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THE ORIGIN OF HIGH-TEMPERATURE ZONES IN VAPOR-DOMINATED GEOTHERMAL SYSTEMS

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ABSTRACT

Vapor-dominated geothermal systems are proposed to originate by downward extension (by the "heat pipe" mechanism) into hot dry fractured rock above a large cooling igneous intrusion. High temperature zones found by drilling are shallow parts of the original hot dry rock where the penetration of the vapor reservoir was limited, and hot dry rock may extend under much of these reservoirs. An earlier hot water geothermal system may have formed during an early phase of the heating episode.

INTRODUCTION

Intensive drilling at The Geysers and Larderello has shown that these large geothermal fields have vapor-dominated reservoirs over most explored areas and depths. Recent deep drilling at Larderello and exploration of the northern edges of The Geysers have encountered zones with temperatures substantially higher than those extrapolated from the temperature gradient of the vapor-dominated reservoirs, suggesting a different type of reservoir. Although available drilling data and physical measurements from Larderello are limited (Cappetti et al., 1985), a high-temperature zone in the northern Geysers is well documented (Drenick, 1986; Walters et al., 1988). The presence of these high-temperature zones should be accommodated in existing models of vapor-dominated systems or new models should be formulated. This paper discusses this problem and suggests a conceptual model based in part on earlier published work but with some individual features. This model is being studied by numerical simulation at the Lawrence Berkeley Laboratory.

OBSERVATIONS

In major and minor vapor-dominated geothermal systems, pressures and temperatures in the reservoir increase slowly with depth, and high heat flow with little fluid flow is observed at the surface. Wells drilled into these systems produce saturated or superheated steam often with some initial liquid. The top of these reservoirs tend to be at 235°C and 32 bars abs, although exceptions are observed. Since the early 1970's there has been general agreement that in the natural state these reservoirs contain counterflows of rising steam and descending condensate that constitute "heat pipes" (White et al., 1971). Observed condensation of steam at the top of the reservoir contributes high heat flow to overlying rocks, but the origin of the steam (and the fate of the condensate) has never been observed. Boiling liquid below a liquid-vapor interface has been assumed by most workers and lateral transport of liquid below such an interface is necessary to explain gas concentration patterns due to steady-state Rayleigh condensation. Salts leached by descending condensate have been assumed to accumulate in the boiling liquid forming a brine.

Recent detailed observations of dry high-temperature zones at The Geysers (Drenick, 1986; Walters et al., 1988) and observations of deep high temperatures at Larderello (Bertini et al., 1955; Batini et al., 1985; Cappetti et al., 1985; Pruess et al., 1987) provide the first direct evidence of the character of these systems below the vapor-dominated reservoirs. The Larderello observations are not very detailed but show that some deep wells (VC-11, PC-29, Sasso 22, and San Pompeo 2) have bottom-hole temperatures of 350-400°C that lie well above the depth-temperature relation for the normal vapor-dominated reservoir (fig. 1 modified from Pruess et al., 1987). An analytical and numerical study by Pruess et al. (1987) concluded that the temperatures measured were originally those of a liquid-dominated heat pipe below the vapor-dominated reservoir. The highest temperatures (383°C at 4000 m depth and 394°C at 2560 m) reported by Cappetti et al. (1985) are above the critical point of pure water.

The high-temperature zone(s) of the NW Geysers have been encountered by wells drilled by several companies. Evidence for the existence of high temperatures and distinct fluids in wells owned by Geothermal Resources International-GEO Operator Corp. (now Coldwater Creek Operator Corp.) has been published by Drenick (1986) and Walters et al. (1988). These accounts are highly detailed and only the observations of most importance to this paper are summarized.

The GEO wells penetrated the normal vapor-dominated reservoir with temperatures near 245°C and entered an underlying high-temperature reservoir at depths between 1700 m and 2000 m. Flowing steam temperatures measured in the well exceeded 335°C in some instances and bottom-hole temperatures measured during drilling may have exceeded 347°C. The high-temperature steam was distinctive chemically with 2 to 10 times higher gas than steam from the normal reservoir, about 200 ppm HCl (normal steam has < 1 ppm), and was enriched in hydrogen and oxygen isotopes. The transition from the normal to the high-temperature reservoir is very sharp. In figure 6 of Walters et al. (1988), the transition from bottom-hole temperatures (cooled by drilling air) of about 200°C to (cooled) bottom-hole temperatures greater than 300°C occurs within 150 to 200 m, and the transition of return air temperatures from 210°C to 260°C was even more abrupt (< 100 m?). Measured pressures were essentially identical in the two reservoirs,and there was no mineralogical or drilling evidence of a low permiability barrier. Models based on these observations were proposed by Drenick (1986) and Walters et al. (1988) and will be discussed later.

MODELS OF VAPOR-DOMINATED SYSTEMS

General agreement concerning the structure and properties (origin of superheat, etc.) of vapor-dominated reservoirs has existed since the early 1970's when White et al. (1971) suggested that the exploited reservoir in the natural state contains counter-flowing steam and condensate functioning as a heat pipe. About the genesis of this reservoir there is less agreement, although the formation of vapor-dominated reservoirs from hot-water reservoirs has been simulated in several studies (Pruess and Truesdell, 1981; Pruess, 1985; Ingebritsen and Sorey, 1988). The high-temperature zones observed in the field were not produced in these simulations and are not consistent with the White et al. (1971) model. For this reason it will be useful to reexamine other models to see if they hold any clues.

ORIGINAL VAPOR MODELS

Goguel (1953) hypothesized that at Larderello an igneous intrusion at ~5000 m depth heated meteoric water and generated a current of supercritical steam rising along large fissures that eventually cooled below the critical point and condensed in the reservoir to heat the rock and augment a downflowing current of cold water. When produced to a well, the steam flow was increased by liquid evaporated by heat transfer from the rock. Since the downflowing current of cold water started outside the reservoir, the limit on production was the store of heat, not fluid. The origin of the upflowing steam was evaporation of the downflowing current of water, so there was no water-saturated zone at the bottom of the vapor reservoir. Sestini (1970) modified this model to allow condensed water to initially circulate within the reservoir itself. As this water was evaporated and produced it was replaced by deep superheated steam, so that steam temperatures increased and production rates stabilized to equal those of the deep recharge.

ORIGINAL LIQUID MODELS

These models by Facca and Tonani (1964), Ferrara et al. (1970), and Weres et al. (1977) assert that in the natural state the reservoir was water filled and only became steam filled as a result of exploitation. The problems of producing dry steam from an initially water-saturated reservoir are discussed by Truesdell and White (1973). In these models vapor systems are considered identical in origin to hot-water systems. This is also true of theories related to steam formed above boiling water that ascends to a water table and after losing steam, flows away laterally (steaming ground models). As originally proposed by Elder (1966) and followed by James (1968), vaporization was entirely at the interface of the vapor reservoir (containing no liquid) and the boiling water table. This process occurs on a small scale in hot-spring areas. The supply of steam is constant because water after boiling flows away along the water table. Scaling up this process to form a major vapor reservoir is not possible.

HEAT PIPE MODELS

These models have won general acceptance from scientists concerned with vapor-dominated systems (see earlier references). Upward flowing vapor, condensation at the top of the reservoir, and downward percolating condensate can produce essentially all observed phenomena in these systems, including high surface heat flow, low-pressure gradients, and changes in gas chemistry with time. These models have been tested by numerical simulation and found workable.

The deep end of the heat pipe, where condensate boils to form steam, was originally considered to be brine-saturated rock heated from below by fluid convection and ultimately by conduction from an igneous source (White et al., 1971). This part of the heat pipe has not been intersected by drilling except possibly by the few high-temperature wells described earlier. No samples of the deep brine have been recovered; the high-Cl steam that appeared in the 1960's at Larderello was attributed to evaporation of this brine (D'Amore and Truesdell, 1979), but it now appears more likely that general drying out of the reservoir allowed Cl to reach well bottoms at that time (Truesdell et al., 1989).

The only clear evidence for a liquid-saturated layer at the bottom of at least some parts of the Larderello reservoir is the distribution of gases and isotopes around centers of high temperature and production, which follow a Rayleigh condensation pattern. In a steady-state process this condensation implies centrifugal lateral steam flow that must be balanced by a centripetal liquid flow only possible in saturated rock (D'Amore and Truesdell, 1979). Such a deep, sloping water table was found at Larderello from levels in nonproducing wells (Calore et al., 1980).

FORMATION OF HIGH TEMPERATURE ZONES

Although the evidence for high-temperature zones at Larderello is incomplete, a numerical model by Pruess et al. (1987) has shown that most of the observations may be explained by the presence of a liquid-dominated heat pipe below the vapor-dominated reservoir. The liquid-dominated heat pipe consists of a column of boiling water in which hydrostatic pressure increases downward and temperatures increase along a "boiling-point-to-depth" curve referred to the temperature and pressure at the bottom of the vapor-dominated reservoir at 2500 m. The measured temperature of 394°C at 2960 m in the San Pompeo 2 well (fig. 1) is not consistent with a liquid-dominated heat pipe and must indicate superheated vapor or the absence of fluid.

Models of relatively shallow high-temperature zones based on experience by GEO in the NW Geysers have been proposed by Drenick (1986) and elaborated on by Walters et al. (1988). Drenick proposed three models: (1) An active liquid-dominated reservoir at high temperature and pressure was separated from the vapor-dominated reservoir by an impermeable barrier. There was no evidence for high pressure or impermeable rocks so Drenick rejected this hypothesis. (2) Local heating by an igneous intrusion left hot dry rock within the vapor-dominated reservoir. Steam from the normal reservoir passed through the hot rock on the way to the wells.

Although this idea has considerable merit, Drenick (and Walters et al.) preferred his third model (3) in which a liquid-dominated reservoir below a vapor-dominated reservoir has boiled dry leaving hot rock containing vapor and adsorbed water at temperatures above those in the vapor-dominated reservoir. The situation before the final boildown would be similar to that found in simulations of the development of vapor-dominated reservoirs from water-filled systems (e.g., Pruess, 1985; Ingebritsen and Sorey, 1988). Drying out a high-temperature liquid without disrupting an overlying, cooler vapor-liquid reservoir seems difficult.

This "fossil liquid-system" model is consistent with the observed pressure continuity and lack of an impermeable boundary, but does not agree with the sharp temperature gradient observed. If liquid in saturated rock had boiled dry, the temperature of the rock should be reduced by the heat required to convert liquid to vapor and the final temperatures would fall below the boiling-point curve. A water-saturated rock with 5% porosity at 240°C would cool by 40°C if it boiled dry (data in Truesdell and White, 1973). The amount of cooling would be greater with higher porosity and less at higher temperatures as the latent heat of vaporization decreases. The presence of dissolved salts raises boiling temperatures, so boiling temperatures in boiling brine increase more rapidly with depth than those of pure water.

Figure 2 shows boiling points to depth calculated for pure water and for 25% NaCl solutions using data from Haas (1971) and Nathenson (1980). The boiling curves are shown for a hot-water system and for a vapor-dominated system underlain by boiling liquid. The vapor-dominated system was assumed to have a liquid-saturated layer from ground surface to 400 m depth, a vapor-dominated reservoir from 350 m (and 236°C, the enthalpy maximum of saturated steam) to 2000 m and a boiling liquid at greater depths. If this deep liquid boiled dry without any external heat added, then the original boiling-point-to-depth curve would represent the maximum temperatures of the remaining dry rock. If heat in the rock was required to vaporize the original liquid, then temperatures would be lower as discussed above.

It can be seen that the minimum distance from bottom of the vapor-dominated reservoir at 242°C to a point in the underlying dry rock at 342°C (100°C higher) is about 1500 m for pure water and 900 m for 25% NaCl solution. If heat required to vaporize liquid is included, these distances are increased. The observed distance in the northern Geysers from normal vapor reservoir temperatures of 246°C to high-temperature zone temperatures of 345°C was less than 200 m (Walters et al., 1988). This is not consistent with the high-temperature zone being a fossil hot-water reservoir. Of the models proposed by Drenick (1986), the "local heat source" appears the most reasonable.

PROPOSED MODEL

Given the difficulties of the earlier models in explaining observations of a high-temperature zone (to 345°C) immediately beneath the normal vapor-dominated reservoir at the NW Geysers and of near 400°C temperatures at 2900 m at Larderello, I propose a somewhat different model that may apply to much of The Geysers and perhaps Larderello. This model has features adopted from earlier proposals, in particular by Goguel (1953) and Drenick (1986). It differs from their models particularly in the timing of events and in the assumed generality of its application.

Almost all models with the exception of that of Goguel (1953) and Sestini (1970) have assumed that a boiling-liquid layer existed at the base of the vapor reservoir. This boiling liquid was assumed necessary to feed steam to the vapor reservoir and accept condensate, consistent with the generally accepted heat pipe mechanism. In fact, the observations do not require a deep liquid layer except in those areas (chiefly at Larderello) where lateral steam flow and Rayleigh condensation is found. Evaporation of condensate and generation of steam can occur equally well on hot dry rock surfaces as in a liquid layer. Temperatures of hot dry rocks, unlike a boiling-liquid layer, are not limited by boiling-point-to-depth and, because of the moderate thermal conductivities of dry rock, can tolerate steep gradients. Thus, in Drenick's "local heat source" model, 350°C temperatures could exist very close to the normal 245°C reservoir.

The new model involves drying out the deeper parts of a preexisting geothermal system over a broad area, possibly the entire Geysers. This drying could have been accomplished by an increase in conductive heating over numerous igneous intrusions at depths of greater than 2000 m (in the southern Geysers) to greater than 4000 m (in the northern Geysers). After drying we propose that a vapor-dominated reservoir establishes itself by the heat pipe mechanism.

Simulations of the formation of vapor reservoirs from liquid reservoirs have shown that the vapor reservoir extends to greater depths with greater heat input, greater discharge relative to recharge, and longer times (Pruess, 1985; Ingebritsen and Sorey, 1988). None of these simulations has reached such extreme conditions that the vapor-dominated liquid-vapor reservoir was replaced by a vapor-only reservoir at the bottom of the simulated system but such a process is almost certainly possible. Near active volcanoes, subsurface temperatures increase rapidly with depth until liquid water disappears and only superheated steam or a supercritical fluid is found. This process would be expected in a geothermal system intruded at depth by an igneous body of sufficient size.

Formation of a vapor-dominated reservoir underlain by a high-temperature zone would occur in three phases (figs. 2-4). In the first stage, moderate heating might establish a hot-water system (fig. 2) that would deposit hydrothermal minerals, seal some small fractures, and produce brittle rock more likely to sustain open fractures in later stages. If a vapor-dominated reservoir were produced in this stage, NaCl leached from the rock would accumulate in a deep brine (fig. 2). However, the lack of intense fracturing may not provide the dual porosity required for the formation of a vapor-dominated reservoir at this stage.

Increased igneous activity in the second stage would increase temperatures until the geothermal system dried out from the bottom. This stage would involve fracturing and vigorous boiling, possibly that described by Moore et al. (1989) which occurred at temperatures as much as 50°C above boiling-point-to-depth for present topography. Depending on the intensity of heating, the dried zone may extend to the near surface as shown in figure 3. An idealized conductive gradient would be linear as shown, but the real gradient is complex and depends on the heating history, rock conductivities, the heating effect of steam formed at greater depths, and other factors. Fluid inclusions from Larderello containing hypersaline brine trapped at 300 to 350°C (Belkin et al., 1985) may have been formed from an earlier deep brine or from boiling during the heating stages. Higher temperature inclusions and mineral assemblages at 400°C to >550°C (Cathelineau et al., 1989) may be related to the heating maximum.

The third stage (fig. 4) represents a cooling of the top high-temperature dry rock by the formation of the modern vapor-dominated reservoir. The intense fracturing of the earlier heating episode in addition to tectonic fracturing allows surface waters to penetrate the heated rock. At the surface the rocks are saturated and altered with decrease in permeability, but at slightly greater depths a vapor-dominated heat pipe formed and cooled the hot rock by evaporation of descending water. Cooling produced by this mechanism would be much greater than that of cooling by conduction so the temperature gradient below the vapor-dominated reservoir would be very steep (idealized in fig. 4) in agreement with measured temperatures in GEO drill holes (Walters et al., 1988).

The rate of cooling and therefore the thickness of the vapor-dominated reservoir depend on the supply of surface water and the rate of conductive heat transfer from the top of the reservoir to the surface. Both water supply and conduction would be greater if the top of the reservoir was closer to the surface. At The Geysers this effect may have observable consequences. Where the reservoir top is shallowest, it is also thickest, and where its top is deep, the reservoir is relatively thin (Ken Williamson, pers. commun., 1990). By this mechanism the reservoir may have become lenticular as observed at Larderello (Calore et al.,1980). At the sides of the reservoir, particularly in the north, the high-temperature zone occurs at shallow depths under a relatively thin vapor-dominated reservoir. In the center of the field the top of the reservoir is nearer the surface and the high-temperature zone has been pushed below 3000 to 4000 m.

The felsite intrusions found in the central and southern Geysers could represent some of the intrusions producing the heating and drying. Because these rocks were near the surface they were probably cooled and solidified at an early stage so that they fractured along with the greywacke during further heating. In the last stage the vapor-dominated system extended into these rocks but fractures were more limited than in the greywacke. The lesser degree of fracturing may have caused the heat-pipe-driven vapor-dominated system to extend only a short distance into the intrusion. Thus, the high-temperature zone in the southern Geysers may exist in solidified igneous rocks with little porosity so that the amount of high-temperature steam is limited.

The distinctive chemistry of the steam contained in the dry rock of the high-temperature zone could have resulted from intense reactions with rock at high temperatures with possibly some magmatic contribution. High CO2 concentrations are typical of igneous gases and could be generated by metamorphism of calcite; exchange with rock at high temperatures would produce high O-18 steam; and high concentrations of HCl could be generated by reaction with rock containing halite and aluminosilicates (D'Amore et al., 1990). Halite could have been formed in the drying phase when brine from continued boiling below the vapor zone was finally dried. Steam and gases in the high-temperature rock would not tend to mix with those in the normal vapor reservoir because pressures would be equal until disturbed by exploitation. Gases that entered the vapor-dominated reservoir would be removed by reaction with rock minerals (HCl and other acid gases) or diluted by steam produced from evaporation of meteoric water (CO2, O-18). Dilution would be greater where the vapor-dominated reservoir is thicker and less where it is thinner.

SUMMARY

Observed temperatures in normal and high-temperature reservoirs of the northern Geysers can best be explained by recent downward extension of the vapor-dominated reservoir into dry rock heated by igneous intrusion. The igneous episode was probably preceded by a hot-water geothermal system. The modern vapor-dominated reservoir lies above the remaining hot rock with a thickness depending on the amount of heat removed and water added at the surface.

This model suggests that a high-temperature zone may exist under much of The Geysers. This high-temperature zone may contain steam with high HCl and gas in parts of the field where it is shallow enough to be fractured and particularly where it is developed in greywacke. If this is true, then continued production may lower pressures sufficiently to cause steam from high-temperature zones to enter wells even in the central and possibly southern areas.

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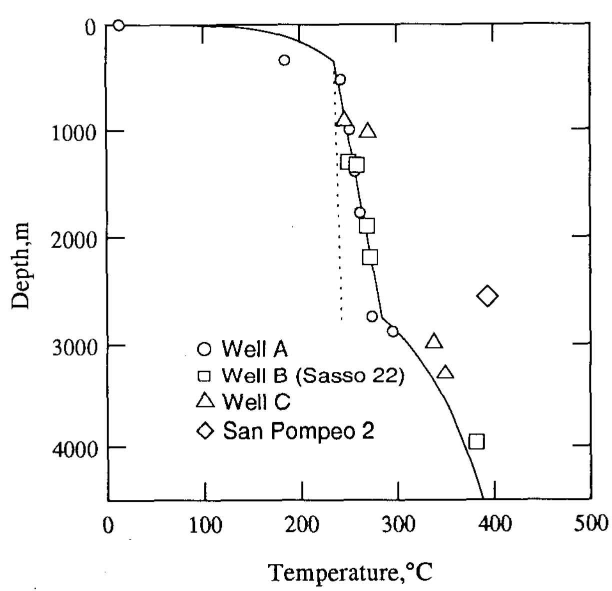

Figure 1. Measured temperatures for three deep wells in the central area of Larderello from Pruess et al. (1987), with an additional temperature from the San Pompeo 2 well. Solid lines show a hypothetical vapor-dominated system with boiling water below 3000 m. Dotted line is for a static vapor column.

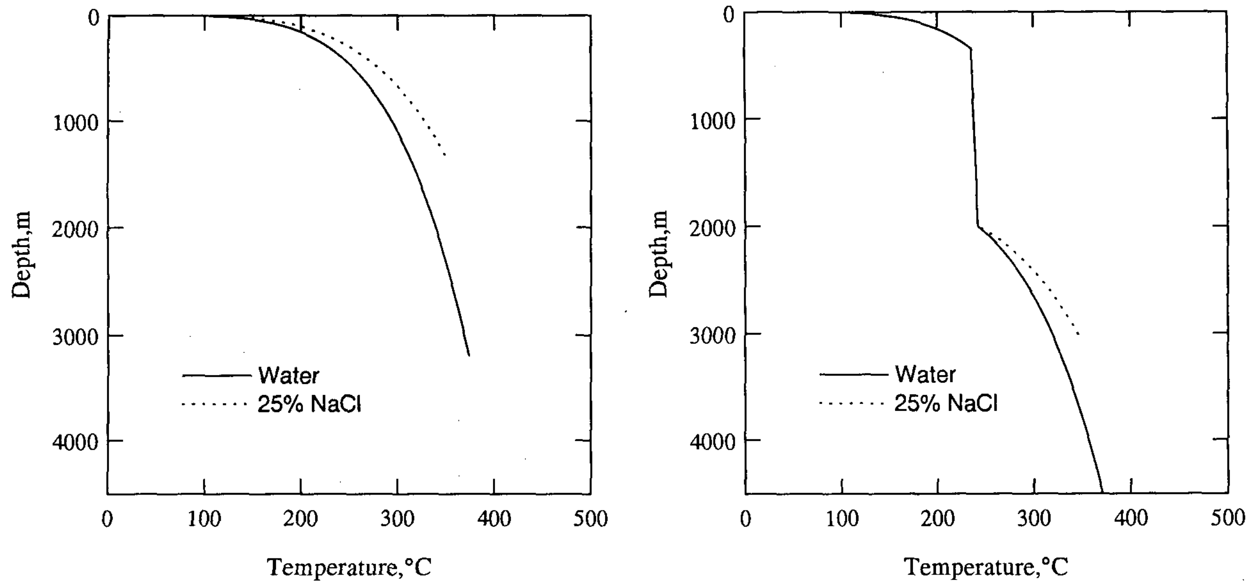

Figure 2. Calculated static boiling-point-to-depth curves for pure water (solid line) and 25% NaCl solution (dots). The left figure shows a hot-water system and the right figure shows a vapor-dominated system with boiling water or salt solution below 2000 m.

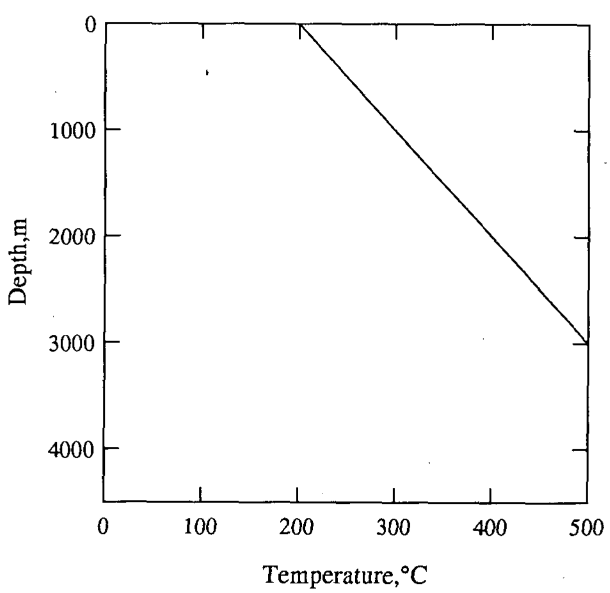

Figure 3. Hypothetical temperature profile for heat conduction in dry rock between an igneous intrusion at 6000 m and 800°C to a near surface temperature of 200°C.

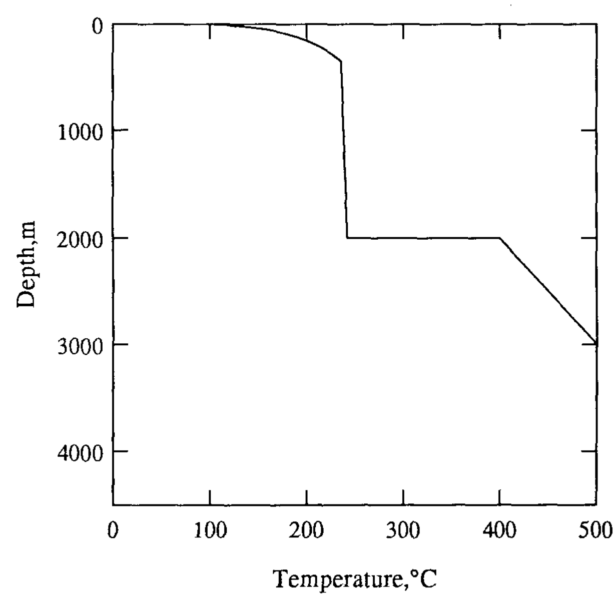

Figure 4. Hypothetical temperature profile of a vapor-dominated heat pipe removing heat and cooling hot rock originally with the temperatures shown in figure 3. Temperatures are for static conditions.