NaCl and had temperatures over 300°C (Musgrave and Norman, in press). The salinity of the system has since decreased, and the presence of 220°C fluids at the current land surface can be explained by the existence of caldera lake and eroded bottom sediments. Subsequent drainage of the lake, when the caldera walls were breached, decreased the hydraulic head on the system by approximately 160 m; erosion and landslides in the area lowered the water table 200 m below the present surface in the Sulphur Springs area (Musgrave and Norman, in press).



A cross-section of the Jemez volcanic field and Valles caldera showing the strata and their depths. Temperatures within the caldera are as high as 648°F, which is an indication of the youth of this volcanic field and its active geothermal systems. The western margin of the Río Grande Rift, a major north-south depression that divides New Mexico, underlies the Valles caldera.



This conceptual shows the possible evolution of the western half of the Valles caldera subsystem between 0.8 Ma and the present. The aquitard is now 900 m below surface level, and the water table lies approximately 250 m below the surface. (The open stipple pattern denotes high-level molybdenite mineralization.)



The geothermal system has since reestablished itself with a steam cap occupying the upper 200 m of the system, and fluid levels are now approximately 400 m lower than before 0.5 Ma (Musgrave and Norman, in press).

One surprise in the Sulphur Springs area was the discovery of molybdenite mineralization in hydrothermally brecciated quartz-sericitized tuff only 25 to 125 m below the surface. Fluid inclusions indicate that the molybdenite was deposited at 200 to 240°C from fluids with salinities similar to those of present hydrothermal fluids (Goff *et al.*, 1992; Musgrave and Norman, in press).

Corehole VC-2B

The last corehole drilled in the Sulphur Springs area, VC-2B — the deepest, hottest continuously cored hole in North America — was completed in October 1988, with 99% core recovery. The corehole reached 1762-m depth and had a bottomhole temperature of 295°C.

Samples taken from this corehole indicate that the fluid column in the upper part of the corehole had boiled. Nowhere before has such a detailed suite of samples been obtained throughout the boiling interface in a geothermal well. Fluid inclusion data indicate that the hydrothermal system has boiled intermittently throughout its history to depths of at least 1500 m (Musgrave and Norman, in press). These data allow detailed evaluation of the effect of boiling on fluid composition, elemental deposition, and possible elemental deposition in the boiling transition zone. Currents of superheated water circulating through cracks and fractures leach elements from the surrounding rock, and where conditions are right, ores and minerals are precipitated to produce veins of economically valuable materials. The results of these studies give scientists a close look at a geological system that is actively forming ore deposits such as silver, copper, and molybdenum (Interagency Coordinating Group for CSDP, report to Congress, 1991).

Fluid Samples

Fluid samples like those taken from VC-2B help geologists understand the subsurface chemical evolution of geothermal systems. Stable isotope and tritium analysis indicates that infiltration of cold meteoric waters in the area of the resurgent dome and the northern and eastern basins recharges the Valles geothermal system (Goff *et al.*, 1985; Vuataz and Goff, 1986). These fluids equilibrate 2 to 3 km below the surface and reach temperatures of 300°C in the caldera-fill tuffs and precaldera volcanic rocks (Goff *et al.*, 1989).

Thermal waters convectively rise to a depth of 500 to 600 m. Flowing laterally across the caldera wall, they continue along the Jemez fault above Precambrian basement rocks. The upper surface of the liquid-dominated system forms the boiling horizon that is capped by a vapor zone of approximately 200°C and extends from the western edge of the ring-fracture zone to the western flanks of the resurgent dome (Goff *et al.*, 1989).

One method employed to examine these subterranean fluids is the wellhead discharge test, which examines the physical parameters of the system and allows scientists, using geochemical thermometers and other tools, to determine the chemical composition and temperatures of reservoir fluids, their origins, and the chemical equilibrium of the fluids with the surrounding formations.

Another sampling technique uses containers, triggered to close either electronically or with mechanical timers, that are lowered into the corehole to recover geothermal fluid samples from specific depths. These samples reveal the compositions, origins, and temperatures of subterranean fluids in particular downhole areas.

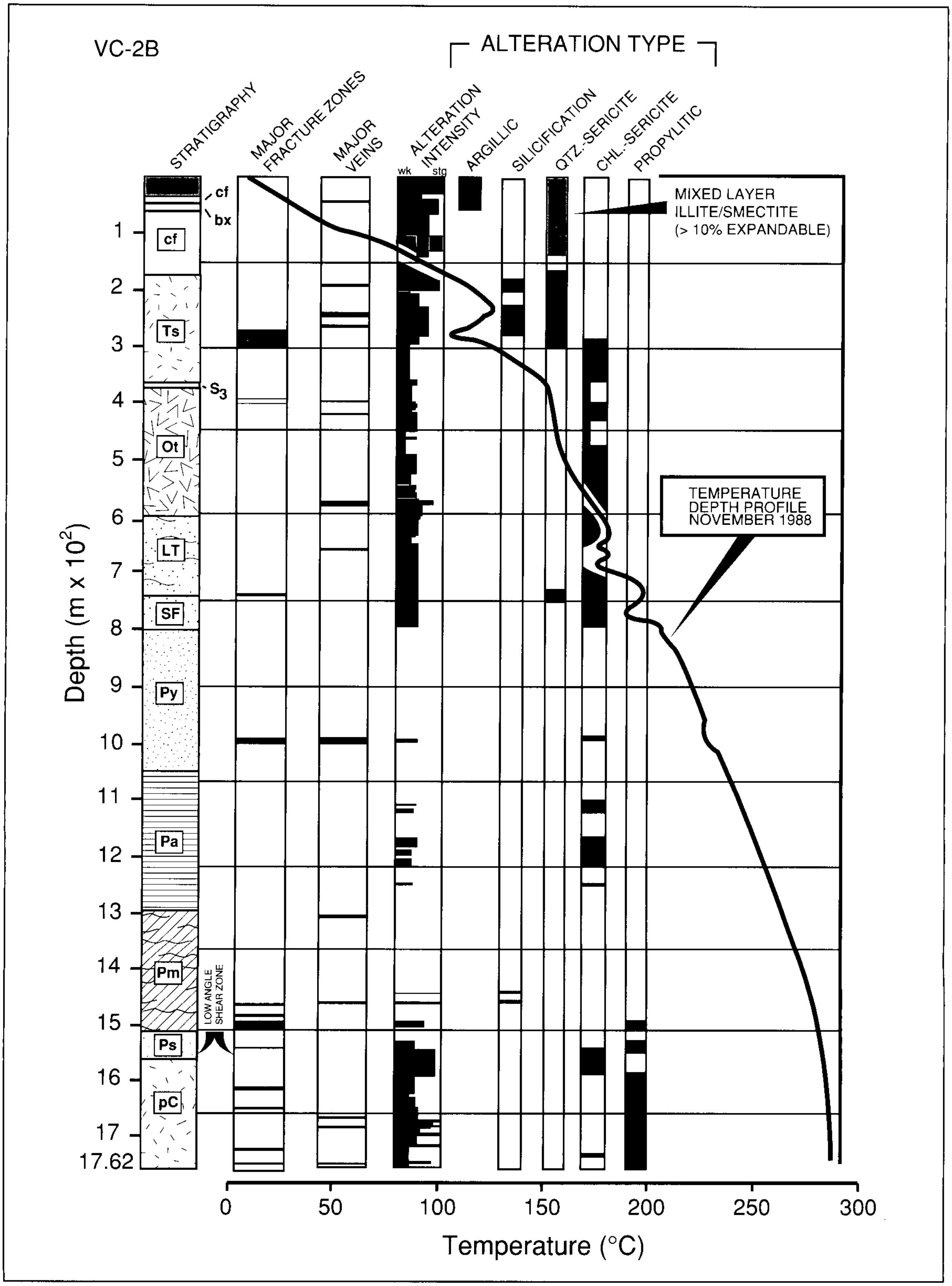
A more innovative procedure for obtaining present-day fluid samples in this very hot environment involves growing crystals within a fractured piece of quartz — a technique developed by P. Bethke of the U.S. Geological Survey. Each crystal is lowered to a different depth in the corehole and is left there for several weeks. As the fractures within the crystals heal, they entrap tiny droplets of fluid (fluid inclusions) that are later chemically analyzed by microanalytical techniques. These fluid inclusions provide the data necessary to study hydrothermal processes in active geothermal systems where conventional sampling techniques are difficult or impossible.

Technology Transfer

Because the CSDP thermal regimes research has required drilling into extremely hot rocks and corrosive fluids, conventional drilling technology has been pushed to the limit. Some of the novel methods developed at Los Alamos to deal with the harsh environment of the caldera's geothermal system became instantly available to the drilling companies that offered their technical support and expertise during the project.

For example, ordinary laundry detergent, already an ingredient in the drilling mud that lubricates the drill bit, in larger quantities made it possible to continue drilling into the hotter rocks of the caldera. This discovery will save valuable time later as drilling companies continue to tap into geothermal reservoirs around the world to provide an alternative source of energy.

In addition, cements, as well as steels for drill bits and other tools, were developed to withstand acidic, high-temperature conditions found in the harsh environment of a caldera hydrothermal system.



Generalized lithologic structural, alteration, and vein mineralization log for core hole VC-2B, Sulphur Springs, Valles caldera, New Mexico. Stratigraphic designations: cf = caldera-fill debris-flow deposits and volcaniclastic sandstones; bx = hydrothermal breccia and dacite porphyry zone; Ts = Tshirege Member, Bandelier Tuff; S_3 = clastic deposits; Ot = Otowi Member, Bandelier Tuff; LT = lower tuffs; SF = sandstone, Santa Fe Group; Py = Permian Yeso Formation; Pa = Permian Abo Formation; Pm = Pennsylvanian Madera Limestone; Ps = Pennsylvanian Sandia Formation; pC = Precambrian porphyritic quartz monzonite (Modified from Hulen et al., *1989).*

Future Efforts

During the last 15 years, the Valles caldera complex has been a focal point of geothermal exploration and research because of its relative youth and abundant geothermal manifestations. The Valles caldera represents an economically important and scientifically interesting active magma/hydrothermal system that is analogous to older, eroded, ore-bearing caldera complexes.

Ongoing research at the Valles caldera is helping to verify theories about the manner in which minerals such as gold, silver, and base metals were deposited within geothermal systems. Our observations confirm hypotheses that the hot water dissolves many elements from rocks within the caldera and deposits these elements in zones where the waters cool as they move toward the surface or out into colder rocks.

As a part of the continuing research in the Valles caldera, scientists have proposed more drillholes. One proposed hole would involve continuously coring for 5 km into the resurgent dome where temperatures may reach 480°C. Until additional holes are drilled, our understanding of the Valles caldera and its associated hydrothermal system as well as other caldera complexes throughout the world will remain incomplete.

We have learned a great deal about geothermal systems through our studies of the analogy between the Valles caldera and older, similar systems exposed over time by erosion. However, we need still more information about the dynamics of volcanic and geothermal systems. To better understand geothermal systems and use their gifts, such as renewable geothermal energy and mineral deposits, we must drill into them and determine the mechanisms that formed and altered them.

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More about the Valles caldera and CSDP will appear in future issues of ***Journal of Volcanology and Geothermal Research*** *and* ***Journal of Geophysical Research.***

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