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Temperature memory gauge survey and estimation of formation temperature of the USDP-4 conduit hole at Unzen Volcano, Japan

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ABSTRACT

The Unzen Scientific Drilling Project was initiated in 1999 to investigate a magma conduit that had recently fed a volcanic eruption. The conduit hole, USDP-4, was drilled to 810 m in 2003. In 2004, the hole was extended with intention of reaching the conduit at a drilled depth of about 2000 m. This objective was achieved, and the final measured depth of USDP-4 was 1995.75 m.

A new temperature memory gauge for rotary drilling application was designed and developed for the project in order to measure borehole temperatures as often as possible in the expected high temperature environment near the conduit. Temperature ratings of the tool are up to 250 °C with dewar. A total of 10 surveys were conducted at depths of 1555–1995.75 m. This tool was used in six surveys, and borehole temperature data was successfully obtained from all surveys. Based on the measured temperatures, it is apparent that the thermal energy potential of the conduit regime (*i.e.* thermal supply from conduit) is not large compared to that of most known geothermal systems.

Formation temperatures along the conduit hole were estimated from measured temperatures by using a borehole temperature simulator, which we developed and subsequently modified. According to the simulation, the maximum in the formation temperature profile is located at a depth of about 1970 m, and its temperature was about 170 °C before the drilling operation started. This maximum approximately coincides with the center of the conduit, but is surprisingly low for a system that ceased eruption only 9 years before the temperature survey.

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1. Introduction

Unzen volcano, located on the Simabara peninsula, Nagasaki prefecture, Japan (Fig. 1), started its most recent eruption in November 1990. Dacite lava extrusion began in May 1991 and continued for about 4 years. The eruption ceased in February 1995.

The Unzen Scientific Drilling Project (USDP) was started in 1999 with the goal of investigating volcano structure, volcano formation and eruption mechanisms by taking cores through the volcano's flanks and conduit (Uto et al., 2000; Nakada et al., 2005). USDP was divided into two phases. Phase 1, from 1999 to 2001, focused on verification of the history of the volcano. Two flank core holes, USDP-1 and USDP-2, and a pilot conduit hole (USDP-3) were drilled. During phase 2, from 2002 to 2004, a conduit hole (USDP-4) was drilled. The final drilled depth was 1995.75 m, and spot cores were taken 16 times at depths of 1555–1995.75 m (Sakuma et al., 2008-this issue).

Several difficult issues were identified prior to drilling the conduit hole. High formation temperature was regarded as one of the technical difficulties (Saito and Hatakeyama, 2001). The conduit temperature was estimated to have been about 850 °C during 1991 to 1995 when magma was flowing to the surface (Nakada and Motomura, 1999). Tomiya et al. (2000) performed thermal calculations to estimate conduit temperature in 2003, when the conduit hole was to be drilled. They assumed that the uniform thermal gradient of formation was 170 °C/km, the magma temperature was constant at 850 °C for 4 years, the conduit thickness was 20 m, and the thermal diffusivity and latent heat of crystallization were given as 1.0 mm^2/s and 420 kJ/kg, respectively. According to their calculations, the conduit temperature was predicted to be between 650–750 °C in 2003. In addition, Saito and Hatakeyama (2001) predicted a similar temperature range using another simulator but with the same assumptions.

One issue for conduit drilling was how to identify the conduit position while drilling. We needed to know the position of the conduit relative to the bottom of the hole from time to time. Another issue was how to monitor borehole temperature in order to prepare appropriate countermeasures for safe drilling. Saito and Henfling (2002) suggested to measure borehole temperature as often as possible, and selected a memory gauge tool as a temperature measurement device. Memory

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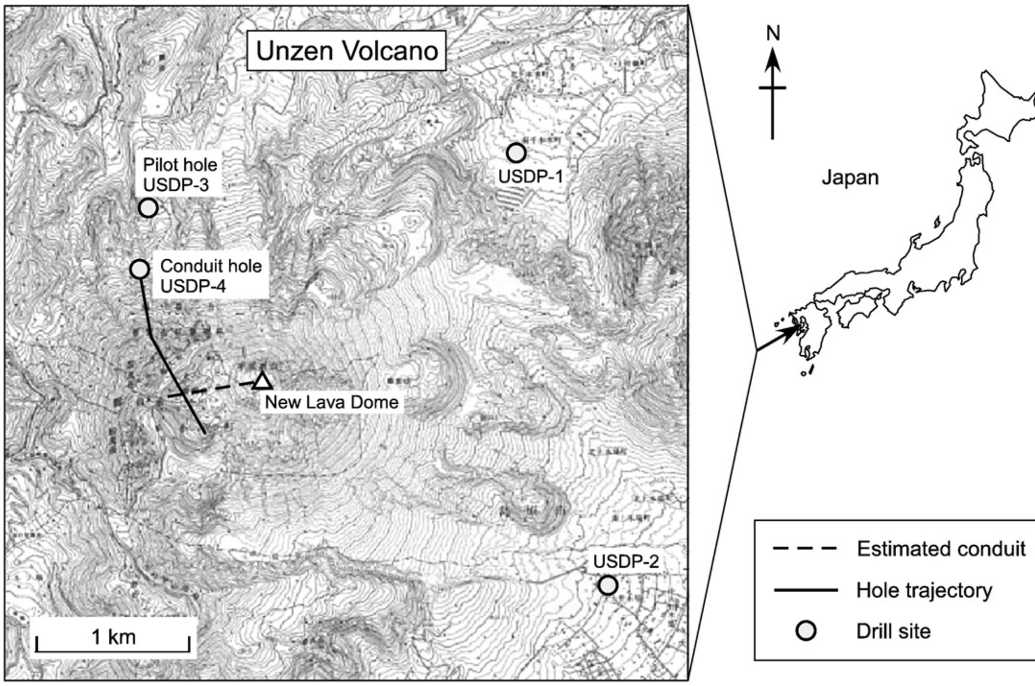

Fig. 1. Location map of Unzen Scientific Drilling Project (modified from Saito and Henfling, 2002).

gauge tools were considered as the most suitable method for the project from both a cost aspect and operational safety aspect. In order to verify the capabilities of temperature memory tools, an existing Sandia-memory tool (CTDL: Core Tube Data Logger) was tested while drilling USDP-2. The device obtained the borehole temperature data successfully, and demonstrated the advantage of using memory-gauging tools.

In addition, new memory tool, the Downhole Data Logger (DHDL) was designed and fabricated, with a higher temperature rating and strength to be suitable in the harsh rotary drilling environment. Borehole temperature was measured as often as possible, and the formation temperature was estimated by using a borehole temperature simulator.

2. Temperature survey method

2.1. DHDL memory tool

The DHDL memory tool is high-temperature memory tool applications not involving coring. The DHDL tool can operate up to 150 °C continuously without a dewar, and up to 250 °C for 10 h with a dewar. It has two modes of deployment: as a magnetic single shot tool, or as in place from bit change to bit change. The DHDL tool consists of an electronics part, a temperature sensor part, a pressure sensor part, and a battery-pack part, and a pressure housing. The software for the tool is compatible with the Windows operating system. The required interface is a RS232 (COM) port, which is available on any computer.

Two types of housing were prepared. One is a steel housing and the other is a dewar/flask housing. The steel housing allows the DHDL tool to be used just above the bit during penetration. In addition, the tool can be dropped through the drill-pipe to the bottom of the hole. In a very shallow angle well, such as with USDP-4, using this tool was extremely useful in obtaining borehole temperature data in less time and with lower costs than other methods.

The tool with the steel housing has a 44.5 mm O.D. and is approximately 1.6 m in length. The other tool with the dewar/flask housing has a 44.5 mm O.D. and is approximately 2.1 m in length. The tools measure borehole temperature and pressure. The accuracy of temperature measurement is ±0.5 °C, and that of pressure measurement is ±0.5%. The time constant for the temperature sensor is 10.9 s. A special battery-pack is needed for the high-temperature environment. The battery-pack consists of a lithium/sulfuryl chloride 12-volt battery. The battery life is approximately 4 days. Temperature rating of this battery is less than 150 °C without dewar.

2.2. Temperature surveys with DHDL

In normal drilling operations, a series of operations are followed: bit change, running in the hole (RIH), drilling or coring with fluid circulation, and pulling out of the hole (POOH). Because the mud temperature is lower than formation temperature, the borehole is cooled by circulation of mud during drilling. Therefore, the time when fluid circulation is stopped is the time when the borehole is cooled most, after which the borehole temperature increases gradually over time until the next interval of fluid circulation activity. This period without fluid circulation is called the temperature recovery. A temperature survey is usually conducted long after the fluid circulation stopped. The period from the end of circulation, to the commencement of pulling the survey tool out of the hole, is called the Standing Time (ST). In USDP-4, many temperature surveys were conducted after various standing times because of the need to survey as often as possible.

A total of 10 surveys were conducted at a depth of 1555–1995.75 m (the 6-1/4" hole section). Fig. 2 and Table 1 show the summary of the surveys. The DHDL tool was used for 6 surveys (C, E, F, H, I, and J in Fig. 2 and Table 1) and a conventional memory gauge was used for 4 surveys. In the last 2 surveys (I and J), the DHDL tool was used with the dewar/flask housing. In USDP-4, the DHDL tool was only deployed with the single shot tool. This means that the DHDL tool was not used while drilling or coring.

The survey procedure with the DHDL tool in USDP-4 was as follows: (*i*) connect the tool to the landing assembly for the single shot tool, (*ii*) send it to the bottom of the hole, and (*iii*) pull it out of the hole with the Bottom Hole Assembly (BHA). There were 3 scenarios were followed in sending the tool to the bottom. Pattern 1: When a BHA was at the bottom immediately after drilling, the DHDL tool was dropped and pumped down. Pumping was needed due the shallow angle of the hole. Pattern 2: When a BHA was pulled out of the casing shoe after

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