Scientific Results of Conduit Drilling in the Unzen Scientific Drilling Project (USDP)

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Abstract

Directional drilling at Unzen Volcano in Japan during mid of 2004 penetrated the magma conduit and successfully recovered samples of the lava dike that is believed to have fed the 1991–1995 eruption. The dike was sampled about 1.3 km below the volcano's summit vent and is intruded into a broader conduit zone that is 0.5 km wide. This zone consists of multiple older lava dikes and pyroclastic veins and has cooled to less than 200°C. The lava dike sample was unexpectedly altered, suggesting that circulation of hydrothermal fluids rapidly cools the conduit region of even very active volcanoes. It is likely that seismic signals monitored prior to emergence of the lava dome reflected fracturing of the country rocks, caused by veining as volatiles escaped predominantly upward, not outward, from the rising magma. Geophysical and geological investigation of cuttings and core samples from the conduit and of bore-hole logging data continues.

Introduction and Drilling Operation

The volcanic eruption at Unzen, Japan, during 1991–1995 took a heavy toll on life and property through devastating pyroclastic flow events. To understand the structure and growth history of the volcano and to clarify the eruption mechanisms of SiO_2-rich viscous magmas, the Unzen Scientific Drilling Project (USDP), a six-year project consisting of two phases, was started in April 1999 (Uto et al., 2000). In the first phase, two holes were drilled into the volcano's flank (USDP-1 and -2 wells). In the second phase, drilling penetrated the magma conduit that fed a lava dome at the summit during the 1991–1995 eruption. The conduit drilling reported here was carried out as a joint research project with the International Continental Scientific Drilling Program (ICDP). The detailed design and targets of the conduit drilling were determined in the first phase. The design and decision process involved negotiations with federal environmental and forestry agencies, explaining the project to local residents, a one-year-long environmental assessment of possible drilling sites, the drilling of a pilot hole (USDP-3 well), and the convening of an international workshop on drilling techniques (Nakada et al., 2001).

The magma conduit, especially its upper part, is believed to be the site of effective degassing that is the major factor controlling eruption styles. The pressure-dependent nature of solubility of volatiles, principally water, accelerates vesiculation as magma approaches the surface and produces geophysical signals (earthquakes and inflation) in the shallow conduit region. Drilling into this region allowed us the first in situ observations and sampling of the still-hot conduit and wallrocks of a recent, well-observed eruption (Nakada and Eichelberger, 2004).

Geothermal modeling prior to drilling had suggested a temperature of over 600°C at the center of the conduit, if it cooled by conduction only. The drilling target was set in the hypocenter region of isolated tremors that occurred prior to magma extrusion in 1991. Drilling started vertically at 840 m above sea level and 1000 m north of the summit of Mt. Unzen in January 2003, and then was deviated toward the target below the summit at sea level (Figs. 1 and 2). The USDP-4 well required several infrastructure projects such as constructing a new mountain road, drilling water wells, and laying a water pipeline. Most of this preparatory work was performed in 2002 (Nakada, 2003).

The worst difficulties of the conduit drilling were expected to be (1) trajectory control in loose young volcanic formations, especially in the early large-diameter drilling phase, and (2) drilling, sampling, and logging within high-temperature formations in and around the conduit. Cavities in shallow formations encountered by USDP-4 made it difficult to maintain the scheduled trajectory and time. This problem arose because the drilling site was situated in a small basin in the upper slope of the volcano that had formed along an active fault associated with activity of the Unzen graben. Total loss of drilingl mud circulation, wall collapse, and accidental deviations of well trajectory occurred frequently, and the operation was brought to a halt soon after it started in early 2003. After reviewing these troubles, it was decided to use aerated drilling mud, water supplies enhanced by double water wells, and a top-drive system and also to establish a safety and oversight committee for conduit drilling. The operation was resumed with a new trajectory in late 2003. With orientation of the well controlled by the electromagnetic measurement-while-drilling technique (EM-MWD), the well reached its maximum planned inclination of 75° from vertical at 794 m drilled depth. A furlough then began to await the new federal fiscal year.

Before the 2004 operation, the drilling target was relocated 250 m to the east based on reanalysis of seismic and geodetic data gained during this project. Although this lengthened the drilling depth, the drilling operation in 2004 advanced faster than planned because formations in middle and deeper parts were more stable than the shallow part. Given that, it was easy to maintain the well inclination at about 75°, and wall collapse seldom occurred. Well orientation was again controlled with EM-MWD from 800–1550 m depth. After 7" casing was set down to 1550 m, drilling proceeded without deviation, straight toward the target (Fig. 3).

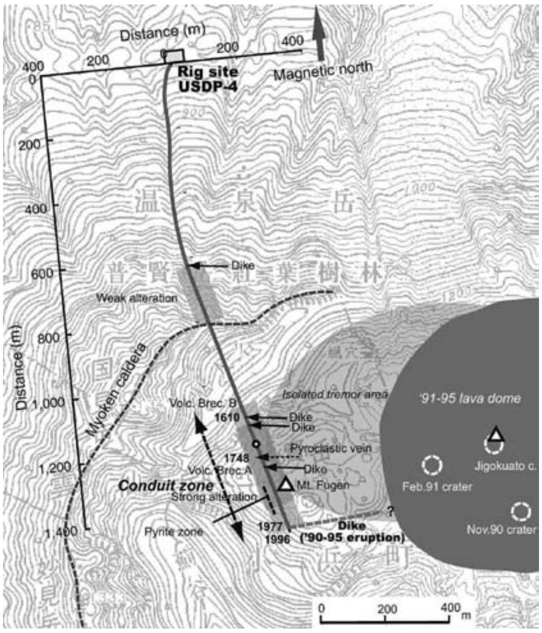

Figure 1. Map showing the summit area of Unzen Volcano and the plane view of the USDP-4 trajectory. The conduit zone, consisting of multiple lava dikes and pyroclastic veins in homogeneous volcanic breccia (vent breccia), is as thick as 0.5 km under the volcano summit. A small circle on the trajectory line was the drilling target (at sea level) of the 2004 operation.

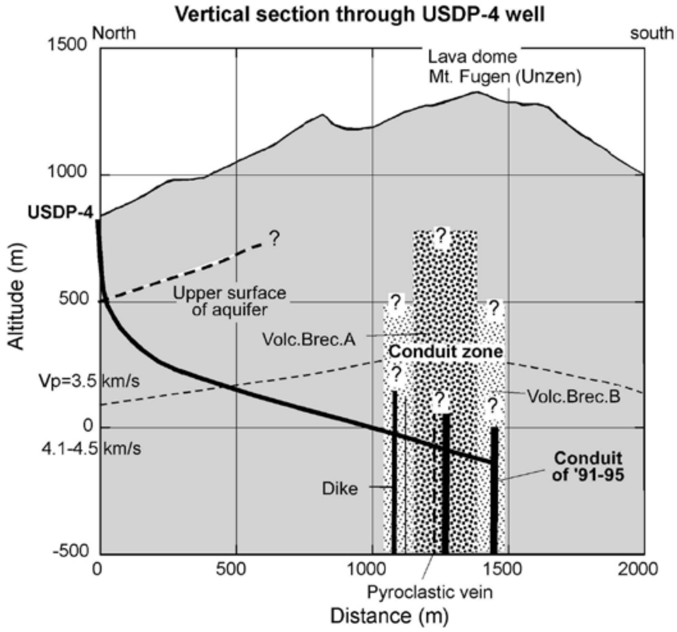

Figure 2. Vertical section along the USDP-4 well. Types A and B of the breccia are different in lithology (see Fig. 4). A lava dike that is considered to be the conduit of the 1990–1995 eruption was located at the deepest part of the well.

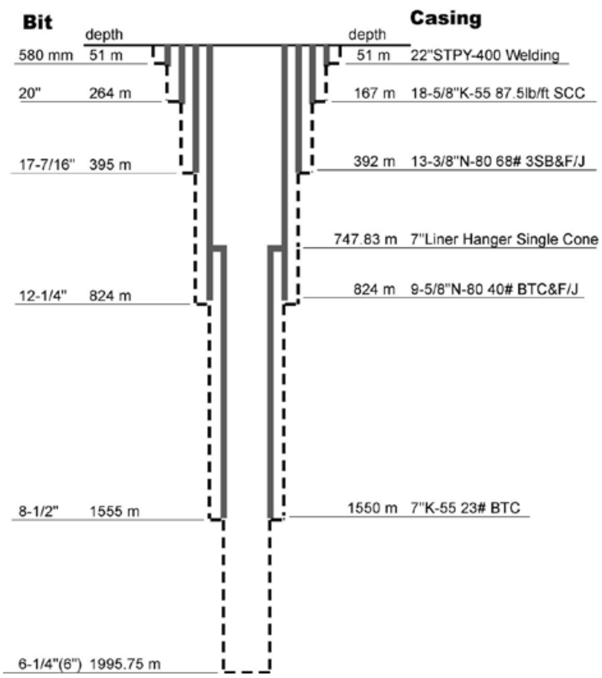

Figure 3. Casing system employed in the USDP-4 well.

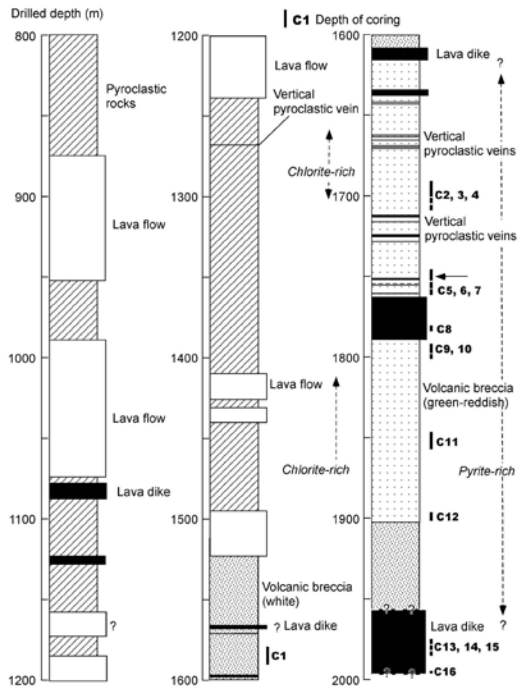

Figure 4. Geologic section along the USDP-4 well. Types A and B of volcanic breccia are colored in green to red and white-colored, respectively, due to difference in the extent of hydrothermal alteration. The pyroclastic vein in Fig. 5 is found at the level with an arrow (1748 m drilled depth).

Formations around the conduit contain few cracks (no circulation lost), suggesting that the conduit area at the drilling depth has limited fracture porosity into which volcanic gas can escape (Fig. 4). As the target area was approached in early June 2004, spot coring and logging were conducted. Points of spot coring were determined on site by scientists who were stationed around the clock, conducting mud logging and negotiating drilling operation with the drillers. The conduit region was reached near sea level (~2000 m drilled depth, or ~1300 m vertically below the crater). Rock sampling and logging in and around the conduit succeeded; however, logging was not done beyond 1800 m because of delays in reaching the target, the expectation of very high temperature in the conduit area, and the lead time necessary to order logging. Logging covers density, resistivity, acoustic wave velocity, porosity, gamma ray, temperature, self-potential, and borehole imaging. vertical seismic profiling (VSP) experiments were also conducted in the final stage of the drilling operation within the cased portion of the borehole.

The drilling operation was terminated at the end of July 2004, leaving USDP-4 cased down to 1550 m and plugged to the same depth for the next trial of drilling.

Conduit Zone

Drilled formations under the volcano peak consisted mainly of massive and homogeneous volcanic breccia, lacking any features indicative of sedimentation at the ground surface. Their porosity is less than 0.2% and density is close to 2.5 g cm^{-3}. These measurements are consistent with the fact that mud loss seldom occurred during drilling in the volcanic breccias of the conduit zone, implying little fracture development and very low permeability. The mass of volcanic breccia is intruded by seven lava dikes, ranging in thickness from 7 to 40 m, and by multiple pyroclastic veins up to several tens of centimeters thick (Fig. 2). The lava dikes are interpreted to be magma conduits of older eruptions; they are not pipe-shaped, but rather plate-like under the anisotropic tectonic stress field. Based on analysis of formation microimages (FMI) and formation microsonde (FMS), the dikes and veins are nearly vertical and parallel to each other, trending in an east-west direction that is perpendicular to the minimum horizontal stress component exerted on this volcano. The zone intruded by dikes and veins is as wide as 0.5 km in the north-south direction. We refer to this as the conduit zone of Unzen volcano.

Lava dikes are commonly accompanied by vertically layered pyroclastic margins (probably sheared margins), judging from the FMS images. Some of the lava dikes are composite, consisting of multiple dikes with the same composition. The dikes are dacite in composition but with chemical contrasts among them, suggesting different formation ages

Figure 5. Photograph showing a core sample including pyroclastic vein. As the core was recovered from the hole inclined about 75˚, the contacts of the vein were nearly vertical. Black-colored clasts in the vein are quenched blobs of molten magma that were originally glassy.

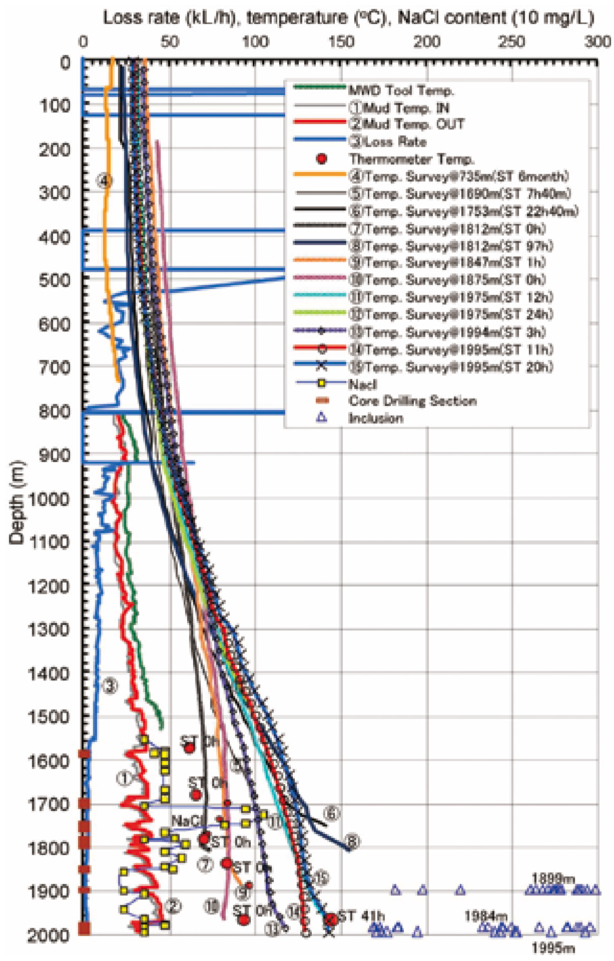

Figure 6. Profiles of temperature measured during drilling. Loss rate of mud circulation and NaCl content, calculated with mud chemistry, are also shown. Lost circulation became smaller as the depth increased and was minimum in the conduit zone (deeper than 1500 m). Values of the homogenization temperature for fluid inclusions in plagioclase crystals are also shown in the conduit zone. The minimum values are close to the highest temperatures during drilling. ST is standing time. NaCl contents are highest in the middle of the conduit zone (around 1750 m).

because magma of every eruption at Unzen volcano has a unique chemistry, but with little variation within an eruptive episode. Dike lavas are denser, higher in resistivity, and lower in porosity than the surrounding volcanic breccia. Pyroclastic veins are composed of fragments of lava and host volcanic breccia (ash to lapilli in size) in various proportions. Sedimentation structure of ash and lapilli can be seen in some veins in the core samples. The samples of pyroclastic veins obtained from a drilled depth of 1748 m are relatively fresh and contain many originally glassy clasts (Fig. 5).

The freshest dike (though already altered) was encountered in the 1975–1995 m interval of drilled depth. The temperature at this depth was 180˚C, much cooler than expected (Fig. 6). It is likely that hydrothermal fluid circulation within the conduit zone accelerated cooling and alteration of even this newest conduit. Unfortunately, samples of the boundary of the conduit of the last eruption were not recovered because of difficulty in timing the spot-core sampling. Identification of lava in this dike as being from the 1991–1995 eruption was based on its chemical consistency with that of dome lava formed by that eruption. Major and trace element compositions and the strontium isotopic ratio of the lavas from the 1975–1995 m depth interval are essentially identical to those of the dome lava (Fig. 7).

Petrology and Discussion

The lava thought to be from the conduit of the last eruption is porphyritic dacite (66–67wt% SiO_2) with phenocrysts of plagioclase, biotite, and hornblende, the latter of which is replaced by chlorite, carbonate, and rutile due to hydrothermal alteration (Fig. 8). The groundmass was originally glassy but now consists of feldspars and silica minerals reflecting complete devitrification, even in dark-colored (relatively quenched) samples near the dike margin. Small euhedral crystals of pyrite are also contained in the groundmass due to hydrothermal alteration. Few bubbles occur in the conduit lava because of either destruction during devitrification or complete escape or resorption of bubbles before solidification.

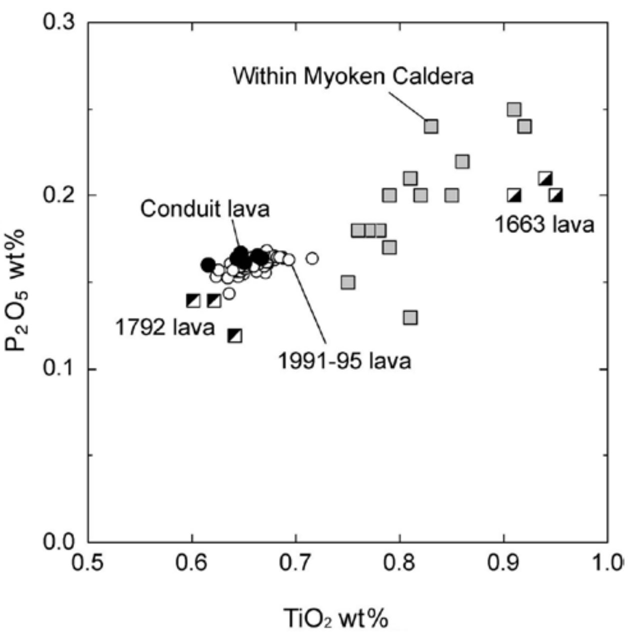

Figure 7. Chemical comparison of the conduit lava with lavas exposed at the summit area, including the 1991–1995 lava. All lavas inside the Myoken Caldera (see Fig. 1) are shown. Conduit lava samples are samples from cores 13 to 16 (Fig. 4).

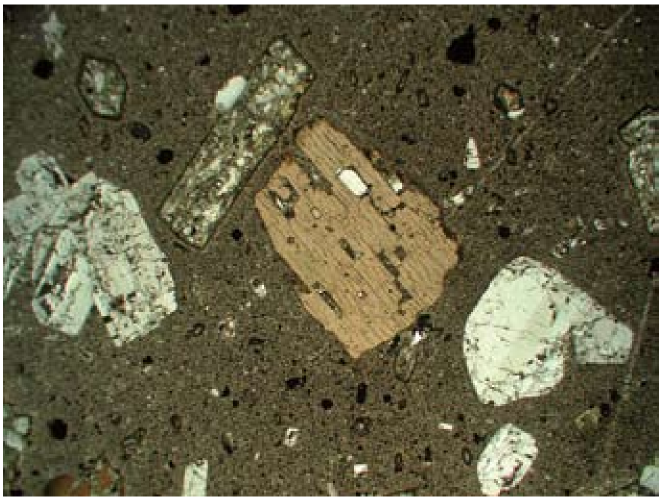

Figure 8. Microphotograph of the conduit lava, showing hydrothermal alteration. The groundmass is cryptocrystalline (devitrified), and hornblende (upper left) is replaced with assemblage of chlorite, carbonate, and rutile, contrasting to fresh biotite crystal (center). The field of view is about 2 mm wide.

Direct measurement of water content in the dikes and pyroclastic veins is not meaningful because of the absence of glass. The melt would have retained about 3 wt% water at the pressure (about 40 MPa) corresponding to the drilled depth (about 1.3 km). As the initial water content of melt within the magma reservoir was about 6 wt% (Sato et al., 1999), half of the initial water should have been lost by the time the magma reached this drilled depth. Permeable degassing from fast-ascending magma into the wallrock is unlikely for the reasons described above; therefore, degassing may have occurred first through cracks that propagated vertically ahead of the ascending magma (conduit) and contributed to the precursory phreatomagmatic summit activity and then continued along brecciated (sheared) margins of the conduit after the magma column was connected to the surface.

Microlites in the groundmass, which form in melt due to decompression-induced dewatering, are sparse in volume (low crystallinity) compared to the groundmass of the dome lavas. Microlite number density, however, is almost the same between the dome lava and the conduit samples (S. Noguchi et al., in prep.). Such a condition is possible if nucleation rather than crystal growth is dominant at the drilled depth. Growth of microlites, as observed in the dome lava, occurred as magma continued to ascend above the drilled depth.

It is important that the conduits of different eruption events are not bundled into the other ones but isolated from one another. This means that magma of each eruption event prefers an intrusion path independent of older conduits. This is consistent with our observation that cooling of a conduit is very rapid following an eruption. Normal repose periods are more than an order of magnitude longer than cooling times, so there is no thermal influence of one eruptive episode on the next. In contrast to the limited number of lava dikes, pyroclastic veins are abundant in the conduit zone. It is likely that isolated tremor events reflect formation of cracks in the country rocks, along which volatiles and volcanic ash intruded, before magma ascended along only one vein.

Investigations of core samples and drilling mud recovered from the USDP-4 well, as well as the logging records, are continuing. The research team of the project is comprised of scientists from Japan, the United States, Germany, and France.

Conclusions

1) Physical measurements and analysis of spot cores indicate that the conduit of the last eruption and its host rocks were successfully penetrated by USDP-4 at Unzen Volcano.
2) The conduit zone of the volcano is about 500 m wide in a north-south direction and consists of multiple parallel dikes and veins of different ages intruded within a vent breccia. The conduit zone dikes are up to 40 m thick.
3) The feeder dike of the most recent eruption has cooled from 850°C to less than 200°C in nine years by effective hydrothermal circulation. The dike lava is devitrified and hydrothermally altered.
4) Degassing of ascending magma at the drilled depth probably occurred along cracks propagated by magma gas pressure ahead of the dike and later along brecciated margins of the established conduit. It is likely that formation of cracks and the accompanying gas migrations are responsible for volcanic tremor events.
5) Microlites of the conduit lava are smaller in size but similar in number density than those in the dome lava, suggesting that magma ascended slower as it reached shallower depth and/or that most microlite growth occurs during the second half of dewatering.

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