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Results of Deep Drilling in the Western Moat of Long Valley, California

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In 1985, Unocal drilled the first deep test well in the western moat of Long Valley caldera, ~1 km east of the Inyo Craters. Well IDFU 44–16 penetrated a thinner section of Bishop Tuff than that found in earlier deep exploration wells on the resurgent dome. Precaldera volcanics were encountered at 1183 m and metamorphic basement at 1615 m. The precaldera volcanics yielded a radiometric age of 1.98±0.1 Ma and are tentatively correlated with Tertiary andesites and dacites on the caldera's western wall. These stratigraphic relations suggest that the caldera's structural margin is at least 4 km east of the current topographic margin. Temperatures reach a maximum of 218°C at 1100 m in IDFU 44–16; however, temperature reversals occur below this depth. Temperature and permeability measurements indicate a lateral outflow of hot water over cold recharge near the caldera's structural margin. While these discoveries support the existence of high-temperature fluids in the western moat of Long Valley caldera, the ultimate source of the geothermal system remains to be discovered.

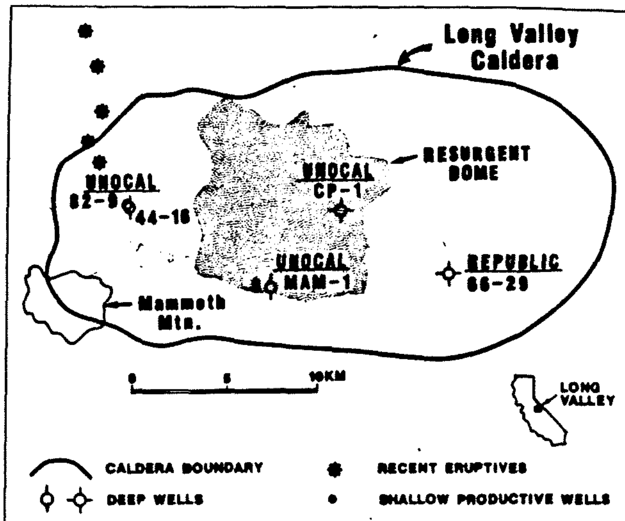

Fig. 2 Map of Long Valley Caldera, showing major geologic features and locations of drill holes discussed in the text.

Introduction

Long Valley caldera, located in eastern California (Figure 1), has been an important geothermal prospect since the 1960s. Numerous public and private exploration efforts have been directed toward assessing the caldera's geothermal potential. After an extensive geothermal research program in the early 1970s, *Muffler et al.* [1978] estimated the initial resource potential of Long Valley at 2100 mW (electrical). The caution to this assessment was that a "full understanding of the Long Valley geothermal system and an accurate determination of its geothermal resource potential must await a series of deep wells," [*Muffler and Williams*, 1976].

Of the four deep wells drilled within the caldera since 1976, three were drilled by Unocal. Much of the data from two earlier wells had been released in 1981. The emphasis in this paper is on the results of Unocal's most recent deep test well, drilled in 1985 in the western caldera moat.

Geology

Long Valley caldera was created by the eruption of an estimated 600 km³ of Bishop Tuff [*Bailey et al.*, 1976]. A large portion of the erupted material is thought to have filled the 17 × 32 km depression left by the foundering of the caldera's floor. Smaller but significant postcaldera eruptions have continued to fill the caldera over the last 600,000 yr. The 600-yr-old eruptions of the Inyo volcanic chain are the most prominent surficial evidence of an active magmatic system in Long Valley.

The hydrothermal system of Long Valley caldera has varied through time [*Bailey et al.*, 1976; *Sorey et al.*, 1978]. From 300,000 to 130,000 years ago the caldera supported an intense hydrothermal system that produced widespread hydrothermal alteration in and around the resurgent dome. The current hydrothermal system has probably been active for only the last 40,000 yr [*Sorey*, 1984]. Most of the present surficial manifestations are found in the central portion of the caldera, with as much as 80% of the current hydrothermal discharge occurring at Hot Creek on the southeastern edge of the resurgent dome [*Sorey et al.*, 1978]. Geochemical estimates of reservoir source temperatures range from 200°C to 280°C [*Sorey et al.*, 1978; *Fournier et al.*, 1979].

Early Exploration

The first geothermal wells in the caldera were drilled in the 1960s around the hot springs and fumaroles at Casa Diablo (Figure 2). These wells were generally less than 300 m deep and produced 170°C fluids at rates of 60 kg/s from a shallow aquifer beneath Casa Diablo. By 1976, one deep well had been drilled east of the resurgent dome to a depth of 2.1 km [*Smith and Rex*, 1977]. The maximum temperatures encountered were less than 80°C, which did not encourage further exploration in the eastern caldera.

Unocal's early drilling efforts were directed toward assessing lease offerings on the caldera's resurgent dome. Two deep test wells were started during the 1979 exploration season. One of these wells, Clay Pit 1, was drilled near the center of the resurgent dome (Figure 2) to a depth of 1.8 km and encountered bottom hole temperatures of 148°C (Figure 3a). A second well, Mammoth 1, was drilled at Casa Diablo (Figure 2) to a depth of 1.6 km to test for a potential deep source of the hot springs. The temperature profile from this well revealed a complex aquifer system (Figure 3b). The maximum temperature was 169°C at 100 m, slightly lower than the productive aquifer at Casa Diablo. A deeper temperature peak occurs at 1 km within the Bishop Tuff; however, at 151°C, it cannot be the deep source of the shallow production zone. Mammoth 1 was also drilled 200 m into metamorphic basement rocks and terminated at 1.6 km. The temperature gradient in the lowest portion of the basement section was 9.1°C/km, and the bottom hole temperature was only 100°C. The source of Casa Diablo's shallow production did not appear to be located directly beneath the surface springs.

Recent Exploration

Since 1979, Unocal has concentrated its exploration efforts on the western part of the caldera, where data were sparse and no surface manifestations exist. A deep temperature gradient hole, designated 82–9, was drilled to 1.1 km near the Inyo Craters (Figure 2) to evaluate new lease offerings in the western caldera moat. The bottom hole temperature in this well was 221°C, within the range of temperatures predicted for the ultimate source of the hydrothermal system of Long Valley.

On the basis of these results, Unocal acquired leases in the western caldera and drilled a deep test well in 1985 in the western caldera moat (Figure 2). That well, Inyo Domes Federal Unit 44–16, was drilled on the same site as 82–9 to a total depth of 1.8 km on the first penetration. A second penetration was attempted because of potential formation damage from mud drilling on the first hole. The sidetrack was drilled from 1.0 km to 1.7 km.

Geologic Data

The geology of IDFU 44–16 is summarized in Figure 4. This well drilled the same sequence of postcaldera fill found in the 82–9 gradient hole and entered Bishop Tuff at a depth of 915 m. The well remained in Bishop Tuff for only 250 m, encountering a section of dacites and andesites from 1168 to 1634 m. These rocks probably correlate with the precaldera volcanics of San Joaquin ridge on the west rim of the caldera [*Bailey et al.*, 1976; *Bailey and Koeppen*, 1977]. At a depth of 1616 m the well entered metamorphic basement. These rocks are calc-silicate hornfels, similar to Paleozoic roof pendants exposed to the south and west in the Sierra Nevada.

Three cores were cut in the lower part of the well in the intervals from 1350 to 1352 m, from 1596 to 1603 m and from 1797 to 1798 m. Analysis of the cores indicated none of the unfractured rock had permeabilities to air greater than 0.01 md. The maximum measured porosity was 10.5% in a fractured, argillicly altered andesite from 1599 m.

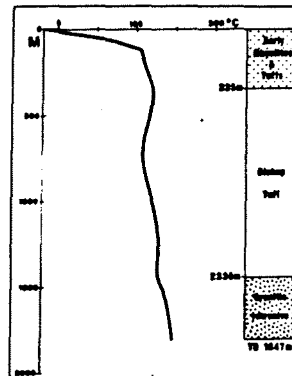

Fig. 3a Temperature and lithologic data for the Clay Pit 1 hole.

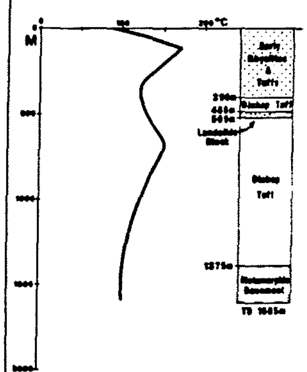

Fig 3b Temperature and lithologic data for the Mammoth 1 hole.

Reservoir Data

Temperature data from IDFU 44–16 are also shown on Figure 4. After attaining temperatures of 218°C at a depth of 1.1 km, the temperatures reverse by 95°C. The reversal occurs at the base of the Bishop Tuff at the contact with the underlying volcanics. In the lower portion of the well, beneath the Bishop Tuff, temperatures increase to 192°C and then reverse again to a temperature of 181°C at the bottom of the hole.

The pressure profile of the well (Figure 5) suggests a water level at approximately 183 m. This is consistent with the relatively flat and deep water table inferred for the western caldera by *Sorey et al.* [1978] and *Farrar et al.* [1985] from water levels measured in shallow core holes.

The second penetration of IDFU 44–16 was completed with a slotted liner to total depth of 1687 m. Perforations exposed the lower portion of Bishop Tuff, the hottest section of the wellbore, and all of the potential reservoir rock below the Bishop Tuff. Attempts were made to stimulate production on the second penetration of IDFU 44–16. The well flowed in a series of 20-minute to 60-minute slugs but would not sustain the flow without stimulation. A total of approximately 2 wellbore volumes (160,000 L) was produced during the test attempts. An injection test began immediately after the attempt at production in the well. Evaluation of pressure recovery after injection indicated a permeability of 6.1 darcy meters for the reservoir section exposed by the well. Temperature and pressure data from the injection test indicate that the highest permeabilities probably occur at the base of the Bishop Tuff.

Interpretation

The rocks in the lower section of the IDFU 44–16 wellbore represent precaldera basement displaced at least 1.5 km down from the western caldera wall. Some of the displacement may be the result of precaldera faulting, but much of it probably represents caldera subsidence. IDFU 44–16 encountered only 250 m of Bishop Tuff while Mammoth 1 penetrated 862 m and Clay Pit 1 penetrated 1085 m. Evidently, the Bishop Tuff draped over some preexisting topography before foundering to its current level during caldera subsidence.

IDFU 44–16 established that permeability exists in the deep intracaldera fill of Long Valley. Permeability in the upper part of the well is apparently related to stratigraphic changes, and the hottest part of the well is confined to the Bishop Tuff. Temperature reversals in the upper part of the well occur in the most permeable zone, at the contact with the precaldera volcanics underlying the

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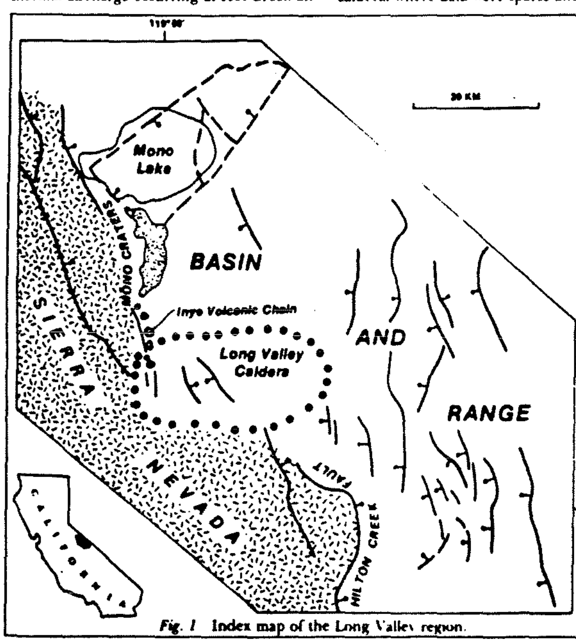

Fig. 1 Index map of the Long Valley region.

Bishop Tuff. In contrast, permeability in the lower section of the wellbore appears to be related to fracturing. Core analysis indicates that the unfractured precaldera rocks are virtually impermeable. Some hydrothermal circulation must occur in the precaldera volcanics, however, because the temperatures in that section reach 192°C (Figure 4) and temperatures after injection indicate fluid losses in that part of the wellbore. Data from the mud logs indicate that fluid entries, peaks in mud gases, and temperature increases logged during drilling all occurred in discrete zones in the lower part of the wellbore and do not have an apparent relationship to stratigraphic changes in the precaldera volcanics.

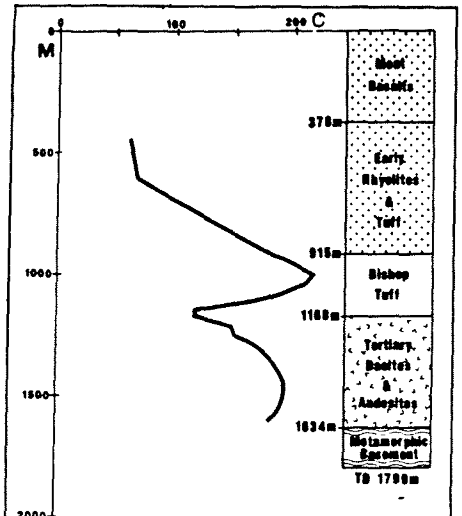

Fig. 4 Temperature and lithologic data for the 44–16 hole.

The temperature regime in IDFU 44–16 is the result of outflow from a deep convecting geothermal system rather than upflow within the system. Isotopic data [*Sorey et al.*, 1978; *Fournier and Truesdell*, 1979; *Farrar et al.*, 1985] suggest the principal recharge of cold water to the caldera occurs on the western caldera rim, with discharge occurring at lower elevations to the east. In a manner consistent with a hydrologic model suggested by *Blackwell* [1985], the temperature peaks and

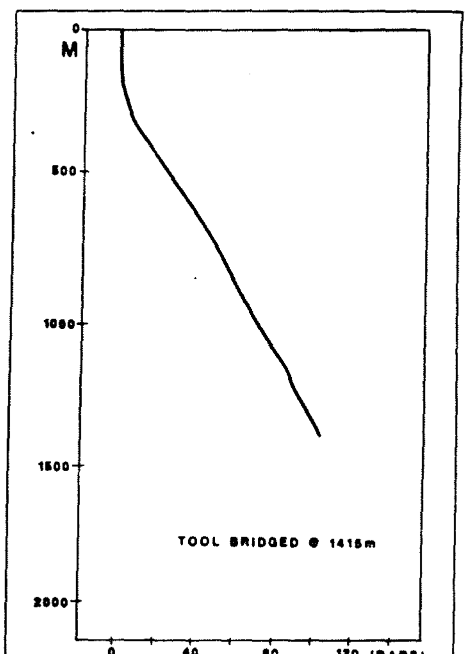

Fig. 5 Pressure as a function of depth in hole 44–16.

mal water floating over deeper colder recharge water from the caldera's western wall. The basement section of IDFU 44–16 shows some evidence of deep heating because the bottom hole temperature is 181°C, the highest basement temperature in the caldera. Temperature reversals in the impermeable metamorphic basement rocks underlying the precaldera volcanics are probably related to deep influx of cold water along a complex of precaldera or ring fracture faults. There is no evidence in the temperature profile of IDFU 44–16 for a deep upwelling hydrothermal system beneath the Bishop Tuff in this part of the western caldera moat.

Acknowledgments

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