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RESULTS OF DEEP DRILLING IN THE WESTERN MOAT OF LONG VALLEY CALIFORNIA

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Abstract

Long Valley caldera has been explored for its potential geothermal resources for at least two decades. Unocal Geothermal drilled two deep test wells on the resurgent dome of the caldera during 1979. Neither of these wells encountered a deep, high temperature geothermal reservoir. The results from these wells and other geologic data focused exploration on the western caldera moat. Encouraging temperature gradient data in 1982 led to the drilling of a deep test well in 1985. That well, IDFU 44-16, encountered deep temperature reversals and a sequence of rocks unlike the previous penetrations on the resurgent dome. Evidently the well is still within the ring fracture system of the caldera and not within a central, upwelling, hydrothermal system which supplies the caldera's discharge.

Introduction

Long Valley caldera, located in eastern California (figure 1), has been an important geothermal prospect since the 1960's. 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 1970's, Muffler and others (1978) estimated the initial resource potential of Long Valley at 2100 mw (e). 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, Unocal has drilled three of these. 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 resulted from the eruption of an estimated 600 km^3 of Bishop Tuff (Bailey and others, 1976). The majority of the erupted material is thought to have filled the 17 x 32 km depression left by the foundering of the caldera's floor. Smaller but significant volumes of post caldera eruptions have continued to fill the caldera over the last 600,000 yrs. The 500 year 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 and others, 1976; Sorey and others, 1978). From 300,000 to 130,000 years ago the caldera supported an intense hydrothermal system which produced widespread hydrothermal alteration in and around the resurgent dome. The current hydrothermal system has probably been active for only the last 40,000 yrs (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 and others, 1978). Geochemical estimates of reservoir source temperatures range from 200°C to 280°C (Sorey and others, 1978; Fournier and others, 1979).

Early Exploration

The first geothermal wells in the caldera were drilled in the 1960's 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 >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. 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 spud 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 1.85 km and encountered bottom hole temperatures of 148°C (figure 3). 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 4). 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 also drilled 200 m into metamorphic basement rocks from 1.4 km to the well's total depth of 1.6 km. The temperature gradient in the lowest portion of the basement section was 9.1°C/km however 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's exploration efforts have concentrated 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 1.06 km near the Inyo Craters (figures 2 and 5) 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.

Based on 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 side-track was drilled from 1 km to 1.68 km.

Geologic Data

The geology of IDFU 44-16 is summarized in figure 6. This well drilled the same sequence of post caldera 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 and encountered a section of dacites and andesites from 1168 m to 1616 m. These rocks probably correlate with the pre-caldera volcanics of San Joaquin ridge on the west rim of the caldera (Bailey and others, 1976; Bailey and Koeppen, 1977). At a depth of 1616 m the well entered metamorphic basement. These rocks were 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 m to 1352 m, from 1596 m to 1603 m and from 1797 m to 1798 m. Analysis of the cores indicated none of the unfractured rock had permeabilities to air greater than .01 md. The maximum measured porosity was 10.5% in a fractured, argillicly altered andesite from 1599 m.

Reservoir Data

Temperature data from IDFU 44-16 are also shown on figure 6. After attaining temperatures of 220°C at a depth of 1.1 km, the temperatures reverse by 93°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 bottom hole temperature of 181°C.

The pressure profile of the well (figure 7) suggests a water level at approximately 183 m. This is consistent with a relatively flat and deep water table inferred for the western caldera by Sorey and others (1978) and Farrar and others (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. Slotted intervals occur at 1012 m to 1073 m, 1101 m to 1336 m, 1364 m to 1437 m, 1465 m to 1490 m, and 1518 m to 1548 m. The perforation intervals were selected from a combination of drilling and well log data which suggested fractured or potentially permeable sections of the well. The 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 was blown dry to a depth of 879 m through open-ended drill pipe and air was circulated continuously for 18 hrs in an attempt to lessen the hydrostatic head in the wellbore. During this time, 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 ($\sim$1000 bbls) was produced during the test attempts.

An injection test began immediately after the attempt at producing the well. In five hours, a total of 2830 bbls of water were pumped into the wellbore at zero wellhead pressures. Evaluation of pressure recovery after injection indicated a permeability of 20,000 md ft for the reservoir section exposed by the well. Temperature and pressure data from the injection test (figure 8) indicate the highest permeabilities probably occur at the base of the Bishop Tuff.

Interpretation

IDFU 44-16 established the existence of the western ring fracture system at least as far east as the Inyo Craters. The rocks in the lower section of the wellbore represent pre-caldera basement displaced at least 1.5 km down from the western caldera wall. Some of the displacement may be the result of pre-caldera faulting. IDFU 44-16 encountered only 250 m of Bishop Tuff while Mammoth-1 drilled through 862 m and Clay Pit-1 drilled through 1085 m. Evidently the Bishop Tuff draped over some pre-existing 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 pre-caldera volcanics underlying the Bishop Tuff. In contrast, permeability in the lower section of the wellbore appears to be related to fracturing. Core analysis indicates the unfractured pre-caldera rocks are virtually impermeable yet some hydrothermal circulation must occur in the pre-caldera volcanics since the temperatures in that section reach 192°C (figure 6) and temperatures after injection indicate fluid losses in that part of the wellbore (figure 8). Mud log data indicates that fluid entries, gas kicks 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 pre-caldera volcanics.

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 and others, 1978; Fournier and Truesdell, 1979; Farrar and others, 1985) suggest the principal cold water recharge to the caldera occurs on the western caldera rim with discharge occurring at lower elevations to the east. In a manner similar to hydrologic models suggested by Blackwell (1985) the temperature peaks and reversals in IDFU 44-16 can be interpreted as evidence of warm thermal 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 since the bottom hole temperature is 181°C, the highest in the caldera. Temperature reversals in the impermeable metamorphic basement rocks underlying the pre-caldera volcanics are probably related to deep cold water influx along a complex of pre-caldera or ring fracture faults. Through pre-caldera volcanics and into metamorphic basement rocks 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.

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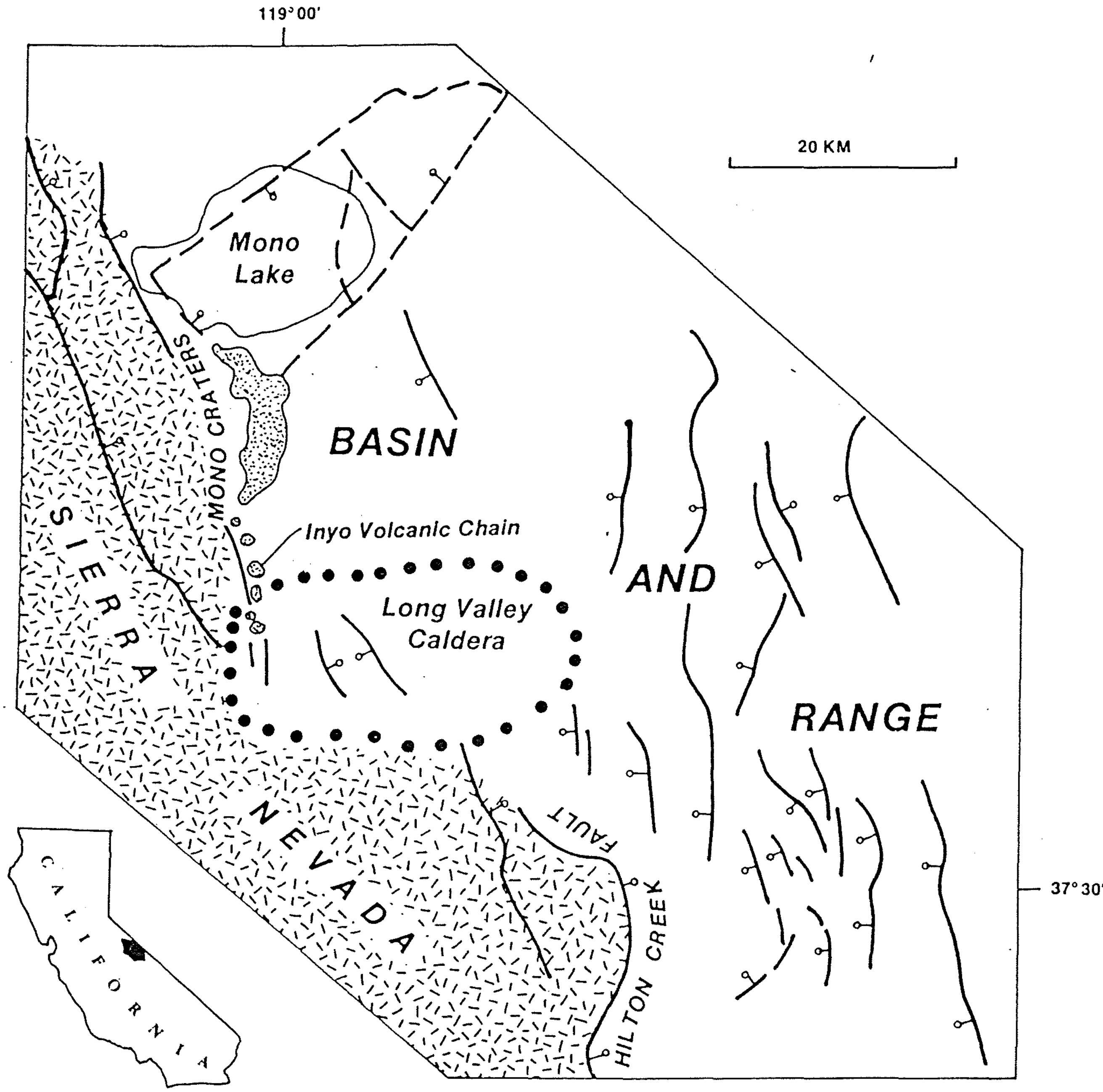


Figure 1.

Index map and generalized geology of the Long Valley region.

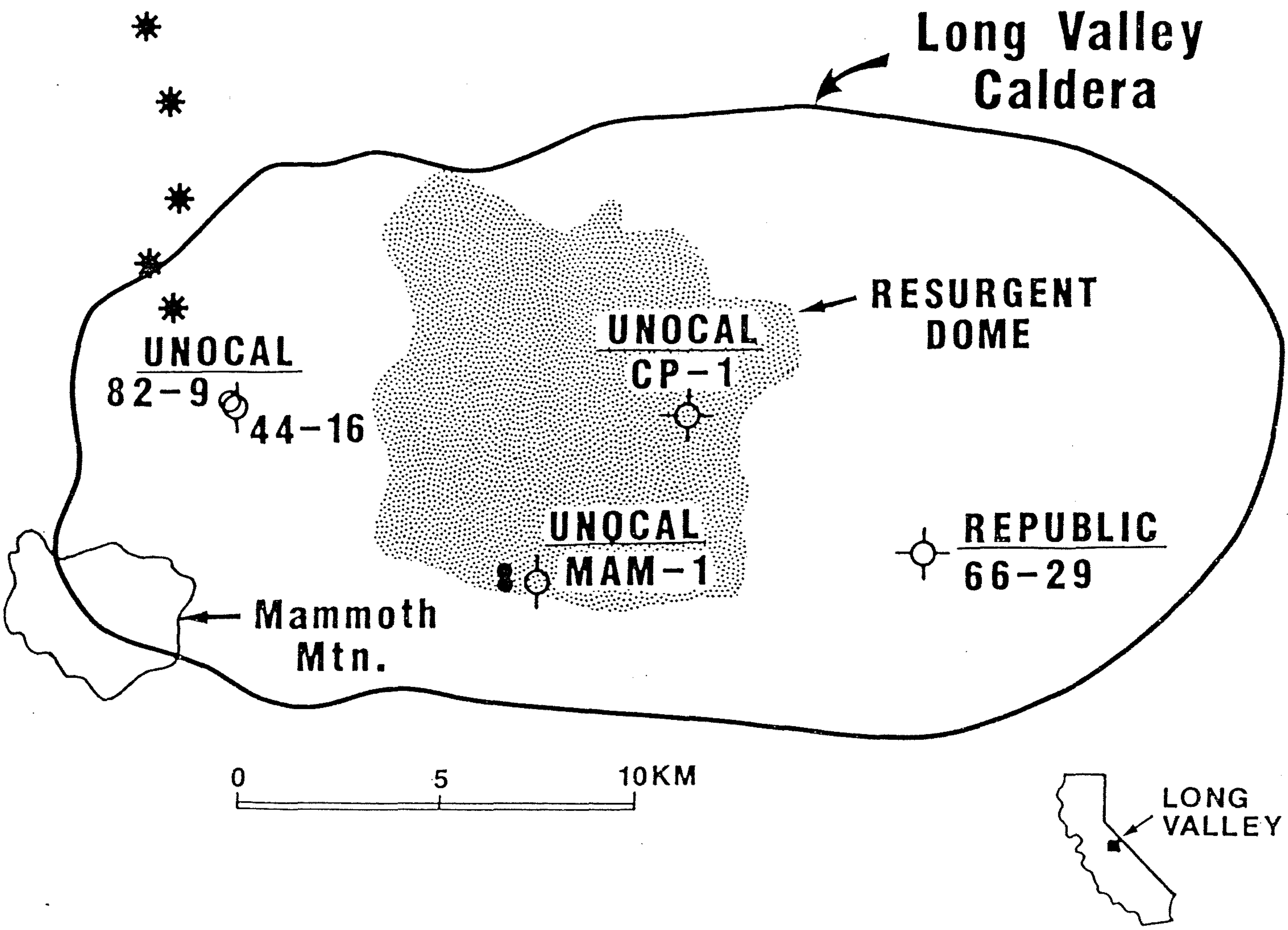


Figure 2. Generalized geology of Long Valley caldera.

EXPLANATION

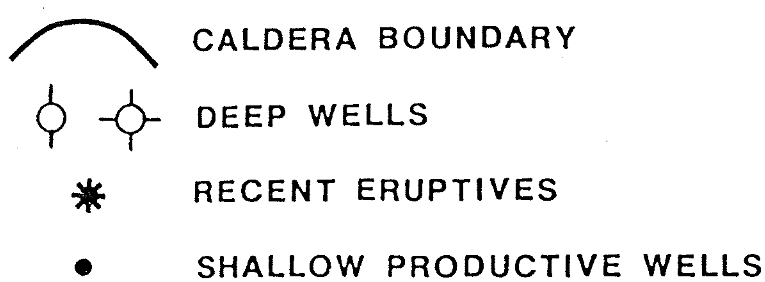
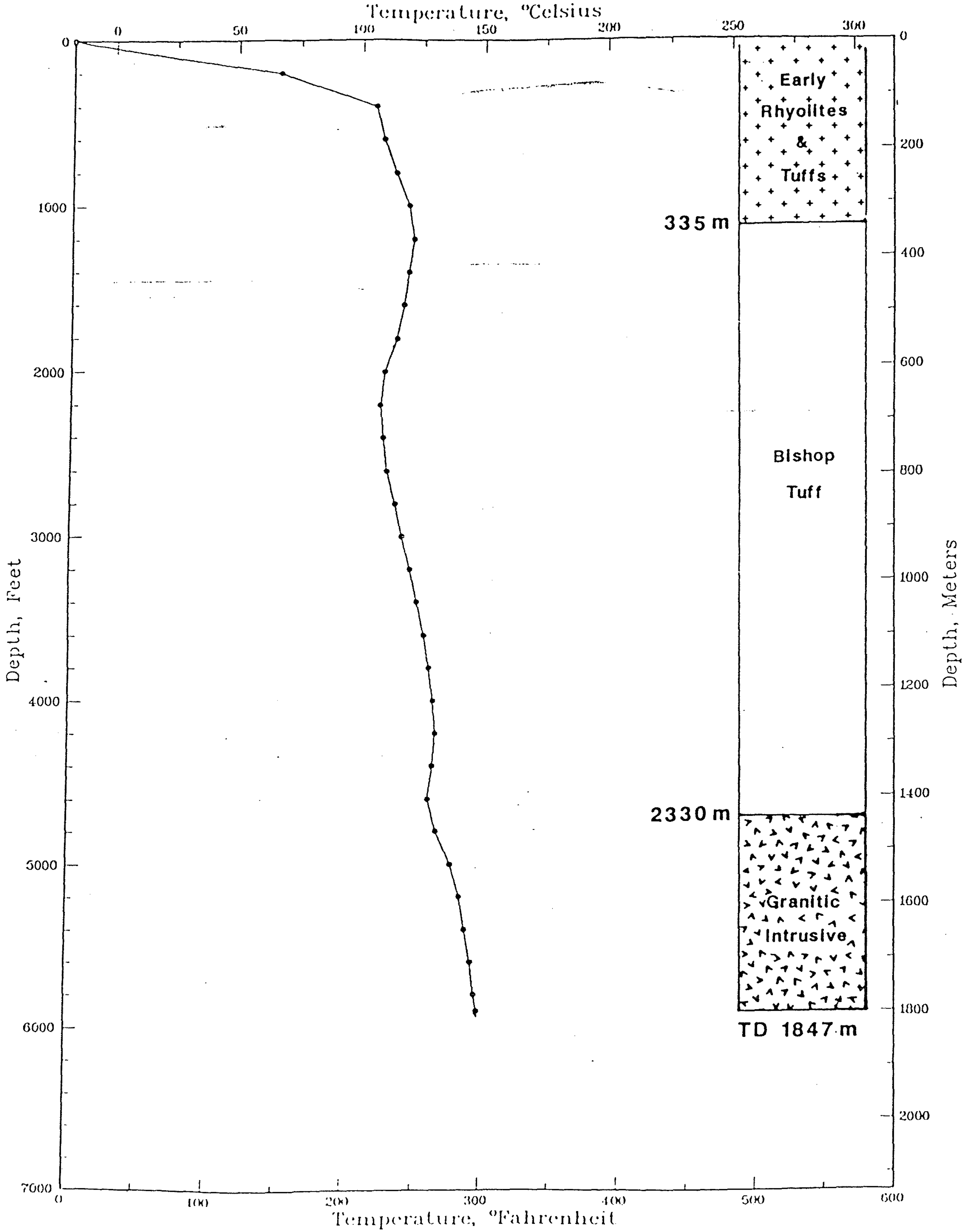


Figure 3 CLAY PIT 1 TEMPERATURE DATA



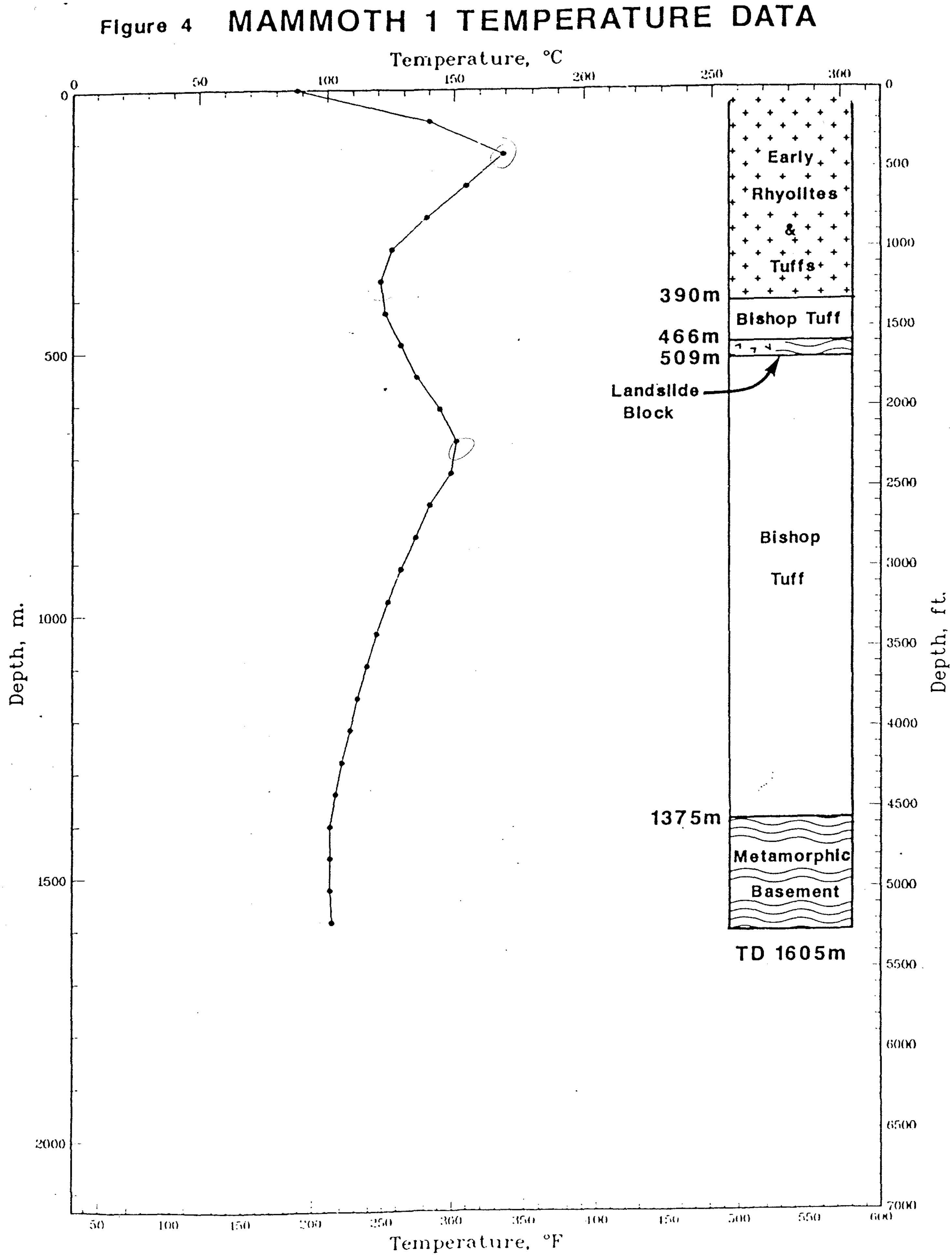


Figure 4 MAMMOTH 1 TEMPERATURE DATA
Temperature, °C
0 50 100 150 200 250 300
Depth, m.
0 500 1000 1500 2000
Depth, ft.
0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000 5500 6000 6500 7000
Temperature, °F
50 100 150 200 250 300 350 400 450 500 550 600
Early Rhyolites & Tuffs
390m
Bishop Tuff
466m
509m
Landslide Block
Bishop Tuff
1375m
Metamorphic Basement
TD 1605m

Figure 5 82-9 TEMPERATURE DATA

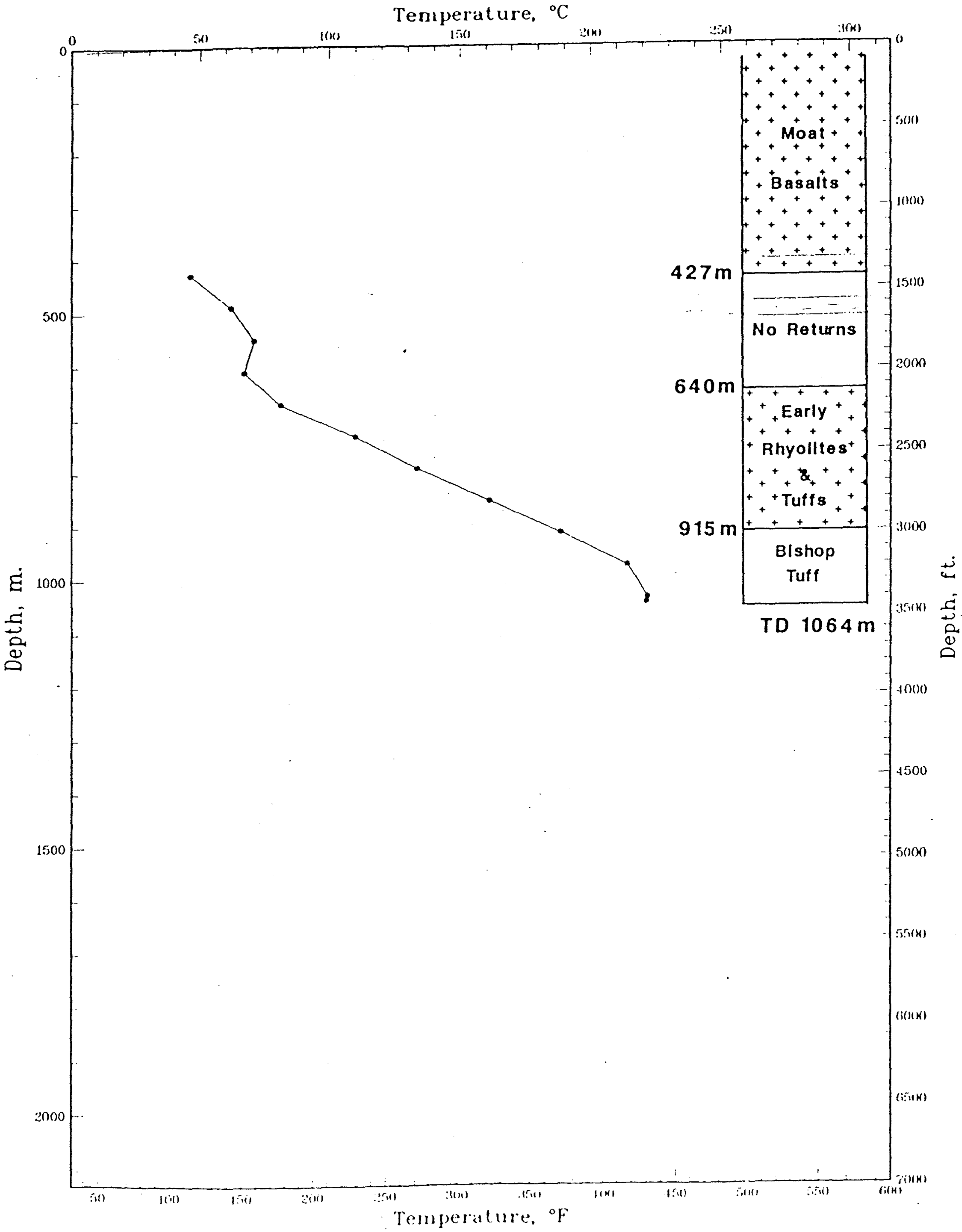


Figure 6 IDFU 44-16 TEMPERATURE DATA

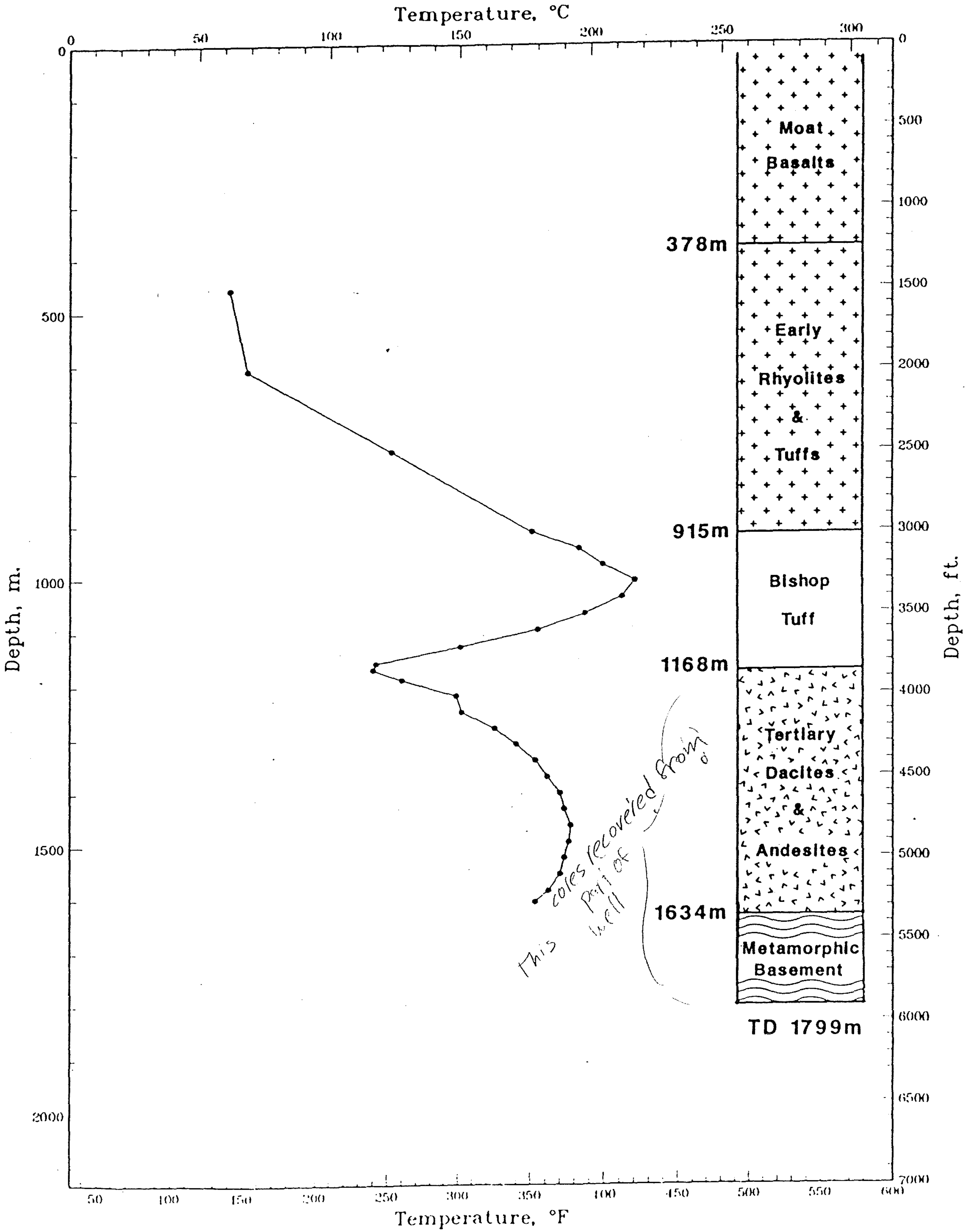


Figure 7 **IDFU 44-16 SUBSURFACE PRESSURE SURVEY**

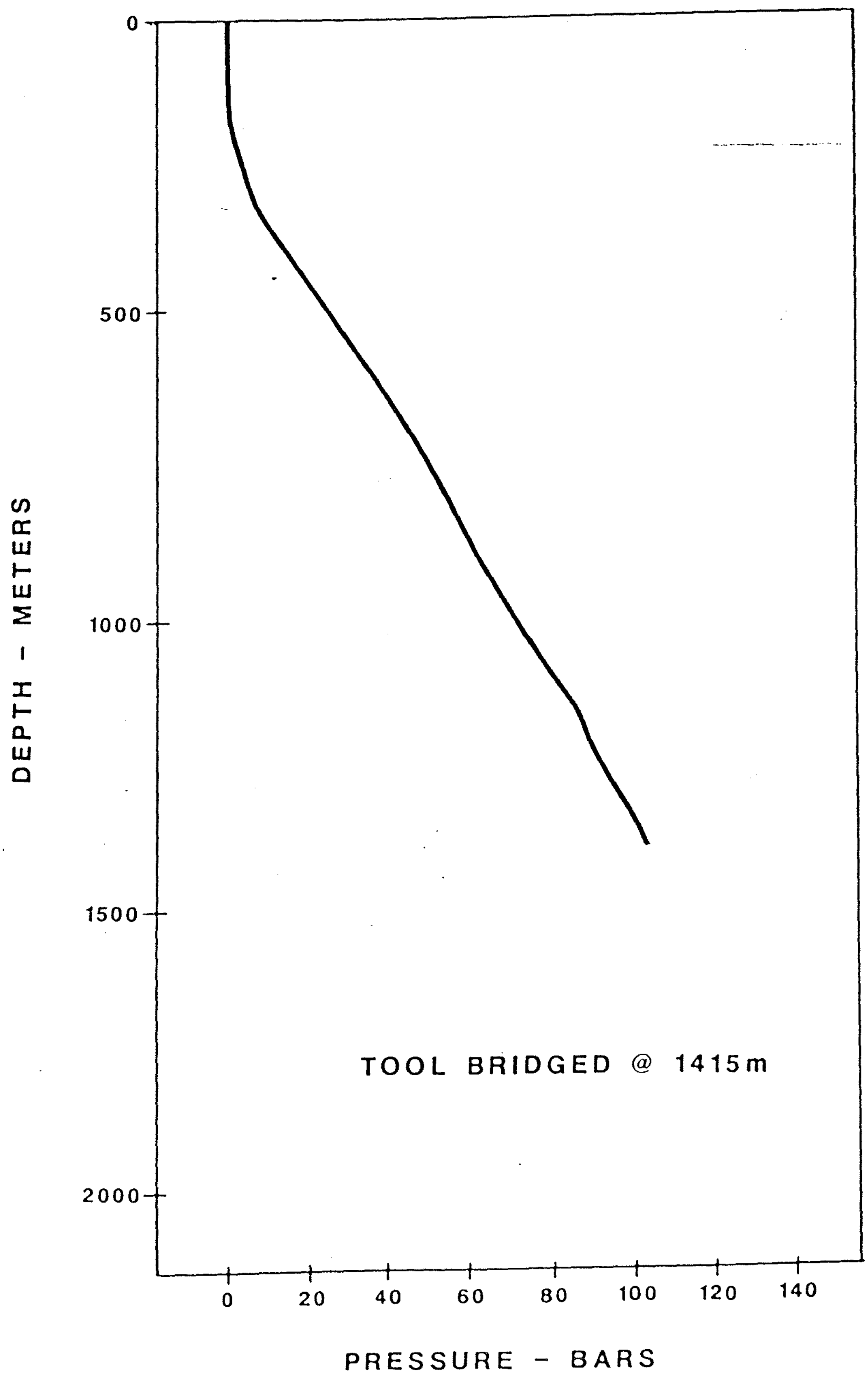


Figure 8 IDFU 44-16 TEMPERATURES BEFORE & AFTER INJECTION TEST