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Physical rock properties in and around a conduit zone by well-logging in the Unzen Scientific Drilling Project, Japan

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ABSTRACT

The objective of the Unzen Scientific Drilling Project (USDP) is not only to reveal the structure and eruption history of the Unzen volcano but also to clarify the ascent and degassing mechanisms of the magma conduit. Conduit drilling (USDP-4) was conducted in 2004, which targeted the magma conduit for the 1990-95 eruption. The total drilled length of USDP-4 was 1995.75 m. Geophysical well logging, including resistivity, gamma-ray, spontaneous potential, sonic-wave velocity, density, neutron porosity, and Fullbore Formation MicroImager (FMI), was conducted at each drilling stage. Variations in the physical properties of the rocks were revealed by the well-log data, which correlated with not only large-scale formation boundaries but also small-scale changes in lithology. Such variations were evident in the lava dike, pyroclastic rocks, and breccias over depth intervals ranging from 1 to 40 m. These data support previous models for structure of the lava conduit, in that they indicate the existence of alternating layers of high-resistivity and high P-wave velocity rocks corresponding to the lava dikes, in proximity to narrower zones exhibiting high porosity, low resistivity, and low P-wave velocity. These narrow, low-porosity zones are presumably higher in permeability than the adjacent rocks and may form preferential conduits for degassing during magma ascent.

1. Introduction

As part of the Unzen Scientific Drilling Project (USDP), a comprehensive program of drilling, downhole measurements and sampling was conducted to target the magma conduit of the Unzen volcano, Kyushu, Japan, from FY 2003 to 2004. The goal of USDP conduit drilling is to clarify the ascent and degassing mechanisms of magma and to evaluate models proposed for the 1990-95 Unzen eruption (Nakada et al., 2005). Some of these eruption models postulate that whether an eruption will be explosive or effusive depends on the efficiency of degassing as the magma ascends toward the surface through the conduits. To evaluate these and other models, we need to understand the characteristics of these conduits, such as their internal structure, geometry and rock physical properties.

Although up until now volcanic conduits have never been drilled shortly after an eruption, an 861-m-long hole was drilled into the conduit zone directly beneath South Inyo Crater in the Long Valley Caldera, California (Eichelberger et al., 1988). Breccias zones that intrude the caldera fill were intersected, and the maximum temperature was only 80 °C at an approximate depth of 500 meters, where rocks had already cooled down since the last eruption 600 years ago. In the Hawaii Scientific Drilling Project (HSDP), geophysical downhole measurements and sampling were performed to a depth of 3200 m in the 3340 m deep borehole (Pechnig et al., 2000). The HSDP hole was drilled within the flank of a shield volcano, but this drilling project never aimed to go directly into the conduit. On the other hand, since the Unzen volcano has erupted numerous times over the past several hundred years (in 1657, 1792 and 1990-1995) the USDP conduit drilling provides a rare opportunity to study the characteristics of a conduit constructed by recent eruptions.

Since Unzen conduit drilling was performed shortly after the most recent eruption, difficult conditions related to loose volcanic materials and high temperatures in and around the conduit required a cautious approach to drilling and geophysical logging methods. Preceding conduit drilling with borehole USDP-4, two boreholes USDP-1 (752 m-deep) and USDP-2 (1463 m-deep) were drilled into the flank of the volcano to reveal the structure and growth history of the Unzen volcano (Fig. 1). We also conducted geophysical wireline logging and an injection test in these boreholes and performed an integrated study of in-situ stresses, fracture geometry, permeability, and rock material properties (Ikeda et al., 2003a,b). This experience provided us with a lot of useful information on in-situ structure and properties in a volcano area. After that, a high inclination (deviation from vertical) borehole (USDP-4) was drilled higher up the volcanic edifice, and geophysical well logging and intermittent coring were conducted to characterize the feeder conduit

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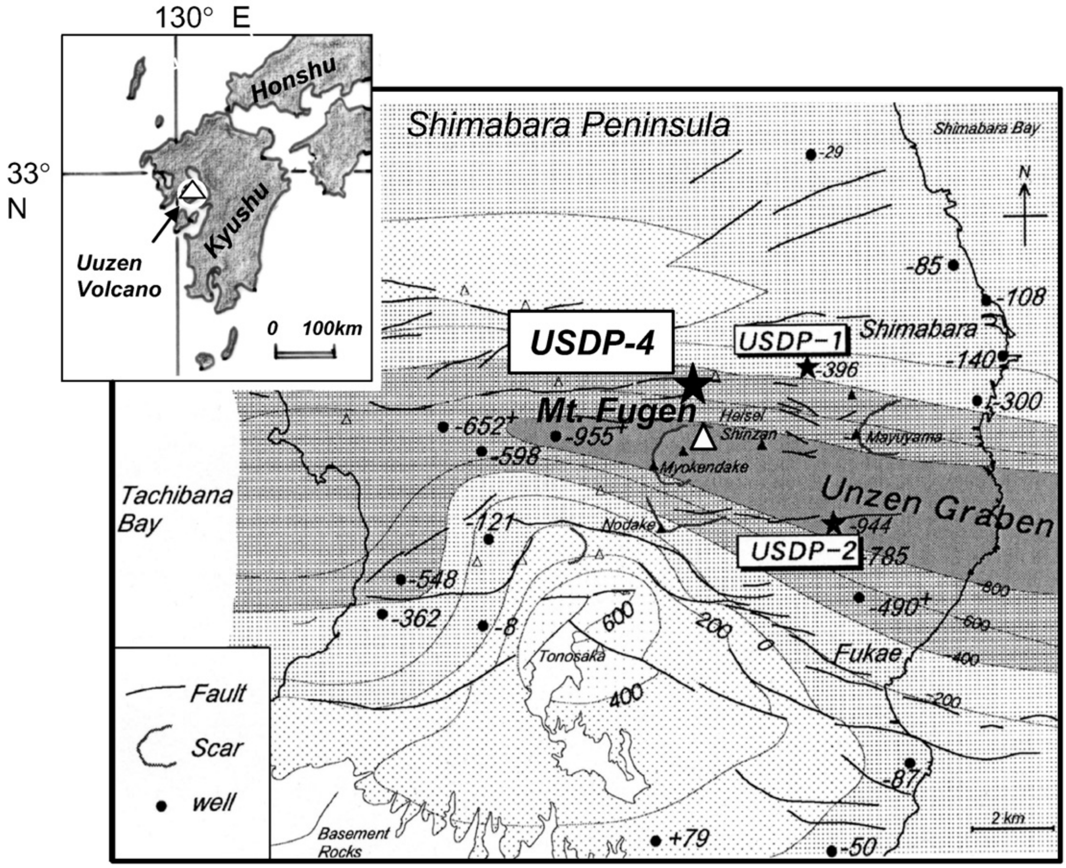

Fig. 1. Topography around the Unzen volcano and graben, modified from Hoshizumi et al. (2002). Stars (★) are locations of boreholes: USDP-1, USDP-2 and USDP-4 (conduit drilling). Thick solid lines show normal faults, and contours indicate the depth of basement rocks, which was estimated from the other nearby drill holes (●). The numbers denote altitude above sea level of the top surface of basement rocks (after Hoshizumi et al., 1999).

for the most recent eruptions (Nakada et al., 2005; Kajiwara et al., 2005; Sakuma et al., 2005, 2008-this issue). These geophysical log data provide us with important information regarding the structure of and the material properties in the volcano. In this paper, we focus on log data acquired in USDP-4 data from a feeder dike zone and its surrounding formations below the depth of 1550 m in order to constrain the geometry and structure of the conduit zone. We also present results from an analysis utilizing cross-correlation plots of the log data, such as resistivity vs. velocity, natural gamma radiation and porosity to investigate in more detail the structure of the conduit zone and the associated rock physical properties. These analyses allowed us to identify lithological boundaries and their subdivisions and identify zones with anomalously high porosity and low resistivity, which may represent conduits for degassing during recent volcanic eruptions.

2. Drilling and logging

In Fig. 1, the locations of all drill holes for the USDP are shown along with other boreholes and hot springs used for geothermal surveys (Hoshizumi et al., 2002). The drilling site of USDP-4 is located at an altitude of 840 m on the northern slope of the Unzen volcano. It was drilled in a south-southeast direction to an area below the summit of Mt. Unzen. The borehole reached the conduit zone near sea level, and the total length of the drilling was 1995.75 m. Details of the drilling strategy and trajectory are described by Sakuma et al. (2005, 2008-this issue). Note that all depths referred to in this paper are as measured along the borehole, and are not to be confused with true vertical depths. The hole was drilled to a depth of 396 m with a diameter of 17-1/2 inches and an inclination from the vertical of 25 degrees. The inclination was then built up to 75 degrees, drilling to a depth of 795 m in a 12-1/4 inch hole. After that, an 8-3/4 inch hole was drilled and 7 inch casing emplaced to the depth of 1550 m at approximately the same inclination. Finally, a 6-1/4 inch diameter hole was extended to the depth of 1995.75 m with stable inclination and azimuth and left as an open hole. Spot coring was performed at 16 locations from the depth of 1582.20 to 1995.75 m.

Some difficulties were expected in obtaining geophysical log data because of the possibility of the borehole collapsing and the formation temperature rising to higher than 500 °C. However, the estimated formation temperature in the open-hole interval based on temperature logs was from 160 to 180 °C and stable well conditions were maintained below the depth of 1550 m (Sakuma et al., 2008-this issue). Consequently, good logging data were obtained from the deeper part of this well and no correction for borehole environmental effects had to be applied to the logging data. Geophysical well logging was conducted throughout most of the drilled section. However, some small intervals could not be logged due to the drilling and casing schedule and borehole conditions. The logging was run in four stages as follows: 1st run between the depths of 166.5 – 463.5 m; 2nd run from 417 –650 m; 3rd run from 770 – 1542 m; and 4th run from 1550 – 1795 m. The Tough Logging Condition System (TLCS) was used below the depth of 800 m where borehole inclination was up to 75 degrees. Logging sondes used were natural gamma-ray (GR: at depths of 166.5 – 1787 m), resistivity (RES: 166.5 – 1795 m), spontaneous potential (SP: 166.5 – 1775 m), density (392 – 1782 m), neutron porosity (POR: 770 – 1777 m), sonic velocity (Vp: 392 – 1787 m), Fullbore Formation MicroImager (FMI: 166.5 – 1542 m), Formation MicroScanner (FMS: 1550 – 1791.5 m) and Vertical Seismic Profiling (VSP; 237 – 737 m). The well was deepened beyond the initially planned total depth of 1800 m in an effort to obtain cores from the magmatic conduit of the 1990-95 eruption, and 6 spot