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A NEW DISCOVERY WELL IN THE UPPER AGUA DE PAU GEOTHERMAL SYSTEM, SÃO MIGUEL ISLAND, AZORES: RESULTS OF DRILLING AND TESTING

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ABSTRACT

A successful exploration well, CL-1, was completed in February, 1989 in the upper Agua de Pau geothermal system on São Miguel. The 2022-meter-deep well encountered a high-temperature (>220°C) geothermal reservoir with permeable zones distributed between about 725 m and 1,800 m depth in fractured volcanic rocks. The reservoir penetrated by CL-1 is predominantly single-phase hot water, but temperature surveys and results of flow testing indicate that the top of a reservoir contains a steam cap, which underlies a cap rock of clay-rich altered pyroclastics. Three weeks of flow testing in 1989 yielded total mass flow rates of at least 125 tons/hr. The calculated transmissivity and productivity index of CL-1 are average for a deep, self-flowing geothermal well, and reservoir fluid chemistry is typical of volcanic-hosted meteoric hydrothermal systems. No evidence for calcite scaling, which has caused problems in earlier wells drilled in the lower Agua de Pau system, was found during testing.

INTRODUCTION

A new exploration well, CL-1, was completed and successfully tested by the Sociedade Geotérmica dos Açores (SOGEO; formerly the Consórcio Geotérmico de São Miguel) in 1989, signalling a successful start to a renewed program of geothermal development on São Miguel. Results of CL-1 indicate great promise for achieving the current program's objective of developing and installing approximately 10 MW of geothermal power generating capacity. Such a development will provide a major portion of the power requirement for São Miguel's population of about 140,000 (Figure 1).

Geothermal exploration on São Miguel was spurred by the 1973 discovery of water as hot as 210°C at depths less than 600 m, in a scientific corehole drilled in the Ribeira Grande area, on the northern slope of the Agua de Pau volcano (Figure 2; Muecke *et al.,* 1974). Shortly thereafter, the Regional Government of the Azores sponsored a geothermal exploration program on Agua de Pau. Of the three major active silicic volcanoes on São Miguel, Agua de Pau was considered to be the most attractive for exploration because of (1) its proven high-temperature resource, (2) its proximity to the major population centers of São Miguel, and (3) the lack of sensitive scenic or tourist areas in the prospective exploration area.

The initial exploration and subsequent development program took place from 1976 to 1980. Exploration work consisted primarily of (1) geophysical surveys, including electrical resistivity methods; (2) a comprehensive geochemical survey; and (3) drilling of a series of shallow temperature gradient holes. These

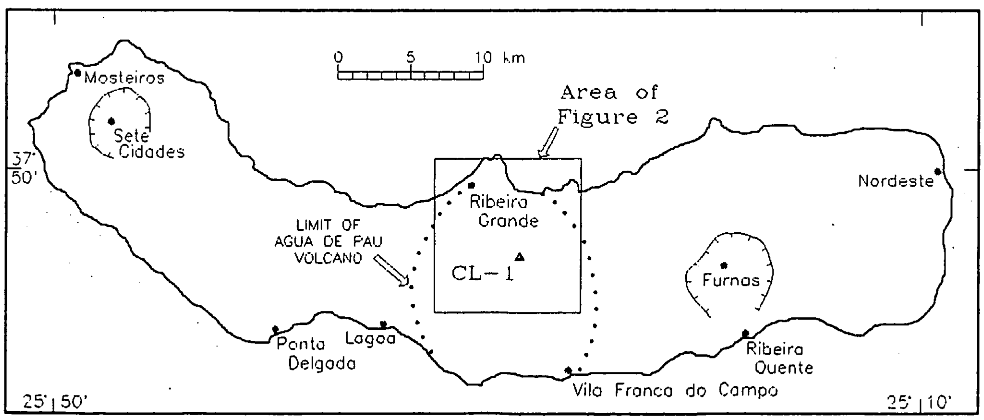

Figure 1. Location of well CL-1 and Agua de Pau volcano on São Miguel

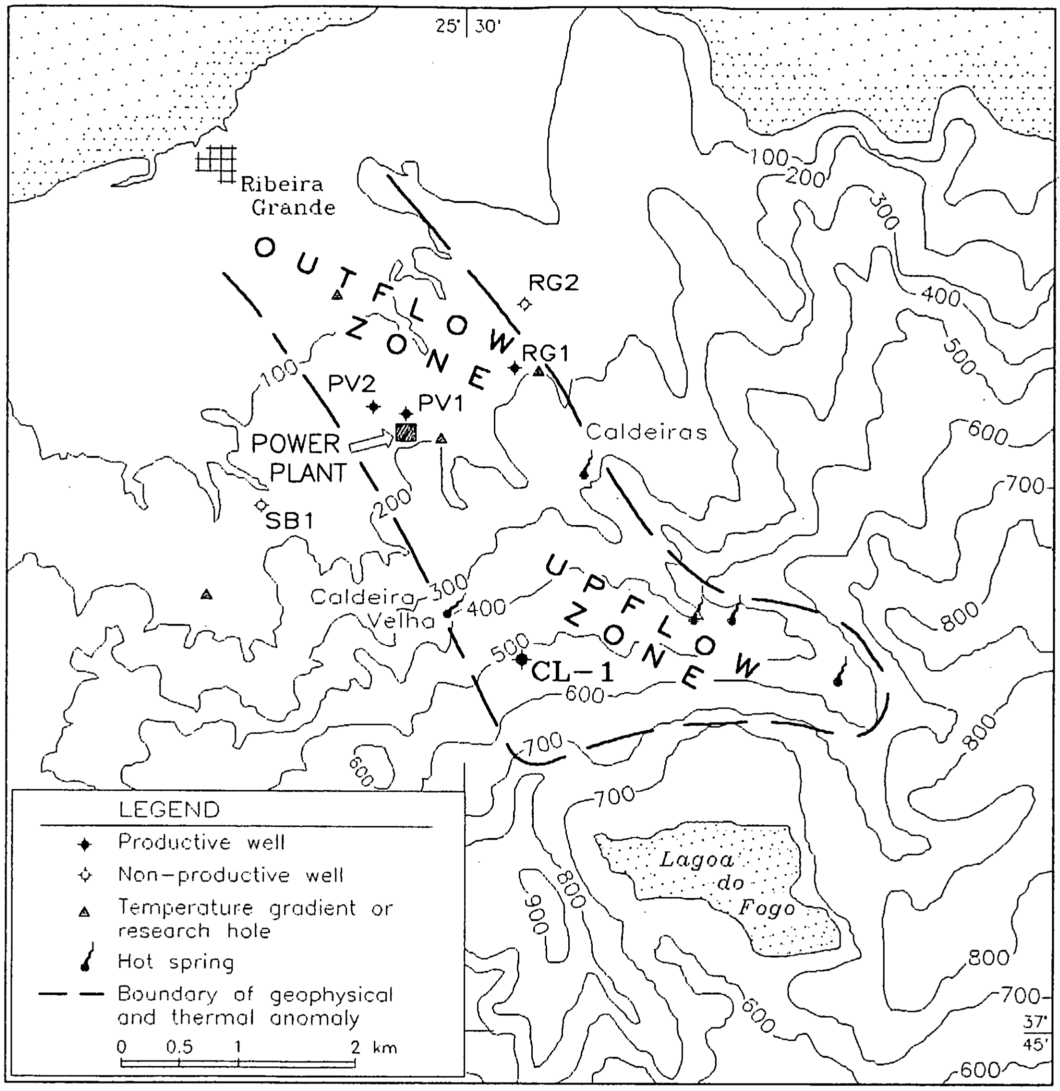

Figure 2. Map of northern flank of Agua de Pau volcano, showing hydrothermal features and completed drillholes

surveys identified a significant geophysical and thermal anomaly in the vicinity of Ribeira Grande. This anomaly is now recognized to be the outflow zone of a more extensive Agua de Pau geothermal system.

Five deep production-diameter holes were drilled in the development phase of the early program. Three of these (PV-1, PV-2 and RG-1) produced high-temperature fluids, and this success led to the purchase and installation of a 3-megawatt pilot plant at Pico Vermelho (Figure 2; Tahara, 1981). Unfortunately, mechanical damage in PV-2 and calcite scaling in PV-1 and RG-1 severely limited production capacity, and the Pico Vermelho plant, supplied only by PV-1, has seldom operated at an output greater than 1 MW.

The geothermal resource potential proven by the early drilling led to a renewed development effort that began in 1984. The Consórcio Geotérmico de São Miguel (now SOGEO), consisting of the Regional Government as majority participant plus 12 Portuguese banks and other private entities, was formed to fund and direct the new project.

Because of the severity of calcite scaling in the early wells, it was decided that new drilling should be aimed at exploring the postulated upflow zone of the Agua de Pau system, where fluids of higher temperature and lower scaling potential could be expected. Geological and geophysical modeling (Duffield and Muffler, 1984; Hoover *et al.,* 1985) and the distribution of fumaroles and hot springs indicated that the upflow zone was located beneath the upper northern flank of the Agua de Pau massif, in the Cachaços-Lombadas area (Figure 2). Further geophysical and geological work sponsored by the Consórcio supported these conclusions and refined the location at the postulated upflow zone. Two drilling pads were constructed in the Cachaços-Lombadas area near Caldeira Velha and drilling of well CL-1 began on the western pad in November 1988.

GEOLOGICAL SETTING

Agua de Pau is a predominantly trachytic stratovolcano that forms the central portion of São Miguel (Moore, 1986). The summit of the volcano is dominated by Lagoa do Fogo, a lake occupying a caldera-like collapse depression. The caldera is the primary eruptive center, which most recently erupted in A.D. 1563. Flank eruptions, which are generally basaltic compared with the usually trachytic summit eruptions, are also common. The most recent flank eruption took place in A.D. 1652. The volcano is therefore composed of a series of trachytic pyroclastic deposits and trachytic and basaltic lava flows, the last being more abundant at lower elevations. The extent of most volcanic units is quite limited; therefore, continuity of specific units over the 4 km between the earlier wells and CL-1 was not expected.

Distinct structural trends on the northern flank of Agua de Pau are revealed by analysis of topography and aerial photographs. A strong NNW trend suggests that the location of the outflow zone of the Agua de Pau system is controlled by a graben structure formed by faults with this trend. An ENE trend is also evident; structures with this trend may affect fluid upflow.

Surface thermal manifestations are few considering the apparently large extent of the Agua de Pau system, and consist mainly of fumaroles and hot springs fed by steam condensate at Caldeiras, Lombadas and Caldeira Velha (Figure 2).

DRILLING OF CL-1

Well CL-1 was planned as a 2,500 m production-diameter exploration well to be deviated to the northeast, where productive fractures and high temperatures were anticipated. Despite the use of state-of-the-art equipment and drilling practices, significant drilling problems occurred that forced the well to be sidetracked twice, and ultimately drilled as a vertical well of 2,022 m depth. Even though the drilling target was not reached, the well successfully encountered zones of high-temperature production.

CL-1 penetrated a sequence of trachytic lava flows and mixed pyroclastic rocks, including tuffs, tuff breccias and scoria deposits. Pyroclastics encountered between about 150 m and 550 m depth appear to be largely impermeable, whereas substantial fracture permeability is present in the lavas (Figure 3). This high permeability necessitated frequent plugging operations, extensive blind drilling and difficult casing cement jobs.

Hard drilling and numerous circulation losses were encountered in a 125 m-thick surficial trachyte flow (Figure 3). Beneath this flow, rapid drilling through pyroclastics took place and 13-3/8-inch casing was set at 346 m below kelly bushing (KB). The hole was deviated beginning at 600 m, and drilled directionally to 776 m, where circulation was lost. After drilling to 867 m with partial to total losses, a cement plug was set back to 700 m to cure the loss zones.

The wellbore was unintentionally sidetracked near 720 m while drilling out cement, and a new track was drilled to 1025 m, with circulation losses from 801 m onward. Caving and sloughing in clay-rich altered pyroclastics caused the drill string to become stuck at drilled depths of 796 m and 1025 m. The first time the drill string was successfully backed off and recovered, but on the second occasion continued sloughing made fishing impossible, and the wellbore was plugged back to 449 m with 144 m of fish left in the hole.

To avoid the continuing problems associated with directional drilling, circulation losses and zones of unstable rock, the second sidetrack was drilled vertically to a total circulation loss zone at 735 m, and 9-5/8-inch production casing was immediately set at 709 m. The rest of the well was drilled vertically without returns, to a total depth of 2029 m KB (2022 m below ground level). A seven-inch slotted liner was run, completion tests were performed, and the rig was released on February 27, 1989.

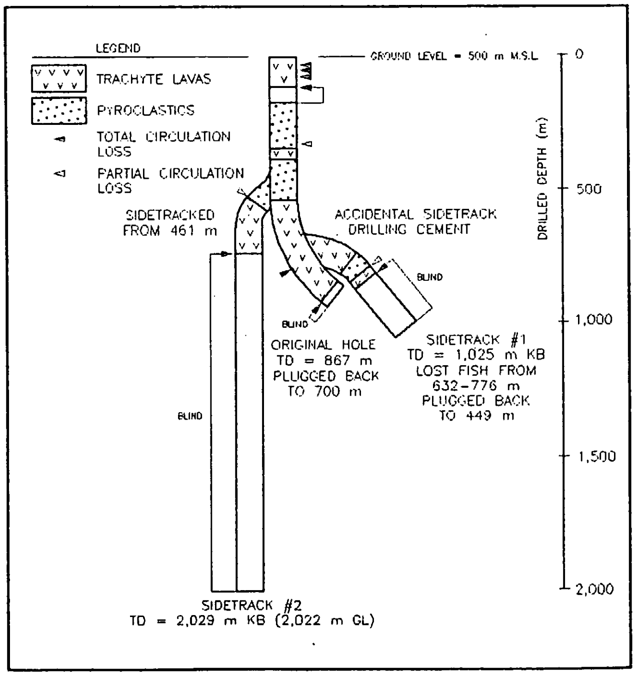

Figure 3. Schematic wellbore diagram of well CL-1

DRILLING AND HEAT-UP RESULTS

The presence of multiple permeable zones between depths of 725 m and 1800 m was indicated by circulation losses encountered during drilling, and by temperature surveys conducted as the well heated up after completion (Figure 4). The most significant permeable zone occurs from 725 to 800 m, with smaller but potentially important zones occurring at greater depths. The distribution of permeability, lithology and drilling rates indicates that permeable zones occur mainly as fractures in the trachyte lavas.

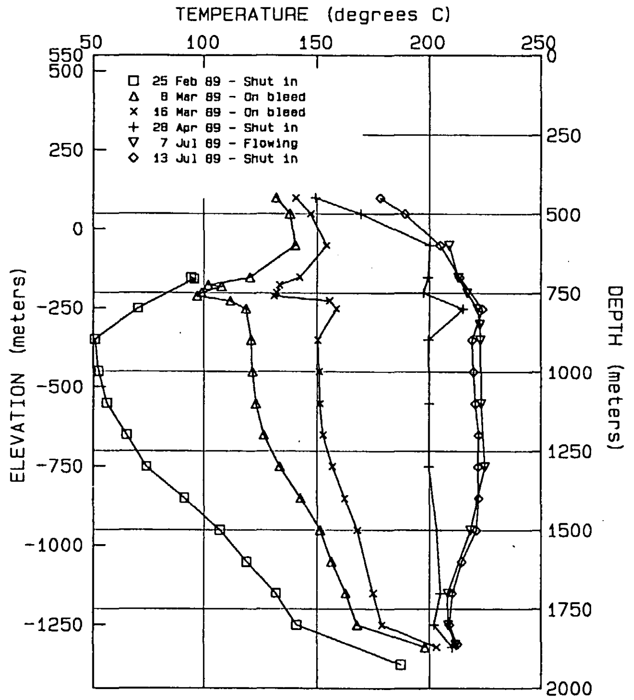

Figure 4. Downhole temperatures measured in well CL-1

An absence of major loss zones, in the interval dominated by pyroclastics (150 to 550 m) indicate that these clay-rich, altered volcanic sediments form an impermeable caprock to the high-permeability reservoir below. After completion, well CL-1 built up a wellhead pressure of about 27 kg/cm^2 within several hours of being shut in. This behavior and the unusual temperature behavior observed in the interval between about 600 and 800 m (Figure 4) suggest that a gas or steam cap exists at the top of the reservoir, beneath the pyroclastic caprock.

Because of extensive periods of blind drilling, stable formation temperatures were not approached until the well had been allowed to heat up for more than two months (figure 4). Stabilized temperatures exceed 220°C over an interval of at least 700 m, with a maximum temperature of 225°C recorded at 1300 m depth during flow testing. A moderate temperature reversal may be present below 1500 m depth; however, it is likely that the deeper parts of the well had not heated fully when the latest temperature surveys were made, some 4-1/2 months after well completion.

Cation geothermometer temperatures calculated for CL-1 and other wells on Agua de Pau exceed 250°C. Higher temperatures are therefore likely to be encountered in wells drilled closer to the center of the indicated geothermal anomaly (Figure 2).

VERTICAL DISCHARGE

After a 73-day heat-up period following well completion, a five-day vertical discharge of CL-1 was conducted in May 1989 to clean the wellbore and demonstrate commercial viability. Flow was initiated by compressing the well under its own gas pressure, and continued uninterrupted for 102 hours.

Preliminary calculations of mass flow based on measured lip pressures indicated that the well's flow rate was approximately 150 tons per hour through a 9-5/8-inch discharge tube. The flow rate increased slightly throughout the test.

HORIZONTAL FLOW TEST

A fully-instrumented flow test was carried out by GeothermEx over a 14-day period during June and July, 1989. The well was discharged through a horizontal flow line into an atmospheric separator, with a weirbox, James tube and in-line orifice plate installed for flow metering. A throttle valve was used to regulate flow over a series of four rate steps. Chemical sampling (including samples of separated steam and brine) and downhole pressure/temperature surveys were conducted during each rate step. Pressure build-up was measured upon shut-in at the end of the test.

Results of the flow test are summarized in Table 1 and Figure 5. Total mass flow rates ranged from about 40 to 125 tons/hour at wellhead pressures of 12.5 to 6.5 ksca. A strong dependence of fluid enthalpy on wellhead pressure is evident in Figure 5. Enthalpy of total flow

Table 1: Summary of Results of Flow Test, Well CL-1

Test dates: June 27 - July 12, 1989

Mass flow rates: 45 to 125 tons/hour

Wellhead pressures: 12.3 to 6.7 ksca

Enthalpy of total flow: 260-310 cals/gm

	Completion Test	Flow Test
Productivity index (tons/hour·ksc)	6.8 - 7.4	8.4
Transmissivity (md·m)	2,520	3,100
Skin factor	--	2.5