

## CONTINUOUS TEMPERATURE OBSERVATIONS IN THE HAWAII NSF/ICDP BOREHOLE - RESULTS AND MODELS

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### ABSTRACT

The borehole of the Hawaiian Scientific Drilling Project (HSDP, 3109 m) penetrates zones of enhanced permeability and low temperature. Transient temperature conditions during different hydraulic stimulation's were monitored using fiber optical measuring (DTS). Several bore hole sections of the Hawaii ICDP hole can be distinguished by increasing or decreasing temperatures with time. The following combined thermo-hydraulic modeling suggests that a downstream of freshwater from the mountain range strongly influences the thermal conditions in the upper part of the borehole. The lower part is also affected by down-streaming freshwater, however, with lower flow velocities and additionally by a circulation of saltwater from the nearby ocean.

### INTRODUCTION

In the pilot hole (KP1, depth 1056 m) at the ICDP drill site in Hilo an irregular temperature pattern was observed in 1993, where in some borehole intervals temperature decreases with depth. Based on this pattern, previous studies suggested a superposition of thermal and hydraulic processes (Thomas et al., 1996). Therefore, it was of interest whether similar observations could be made in the deeper (3109 m) main borehole: HSDP-2 (Fig. 1).

The goals of the project were twofold: (1) measurement of temperature logs and petrophysical properties, (2) investigation by numerical modeling of different scenarios of thermo-hydraulic conditions that fit the measured temperature pattern.

It is important to record the dynamic temperature behavior if the influence of the hydraulic system on the temperature field should be investigated. Conventional temperature logging systems have the disadvantage that repeated measurements of the entire profile can only be performed in different logging runs. In contrast, the Distributed

Temperature Sensing (DTS) allows continuous temperature monitoring with time without moving the logging cable. With this technique it is possible to observe dynamic conditions in the borehole in a short period of time and thus to distinguish between zones of different hydraulic properties.

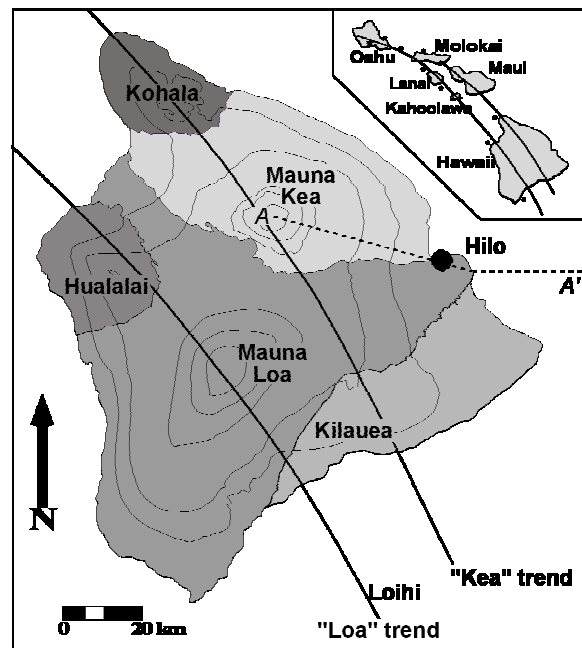


Fig. 1. Island of Hawaii showing the five volcanoes and their boundaries. The dot indicates the location of the Hawaiian Scientific Drilling Project. The black lines show the "Kea" and "Loa" trend. The dotted line represents the profile (A-A') from the 2-D modeling. The inset shows all Hawaiian Island including the Island of Hawaii (adapted from DePaolo et al., 2001).

### TEMPERATURE MEASUREMENTS

Temperature logs in different stages of borehole development were observed in April (Fig. 2) and in July and after cessation of drilling in October 1999 (Fig. 3). In the upper part of the borehole temperature

changed in time, reflecting different dynamic temperature conditions and in advection-dominated thermal regime. As already observed in the pilot hole, a temperature decrease with depth is prominent between 400 and 600 mbsl (meter below sea level) in all logging runs in the HSDP2 borehole. This zone is characterized by a strong transient temperature behavior (Fig. 2). This is due to the enhanced permeability in that zone. The underlain soil zone respond as an aquiclude. But there are also other zones with a strong transient behavior because of the enhanced hydraulic activity, e.g. at the transition between Mauna Loa and Mauna Kea.

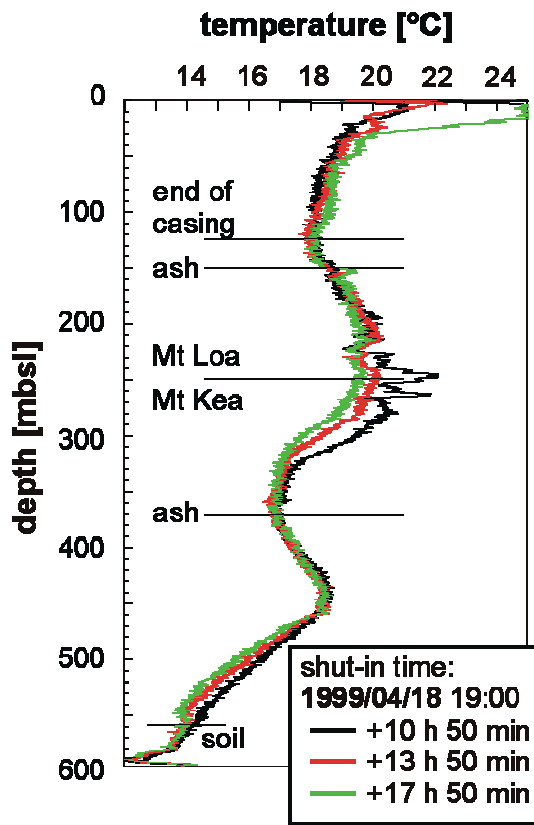


Fig 2. Compilation of continuous temperature logs measured in April 1999. The depth are corrected to sea level. All logs represent average values measured over a time span of 15 minutes and a depth interval of 5 m.

The last log, representing steady state conditions, from the University of Hawaii/USGS is shown in Fig. 3 (see also DePaolo et. al, 2001).

The relatively low temperature could be explained by a down streaming of freshwater. This water (temperature 12 °C) is derived from a recharge area on the island at an average elevation of 2000 m. The depth interval between 600 mbsl and 1100 mbsl is characterized by increasing temperature with depth. The temperature gradient in this zone is relatively small (7 - 8 °C/km).

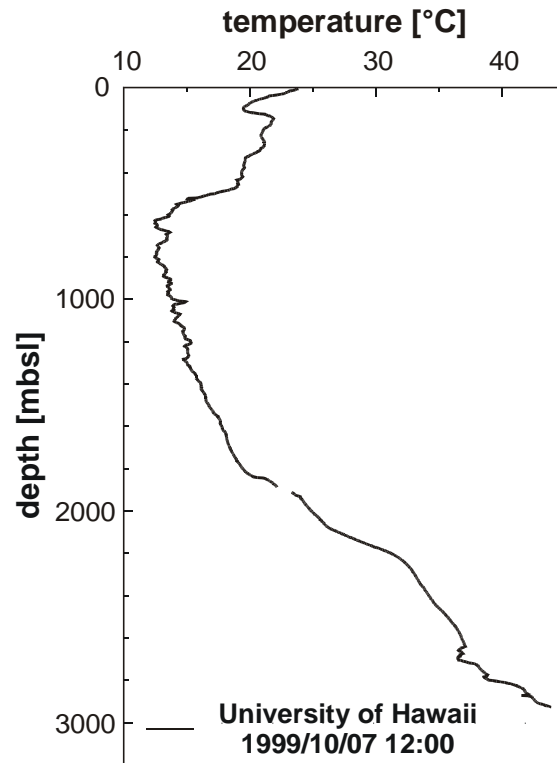


Fig. 3. Temperature log in the HSDP2 by University of Hawaii at 7<sup>th</sup> of October 1999. The depth is in meter below sea level (mbsl).

Below 1100 mbsl (to the total depth), in contrast to the pilot hole, a positive temperature gradient is evident. From 1800 mbsl to the total depth, a temperature gradient of about 18 °C/km is obvious. It is likely that here hydraulic effects are not as strong as in the upper part and that the conditions change from an advective-dominated to a conductive-dominated regime.

#### LABORATORY MEASUREMENTS

Petrophysical properties, such as porosity, density, permeability and thermal conductivity, were measured on 34 rock samples (see Fig. 4).

The rock samples were selected along the entire borehole column with a constant spacing of 91.44 m, so that they represent the different lithological units. The subaerial lava flows (aa-lavas, pahoehoe-lavas and massive-lavas) cover the upper 1079 m of the borehole followed by a submarine section (massive-lavas, hyaloclastite and pillow-lavas).

Laboratory measurements confirm the variability of porosity of basaltic rocks known from literature (e.g. Robertson and Peck, 1974). Between 0 and 1700 m, porosity ranges from 4 to 52 %. The variation is a result of different vesicle texture of the rocks. Below 1700 m, porosity is lower and varies from 0 to 12 % because rocks here are devoid of vesicles.

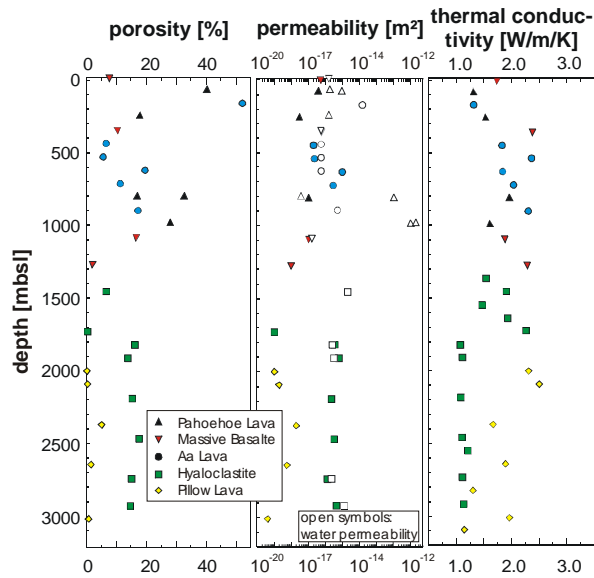


Fig. 4. Overview of the measured petrophysical parameters: porosity, gas and water permeability (filled and open symbols, respectively) and thermal conductivity. The different lithologies are coded by different symbols and colors. Depth in meter below sea level (mbsl).

The permeability ( $k$ ) differs in subaerial and submarine lava flows. The values in the uppermost part of the borehole (down to 1079 m) are variable ranging from  $1 \cdot 10^{-18} \text{ m}^2$  to  $2 \cdot 10^{-11} \text{ m}^2$ . From some rock samples a correlation between porosity and permeability is observed. Whether the two parameters correlate or not depends on the network between the separate vesicles. The permeability of the sediment-like hyaloclastites ( $k = 7 \cdot 10^{-16} \text{ m}^2$ ) differs from the one of compact pillow lavas ( $k = 5 \cdot 10^{-20} \text{ m}^2$ ) in the submarine section.

However, all permeabilities measured are lower than those determined from geophysical measurements or hydraulic tests made in oceanic basalts (Fischer, 1998; Souza and Voss, 1987). These literature values finally were used, because in regional numerical modeling values are needed reflecting a larger scale than laboratory data.

The measured thermal conductivity of water-saturated samples is very variable across the lithological section. Above 1700 mbsl, thermal conductivity ranges from 1.1 W/m/K to 2.4 W/m/K. Below 1700 mbsl, variability is smaller (1.1 to 1.4 W/m/K), except 5 values with a thermal conductivity  $> 1.7$  W/m/K. The thermal conductivity calculation for the solid phase of the rocks shows a strong correlation to mineral composition (especially in rocks with olivine- and plagioclase content).

## NUMERICAL MODELING

The 2-D modeling (Profile see Fig. 1 A-A') of the thermo-hydraulic field of the region uses the borehole measurements as constraints and the petrophysical data as input. The geological structure for the model is derived from seismic observations and gravity data (Hill and Zucca, 1987; Zucca et al., 1982). The 5- km thick oceanic crust dips from  $3^\circ$  (under the submarine flank) to  $8 - 10^\circ$  (under the island). The composition of the oceanic crust (deep sea sediments, pillows and gabbros) and the lithospheric mantle (to 100 km depth) was used according to previous studies. The volcanic edifice (Fig. 5) is subdivided into different units. The upper part consists of subaerial lavas with variable permeabilities. The transition into the submarine part is formed by a layer of hyaloclastites, followed by less permeable pillows.

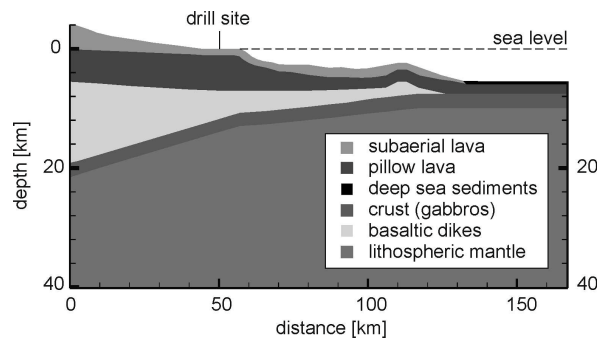


Fig. 5. Geological structure of the upper part of the model. The vertical exaggeration is 2:1.

A step by step completion, refinement and validation of modeling was necessary to fit the observed conditions. This was done using different modeling scenarios. The modeling of the thermal field considering the conductive case (scenario 1, not shown), where fluid flow through the volcanic edifice is not taken into account, results in a geothermal gradient of about  $28 \text{ }^\circ\text{C/km}$  in the deeper part of the borehole (below 1800 m). However, this modeled gradient does not fit the temperature gradient ( $18 \text{ }^\circ\text{C/km}$ ) measured in the same part of the borehole. The heat-conduction scenario 1 also cannot explain a negative temperature gradient observed in the upper part of the borehole section. Therefore, an extension to a coupled thermo-hydraulic modeling is considered different densities and different salt concentrations of the water (scenario 2).

In scenario 2 (Fig. 6) the upper part of the borehole is affected by water recharged at an elevation of 2000 m. To fit the calculated to the observed temperature profiles different layers of different permeability have to be considered in the model. The lower part of the borehole is affected by the invading seawater under the island.

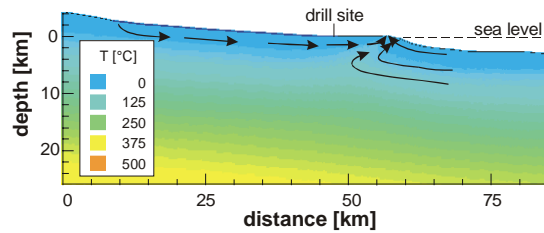


Fig. 6. Temperature distribution from the thermo-hydraulic modeling including the drill site an sea level. The arrows represent the flow paths of the two main hydraulic systems (fresh water and sea water, respectively).

## **CONCLUSIONS**

The deeper main hole (HSDP2) show in the upper part a similar temperature behaviour as in the pilot hole (KP1).

The modeling of the thermal field considering the conductive case resulted in a geothermal gradient of about 28 °C/km. This modeled gradient does not fit the temperature gradient (18 °C/km) measured in the same part of the borehole. Scenario 1 also cannot explain the negative temperature gradient observed in the upper part of the borehole section. Therefore, a superposition of hydraulic effects is very likely.

The combined thermo-hydraulic modeling (scenario 2) suggests that a downstream of freshwater from the mountain range strongly influences the thermal conditions in the upper part of the borehole. The lower part is also affected by down-streaming freshwater, however, with lower flow velocities and additionally by a circulation of saltwater from the nearby ocean. However, the results of scenario 2 results give a plausible explanations for the observed

unusual temperature-depth-profiles of the HSDP2 borehole.

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