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THE SULPHUR SPRINGS HYDROTHERMAL SYSTEM, PAST AND PRESENT: INITIAL RESULTS FROM CONTINENTAL SCIENTIFIC DRILLING PROGRAM COREHOLE VC-2B, VALLES CALDERA, NEW MEXICO

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ABSTRACT

Diverse, variably fractured, Precambrian to Pleistocene rocks penetrated by scientific corehole VC-2B (TD 1762 m; bottom-hole temperature 295°C) bear witness to complex interaction with high-temperature hydrothermal fluids. Whereas high-level, Pleistocene ignimbrites and deep Precambrian quartz monzonite in VC-2B are extensively altered and hydrothermally veined, intervening Paleozoic strata apparently remain relatively fresh. Fluid-inclusion microthermometry indicates that past (and perhaps contemporary) deep fluids were (are?) hotter and much more saline than those circulating at higher elevations. These deep fluids may have been confined principally beneath the tight Paleozoic sequence, only locally mixing with the more dilute fluids of shallower levels.

INTRODUCTION

VC-2B, the third Continental Scientific Drilling Program (CSDP) corehole in the Valles caldera (Fig. 1) was completed late in 1988 at a depth of 1762 m and a bottom-hole temperature of 295°C. A collaboration involving Los Alamos National Laboratory (LANL), the Geoscience Research Drilling Office (GRDO) of Sandia National Laboratories, the University of Utah Research Institute (UURI), and Tonto Drilling Services, VC-2B was drilled principally to determine the physical-chemical conditions of an active, high-temperature, liquid-dominated hydrothermal system throughout as much as possible of its full vertical extent. A second important objective was (and remains) tracing the development of that system since its inception. Core from VC-2B (recovery >99%) will help achieve these goals, since it preserves diagnostic textures and paragenetic relationships obliterated during production of drill cuttings (prior to the CSDP effort essentially the only samples available for the Valles caldera). This paper first briefly describes alteration mineralogy and zoning as well as vein and breccia mineralization in the VC-2B core, then discusses the implications of these features for understanding the geometry and evolution of the Sulphur Springs hydrothermal system.

GEOLOGIC SETTING

The Sulphur Springs site, in the western Valles caldera complex (Fig. 1) was selected for deep scientific drilling in part because of its vigorously active thermal features and associated, intense, surficial alteration (Goff and Gardner, 1980; Goff et al., 1987). The alteration, comprising an acid-sulfate assemblage superimposed on exhumed, quartz-sericitized rocks, is developed in a Quaternary caldera-fill volcanic and volcaniclastic sequence, particularly along high-angle normal faults and their intersections (Fig. 1).

Figure 2 is a 3-D geologic block diagram of the Sulphur Springs area based largely on samples and logs from previously completed geothermal and scientific drill holes. Younger caldera-fill rocks have been imaginarily removed in portions of the diagram to clarify important structural relationships. Basement rock in this part of the caldera is Precambrian quartz monzonite, overlain by Paleozoic carbonate and siliciclastic strata thinly blanketed by Miocene volcanic and volcaniclastic deposits. These are overlain primarily by a thick sequence of young ignimbrites, eruption of which led to catastrophic caldera collapse at ~1.75 Ma, 1.45 Ma, and 1.12 Ma (Self et al., 1986; T. Spell, pers. comm., 1989) Several of the ring faults along which this collapse occurred are shown schematically at the western margin of the block diagram. Other faults in the area, including the Sulphur Creek fault

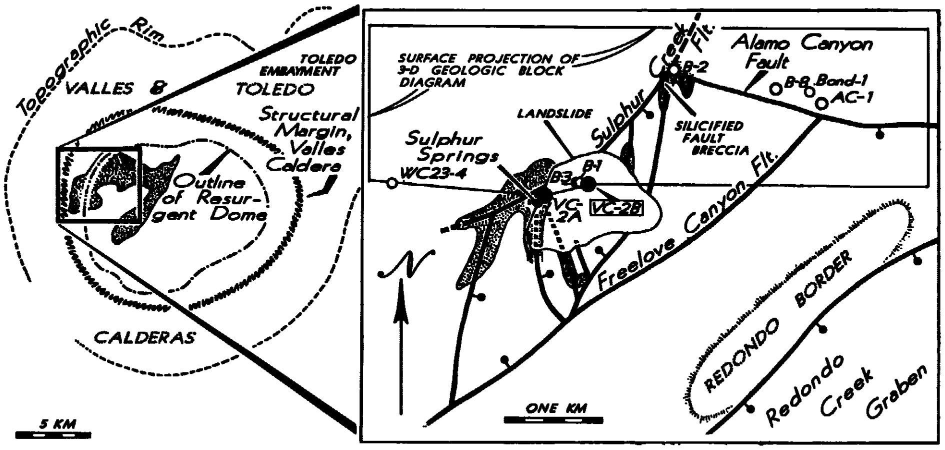


FIGURE 1. LOCATION MAP, SHOWING POSITION OF CSDP COREHOLE VC-2B RELATIVE TO MAPPED FAULTS, SURFICIAL ALTERATION (STIPPLED), AND PREVIOUSLY DRILLED GEOTHERMAL WELLS AND SCIENTIFIC COREHOLE VC-2A, IN THE SULPHUR SPRINGS AREA OF THE VALLES CALDERA COMPLEX.

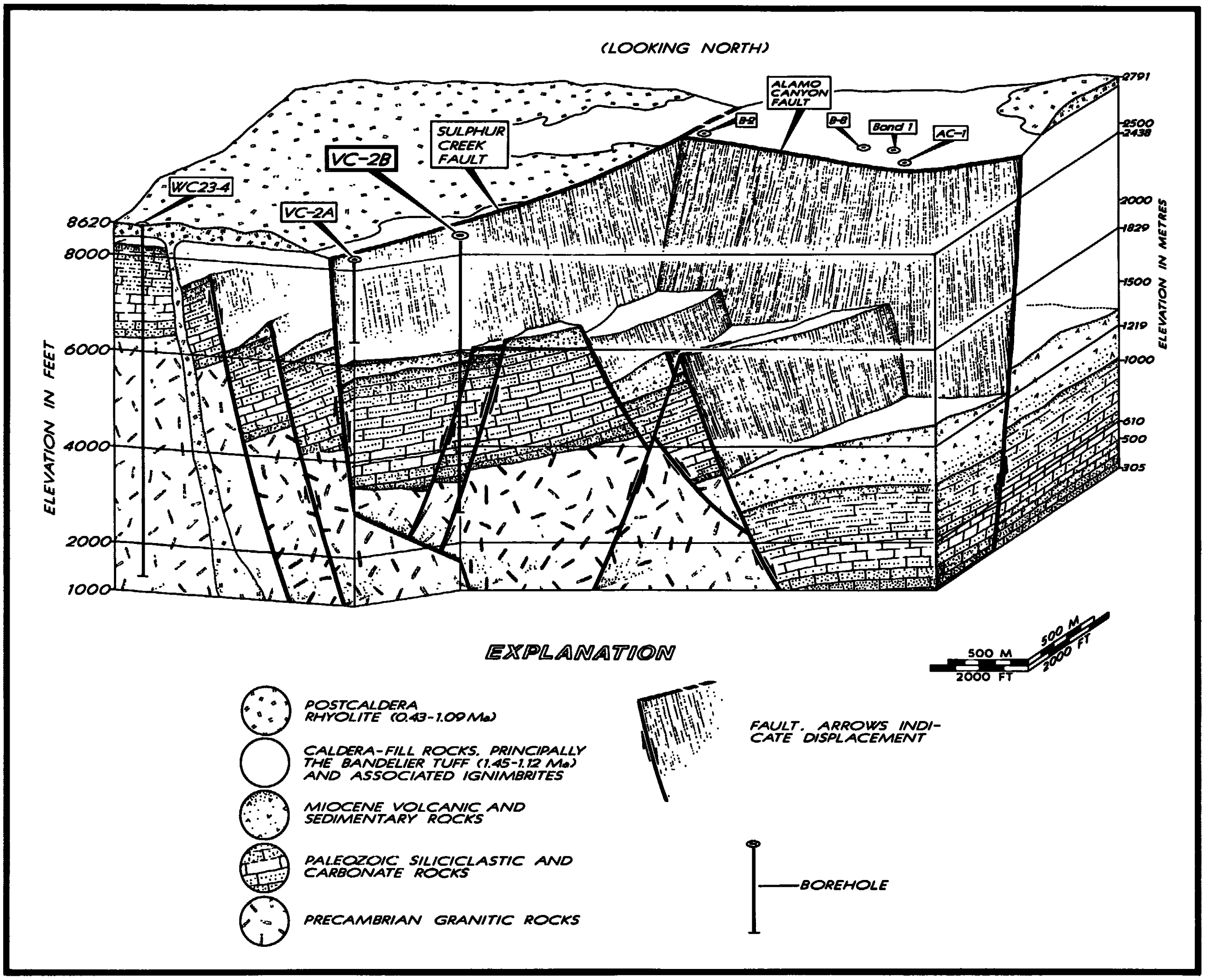


FIGURE 2. 3-D GEOLOGIC BLOCK DIAGRAM OF THE SULPHUR SPRINGS AREA AND VICINITY. POST-MIOCENE ROCKS SOUTH OF THE ALAMO CANYON FAULT AND EAST OF THE SULPHUR CREEK FAULT IMAGINARILY REMOVED FOR CLARITY.

(Figs. 1, 2), appear to involve reactivation of older basement structures.

Prior geothermal and scientific drilling at Sulphur Springs has shown that surficial alteration overlies a shallow vapor cap, probably 300-500 m in thickness, in turn developed above a deep, dilute, neutral-chloride, liquid-dominated hydrothermal system (Goff et al., 1985), circulating primarily in caldera-fill ignimbrites and subjacent Miocene volcanic and volcaniclastic rocks. CSDP corehole VC-2A, an intermediate-depth companion to VC-2B completed in 1986, penetrated the top of this deep system (Figs. 1, 2; Goff et al., 1987); thermal water collected at a depth of 490 m and temperature of 210°C yielded a chloride analysis of 2945 ppm. The entire rock column penetrated by VC-2A is hydrothermally altered, particularly in the upper 165 m of the corehole. Rocks in this zone are quartz-sericitized and locally host anomalous concentrations of poorly-crystalline molybdenite (Hulen et al., 1987). Below 165 m, chlorite-sericite alteration prevails.

STRATIGRAPHY AND STRUCTURE

The rocks cored by VC-2B (Fig. 3) can be correlated readily with those exposed within and near the Valles caldera or penetrated by previous geothermal and scientific drill holes. Beneath a 35 m-thick landslide deposit, VC-2B penetrated, to a depth of 742 m, most of the Valles intracaldera ignimbrite sequence, ranging in age from the Lower Tuffs (about 1.75 Ma; T. Spell, pers. comm., 1989) through the Tshirege Member of the Bandelier Tuff (1.12 Ma; Self et al., 1986); the post-Bandelier Upper Tuffs of Nielson and Hulen (1984) appear to have been removed by erosion. Beneath these caldera-fill rocks, the corehole encountered, in sequence: Miocene sandstone of the Santa Fe Group (742-798 m); Permian Yeso Formation (798-1047 m); Permian Abo Formation (1047-1296 m); Pennsylvanian Madera Limestone (1296-1513 m); Pennsylvanian Sandia Formation (1513-1558 m); and biotite quartz monzonite of Precambrian age (1558-1762 m/TD). For descriptions of these units, the reader is referred to a companion paper by Gardner et al. (1989; this volume).

The entire stratigraphic sequence penetrated by VC-2B has undergone at least local fracturing of both tectonic and hydrothermal origin, but the intensity of this disruption is strongly dependent both on rock type and elevation in the Sulphur Springs hydrothermal system. Major contemporary fracture zones are shown diagramatically on Figure 3. Much of the high-level ignimbrite sequence is strongly fractured; the deep Precambrian basement is similarly though in general only moderately fractured. Curiously, however, the intervening Paleozoic sedimentary sequence is overall only weakly fractured, and these rocks closely resemble corresponding unaltered outcrops outside the caldera.

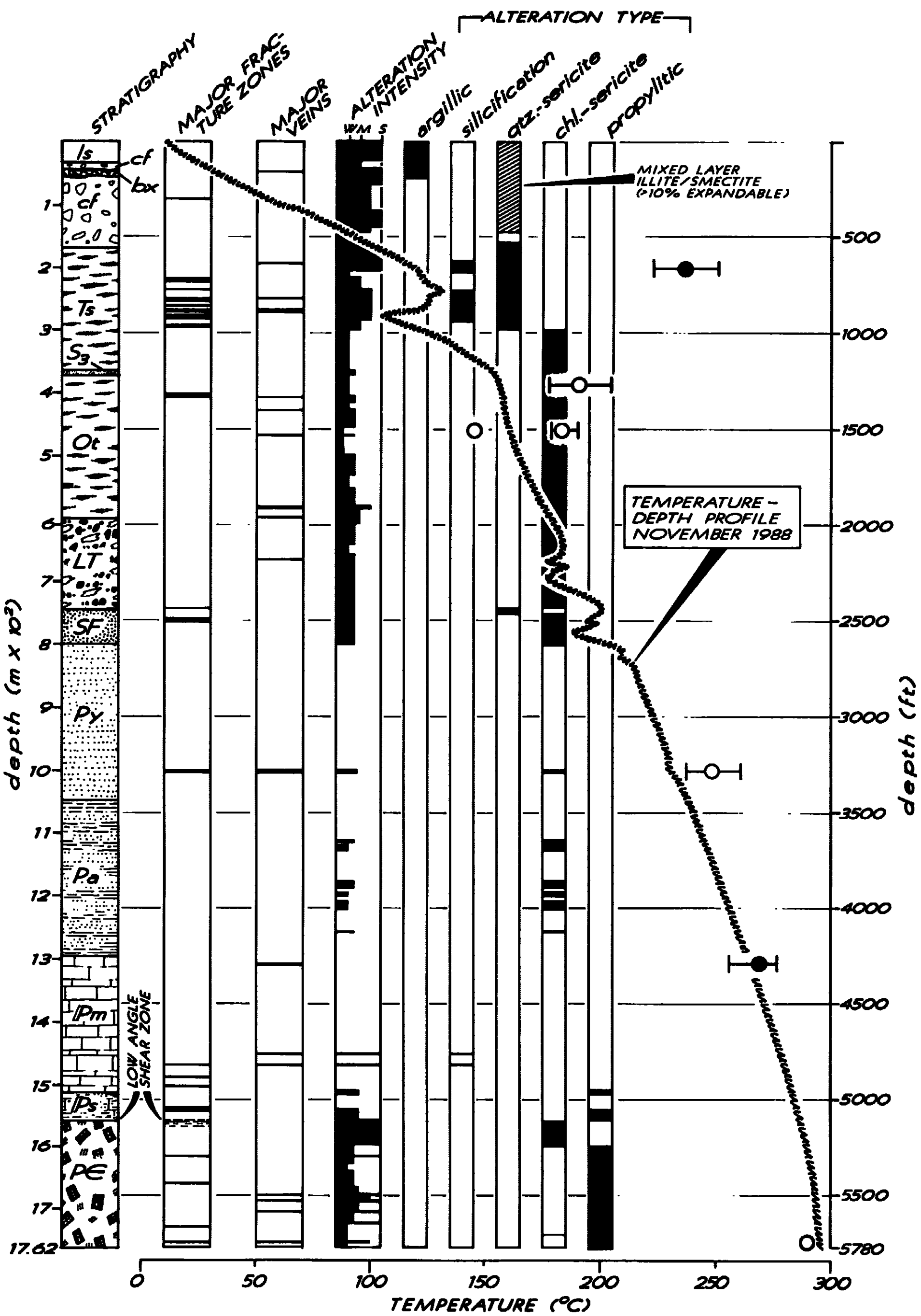
Hydrothermal breccias and hydraulic fracture networks are common in VC-2B, and have clearly played an important role in creating secondary permeability for thermal fluid flow. For example, the interval 403-481 m (Fig. 3), in the Otowi Member of the Bandelier Tuff, is extensively disrupted by "jigsaw-puzzle" stockwork fractures and breccias with locally abundant open space. These secondary vugs are partially filled with "fishscale" calcite, a morphology believed to indicate deposition from a boiling hydrothermal fluid (e.g. Tulloch, 1982). It may be that the fluids responsible for hydraulic rock rupture deposited this calcite due to resultant decompression, boiling and CO_2 depletion.

A temperature log for VC-2B (Fig. 3), completed the month after drilling, shows the influence of major open fracture zones, many of which have been invaded and cooled by drilling mud. Other zones of cooling not related to fracturing signal relatively high, primary intergranular porosity.

HYDROTHERMAL ALTERATION MINERALOGY AND ZONING

Megascopically visible hydrothermal alteration and mineralization in VC-2B reflect the distribution of fractures and breccias as well as primary permeability in certain clastic rocks and non- to weakly welded tuffs. Accordingly, the high-level ignimbrite sequence and the deep Precambrian basement are extensively altered and mineralized but, with few exceptions, the intervening Paleozoic sequence appears to be essentially unaltered (Fig. 3). Either these apparently unaffected rocks have been impermeable to hot fluid flow, or alteration effects are too subtle to be readily recognized.

Alteration in the VC-2B intracaldera ignimbrite sequence (Fig. 3) is similar to that encountered in VC-2A. In both holes, quartz-sericite alteration predominates at higher elevations and chlorite-sericite



EXPLANATION

FLUID-INCLUSION HOMOGENIZATION TEMPERATURE (RANGE AND MEAN): CLOSED=PRIMARY, OPEN=SECONDARY

STRATIGRAPHIC DESIGNATIONS: ls—LANDSLIDE DEBRIS; cf—CALDERA-FILL DEBRIS-FLOW DEPOSITS AND VOLCANICLASTIC SANDSTONES; bx—HYDROTHERMAL BRECCIA AND DACITE PORPHYRY ZONE; Ts—TSHIREGE MEMBER, BANDELIER TUFF; S_3—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; IPm—PENNSYLVANIAN MADERA LIMESTONE; IPs—PENNSYLVANIAN SANDIA FORMATION; P€—PRECAMBRIAN PORPHYRITIC QUARTZ MONZONITE.

FIGURE 3. VC-2B -- GENERALIZED STRATIGRAPHIC, STRUCTURAL, ALTERATION AND VEIN LOG.

alteration is dominant at depth. In VC-2B, however, the phyllic alteration zone extends somewhat deeper (about 300 vs 165 m), and toward the surface is characterized by mixed-layer illite/smectite (up to 25% expandable interlayers) rather than illite (<10% expandable interlayers). Moreover, in VC-2B, the illite/smectite zone is also overprinted by near-surface kaolinization.

Deep alteration in VC-2B is predominantly propylitic (calcite-chlorite-epidote-sericite-pyrite), but a prominently sheared zone in the upper portion of the Precambrian quartz monzonite is moderately to intensely chlorite-sericitized (Fig. 3). Propylitized strata of the Pennsylvanian Sandia Formation contain trace to minor amounts of wairakite and, locally, euhedral, sieve-textured anhydrite porphyroblasts.

Clay mineralogy of much of the Pennsylvanian Madera Limestone presents a contradiction to empirically-derived but generally useful sericite geothermometry (for example, Środoń and Eberl, 1984). Figure 4 is an X-ray diffractogram of the clay fraction extracted from Madera core retrieved from a depth of 1339 m, where the measured temperature is now about 270°C. This clay fraction contains, in addition to illite and chlorite, R1-ordered, mixed-layer illite/smectite, which according to methods outlined in Środoń and Eberl (1984), contains about 40% interlayer smectite. At the present temperature at this depth in VC-2B, considering that the Valles hydrothermal system has been active for at least 1 m.y. (Goff et al., 1989), the appropriate micaceous clay should be illite with few or no smectite interlayers. We suspect that the illite/smectite in the Madera is of diagenetic origin, and although at sufficiently high temperature to transform to illite, has been isolated from the hot, potassium-bearing fluids necessary for the transformation.

VEIN MINERALIZATION

Mirroring the intensity of fracturing and hydrothermal alteration, veins (and breccia cements) are common in the VC-2B ignimbrites and deep Precambrian basement, but rare in the intervening Paleozoic sequence. The veins display well-developed filling sequences and cross-cutting relationships which will help constrain the host rocks' hydrothermal history. Vein minerals locally present in various combinations throughout the VC-2B core comprise quartz, sericite (Fig. 5) chlorite, calcite, fluorite and pyrite. Anhydrite and barite occur sparsely in veins below 1000 m; epidote (Fig. 5) and wairakite below 1470 m. Metallic vein minerals are distinctly zoned, with traces of typical epithermal phases (rhodochrosite, pyrargyrite (Fig. 6) and stibnite (?)) only in high-level, quartz-sericitized rocks, and base-metal sulfides (chalcopyrite, sphalerite, galena, and chalcocite) in the deeper reaches of the corehole. In addition, an unknown bismuth telluride was discovered in silicified limestone breccia at a depth of 1449 m. For a full listing of major veins and vein minerals discovered to date in the VC-2B core, the reader is referred to Hulen and Gardner (1989).

FLUID INCLUSIONS

Hydrothermal quartz, calcite and fluorite in VC-2B host large and abundant, primary and secondary fluid inclusions, ideal for reconnaissance microthermometry. All inclusions analyzed for this study are liquid-rich, two-phase (liquid plus vapor) at room temperature, and homogenize to the liquid phase upon heating to the appropriate temperature; locally coexisting vapor-rich inclusions document periodic boiling of the fluids. Homogenization temperatures (T_h) for the liquid-rich inclusions are plotted on Figure 3, and cross-plotted with corresponding ice-melting temperatures (T_m) on Figure 7. In general, inclusions in deeper veins show (as expected) higher T_h's (up to 291°C) than those in veins from shallower depths (commonly <200°C). The deep inclusion fluids also show much lower ice-melting temperatures than their shallow counterparts (as low as -1.7°C, vs 0.0 to -0.4°C). Whereas deeper inclusion fluids tend to follow closely the present temperature profile (Fig. 3), with minor exceptions those from higher elevations (particularly from primary inclusions) exceed corresponding current temperatures. The few inclusions from rare, intermediate-depth vein minerals measured to date show both T_h's and T_m's intermediate between those from shallow and deep veins.

DISCUSSION AND CONCLUSIONS

Considered together, the preliminary data presented above allow an initial assessment of the present configuration and history of the Sulphur Springs hydrothermal system. As in previous geothermal and

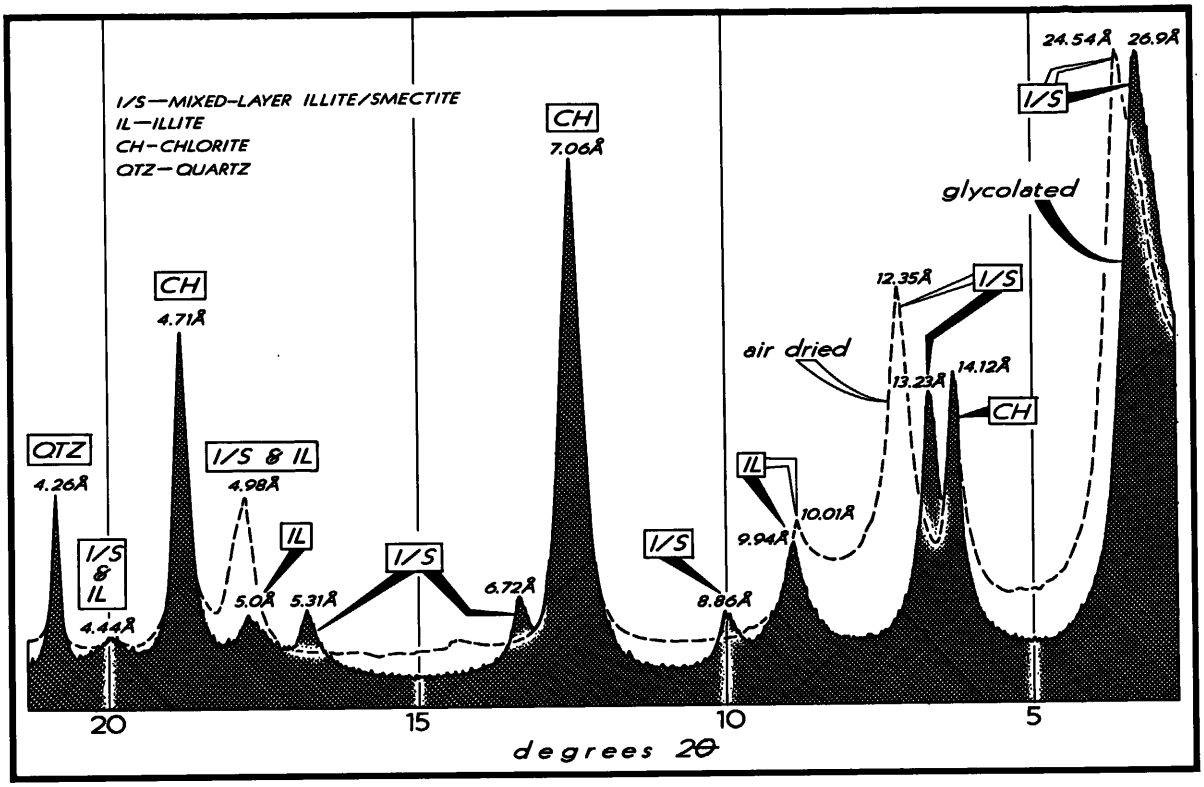


FIGURE 4. X-RAY DIFFRACTOGRAM OF THE <5 MICRON FRACTION EXTRACTED FROM ARGILLACEOUS LIMESTONE OF THE PENNSYLVANIAN MADERA LIMESTONE, COREHOLE VC-2B, DEPTH INTERVAL 1339 M, CURRENT T = 267°C.

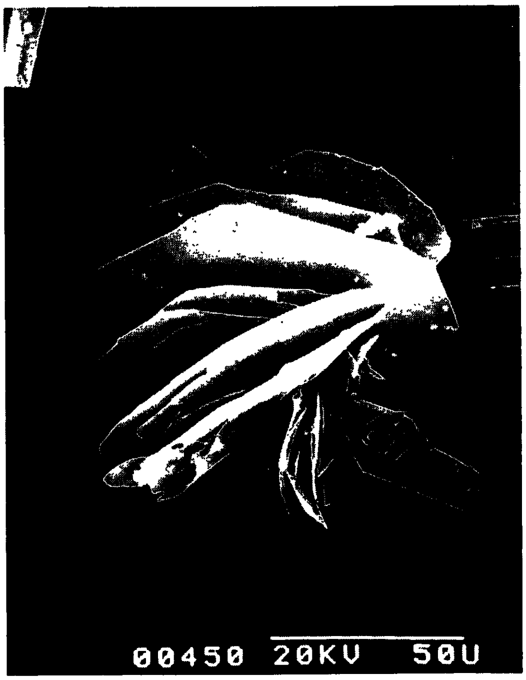


FIGURE 5. SEM PHOTOMICROGRAPH OF SERICITE (FLOWERY AGGREGATE) ON EPIDOTE FROM A VEIN AND PROBABLE CONTEMPORARY FLUID CHANNEL IN QTZ. MONZONITE, COREHOLE VC-2B, DEPTH 1752 M.

FIGURE 6. SEM PHOTOMICROGRAPH OF PYRARGYRITE FROM A VEIN CUTTING QUARTZ-SERICITIZED RHYOLITE ASH-FLOW TUFF, COREHOLE VC-2B, DEPTH 351 M.

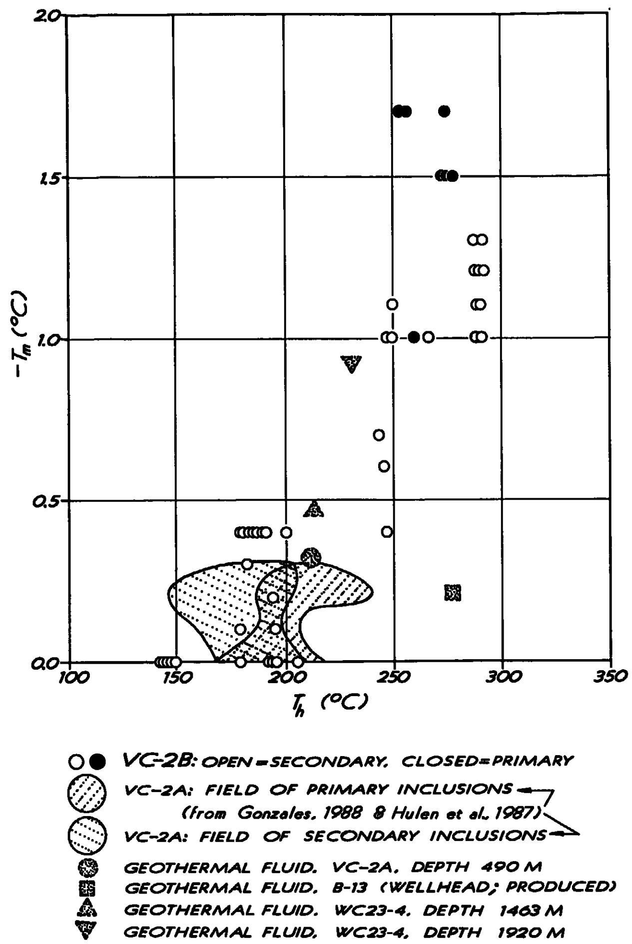


FIGURE 7. PLOT OF T_m VS T_h FOR FLUID INCLUSIONS FROM VEIN MINERALS, COREHOLE VC-2B. SHOWN FOR REFERENCE ARE CORRESPONDING VALUES FOR COREHOLE VC-2A AND CALCULATED VALUES FOR VALLES GEOTHERMAL FLUIDS.

scientific holes drilled in the Valles caldera, there is ample evidence that the deep, liquid-dominated portion of the system has dramatically descended from previously higher elevations. Alteration assemblages even in near-surface rocks penetrated by VC-2B are clearly of water-dominated origin, even though the present water table is believed to be at a depth of about 365 m (a prominent inflection point on the temperature log of Figure 3). Primary fluid-inclusion T_h's for shallow veins strongly support this conclusion, reaching mean values of >200°C where present temperatures are now below 100°C.

Inclusion fluids from shallower VC-2B veins range in equivalent wt. % NaCl from nil to about 0.7 (using the equations of Potter et al, 1978), the latter value being just slightly higher than calculated T_m's (gas-free basis) for "typical" Valles reservoir fluid (White, 1986) and for produced fluid from 490 m depth in VC-2A (Goff et al., 1988). The nil values for VC-2B inclusion fluids may represent either steam condensate from past boiling deeper in the reservoir, or possibly steam-heated ground water. Deep VC-2B inclusion fluids have much higher apparent salinities (1.7-2.9 equiv. wt. % NaCl) than any fluid yet sampled in the Valles caldera. This considerable apparent salinity range, corresponding to a fairly narrow T_h range, could be due to different amounts of trapped gas (mostly CO_2) due to boiling (Hedenquist and Henley, 1985), but even the probable minimum salinity (1.7%) would be nearly four times that of Valles reservoir fluid. Interestingly, however, these deep VC-2B inclusion fluids are quite similar in salinity to contemporary thermal fluid collected from a depth of 1920 m in nearby geothermal well WC23-4 (Figs. 3, 7). Both are from veins/fracture zones in Precambrian quartz monzonite, and may signal a deeper hydrothermal cell distinct from the one known to be circulating in high-level intracaldera-facies rocks.

The presence of abundant, low-temperature, mixed-layer illite/smectite in the Madera Limestone, where present temperatures are now well in excess of 250°C, suggests that at least this portion of the Paleozoic sequence has remained essentially impermeable to Valles hydrothermal fluid. This in turn suggests the possibility that the hypothetical deep, more saline hydrothermal cell may have had only limited communication with the more dilute reservoir above. Apparent salinities and homogenization temperatures of inclusion fluids from vein calcite at 1000 m depth in VC-2B (Figs. 3, 7) may represent local mixing of the two fluid types.

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Appendix -- Methods and procedures: Following detailed preliminary logging of the core, mostly at the drill site shortly after retrieval, representative samples were selected for petrographic study, supplemented as necessary by bulk- and clay-fraction X-ray diffraction (XRD) analysis (methods outlined in Hulen and Nielson, 1988). Reconnaissance fluid-inclusion studies were completed on doubly-polished crystal fragments, about 0.20 mm in thickness, using a Fluid Inc. modified U.S.G.S. heating/freezing system. Duplicate measurements of homogenization temperatures (T_h) and ice-melting temperatures (T_m) were within 0.2°C of original values.