Journal of Volcanology and Geothermal Research 175 (2008) 1–12

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Drilling and logging results of USDP-4 — Penetration into the volcanic conduit of Unzen Volcano, Japan

Sumio Sakuma [a,*], Tatsuya Kajiwara [a], Setsuya Nakada [b], Kozo Uto [c], Hiroshi Shimizu [d]

[a] Japan Metals and Chemicals Co., Ltd. (Japan), 101-1 Hosoyachi, Ukai, Takizawa, Iwate, 020-0172, Japan
[b] Volcano Research Center, Earthquake Research Institute, University of Tokyo (Japan), 1-1-1 Yayoi, Bunkyo-ku, Tokyo, 113-0032, Japan
[c] National Institute of Advanced Industrial Science and Technology (Japan), Central 7 Tsukuba, Ibaraki, 305-8567, Japan
[d] Institute of Seismology and Volcanology, Kyushu University (Japan), 2-5643-29 Shin'yama, Shimabara, Nagasaki, 855-0843, Japan

ARTICLE INFO

Article history:
Accepted 24 March 2008
Available online 22 April 2008

Keywords:
volcanic conduit
scientific drilling
extended reach borehole
spot coring
tough logging

ABSTRACT

Borehole USDP-4 was drilled into the Unzen volcanic conduit 9 years after its last eruption. The sub-surface mechanism of eruption at Unzen Volcano was investigated by taking cores and by geophysical logging. The drilling operations were carried out in 2003–04, as a joint research program sponsored by the Japanese Government and the International Continental Scientific Drilling Program (ICDP). Borehole USDP-4 was a directional 6-1/4 in. (158.8 mm) borehole drilled from a site located on the northern slope of the volcano at 840 m above sea level, and was designed to penetrate into the conduit at sea level with a final deviation angle of over 70° from vertical and a borehole depth of 1800 m.

An igneous dyke with a high likelihood of being the Unzen conduit was encountered at 1996 m depth and core samples were taken from that location. Chemical analysis of drill cores confirmed the identification of the conduit. Geophysical logging, including recording of gamma ray, resistivity, self-potential, density, neutron porosity, sonic velocity, and temperature suggested an alternation of dykes and flows in rock penetrated during the drilling, and in-hole pictures confirmed the lithologic identifications. Although borehole collapse and high temperature had been expected in the conduit, the actual drilling and logging into the conduit experienced no gas or fluid kick, and the measured temperatures within the dyke were below 200 °C.

1. Introduction and drilling target

Detailed structure of volcanic conduits is not well known, A volcanic conduit is the principal site for magma degassing, which is considered as an important control on the explosivity of volcanic eruptions (e.g., Nakada et al., 1997). Drilling into a volcanic conduit was carried out in the Inyo lava dome field, Long Valley (USA) during the 1980s (Eichelberger et al., 1986). The drilled conduit was the pathway for magma from an earlier explosive eruption and also from a later effusive eruption that formed the lava dome. An open system degassing model was proposed as the result of the Inyo Dome conduit drilling (Eichelberger et al., 1986). Encouraged by the Inyo results, we drilled the youngest lava dome at Unzen Volcano (Fig. 1), with the aim of penetrating into the conduit of the most recent eruption in 1990–1995 (e.g., Nakada et al., 1997). The volcanic activity was monitored in detail, and models of the eruption processes and the subsurface structure including the conduit were proposed (e.g., Nakada and Motomura, 1999; Shinohara et al., 2008-this issue). In this paper we give details of the Unzen drilling operation together with the lessons learned during drilling of a volcanic conduit.

The Six-year Unzen Scientific Drilling Project (USDP) has been funded by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. Following a one-year feasibility study in 1998, a project consisting of two phases was started in 1999. The first phase of this project aimed at clarifying the growth history and magmatic evolution of Unzen, by drilling two 1000 m coring boreholes on the flank of the volcano (USDP-1 and 2). In addition, a 350 m section of core was drilled on the northern slope of Unzen (USDP-3) as part of the preparation for drilling the conduit. The purpose of the second phase was to understand the eruption processes of the last eruption and to model the eruption mechanisms of dacite magma by drilling to the conduit area of the last eruption and taking cores. In particular, we hoped to gain a better understanding of degassing processes in the upper part of the conduit, (Uto et al., 2001; Nakada and Eichelberger, 2004). The conduit drilling of the second phase, USDP-4, was carried out as a joint research project with International Continental Scientific Program (ICDP).

The objectives of drilling borehole USDP-4 were as follows;

(1) To penetrate the upper part of the conduit for the last Unzen eruption at multiple elevations.

* Corresponding author. Tel.: +81 19 684 4115.
E-mail address: sakuma@geothermal.co.jp (S. Sakuma).

0377-0273/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jvolgeores.2008.03.039

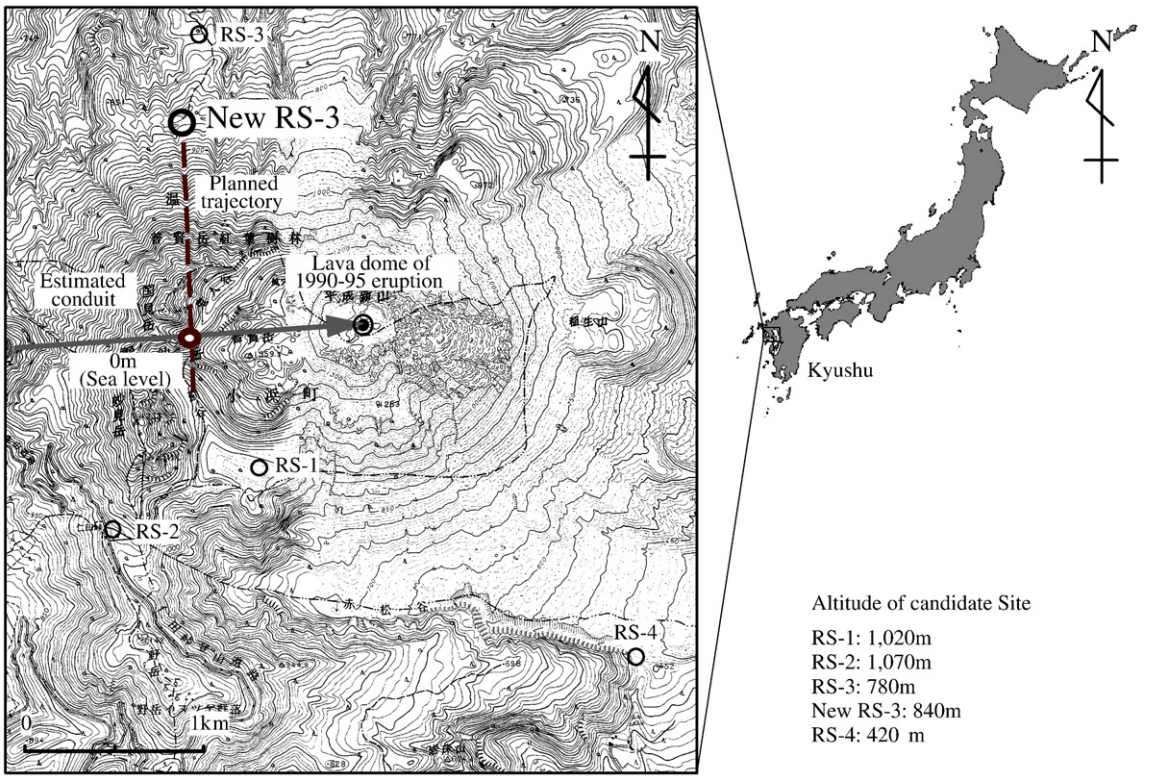

Fig. 1. Index and location map showing Unzen Volcano with the candidate sites (RS: rig site) for borehole USDP-4. Drilling was done from site New RS-3. The conduit of last eruption was considered to be inclined to the west as shown by an arrow, and the target intersects sea level just south of New RS-3.

(2) To take core samples in and around the conduit, with a diameter (larger than 60 mm) sufficient for textural and whole-rock chemical analysis.
(3) To take cuttings every 2 m-depth in non-coring sections for supplementary lithologic information.
(4) To sample juvenile fluids in the conduit area.
(5) To get geophysical properties in the conduit area; e.g. temperature, borehole images, sonic velocity, density, and resistivity.

The conduit was considered to be inclined to the west, based on clusters of hypocenters of isolated volcanic tremors and low-frequency earthquakes which occurred just before and during dome growth, respectively (Shimizu, 1992; Nakada et al., 1999), and its extension at the sea level was estimated to be located beneath an area 1 km west of the summit lava dome. The conduit was considered to be an east-west trending lava dyke with dimensions of approximately 200 m wide by 50 m thick, based on the shape of the lava spine that intruded in the final stage of dome growth (Nakada and Shimizu, 2000; Nakada and Eichelberger, 2004). Thermal modeling suggested that the interior of the conduit was as hot as 600–700 °C, by analogy with cooling by simple heat conduction in a high geothermal gradient observed within the Izu-Oshima caldera (170 °C/km) (Fig. 2) (Tomiya et al., 2000; Saito and Hatakeyama, 2001). Volcanic gas was also expected in the conduit area.

2. Drilling strategy and outline of the operational plan

2.1. Drilling strategy

The degassing process is generally considered to occur in the uppermost part of a volcanic conduit, considering the pressure dependence of volatile solubility in magma, the pressure build-up observed during eruptions, and the shallow source depth of seismic signals. From a scientific point of view, the shallower the hole, the more useful the information that could be obtained. However, a drilling plan satisfying the scientific requirements could not easily be drafted because of scarcity and uncertainty of the geologic data beneath the summit area of Unzen. That is, drilling a near horizontal borehole is very risky without detailed information along the well course. We adopted the following strategy to improve our chances of success. We planned to first drill a main hole and then drill a sidetrack hole at an angle to the main hole. The aims of the main hole drilling were to confirm the conduit location,

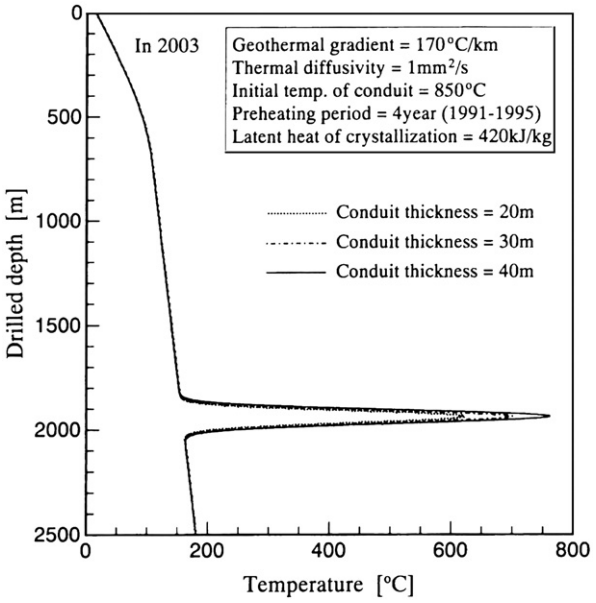

Fig. 2. Simulated temperature profile along the well trajectory planned in 2003 (Saito and Hatakeyama, 2001). Assuming simple heat conduction, the estimated temperature peaks at the conduit assumed to be 20 to 40 m thick.