LA--11165-OBES

DE88 007158

LA-11165-OBES

UC-66b 403

Issued: January 1988

# Lithologic Descriptions and Temperature Profiles of Five Wells in the Southwestern Valles Caldera Region, New Mexico

Lisa Shevenell, Fraser Goff, Dan Miles, Al Waibel,* and Chandler Swanberg**

*Columbia Geoscience, Hillsboro, OR 97124.
**GEO Operator Corporation, San Mateo, CA 94402.



Los Alamos National Laboratory
Los Alamos, New Mexico 87545

## DISCLAIMER

# DISCLAIMER

**Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.**

# LITHOLOGIC DESCRIPTIONS AND TEMPERATURE PROFILES OF FIVE WELLS IN THE SOUTHWESTERN VALLES CALDERA REGION, NEW MEXICO

by

Lisa Shevenell, Fraser Goff, Dan Miles,
Al Waibel, and Chandler Swanberg

## ABSTRACT

The subsurface stratigraphy and temperature profiles of the southern and western Valles caldera region have been well constrained with the use of data from the VC-1, AET-4, WC 23-4, PC-1, and PC-2 wells. Data from these wells indicate that thermal gradients west of the caldera margin are between 110 and 140°C/km, with a maximum gradient occurring in the bottom of PC-1 equal to 240°C/km as a result of thermal fluid flow. Gradients within the caldera reach a maximum of 350°C/km, while the maximum thermal gradient measured southwest of the caldera in the thermal outflow plume is 140°C/km. The five wells exhibit high thermal gradients (>60°C/km) resulting from high conductive heat flow associated with the Rio Grande rift and volcanism in the Valles caldera, as well as high convective heat flow associated with circulating geothermal fluids. Gamma logs run in four of the five wells appear to be of limited use for stratigraphic correlations in the caldera region. However, stratigraphic and temperature data from the five wells provide information about the structure and thermal regime of the southern and western Valles caldera region.

## I. INTRODUCTION

The Valles caldera is located within the Jemez volcanic field in north-central New Mexico and is one of the most studied calderas in the western United States. Numerous geological, geochemical, and geophysical studies (Gardner et al. 1986; Goff et al. 1986; Heiken et al. 1986; Self et al. 1986; Olsen et al. 1986; Vuataz and Goff 1986) have been conducted in the Valles caldera area since the earlier geologic work of the US Geological Survey (Doell et al. 1968; Bailey et al. 1969; Smith et al. 1970). During the 1960s and 1970s, Union Oil Company of California drilled 24 deep geothermal wells within Valles caldera to evaluate the geothermal potential of the area. The data obtained from these boreholes have provided detailed information about the subsurface geology and structure in the region. Detailed studies of Valles caldera have been conducted by Nielson and Hulen (1984), Hulen and Nielson (1982, 1983), and Goff et al. (1985) by integrating Union drill hole data with surface geologic data.

Additional well data have been obtained through the Continental Scientific Drilling Program, the Hot Dry Rock Program, and private ventures. The five wells discussed in this report are located south of (VC-1 and AET-4), west of (PC-1, PC-2), or within Valles caldera (WC 23-4). The purpose of this five-well report is to provide lithologic and temperature data for other scientific investigations concerning the structure and thermal regime of Valles caldera.

## II. GENERAL GEOLOGY

The Jemez volcanic field is located at the intersection of the northeast trending Jemez lineament and the Rio Grande rift. The Jemez lineament is a line of Miocene to Quaternary volcanic fields, with the Jemez Mountains being just one of these volcanic fields (Mayo 1958; Laughlin 1976). The geology of the Jemez Mountains consists of extensive Tertiary to Quaternary volcanic rocks that overlie Tertiary basin-fill sedimentary rocks within the rift and Paleozoic and Mesozoic sedimentary rocks and Precambrian granites, gneisses, and schists west of the rift margin. The most widespread Paleozoic units that occur in the Jemez Mountains are the redbeds of the Permian Abo Formation and the Pennsylvanian Madera Limestone. The geology of the Jemez Mountains was mapped by Smith et al. (1970) and is described by Doell et al. (1968), Bailey et al. (1969), Gardner and Goff (1984), and Gardner et al. (1986).

Volcanism in the Jemez Mountains began >13 m.y. ago with mafic to intermediate lava flows (Gardner et al. 1986). At 1.45 m.y. caldera formation resulted from the eruption of the Otowi Member of the Bandelier Tuff. At 1.12 m.y. the Tshirege Member of the Bandelier Tuff erupted forming Valles caldera, with the total volume of tuff deposited by both members during caldera formation being approximately 600 $km^3$ (Smith 1979). Following caldera formation, extrusion of rhyolitic domes and minor tuffs occurred in the moat zone of the caldera from 1.05 to 0.13 m.y. ago.

## III. STRATIGRAPHY AND TEMPERATURE PROFILES

The five wells discussed in this paper were drilled to achieve various scientific objectives or to evaluate the geothermal potential of an area. Each of the five wells is located on the sketch map of Fig. 1. Stratigraphy, temperature profiles, and gamma-ray logs, where available, are illustrated for each well in Figs. 2-6. Lithologic descriptions of each well can be found in the Appendix. Tables I and II list locations, elevations, depths, and lithologic breaks of each well.

### A. The VC-1 Scientific Core Hole

The VC-1 (Valles caldera #1) core hole was continuously cored in the summer of 1984 by Tonto Drilling Company for Los Alamos National Laboratory under the Continental Scientific Drilling Program to a depth of 856 m (2809 ft). This core hole was drilled on the margin of Valles caldera (see Fig. 1) in order to intersect the "plume" of thermal fluids presumably traveling down the Jemez Fault Zone in San Diego Canyon. Secondary objectives of the hole were to define pulses of hydrothermal activity, define lithologic breaks, study hydrothermal alteration, and evaluate the thermal regime in the southern section of Valles caldera.

The VC-1 core hole first penetrated 148.7 m (488 ft) of the 0.13 m.y. Banco Bonito Member and 12.8 m (42 ft) of the Battleship Rock ignimbrite (Fig. 2). Below these volcanic rocks, the VC-1 core hole penetrated two previously unknown volcanic units. An 18.6-m (61-ft) thick slightly porphyritic obsidian was encountered at a depth of 162 m (530 ft) and was subsequently named the VC-1 rhyolite (Goff et al. 1986). A recent K/Ar age determined on biotite is 0.356 m.y. (Goff et al. 1986). Underlying the VC-1 rhyolite is 118 m (387 ft) of lithic-rich VC-1 tuffs (named herein). Below the VC-1 tuffs is 36.3 m (119 ft) of a volcaniclastic conglomerate. Within the volcaniclastic conglomerate slickensides and shear planes were identified over the depth interval of 317.6-320.3 m (1042-1051 ft). Underlying the moat volcanic rocks is 87.8 m (288 ft) of the Permian Abo Formation. Next, the core hole penetrated 385.9 m (1266 ft) of the Pennsylvanian Madera Limestone. At 807.7 m (2650 ft), the brecciated Sandia Formation was encountered. A fault breccia has been identified between 826.3 and 831.2 m (2711 and 2727 ft) (Hulen and Nielson 1985). Between 841.9 and 856 m (2762 and 2808 ft), Precambrian gneiss was penetrated with a breccia zone being encountered between the depths of 844.3 and 850.4 m (2770 and 2790 ft). Finally, a contorted shale below the Precambrian gneiss, between 852.6 and 856 m (2797 and 2808 ft), is likely to be a fault-displaced block of the

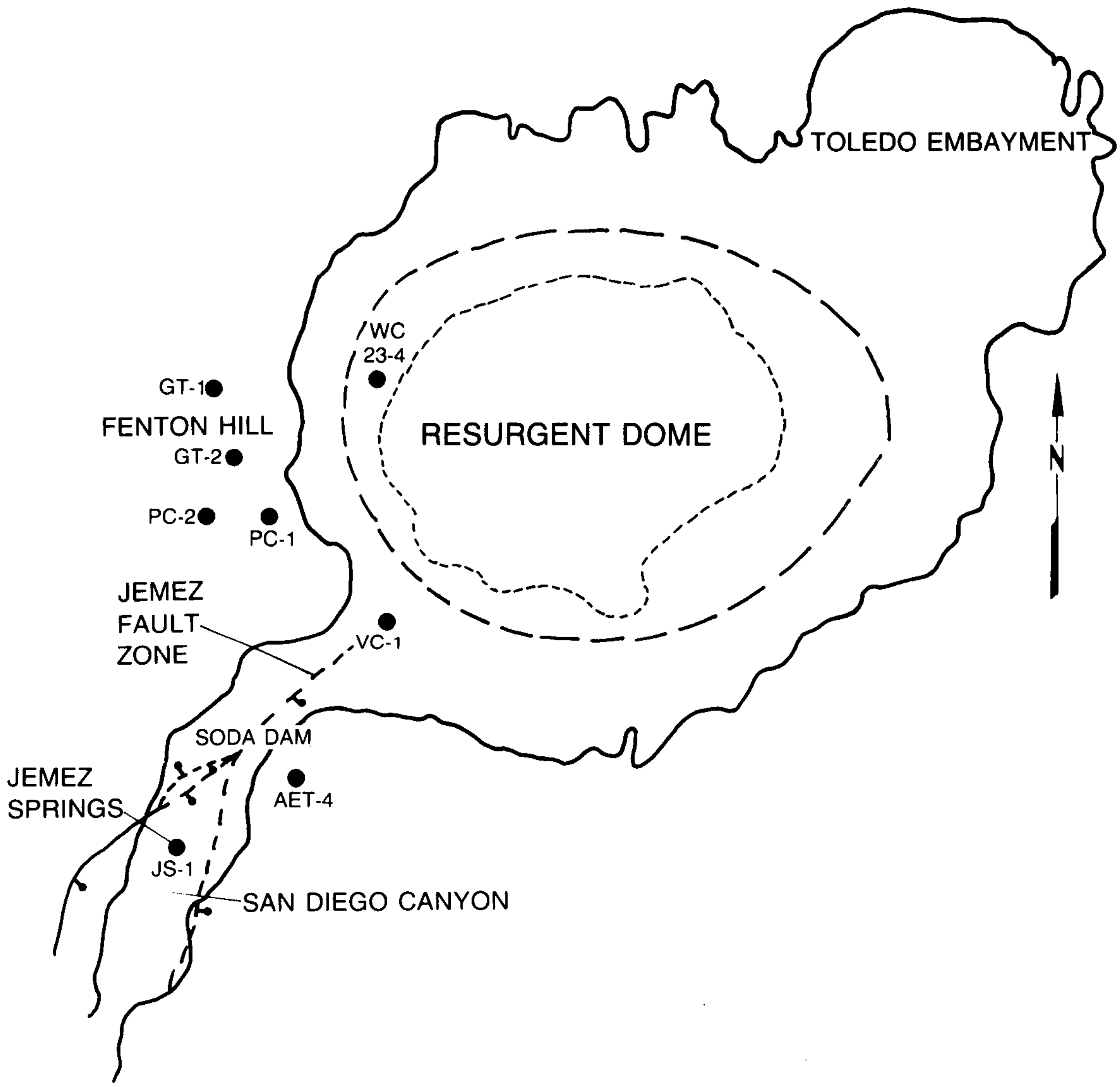


Fig. 1.
Map showing locations of eight geothermal wells in the Valles caldera region. The short-dashed line outlines the border of the resurgent dome within Valles caldera. The long-dashed line shows the inferred position of the Valles caldera ring fracture zone. This figure is a simplified version of Fig. 2 in Goff et al. 1986.

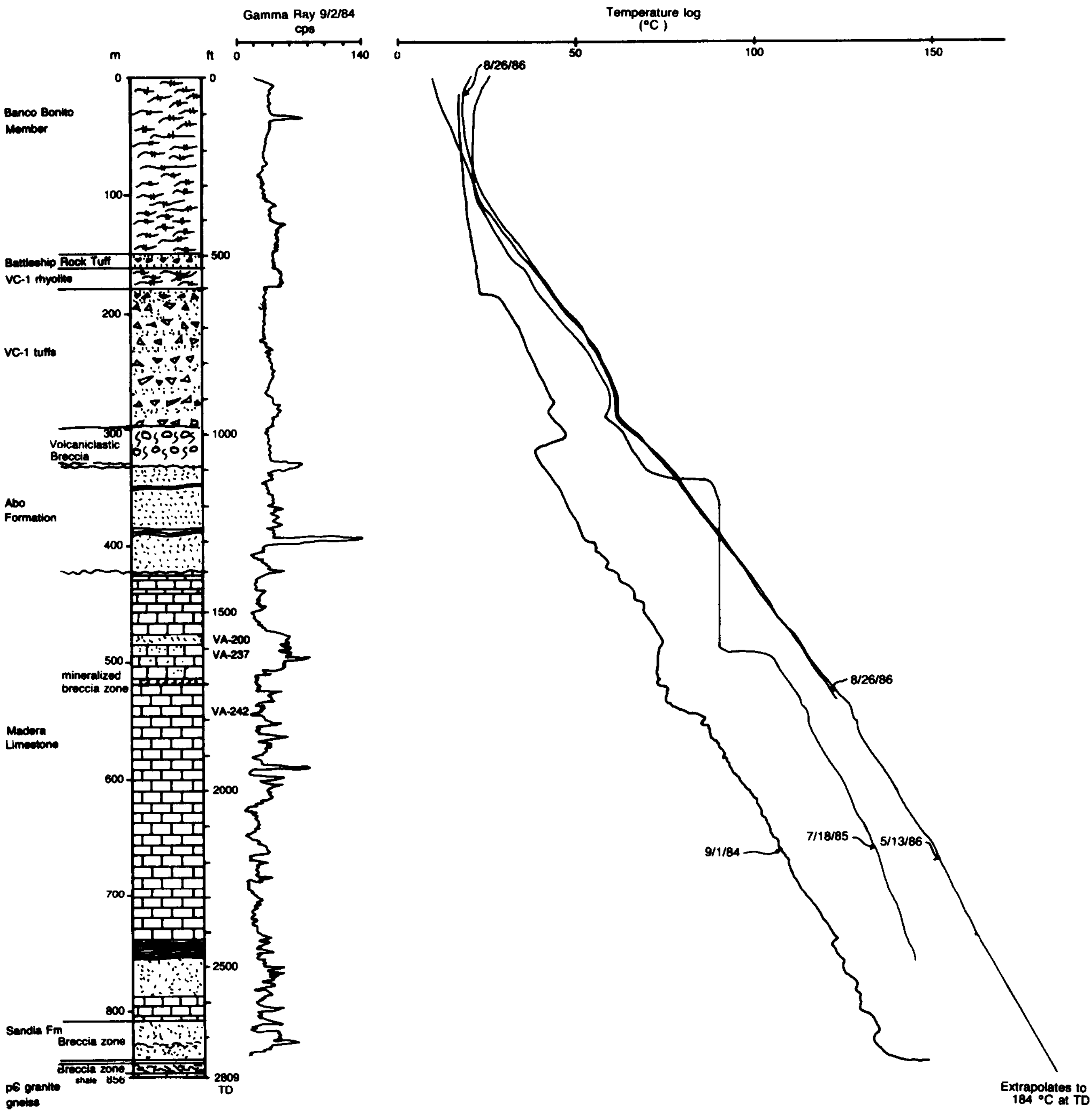


Fig. 2.
Lithologic, temperature, and gamma-ray (in counts per second) logs from core hole VC-1. Temperature and gamma-ray logs were run by Southwest Surveys and Jet West Wireline Services, both of Farmington, New Mexico. Sample numbers identify aquifers that were sampled and analyzed for major- and trace-element chemistry. Chemical analyses of samples VA-200, VA-237, and VA-242 can be found in Goff et al. (in prep.).

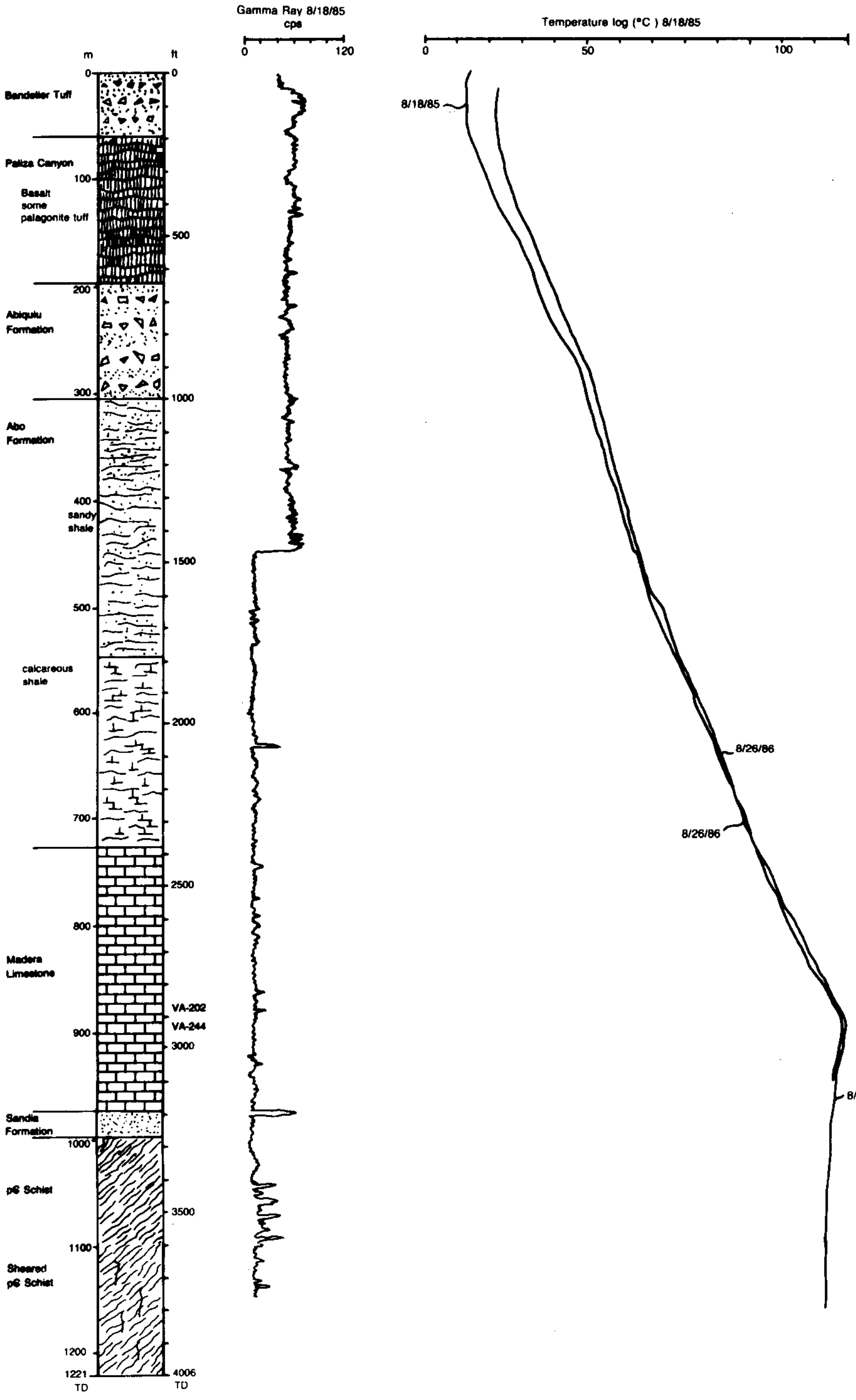


Fig. 3.
Lithologic, temperature, and gamma-ray (in counts per second) logs from well AET-4. Temperature and gamma-ray logs were run by Southwest Surveys of Farmington, New Mexico. Sample numbers identify aquifers that were sampled and analyzed for major- and trace-element chemistry. Chemical analyses of samples VA-202 and VA-244 are located in Goff et al. (in prep.).

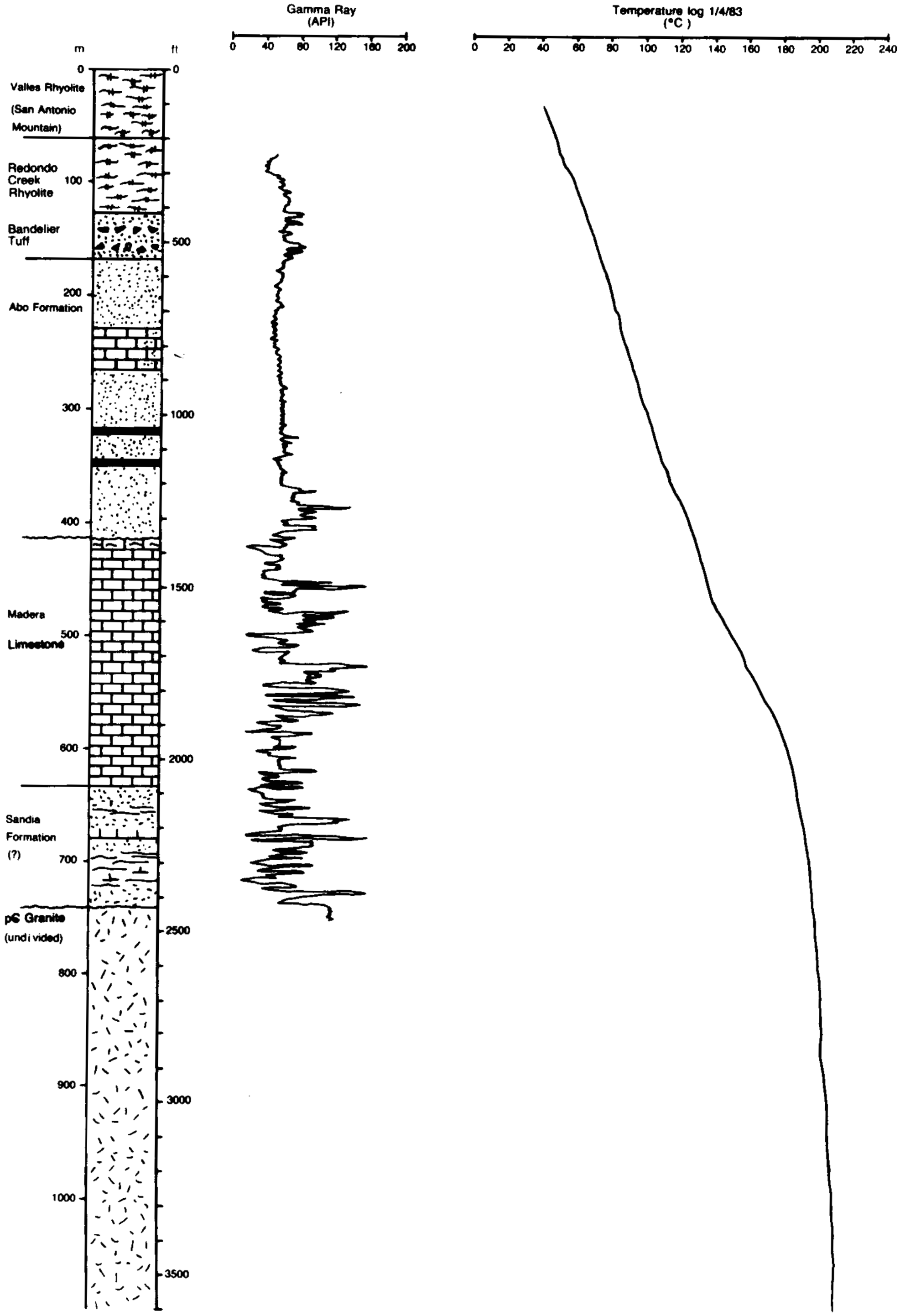


Fig. 4.
Lithologic, temperature, and gamma-ray (in American Petroleum Institute units) logs from the WC 23-4 well. Temperature and gamma-ray logs were run by Los Alamos National Laboratory. Sample numbers identify aquifers that were sampled and analyzed for major- and trace-element chemistry. Chemical analyses of samples VA-113 and VA-116 are located in Shevenell et al. (1987).

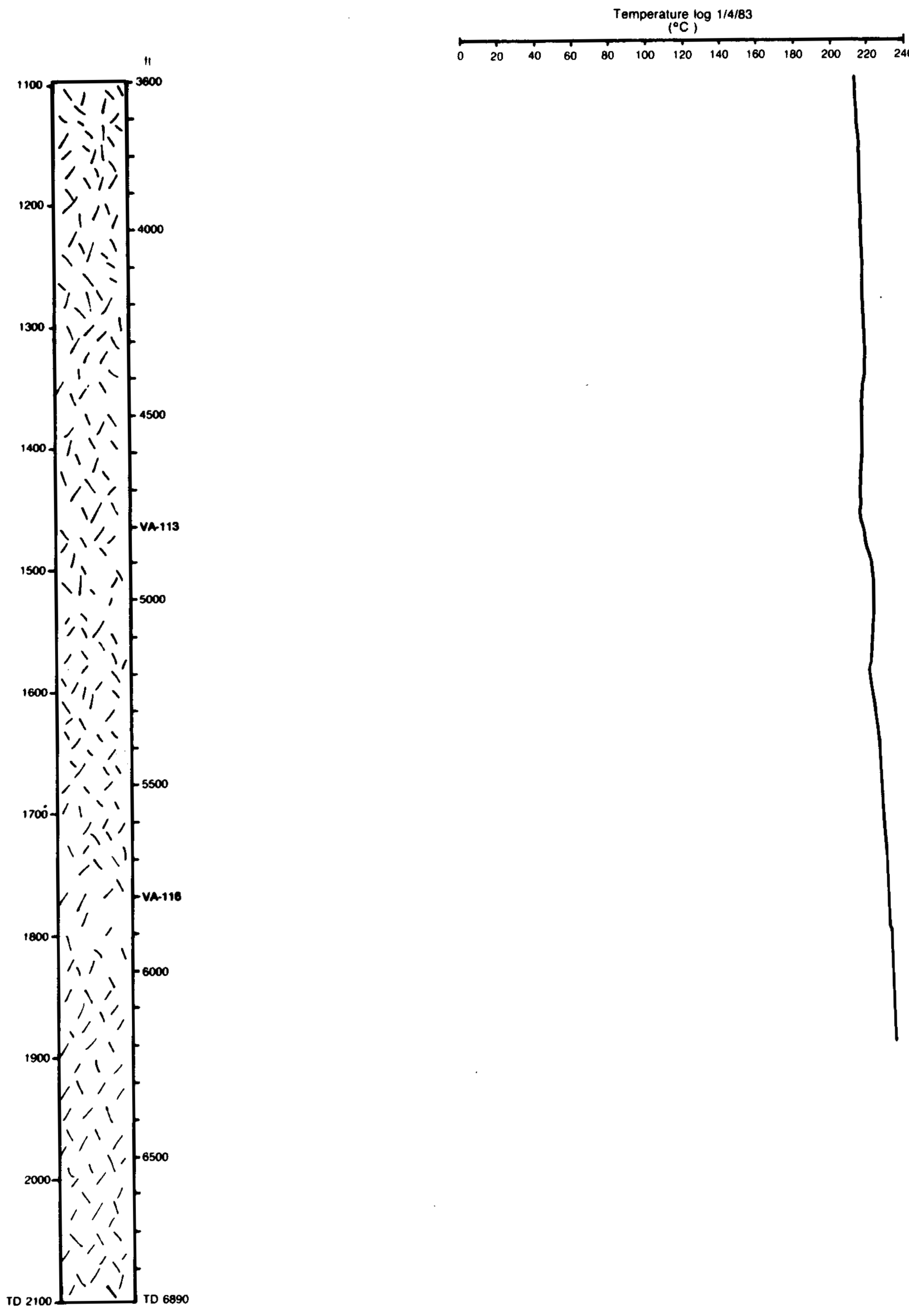


Fig. 4. (Continued)

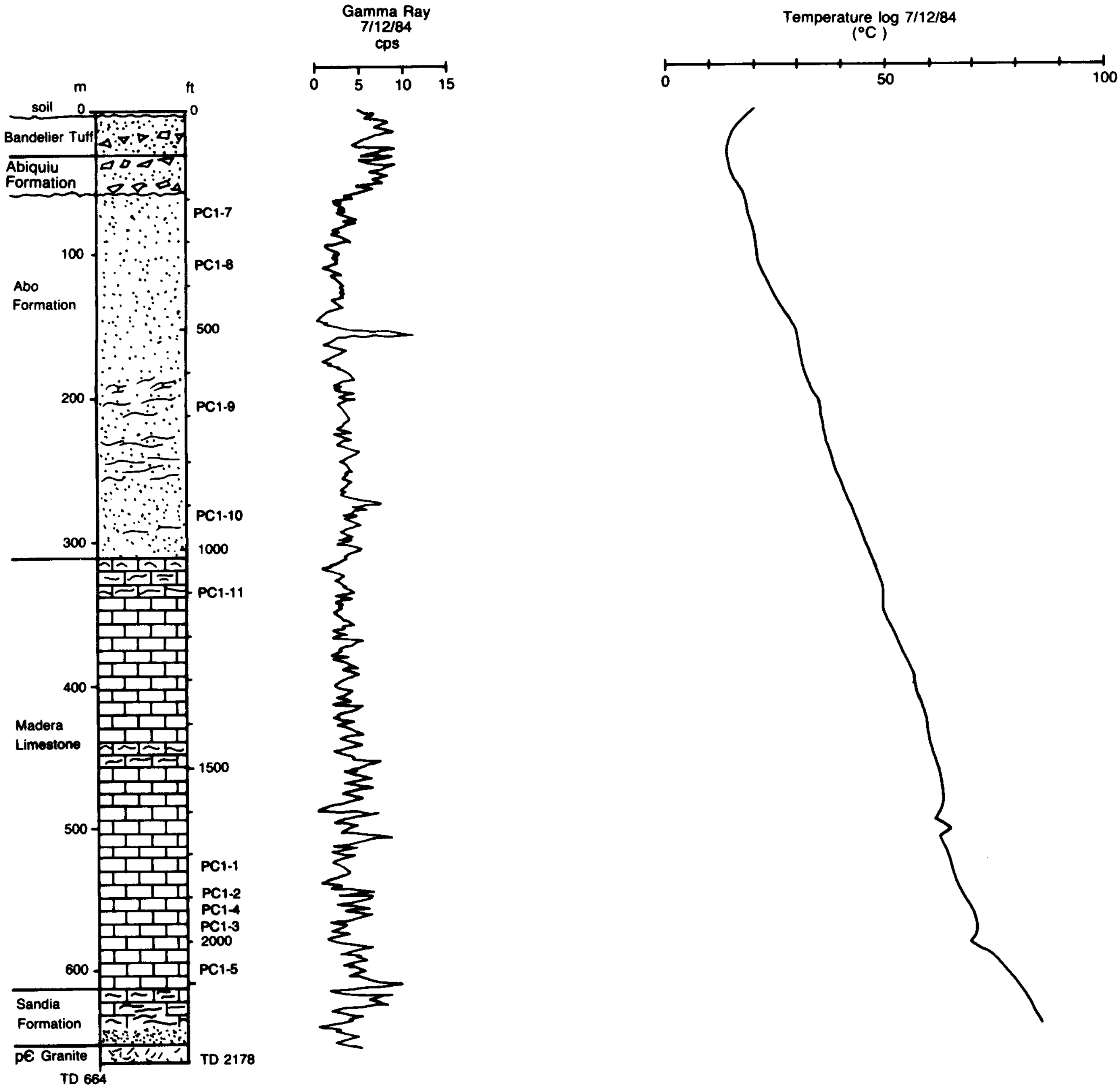


Fig. 5.
Lithologic, temperature, and gamma-ray (in counts per second) logs of well PC-1. The temperature and gamma-ray logs were run by Los Alamos National Laboratory. Sample numbers identify aquifers that have been sampled and analyzed for major- and trace-element chemistry. Chemical analyses of samples PC1-1 through PC1-5 and PC1-7 through PC1-11 can be found in Shevenell et al. (1987).

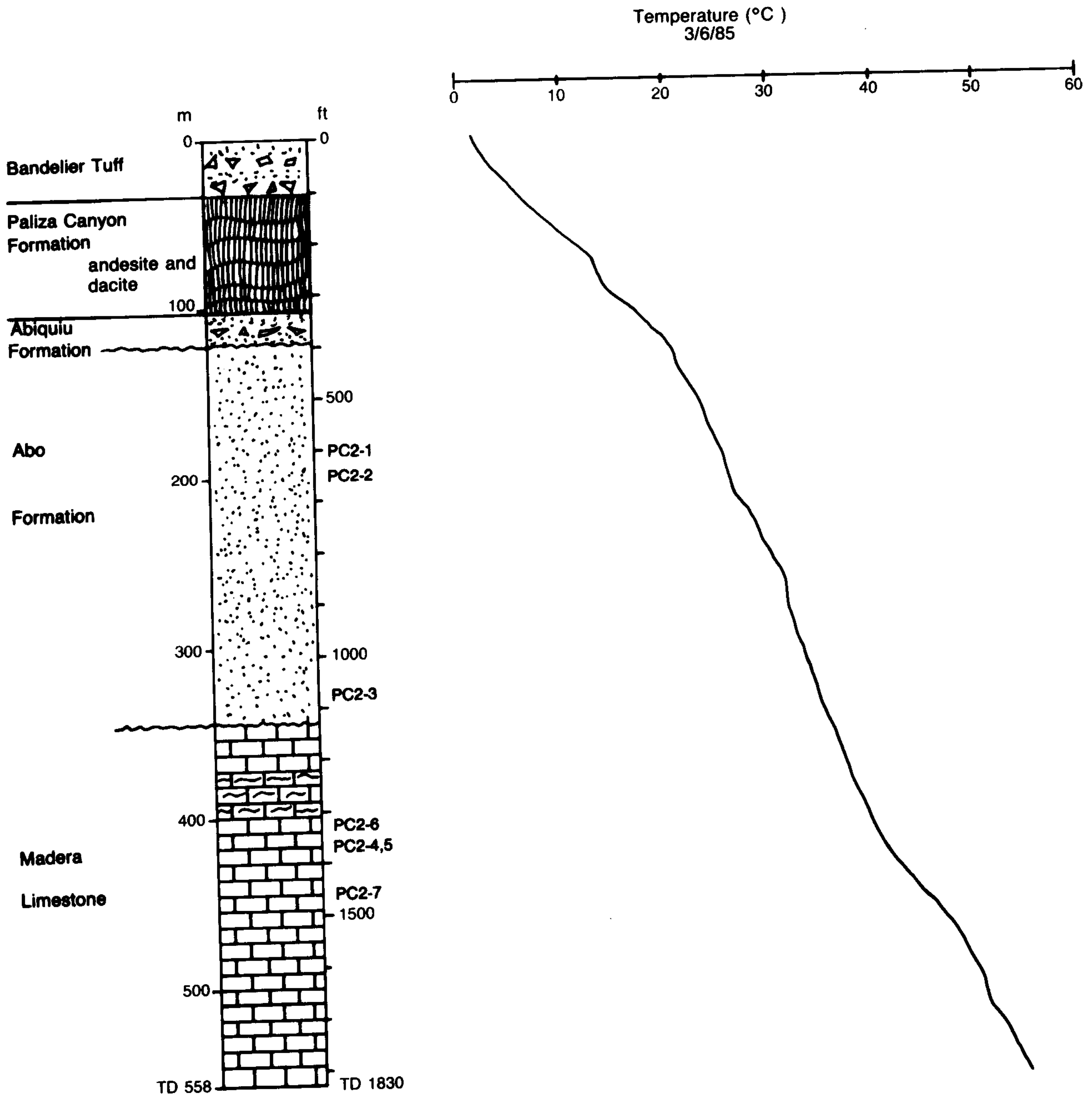


Fig. 6.
Lithologic and temperature logs, run by Los Alamos National Laboratory, of well PC-2. Sample numbers identify aquifers that were sampled and analyzed for major- and trace-element chemistry. Chemical analyses of samples PC2-1 through PC2-7 are located in Shevenell et al. (1987).

## TABLE I

## LOCATIONS, ELEVATIONS, DEPTHS, AND MAXIMUM TEMPERATURES OF THE FIVE WELLS DISCUSSED IN THIS REPORT

| Name | Location | Topographic Sheet | Township | Range | Section | Eleva-tion | Total Vertical Depth (ft) | Hole Diameter (in.) | Maximum Tempera-ture (°C) | Water Entries | Condition of Hole |
|---|---|---|---|---|---|---|---|---|---|---|---|
| VC-1 | Lat. 35°50'27<br>Long. 106°37'13" | Redondo Peak | 19 N | 3E | 33 | 8199 | 2809 | 2-3/4 | 163 at 2420 ft | 1570, 1750 | Collapsed casing at 1743 ft; bottom of hole lost. |
| AET-4 | Lat. 35°47'34"<br>Long. 106°39'13" | Jemez Springs | 18 N | 3E | 18 | 8000 | 4006 | 7 | 129 at 2930 ft | 2935 | Blocked at 3800 ft. |
| WC 23-4 | Lat. 35°54'33"<br>Long. 106°37'54" | Seven Springs | 19 N | 3E | 4 | 8616 | 6445[a] | 7 | 232.6 at 6200 ft | 1998(?) | 6-1/8-in. open hole from 4437 ft to total depth. |
| PC-1 | Lat. 35°52'35"<br>Long. 106°39'43" | Seven Springs | 19 N | 3E | 18 | 8419 | 2178 | 4-1/2 | 84 at 2095 ft | 225, 390 | Bit, stem, and jars stuck in hole at 2131 ft; geophone placed at 2131 ft. |
| PC-2 | Lat. 35°52'33"<br>Long. 106°41'01" | Seven Springs | 19 N | 3E | 13 | 8622 | 1830 | 7 | 54 at 1830 ft | 590, 830, 1070, 1310 | Geophone placed in bottom at 1819 ft. |

[a] Total depth drilled is 6890 ft. The first 1572 ft were drilled vertically; the interval from 1572 to 6890 ft was directionally drilled with an average angle off of the vertical of 2.6°.

TABLE II

LITHOLOGIC CONTACTS OF THE FIVE WELLS DISCUSSED IN THIS REPORT

| WELL | VC-1 | AET-4 | WC 23-4 | PC-1 | PC-2 |
|---|---|---|---|---|---|
| Location[a] Lat. | 50'27" | 47'34" | 54'33" | 52'35" | 52'33" |
| Location[a] Long. | 37'15" | 39'13" | 37'54" | 39'43" | 41'01" |
| Surface Elevation (ft) | 8199 | 8000 | 8615 | 8419 | 8622 |
| Total Depth (ft) | 2809 | 4006 | 6445 | 2178 | 1831 |
| Top of[b]: | | | | | |
| Alluvium | -- | -- | -- | 8419 | -- |
| Banco Bonito | 8199 | -- | -- | -- | -- |
| Battleship Rock | 7711 | -- | -- | -- | -- |
| VC-1 rhyolite | 7669 | -- | -- | -- | -- |
| VC-1 tuff | 7608 | -- | -- | -- | -- |
| San Antonio Mountain rhyolite | -- | -- | 8615 | -- | -- |
| Redondo Creek rhyolite | -- | -- | 8415 | -- | -- |
| Bandelier Tuff | -- | 8000 | 8205 | 8409 | 8622 |
| Paliza Canyon Fm. | -- | 7806 | -- | -- | 8516 |
| Abiquiu Formation | -- | 7355 | -- | 8317 | 8300 |
| Abo Formation | 7103 | 7000 | 8065 | 8226 | 8228 |
| Madera Formation | 6815 | 5620 | 7255 | 7412 | 7491 |
| Sandia Formation | 5549 | 4810 | 6400 | 6410 | -- |
| p€ rocks | 5431 | 4730 | 6197 | 6272 | -- |
| Well Bottom Elevation | 5390 | 3994 | 2170 | 6241 | 6791 |

[a]All latitudes are 35°; all longitudes are 106°.

[b]Top of unit is listed as elevation -- feet above sea level.

Sandia Formation. For a more detailed description of the lithologic units encountered in VC-1, refer to the Appendix.

Figure 2 also illustrates four different temperature surveys run in the VC-1 core hole. The temperature log dated July 18, 1985, was run by Jet West Wireline Services of Farmington, New Mexico, whereas the other three logs were provided by Southwest Surveys of Farmington, New Mexico. From Fig. 2, it appears that the Jet West logging tool encountered a large isothermal zone between 1200 and 1600 ft. However, this apparent isothermal zone resulted from tool failure over this interval. The temperature profile labeled 9/1/84 was obtained immediately after drilling ceased at VC-1, therefore this rather erratic log represents temperatures that are not equilibrated.

From these four temperature profiles, we see that thermal equilibration of the VC-1 core hole may have taken up to two years. Between September 1, 1984 and May 13, 1986, the temperature in the deeper portion of the hole increased by as much as 42°C. However, the temperature gradient in the well remained relatively constant through time, with the thermal gradient between depths of 91.4 and 518 m being 250°C/km and the gradient from 518 m to total depth being 190°C/km.

A gamma-ray log was also run by Southwest Surveys and is included on Fig. 2. Although gamma-ray logs currently appear to have limited use in geothermal environments, this log could potentially be used for correlation between wells. For example, a large spike at 329 m (1080 ft) distinctively identifies the contact between the volcanic breccia and the underlying Abo Formation. However, other lithologic contacts in VC-1 are not as obvious from this log. The large spike at a depth of 396 m (1300 ft) in the Abo section may result from high uranium within the sandstone. This spike could potentially be very helpful in correlating gamma-ray logs from different wells. A discussion of the gamma log responses in VC-1 can be found in Wollenberg et al. (1985). The sudden drop in the gamma response at the contact between the VC-1 rhyolite and the VC-1 tuffs cannot be identified as a lithologic break because the water level in the well at the time the gamma log was run was precisely at this elevation.

## B. The AET-4 Geothermal Well

The AET-4 (A.E. Thomas #4) geothermal hole was drilled in the fall of 1982 by Sunedco (Sunoco Energy Development Company). This geothermal wildcat was drilled south of Valles caldera on Cat Mesa (Fig. 1) to a depth of 1211 m (4006 ft) with a maximum temperature of 129°C. The AET-4 well was given to Los

Alamos National Laboratory in 1984 and is used to pursue scientific objectives (such as studying the thermal "plume" traveling down the Jemez fault zone from Valles caldera) and to test well logging tools.

The AET-4 well penetrated 59.1 m (194 ft) of unaltered Bandelier Tuff (Fig. 3). Underlying the tuff is 137.5 m (451 ft) of altered, porphyritic Paliza Canyon basalt, with clay and hematite alterations occurring in the top half of the unit. Next, the AET-4 hole passes through 108.2 m (355 ft) of poorly cemented sandstones of the Abiquiu Formation(?). Below these sandstones, the well penetrates 420.6 m (1380 ft) of the red shales and sandstones of the Abo Formation. Underlying the Abo Formation is a sequence of limestone belonging to the Madera Formation, which is 246.9 m (810 ft) thick. The limestone of the Madera is locally fossiliferous, silicified, or mud-supported. At a depth of 972.3 m (3190 ft) the Sandia Formation was encountered, which has a local thickness of 24.4 m (80 ft). Finally, the AET-4 well penetrated 224.3 m (736 ft) of Precambrian schists, which exhibit local chlorite alteration. Sheared amphibole schist was identified over the depth interval of 1051.6 to 1082 m (3450 to 3550 ft) (Waibel 1982). More detailed lithologic descriptions of the AET-4 units are located in the Appendix.

The two temperature logs illustrated on Fig. 3 were run by Southwest Surveys in August of 1985 and August of 1986. Both temperature profiles presumably represent equilibrated well temperatures as these logs were run three and four years after the AET-4 drilling was completed. However, above 518 m (1700 ft) the temperature profiles disagree by as much as 10°C. The profiles coincide reasonably well below 518 m (1700 ft), yet they cross over at 685.8 m (2250 ft). Although some discrepancies exist between the two logs, both logs indicate the same thermal gradients over the same intervals within this borehole. For the depth interval above 274.3 m (900 ft), both curves report gradients of 140°C/km. Between 304.8 and 472.4 m (1000 and 1550 ft), the thermal gradient drops to 92°C/km. Between 518 and 883.9 m (1700 and 2900 ft), the gradient rises back to 140°C/km, and below 883.9 m (2900 ft), the temperature gradient in the well drops sharply, with an apparent decrease of temperature with depth. The lower thermal gradients in AET-4 compared with those in VC-1 are not surprising considering the location of the AET-4 hole several kilometers outside of Valles caldera.

Figure 2 also includes a gamma-ray log that was run by Southwest Surveys of Farmington. As with the VC-1 gamma log, there are very few spikes that could be correlated with gamma logs from other wells. However, similar large gamma spikes occur within the lower Abo Formation in both the AET-4 and VC-1 holes. This spike may result from a possible widespread high uranium concentration in this interval of the Abo Formation. In this log, the contact between the Madera Limestone and the Sandia Formation can be identified by the gamma spike at a depth of 972 m (3190 ft). The large drop in the gamma-ray response at approximately 457.2 m (1500 ft) identifies the water level in the well at the time that the log was run.

## C. The WC 23-4 Geothermal Well

The WC 23-4 (Water Canyon 23-4) geothermal wildcat hole was drilled between November of 1981 and January of 1982 by GEO Operator Corporation (GEO). The well was drilled within the western ring fracture zone of Valles caldera to a total vertical depth of 1964.4 m (6445 ft) and a maximum temperature of 232.6°C (Fig. 4). Below 478.5 m (1570 ft), the WC 23-4 well was directionally drilled to a depth of 2101 m (6890 ft). Until December of 1985, all data pertaining to the WC 23-4 well were proprietary. Therefore, the data presented here are the first available from this geothermal well.

The WC 23-4 geothermal well penetrated 61 m (200 ft) of the San Antonio Mountain rhyolite of the Valle Grande Member of the Valles rhyolite. Next the WC 23-4 bore passed through 64 m (210 ft) of the Redondo Creek rhyolite and 42.7 m (140 ft) of Bandelier Tuff. Underlying the volcanic rocks are 246.9 m (810 ft) of Abo Formation shales and sandstones. Beneath the Abo Formation is a 248.4-m (815-ft) sequence of the Pennsylvanian Madera Limestone. Next, the WC 23-4 borehole penetrated approximately 74 m (243 ft) of the Sandia Formation. The top and bottom contacts of the Sandia Formation in this well are only approximate because no distinct lithologic breaks that could uniquely identify the Sandia Formation were found. Finally, the WC 23-4 well penetrated 1363 m (4472 ft) of Precambrian granite (and gneiss?). More detailed lithologic descriptions of units encountered in the WC 23-4 well can be found in the Appendix.

The temperature log illustrated on Fig. 4 was run by the Earth Science Instrumentation Group (ESS-6) of Los Alamos National Laboratory in January of 1983. The temperature log was run exactly one year after completion of the WC 23-4 well and presumably represents equilibrated well-bore temperatures. Distinct changes in the temperature gradient occur at depths of 472.4 and 579.1 m (1550 and 1900 ft). Above 457.2 m (1500 ft), the thermal gradient in the hole is 240°C/km. Between 472.4 and 579.1 m (1550 and 1900 ft), the bore appears to intersect a thermal fluid inflow zone as the thermal gradient rises to 350°C/km. Below 579.1 m (1900 ft), the thermal gradient along the well bore drops sharply to ≤60°C/km, which is equivalent to the regional thermal gradient in the Jemez Mountains. At a depth of 1493.5 m (4900 ft), the log indicates a small temperature reversal, which is the only excursion in the temperature profile in this lower depth interval. Chemical analyses of two aquifers at depths of 1463 and 2073 m can be found in Shevenell et al. (1987).

Los Alamos National Laboratory also ran a gamma-ray log to a depth of 752.2 m (2468 ft) (Fig. 4). The first 357 m (1200 ft) were logged on November 12, 1981, whereas the interval between 357 and 752.2 m (1200 and 2468 ft) was logged on November 29, 1981. As can be seen in Fig. 4, the lower interval appears to have been logged at higher sensitivity, and very large variations in gamma response are recorded in the Madera and Sandia Formations. Comparing this log with Figs. 2, 3, and 5, we can see that correlation of the gamma logs in the Madera and Sandia sections is very difficult.

D. The PC-1 Geophone Emplacement Hole

The PC-1 (Precambrian #1) geophone emplacement hole was drilled by Maness Drilling Company of Farmington, New Mexico, for Los Alamos National Laboratory. PC-1 was drilled in Lakefork Canyon to a depth of 481.6 m (1580 ft), and the rig was released in December of 1983. The decision was made to deepen the hole in March of 1984. On March 21, 1984, the PC-1 hole was completed to a total depth of 663.9 m (2178 ft) and a maximum temperature of 84°C.

The primary objective of the PC-1 hole was to emplace a geophone at the top of the Precambrian crystalline rocks. A second objective of the hole was to test the effectiveness of drilling with cable tools in volcanic and sedimentary rocks through which rotary drilling at Fenton Hill for the Hot Dry Rock Project had been quite difficult. The third objective of the well was to obtain information about the hydrology of the area without utilizing expensive testing methods. Several aquifers, which produced water into the wellbore, were encountered over the following intervals: 117.6 to 119.2 m (386 to 391 ft); 170 to 176.2 m (558 to 578 ft); 208.8 to 210.6 m (685 to 691 ft); 335.3 m (1100 ft) (water source within a fracture); 380 to 381.3 m (1247 to 1251 ft) (a cavernous area within the Madera Limestone); 425.5 to 428.2 m (1396 to 1405 ft); 434.3 to 436.2 m (1425 to 1431 ft); and 643.7 to 647.7 m (2112 to 2125 ft) (Fig. 5). Chemical analyses of the aquifers encountered in PC-1 are listed in Shevenell et al. (1987).

The PC-1 hole was spudded on October 8, 1983, and penetrated 3.05 m (10 ft) of loose soil followed by 28 m (92 ft) of Bandelier Tuff. Next, the PC-1 bore went through 27.7 m (91 ft) of loose sand and volcanic pebbles of the Abiquiu Formation. Underlying the Abiquiu Formation is 248.1 m (814 ft) of the red sandstones and shales of the Abo Formation. The PC-1 hole then penetrated 305.4 m (1002 ft) of the Madera Limestone and 42.1 m (138 ft) of the Sandia Formation. Finally, the borehole bottomed at 663.9 m (2178 ft) after passing through 9.5 m (31 ft) of Precambrian granite.

The temperature log illustrated in Fig. 5 was run by the ESS-6 group at Los Alamos three months after well completion. Because the log was run soon after well completion, the log probably does not represent equilibrated temperatures within the wellbore. The apparent temperature gradient above a depth of 426.7 m (1400 ft) is 113°C/km. Below 582.2 m (1910 ft) the thermal gradient rises to 240°C/km because of a thermal fluid inflow zone between 643.7 and 647.7 m (2112 and 2125 ft) near the Precambrian interface.

The ESS-6 group at Los Alamos also ran the gamma-ray log in this well. The Abo Formation contains a large positive spike in the gamma response. The remainder of the gamma-ray log does not uniquely identify other anomalies or lithologic breaks within the borehole.

## E. The PC-2 Geophone Emplacement Hole

The PC-2 (Precambrian #2) was spudded on August 16, 1984, on US Forest Service land approximately 0.8 km southwest of the Fenton Hill Hot Dry Rock site. PC-2 was drilled to a total depth of 558 m (1830 ft) with cable tools by Maness Drilling Company of Farmington, New Mexico, for the Los Alamos National Laboratory Hot Dry Rock Program. The primary objective of the hole was to emplant a geophone to be used in the Fenton Hill seismic studies. Secondary objectives were to obtain subsurface geologic and hydrologic data in the area of the PC-2 hole. Several aquifers were encountered during the drilling of PC-2. Aquifers at depths between 179.5 and 182.9 m (589 and 600 ft), 253 and 256 m (830 and 840 ft), 326.1 and 332.2 m (1070 and 1090 ft), and between 399.3 and 405.4 m (1310 and 1330 ft) were encountered. A blowout at a depth of 556.3 m (1825 ft) was initiated by high pressures of $CO_2$ at this depth. Chemical analyses of fluids from aquifers in PC-2 are listed in Shevenell et al. (1987).

The PC-2 geophone emplacement hole penetrated 32.3 m (106 ft) of Bandelier Tuff followed by 68.9 m (226 ft) of the Paliza Canyon Formation. Next, the PC-2 hole passed through 18.9 m (62 ft) of the Abiquiu Formation.

Underlying the Abiquiu Formation are 224.6 m (737 ft) of the Permian Abo Formation. Finally, the PC-2 hole passed through 213 m (699 ft) of the Pennsylvanian Madera Limestone before difficulties in drilling caused operations to cease at a total depth of 557.8 m (1830 ft) and a maximum temperature of 54°C. A more detailed description of lithologies encountered in PC-2 can be found in the Appendix.

The temperature profile illustrated on Fig. 6 was provided by the ESS-6 group of Los Alamos on March 6, 1985. This temperature profile shows three breaks in thermal gradient along the PC-2 well bore. From the surface to a depth of 121.9 m (400 ft), the temperature gradient is approximately 140°C/km. Between the depths of 121.9 and 259.1 m (400 and 850 ft) and from 472.4 m (1550 ft) to total depth, the gradient drops to 80°C/km. The lowest gradient identified in the PC-2 hole is 65°C/km between depths of 274.3 and 426.7 m (900 and 1400 ft). No other geophysical logs were run in the PC-2 geophone emplacement hole.

## IV. DISCUSSION

In each of the five wells (VC-1, AET-4, WC 23-4, PC-1, and PC-2), relatively thick sequences of Pennsylvanian limestones and Permian sandstones and shales were penetrated below the volcanic sequences. Thicknesses of the units vary from well to well and pinch out in the upper part of the stratigraphic sequence between the wells.

The gamma-ray responses obtained from each well do not appear to be useful for stratigraphic correlations in the Valles caldera region. The only consistent anomalous response identified in four of the wells is of the large spike within the Abo Formation. Use of gamma logs in stratigraphic correlation between wells appears to be possible, yet quite difficult. The gamma-ray log might be more useful if the gamma responses were compared with other geophysical logs that could be run in the wells.

Temperature gradients vary from well to well depending on the location of each well in relation to the caldera. Wells located outside the western border of Valles caldera (PC-1, PC-2) have the lowest thermal gradients of the five wells discussed. The well located south of Valles caldera (AET-4) has somewhat higher temperature gradients as a result of its location along the Jemez fault zone in the vicinity of the thermal outflow plume. The VC-1 well, located on the margin of the caldera, has higher temperature gradients than the three previous wells, while the one well within the ring fracture zone of Valles caldera (WC 23-4) has the highest geothermal gradient. However, all five wells exhibit relatively high thermal gradients (>40°C/km) resulting from high conductive heat flow associated with the Rio Grande rift and volcanism in Valles caldera and high convective heat flow associated with circulating geothermal fluids.

Figure 7 shows isotherms on a cross section along the wells VC-1, PC-1, and PC-2. The section runs northwest from VC-1 and bends west at the PC-1 well away from Valles caldera. This cross section illustrates that the thermal gradient is higher in VC-1 than in PC-1 or PC-2 as a result of its location within the thermal outflow plume. Figure 8 is a cross section trending north-northwest from AET-4 through PC-1, GT-2, and GT-1 (Purtymun et al. 1974; Pettitt 1975; Purtymun 1973). Just north of the GT-1 well, the section bends directly east across the ring fracture zone of Valles caldera to WC 23-4. The isotherms on this cross section illustrate changes in the thermal regime across the Jemez fault zone and into Valles caldera. Based on the thermal gradients of each well and the distribution of isotherms on the cross sections, it appears that convective thermal upflow and lateral flow dominate the thermal regime within the caldera (WC 23-4 well) and south of the caldera along the Jemez fault zone (AET-4 and VC-1 wells). Conductive heat flow appears to dominate areas outside of the western margin of Valles caldera (PC-1, PC-2, GT-1, and GT-2 wells). Geothermal gradients drop sharply outside of the margins of Valles caldera. Lithologic and map symbols corresponding to Figs. 7 and 8 are illustrated in Fig. 9.

ACKNOWLEDGMENTS

We extend thanks to GEO Operator Corporation for allowing Los Alamos to work in the WC 23-4 geothermal well and to Sunedco for donating the AET-4 well to Los Alamos for scientific purposes. We gratefully acknowledge Jamie N. Gardner for reviewing an early draft and Barbara Hahn for preparing the manuscript. Work was funded by the United States Department of Energy, Office of Basic Energy Sciences.

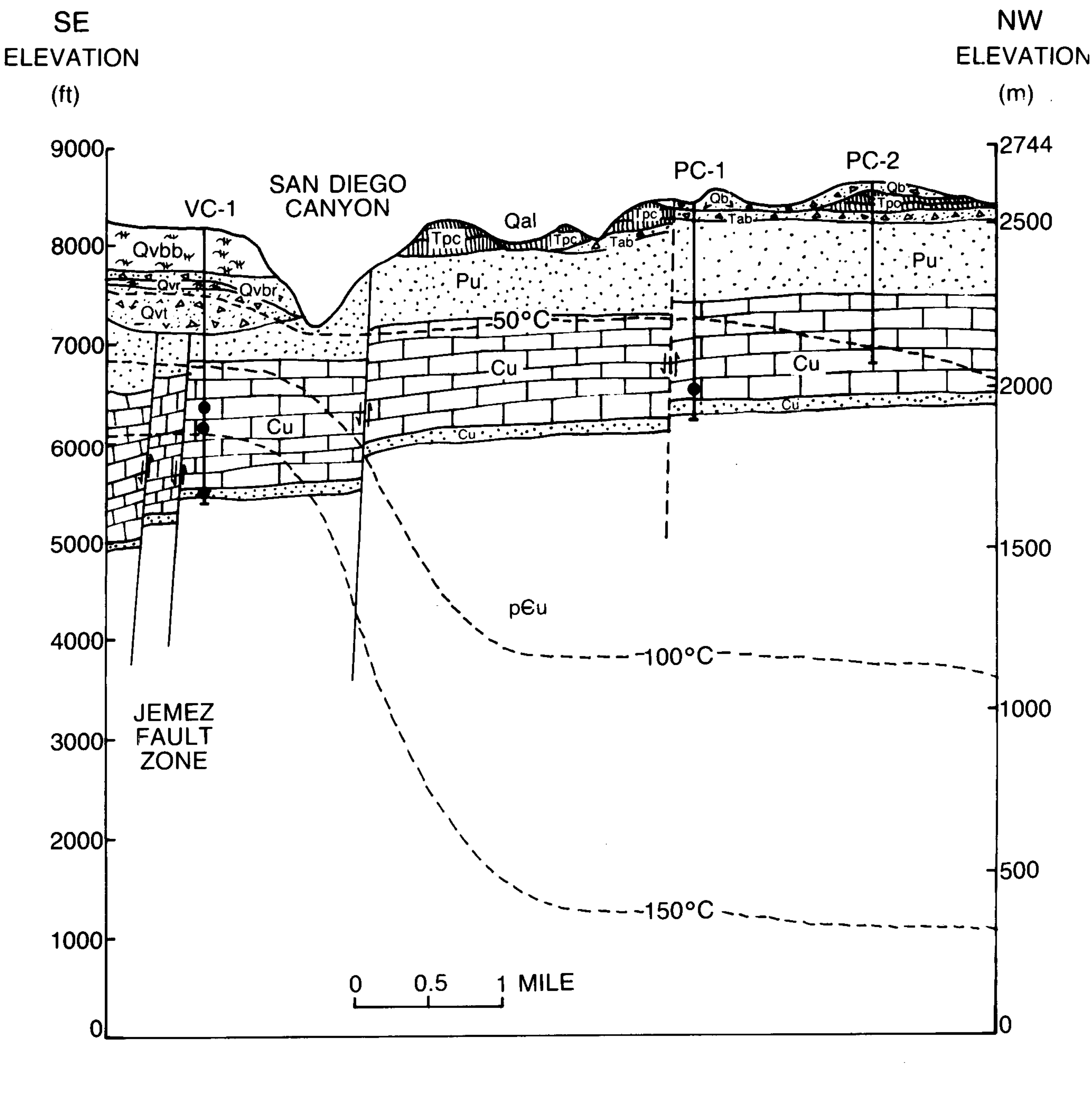


Fig. 7.
Cross section showing lithologic breaks and isotherms across the section cut by wells VC-1, PC-1, and PC-2 (vertical exaggeration is 3.5 X). In the interest of clarity, no patterns were placed in the Precambrian sections. The surface data are from Smith et al. (1970). Large dots identify fluid entries.

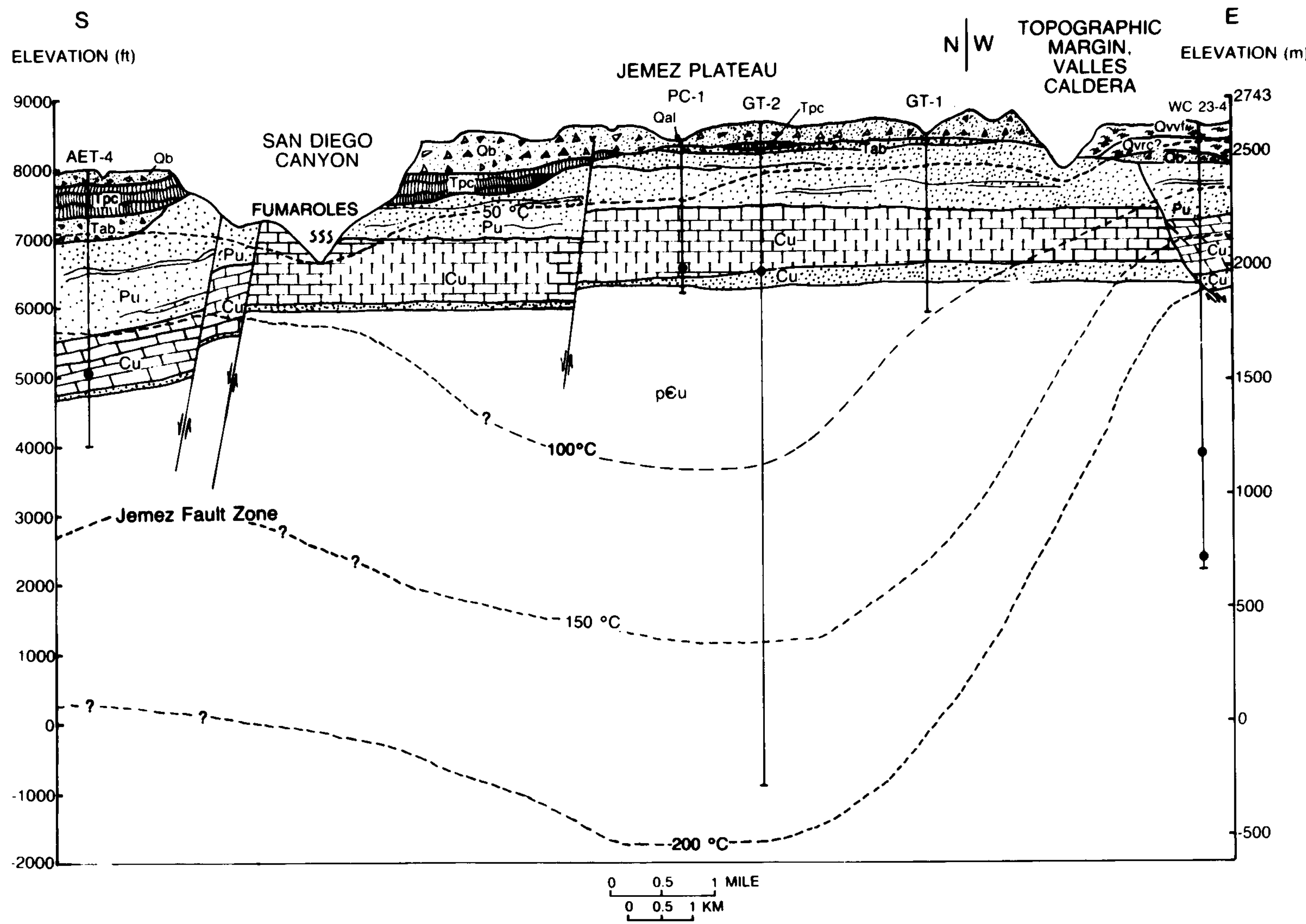


Fig. 8.

Cross section showing lithologic breaks and isotherms across the section cut by wells AET-4, PC-1, GT-2, GT-1, and WC 23-4 (vertical exaggeration is 3.5 X). The geology of the GT-2 well has been described by Purtymun et al. (1974) and Pettitt (1975); temperature logs were provided by Schlumberger International. The geology of GT-1 has been described by Purtymun (1973); surface data are from Smith et al. (1970). For clarity, no symbols have been placed in the Precambrian section. Large dots identify fluid entries.

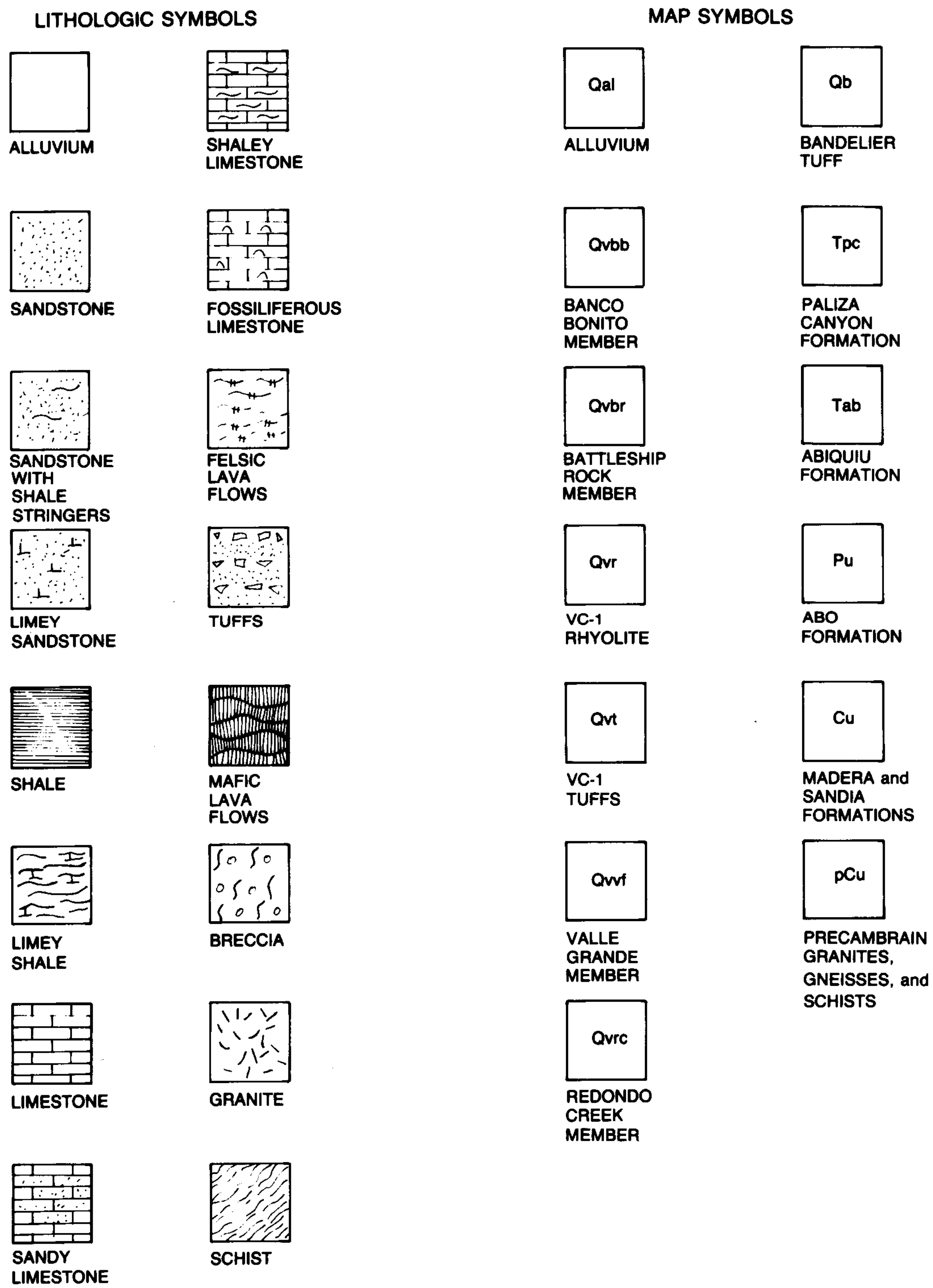


Fig. 9.
Lithologic and map symbols are used in the stratigraphic columns and in the cross sections of Figs. 7 and 8. New map symbols have been used for the VC-1 rhyolite, the VC-1 tuffs, and the Paliza Canyon Formation. Map symbols for other lithologic units have been taken from Smith et al. (1970).

APPENDIX

LITHOLOGIC DESCRIPTIONS OF VC-1, AET-4, WC 23-4, PC-1, AND PC-2,
VALLES CALDERA

## LITHOLOGIC DESCRIPTION OF THE VC-1 CORE HOLE

The following lithologic descriptions are a compilation of the VC-1 descriptions reported in the following sources: Gardner et al. (1987); Wachs and Gardner (unpublished data); Goff et al. 1986; Hulen and Nielson 1985; and daily drilling reports by Los Alamos National Laboratory personnel. For detailed lithologic descriptions over the entire depth of VC-1, see Gardner et al. 1987.

### Banco Bonito Member

| | |
|---|---|
| 0-488 ft | 0-148.7 m |
| 0-338 | Perlitic and brecciated obsidian (upper 150 ft). Tuffaceous rhyolite (16-25 ft); tuff lens (33-35 ft); rhyolite tuff (37-76 ft); dark rhyolite glass (76-84 ft); light buff tuff (84-100 ft); tuff bed (106-107 ft); red obsidian (109-110 ft); gray tuff (118-119 ft); porphyritic gray tuff (126 ft); obsidian. |
| 338-488 | Flow-banded rhyolite, obsidian flow-breccia, and obsidian. |

### Battleship Rock ignimbrite

| | |
|---|---|
| 488-530 ft | 148.7-161.5 m |
| | Welded at top; lightly welded to nonwelded toward bottom; fluid loss zone; gray lithic breccia with thin interbedded soil zone at 520 ft. |

### VC-1 Rhyolite

| | |
|---|---|
| 530-591 ft | 161.5-180.1 m |
| 530-542 | Obsidian flow with 5 ft of breccia at top with sparse lithic fragments. |
| 542-591 | Black, sparsely porphyritic obsidian with alternating zones of flow-banded perlitic, splintered obsidian. |

### VC-1 tuffs

| | |
|---|---|
| 591-976.8 ft | 180.1-297.7 m |
| 591-600 | Dull orange, lithic-rich, welded tuff; upper 5 ft is baked soil. |
| 600-673 | White to pink, lithic-rich, welded tuff. |
| 673-682 | Volcaniclastic sediments. |

| | |
|---|---|
| 673-676 | Gray, lithic-rich ash and lapilli tuff. |
| 676-682 | Lithic-rich tuff or volcaniclastic sediments. |
| 682-728 | White to pink, very lithic-rich, welded tuff; reworked at top. |
| 728-890 | Gray, lithic-rich, densely welded tuff; fewer lithic fragments and increasing fiamme with depth; calcite-filled fracture at 811.0 ft. |
| 890-951 | Gray, densely welded tuff bearing lithic fragments and fiamme; fault zone at 934-937 ft. |
| 951-962 | Pink, welded, lithic-rich tuff; air-fall pumice below 959 ft. |
| 962-964.3 | Coarse, reddish volcanic colluvium. |
| 964.3-976.8 | Pale gray, lithic-rich, welded tuff with silky pumice; pumices leached at 970 ft. |

<u>Volcaniclastic conglomerate</u>

976.8-1096 ft — 297.7-334.0 m

| | |
|---|---|
| 976.8-983 | Dark brown volcanic soil with abundant andesite fragments. |
| 983-998.2 | Pink-orange, very poorly sorted, volcaniclastic conglomerate containing pumice and dominantly andesite lithic fragments up to boulder size. |
| 998.2-999.2 | Very sticky tan clay. |
| 999.2-1016 | Gray to pale brown, poorly sorted, volcaniclastic conglomerate; clay-rich; lithic fragments dominantly andesite and dacite. |
| 1016-1065 | Gray to pale brown, volcaniclastic conglomerate with interbedded clay zones; contains minor sandstone and shale fragments. Slickensides and shear planes at 1042-1051 ft. |
| 1065-1096 | Gray to pale brown, volcaniclastic conglomerate interbedded with clay; lithic fragments dominantly rhyolite and dacite. |

## Abo Formation

| | |
|---|---|
| 1096-1384 ft | 334.0-421.8 m |
| 1096-1185 | Brick red siltstone with sparse fossil tests from 1112 to 1120 ft; white sandstone from 1097-1099 ft. Hydrothermally altered zone at 1135-1143 ft. Brick red siltstone and clay with minor red sandstone below 1143 ft. |
| 1185-1235 | Banded brick red and white sandstone with minor siltstone; carbonate veins at 1186 and 1187 ft. Siltstone and clay between 1195 and 1216 ft. Fossiliferous zone between 1212 and 1215 ft. |
| 1235-1260 | Dominantly brick red siltstone. |
| 1260-1315 | Banded brick red and gray sandstone with minor siltstone; carbonate veins at 1285 ft. |
| 1315-1384 | Mostly brick red siltstone and claystone, with horizons of banded brick red and gray sandstone; hydrothermally altered from 1333 to 1340 ft. |

## Madera Limestone

| | |
|---|---|
| 1384-2650 ft | 421.8-807.7 m |
| 1384-1480 | Bioclastic limestone containing few quartz grains; burrows; zones of siltstone, shale, and silty limestone. |
| 1480-1560 | Fossiliferous limestone breccia with dissolution cavities, chert where rock is rich in sponge spicule fragments. |
| 1560-1670 | Recrystallized sandstone and limestone; minor brecciation. |
| 1670-1725 | Laminated micrite with fossil fragments; top of interval is limestone breccia. |
| 1725-1760 | Gray mudstone and siltstone; upper part of interval is cross-bedded. |
| 1760-1885 | Dark gray siltstone and limestone breccia with burrows and fossil fragments; black, organic-rich clay at 1803 to 1805 ft. |
| 1885-2010 | Gray bioclastic limestone and micrite interbedded with silt and mudstone; dark, clay-rich mudstone from 1885-1900 ft; organic-rich layer at 1990 ft. |
| 2010-2260 | Bioclastic limestone and sandstone interbedded with clay-rich mudstone; burrowed in places. |

| | |
|---|---|
| 2260-2420 | Bioclastic burrowed limestone and micrite interbedded with thin layers of sand and siltstone. |
| 2420-2470 | Bioclastic, clay, and siliceous mudstone. |
| 2470-2580 | Orthoquartzitic silt and sandstone with bioclastic grains; interbedded with thin layers of bioclastic limestone; burrowed in places. |
| 2580-2650 | Gray bioclastic limestone; black shale zone containing calcite fragments at 2620-2626 ft. |

## Sandia Formation

2650-2762 ft 807.7-841.9 m

| | |
|---|---|
| 2650-2762 | Orthoquartzitic siltstone and sandstone cemented with silica; gradational contact at top with bioclastic grains; layers of gray limestone; carbonate, red sandstone, and chert breccia zone between 2711 and 2727 ft. |

## Precambrian gneiss

2762-2809 ft 841.9-856.2 m

| | |
|---|---|
| 2769-2797 | Hydrothermal, gneiss, sandstone, and chert breccia zone. |
| 2797-2809 | Shale, possibly a fault-displaced block of the Sandia Formation. |

## LITHOLOGIC DESCRIPTION OF THE AET-4 GEOTHERMAL WELL

The following lithologic descriptions were largely performed by Al Waibel of Columbia Geoscience (unpublished consulting report) on the cuttings obtained while drilling AET-4. Some comments found in the driller's log have also been incorporated into Waibel's descriptions. Most of the Madera Limestone sequence, including the lithologic contacts, results from the thin-section descriptions of Wachs and Gardner (unpublished data). Other lithologic breaks were identified with the use of Gardner et al. 1986.

### Bandelier Tuff

| | |
|---|---|
| 0-194 ft | 0-59.1 m |
| | Orange to red-brown, locally gray, feldspar- and quartz-bearing, silicic tuff. |

### Paliza Canyon Basalts

| | |
|---|---|
| 194-645 ft | 59.1-196.6 m |
| 194-220 | Dark gray, vesicular, porphyritic, clinopyroxene, plagioclase basalt with magnetite with an aphanitic groundmass. Plagioclase phenocrysts make up 10-15% of the rock. Ferromagnesian minerals show hematite alteration. Vesicles are lined with orange clay. Contains devitrified tuff fragments. |
| 220-325 | Dark gray, porphyritic pyroxene, plagioclase basalt with minor magnetite and olivine, and interstitial hematite alteration and clay alteration. |
| 325-387 | Black, vesicular, glassy, porphyritic, plagioclase basalt with altered ferromagnesian minerals, and palagonite. |
| 387-400 | Gray porphyritic plagioclase basalt with magnetite, and altered ferromagnesian minerals; locally intense clay alteration and moderate hematite alteration. |
| 400-442 | Very dark gray, slightly vesicular, porphyritic, plagioclase basalt and gray to red-brown plagioclase and clinopyroxene palagonite tuff. |

| | |
|---|---|
| 442-480 | Gray, porphyritic, clinopyroxene, plagioclase basalt with minor magnetite and clay alteration. Fluid loss at 450 ft. |
| 480-521 | Orange to brown volcaniclastic sediments. The matrix is tuffaceous and lithic fragments are from mafic volcanics. |
| 521-620 | Black, vesicular, glassy, porphyritic, plagioclase basalt; basaltic tuff and tuffaceous sediments; gray, porphyritic clinopyroxene, plagioclase basalt. |
| 620-645 | Orange-gray, clay- and hematite-altered, porphyritic, plagioclase andesite/basalt with fragments of igneous rocks. |

## Abiquiu Formation

| | |
|---|---|
| 645-1000 ft | 196.6-304.8 m |
| 645-800 | Brown to light orange, very fine-grained, poorly cemented, subrounded quartz and feldspar sandstone. |
| 800-1000 | Brown to light orange arkose with local silica cementing. White to buff sandstone, locally sand-rich (980 ft). |

## Abo Formation

| | |
|---|---|
| 1000-2380 ft | 304.8-725.4 m |
| 1000-1518 | Red to purple, poorly lithified shale and sandy shale with minor gray to white horizons. Increasing clay-rich shale at 1358 ft. Small fluid loss zone between 1460 and 1470 ft. |
| 1518-1643 | Quartz and feldspar subrounded to rounded sandstone with minor hematite-rich red clay matrix. Predominantly clay-rich shale after 1598 ft. Mud loss at 1530 ft. |
| 1643-1768 | Red to purple, poorly to moderately lithified shale and sandy shale with occasional horizons of sandstone. Shale lithification increases with depth. |
| 1768-2020 | Brown to red-orange, moderately calcareous shale, locally grading to lithified sandstone and siltstone. Horizons of dark gray limestone and gray chalky limestone occur throughout. Locally silica indurated. Small fluid loss zone at 2015 ft. |

| | |
|---|---|
| 2020-2160 | Red-brown, moderately lithified calcareous shale and siltstone, with local silica-cemented conglomerates; intercalated with gray to gray-brown cryptocrystalline limestone and mica, feldspar, quartz sandstone. |
| 2100-2134 | Very fine- to medium-grained, angular to subangular, well-cemented quartz and feldspar-rich sandstone, clay zones at 2109 to 2114 ft and 2130 to 2133 ft. |
| 2134-2178 | Light gray to gray-green limestone with calcite-filled fractures interbedded with clean, white, well-cemented sandstone, claystone, and shale. |
| 2178-2228 | Light red, well-cemented sandstone with quartz, feldspar, and mica fragments; interbedded with red-brown to brick red calcareous shale and siltstone with a trace of limestone. Clay zone at 2180 to 2190 ft. |
| 2228-2251 | Red-brown to brick red calcareous shale and siltstone, locally grading to a clay-rich sandstone (50%). Red to light gray limestone with calcite-filled fractures (40%). Granitic-derived sandstone (10%). |
| 2251-2281 | Light to medium red (hematite-stained), granitic-derived sandstone, locally cemented with silica; also locally calcareous. Red-brown to brick red calcareous shale and siltstone brecciated in part with calcite and minor zeolite fracture filling; interbedded with gray limestone. |
| 2281-2372 | Sandstone with traces of mica; minor clay-altered feldspar (65%). Red shale and siltstone. Limestone and minor white chalk (35%). Trace of gray claystone. |
| 2372-2380 | Light gray cryptocrystalline limestone with trace calcite fracture filling. Red-brown to brick red to gray lithified, locally calcareous shale, claystone, and sandstone. |

## Madera Limestone

| | |
|---|---|
| 2380-3190 ft | 725.4-972.3 m |
| 2380-2470 | Red-brown to brick red calcareous shale with bioclastic and quartz grains; chert found in places. |
| 2470-2495 | Micrite with fossil fragments and traces of calcite fracture filling. |

| | |
|---|---|
| 2495-2570 | Micrite containing bioclastic and quartz grains; much quartz in places; chert found in places; in top of unit, quartz and bioclastic grains are coated by mud; interbedded with light gray to gray-brown limestone. |
| 2570-2640 | Micrite with bioclastic limestone, which is mainly mud-supported; no chert or quartz. |
| 2640-2740 | Micrite, bioclastic limestone which is grain and mud-supported, and sandstone composed of quartz grains; chert found in places. |
| 2740-2855 | Micrite with mud-supported limestone; contains mud clasts; silicified chert found in places; pyrite and calcite occur as vein minerals in a few fragments. |
| 2855-2865 | Chert. |
| 2865-2965 | Bioclastic mudstone and limestone; bioclastic limestone is mud-supported, silicified to form chert in places, especially where sponge spicules are abundant; very few quartz grains; fractures and large; mud loss zone at 2935 to 2938 ft. |
| 2965-3005 | Micrite and sandstone composed of quartz and calcite grains; no preserved fossil fragments. |
| 3005-3040 | Bioclastic limestone and micrite with minor quartzitic siltstone; partly silicified to chert. |
| 3040-3070 | Quartzitic sandstone; contains feldspar, hornblende, mica, and occasional disseminated pyrite; interbedded with shale and siltstone; sparse calcite as fracture filling. |
| 3070-3130 | Micrite containing quartz grains and chert in places; silicified limestone with disseminated pyrite and trace calcite veins. |
| 3130-3190 | Bioclastic limestone interbedded with orthoquartzitic sandstone; chert found in places. |

## Sandia Formation

| | |
|---|---|
| 3190-3270 ft | 972.3-996.7 m |
| 3190-3270 | White to light gray orthoquartzite sandstone containing few bioclastic fragments; layers of white to light gray limestone with chert, minor red hematite staining, and trace pyrite. |

## Precambrian schist

| | | |
|---|---|---|
| 3270-4006 ft | | 996.7-1221.0 m |
| 3270-3384 | Dark green to black microcrystalline schist composed of hornblende, feldspar, and quartz with traces of muscovite and magnetite. | |
| 3384-3392 | Light pink, K-spar-plagioclase-quartz gneiss. | |
| 3392-3441 | Dark green biotite (altered to chlorite or vermiculite?), quartz-amphibole gneiss; 20% sheared and altered to green and white chlorite and clay mylonite. | |
| 3441-3642 | Dark green amphibole gneiss, sheared and altered, and pink plagioclase-K-spar-quartz gneiss; fault at 3450-3550 ft. | |
| 3642-3746 | Light green-gray, locally white, sheared and mylonitized, biotite gneiss with chloritized, biotite-quartz gneiss; fluid loss zones at 3643 ft and 3680 ft. | |
| 3746-3802 | Green-gray and white mottled mylonite with biotite-K-spar gneiss. | |
| 3802-3850 | Plagioclase-K-spar-quartz gneiss with minor biotite, and biotite-quartz gneiss with trace K-spar. | |
| 3850-4006 | Pink plagioclase-quartz-K-spar gneiss, grading to biotite-K-spar-quartz gneiss with mylonite. | |

## LITHOLOGIC DESCRIPTION OF THE WC 23-4 GEOTHERMAL WELL

The following lithologic descriptions were done by Dan Miles of Los Alamos National Laboratory (unpublished data) on the cuttings obtained while drilling the WC 23-4 well. The contact between the Madera Limestone and the Sandia Formation was chosen with the help of DuChene (1974).

| | | |
|---|---|---|
| | San Antonio Mountain rhyolite | |
| 0-200 ft | | 0-61 m |
| | Redondo Creek rhyolite | |
| 200-410 ft | | 61-125 m |
| | Bandelier Tuff | |
| 410-550 ft | | 125-167.6 m |
| | Quartz-rich tuff and caldera fill. | |
| | Abo Formation | |
| 550-1360 ft | Abo Formation | 167.6-414.5 m |
| 550-680 | Conglomerate, red shale, and trace light brown limestone; rounded quartz pebbles. | |
| 680-740 | Conglomerate, limestone, and trace siliceous, dolomitic limestone; subangular quartz pebbles and trace pyrite at 710 ft. | |
| 740-950 | Gray limestone and conglomerate; 5% coal at 750 ft; siliceous limestone at 810 ft; pyritic limestone at 830 and 910 ft. | |
| 950-1000 | Gray limestone, conglomerate, and trace black shale; pyrite at 980 ft. | |
| 1000-1080 | Silty gray shale (increasing with depth), gray limestone, and trace black shale and conglomerate; trace coal at 1020 ft. | |
| 1080-1200 | Conglomerate, gray limestone, red sandstone and shale and gray shale; arkosic at 1110 ft; siliceous limestone with dolomite at 1120 ft; maroon shale at 1140 ft; trace gypsum at 1180 ft; angular red sandstone with calcareous cement at 1190 ft. | |

| | |
|---|---|
| 1200-1360 | Red shale, red sandstone, shale, and conglomerate, gray shale, and gray limestone; trace coal at 1210 ft; medium-grained, well-cemented sandstone at 1390 ft. |

Madera Limestone

| | |
|---|---|
| 1360-2175 ft | 414.5-662.9 m |
| 1360-1570 | White to gray to light brown limestone with fusalinids; gray silt and silty shale; dark red silty shale. |
| 1570-1630 | Gray shale, red shale, black shale, gray limestone, and conglomerate; trace coal at 1630 ft. |
| 1630-1710 | Gray limestone, conglomerate, gray shale, and trace red shale; large angular quartz fragments embedded in white limestone at 1650 ft. |
| 1710-1800 | Gray to dark brown limestone and red shale; trace coal at 1740 ft. |
| 1800-1990 | Gray limestone at top of section, white limestone at bottom of section; minor red, gray, and black shale; trace coal at 1870 and 1980 ft; siliceous limestone with leached chert at 1960 ft. |
| 1990-2175 | White limestone at top of section with gray limestone at bottom; light brown to earthy limestone at 2060 ft; trace black shale at 2020 ft. |

Sandia Formation(?)

| | |
|---|---|
| 2175-2418 ft | 662.9-737.0 m |
| 2175-2250 | Light to dark gray to green shale, gray limestone with minor conglomerate and red shale; fossiliferous limestone with fusalinids at 2150 ft; trace of massive quartz at 2210 ft; trace coal at 2240 ft. |
| 2250-2350 | Gray limestone, light to dark gray shale, and trace red shale; trace light reddish gray shale and shaley limestone at 2300 ft; trace angular quartz fragments in limestone cement at 2340 ft. |
| 2350-2418 | Gray to white limestone, red shale, light to dark gray shale with trace conglomerate; trace free quartz at 2370 ft; dark red shale and shaley limestone at 2390 ft; fine-grained silty sandstone with pyrite at 2400 ft. |

Precambrian Granites, undivided

2418-6890 ft | 737-2100 m

Granite with pink and orange feldspar, quartz, and trace biotite.

## LITHOLOGIC DESCRIPTION OF THE PC-1 GEOPHONE EMPLACEMENT HOLE

The following lithologic descriptions were done by Dan Miles of Los Alamos National Laboratory (unpublished data) on the cuttings obtained while drilling the PC-1 well. The contact between the Madera Limestone and the Sandia Formation was estimated with the help of the lithologic descriptions of the Sandia Formation found in DuChene (1974).

### Loose Soil

| | | |
|---|---|---|
| 0-10 ft | | 0-3.1 m |

### Bandelier Tuff

| | | |
|---|---|---|
| 10-102 ft | | 3.1-31.1 m |
| | Nonwelded to moderately welded tuff; mostly loose, coarse, angular sand composed of quartz and sanidine crystals; a few black to light gray volcanic pebbles. | |

### Abiquiu Formation

| | | |
|---|---|---|
| 102-193 ft | | 31.1-58.8 m |
| 102-163 | Mostly loose, angular sand composed of quartz and sanidine crystals; nonwelded to moderately welded tuff; some volcanic pebbles appear dark reddish, possibly arkosic. | |
| 163-193 | Mostly volcanic pebbles and boulders, dark to light colored; some loose sand. | |

### Abo Formation

| | | |
|---|---|---|
| 193-1007 ft | | 58.8-306.9 m |
| 193-340 | Red shale and red subrounded loose sand; gray limestone; embedded volcanics at top of section; trace shiny, angular, medium-sized quartz grains; fresh water entry at 225 ft. | |
| 340-380 | Coarse, subrounded reddish sandstone and conglomerate; minor gray limestone and red shale. | |
| 380-550 | Fine-grained, red, calcareous sandstone and gray limestone; light brown limestone at 435 and 470 ft; silty shale with trace gray sandstone at 480 ft; water entry between 385-391 ft. | |

| | |
|---|---|
| 550-600 | Medium-grained sandstone, red shale, and trace limestone; water entry at 554-574 ft. |
| 600-750 | Red, shaley limestone; fine-grained, angular, calcareous sandstone; sandy and silty shale; water entry at 685-692 ft. |
| 750-850 | Medium-grained, calcareous, subangular sandstone with trace red and gray shale to gypsum; red, silty shale in lower part of section. |
| 850-930 | Medium-grained, subrounded sandstone with trace limestone. |
| 930-1007 | Sandy limestone, sandy shale, and medium-grained, subangular sandstone; trace arkose at 950 ft. |

Madera Limestone

| | |
|---|---|
| 1007-2009 ft | 306.9-612.3 m |
| 1007-1050 | White to light brown, fossiliferous limestone with fusilinids and crinoids. |
| 1050-1130 | White to gray, chalky limestone with sticky gray shale; fresh water entry at 1100-1106 ft. |
| 1130-1240 | Hard siliceous limestone and red and maroon shale. |
| 1240-1340 | Chalky white limestone and fossiliferous brown limestone; cavity between 1217 and 1251 ft; quartzite pebbles at 1270 ft; rounded white quartz pebbles and loose quartz between 1290 and 1300 ft. |
| 1340-1410 | Light brown to white to earthy limestone, translucent in places. |
| 1410-1560 | Medium to coarse, angular sand embedded in limestone, some loose angular sand, and dark micaceous shale. |
| 1560-1670 | Chalky white to light brown limestone; angular quartz fragments at 1580 ft; rounded milky quartz at 1600 ft. |
| 1670-1740 | Siliceous limestone and minor red, green, and purple shale. |
| 1740-1790 | Buff to light brown, earthy limestone with angular quartz embedded in limestone and trace reddish, angular sandstone. |

| | |
|---|---|
| 1790-1900 | Fossiliferous, earthy, siliceous limestone with fusilinids and light brown to white translucent to chalky limestone; red quartz fragments at 1790 ft; pinkish volcanics and water entry between 1845 and 1855 ft. |
| 1900-2009 | Light tan limestone with embedded angular quartz particles and black silty and gray-green silty, micaceous shale; trace pyrite at 1953 ft. |

Sandia Formation

| | |
|---|---|
| 2009-2147 ft | 612.3-654.4 m |
| 2009-2100 | Fossiliferous, brown limestone with massive quartz inclusions and blue-gray shale; brachiopods in limestone. |
| 2100-2147 | Light brown limestone and medium to coarse, mostly angular, loose quartz grains, stained brown; gummy clay at 2133 ft; water entry zone between 2110 and 2125 ft. |

Precambrian Granite

| | |
|---|---|
| 2147-2178 ft | 654.4-663.9 m |
| | Trace weathered feldspar, angular quartz, and granitic wash at top of section; dark yellow glauconite in granite. |

## LITHOLOGIES ENCOUNTERED IN THE PC-2 GEOPHONE EMPLACEMENT WELL

The following stratigraphic breaks and lithologies were identified by Dan Miles of Los Alamos National Laboratory (unpublished data) with the use of the cuttings obtained while drilling the PC-2 well.

### Bandelier Tuff

| | |
|---|---|
| 0-106 ft | 0-32.3 m |

### Paliza Canyon Formation

| | |
|---|---|
| 106-332 ft | 32.3-101.2 m |

### Abiquiu Formation

| | |
|---|---|
| 332-394 ft | 101.2-120.1 m |

### Abo Formation

| | |
|---|---|
| 394-1131 ft | 120.1-344.7 m |
| 394-580 | Loose reddish sand and silt and various sized, rounded, dark limestone pebbles in red shaly to light calcareous matrix. |
| 580-720 | Medium to coarse, loose angular quartz grains with a trace of weathered feldspar, red shale and sandstone, and limestone; fluid entry zone between 589-600 ft. |
| 720-830 | Sandy, micaceous red shale and coarse, angular, red sandstone. |
| 830-920 | Coarse, subangular, calcareous white sandstone and red shale; trace gypsum at 900 ft; fluid entry between 830 and 840 ft. |
| 920-1030 | Subangular to rounded sandstone, limestone, and red shale; white calcareous sandstone at 1020 ft; fluid entry between 930 and 941 ft. |
| 1030-1131 | Coarse, angular to rounded sandstone, red shale, sandstone, and limestone; fluid entry at 1070-1090 ft. |

## Madera Limestone

| | |
|---|---|
| 1131-1830 ft | 344.7-557.8 m |
| 1131-1220 | Light brown and gray fossiliferous limestone, fractures appear tight; calcite-filled fractures, rounded black pebbles in limestone; minor green and purple shale. |
| 1220-1300 | Limy, micaceous, siltstone, and limestone. |
| 1300-1450 | Coarse, angular to rounded, white quartz conglomerate, limestone and green-gray shale; water entry zone between 1310 and 1330 ft. |
| 1450-1600 | Light brown to white limestone and dark brown fossiliferous limestone with bryozoa; minor black shale; trace pyrite at 1460 ft. |
| 1600-1700 | Coarse, angular, reddish quartz fragments embedded in limestone and light gray limestone with black specks; minor conglomerate and gray-green shale; pyrite at 1650 ft. |
| 1700-1830 | White, gray, brown, and earthy siliceous fossiliferous limestone; black fusilinids and mica flakes at 1710 ft. |

## REFERENCES


Bailey, R. A., R. L. Smith, and C. S. Ross, "Stratigraphic Nomenclature of Volcanic Rocks in the Jemez Mountains, New Mexico," US Geol. Surv. Bull. 1274-P, 19 pp. (1969).

Doell, R. R., G. B. Dalrymple, R. L. Smith, and R. A. Bailey, "Paleomagnetism, Potassium-Argon Ages, and Geology of Rhyolites and Associated Rocks of the Valles Caldera, New Mexico," Geol. Soc. Am. Mem. 116, 211-248 (1968).

DuChene, H. R., "Pennsylvanian Rocks of North-Central New Mexico," New Mexico Geol. Soc. Guidebook, 25th Field Conf., 159-165 (1974)

Gardner, J. N., and F. Goff, "Potassium-Argon Dates from the Jemez Volcanic Field: Implications for Tectonic Activity in the North-Central Rio Grande Rift," New Mexico Geol. Soc. Guidebook, 35th Field Conf., 77-81 (1984).

Gardner, J. N., F. Goff, S. Garcia, and R. C. Hagan, "Stratigraphic Relations and Lithologic Variations in the Jemez Volcanic Field, New Mexico," J. Geophys. Res. 91(B2), 1763-1778 (1986).

Gardner, J. N., F. Goff, S. Goff, L. Maassen, K. Mathews, D. Wachs, and D. Wilson, "Core Lithology-Valles Caldera #1, New Mexico," Los Alamos National Laboratory report LA-10957-OBES (1987).

Goff, F., J. Gardner, R. Vidale, and R. Charles, "Geochemistry and Isotopes of Fluids from Sulphur Springs, Valles Caldera, New Mexico," J. Volcan. Geotherm. Res. 23, 273-297 (1985).

Goff, F., J. Rowley, J. N. Gardner, W. Hawkins, S. Goff, R. Charles, D. Wachs, L. Maassen, and G. Heiken, "Initial Results from VC-1, First Continental Scientific Drilling Program Core Hole in Valles Caldera, New Mexico," J. Geophys. Res. 91(B2), 1742-1752 (1986).

Goff, F., L. Shevenell, J. N. Gardner, F.- D. Vuataz, and C. O. Grigsby, "The Hydrothermal Outflow Plume of Valles Caldera, New Mexico and a Comparison with Other Outflow Plumes" (in prep.).

Heiken, G., F. Goff, J. Stix, S. Tamanyu, M. Shafiqullah, S. Garcia, and R. Hagan, "Intracaldera Volcanic Activity, Toledo Caldera and Embayment, Jemez Mountains, New Mexico," J. Geophys. Res. 91(B2), 1799-1815 (1986).

Hulen, J. B., and D. L. Nielson, "Stratigraphic Permeability in the Baca Geothermal System, Redondo Creek Area, Valles Caldera, New Mexico," Geotherm. Resour. Coun. Trans. 6, 27-30 (1982).

Hulen, J. B., and D. L. Nielson, "Stratigraphy of the Bandelier Tuff and Characterization of High-Level Clay Alteration in Borehole B-20, Redondo Creek Area, Valles Caldera, New Mexico," Geotherm. Resour. Coun. Trans. 7, 163-168 (1983).

Hulen, J. B., and D. L. Nielson, "Altered Tectonic and Hydrothermal Breccias in Corehole VC-1, Valles Caldera, New Mexico," Fall AGU (1985).

Laughlin, A. W., D. G. Brookins, and P. E. Damon, "Late-Cenozoic Basaltic Volcanism Along the Jemez Zone of New Mexico and Arizona," Geol. Soc. Am. Abst. w/Programs 8, 598 (1976).

Mayo, E. B., "Lineament Tectonics and Some Ore Districts of the Southwest," AIME Trans. 211, 1169-1175 (1958).

Miles, D., Los Alamos National Laboratory, "Lithologic Descriptions of PC-1, PC-2, and WC 23-4," unpublished data, 1982.

Nielson, D. L., and J. B. Hulen, "Internal Geology and Evolution of the Redondo Dome, Valles Caldera, New Mexico," J. Geophys. Res. 89, 8695-8711 (1984).

Olsen, K. H., L. W. Braile, J. N. Stewart. C. R. Daudt, G. R. Keller, L. A. Ankeny, and J. J. Wolff, "Jemez Mountains Volcanic Field, New Mexico: Time Term Interpretation of the CARDEX Seismic Experiment and Comparison with Bouger Gravity," J. Geophys. Res. 91(B6), 6175-6187 (1986).

Pettitt, R. H., "Planning, Drilling, and Logging of Geothermal Test Hole GT-2, Phase I," Los Alamos National Laboratory report LA-5819-PR (1975).

Purtymun, W. D., "Geology of the Jemez Plateau West of Valles Caldera," Los Alamos Scientific Laboratory report LA-5124-MS (1973).

Purtymun, W. D., F. G. West, and R. A. Pettitt, "Geology of Geothermal Test Hole GT-2, Fenton Hill Site, July 1974," Los Alamos Scientific Laboratory report LA-5780-MS (1974).

Self, S., F. Goff, J. N. Gardner, J. V. Wright, and W. M. Kite, "Explosive Rhyolitic Volcanism in the Jemez Mountains, New Mexico: Vent Locations, Caldera Development, and Relation to Regional Structure," J. Geophys. Res. 91(B2), 1779-1798 (1986).

Shevenell, L., F. Goff, F. Vuataz, P. E. Trujillo, Jr., D. Counce, W. Evans, and C. Janik, "Hydrogeochemical Data for Thermal and Nonthermal Waters and Gases of the Valles Caldera--Southern Jemez Mountains Region, New Mexico," Los Alamos National Laboratory report LA-10923-OBES (1987).

Smith, R. L., "Ash-Flow Magmatism," in "Ash-Flow Tuffs," C. E. Chapin and W. E. Elston, eds., Geol. Soc. Am., Spec. Pap. 180, 5-27 (1979).

Smith, R. L., R. A. Bailey, and C. S. Ross, "Geologic Map of the Jemez Mountains, New Mexico," US Geol. Surv. Misc. Geol. Investig. Map I-571 (1970).

Vuataz, F.- D., and F. E. Goff, "Isotope Geochemistry of Thermal Waters in the Valles Caldera, Jemez Mountains, Northern New Mexico," J. Geophys. Res. 91(B2), 1835-1853 (1986).

Wachs, D., and J. N. Gardner, Los Alamos National Laboratory,"Stratigraphy, Environment of Deposition, and Post-Depositional History of the Madera Limestone in the VC-1 and AET-4 Drillholes, Valles Caldera, New Mexico," 28 pp., unpublished report.

Waibel, A., Columbia Geoscience, "Lithology for Drill Hole A.E. Thomas #4, San Diego Geothermal Project, Jemez Springs, Sandoval County, New Mexico," prepared for Sunoco Energy Development Co., 16 pp., unpublished consulting report, 1982.

Wollenberg, H. A., S. Flexser, and A. R. Smith, "Investigation of Radiometric Anomalies in the VC-1 Hole, Valles Caldera, New Mexico, AGU Trans. 66(46), 1081 (1985).



☆ U.S. GOVERNMENT PRINTING OFFICE: 1987—773-103/60071