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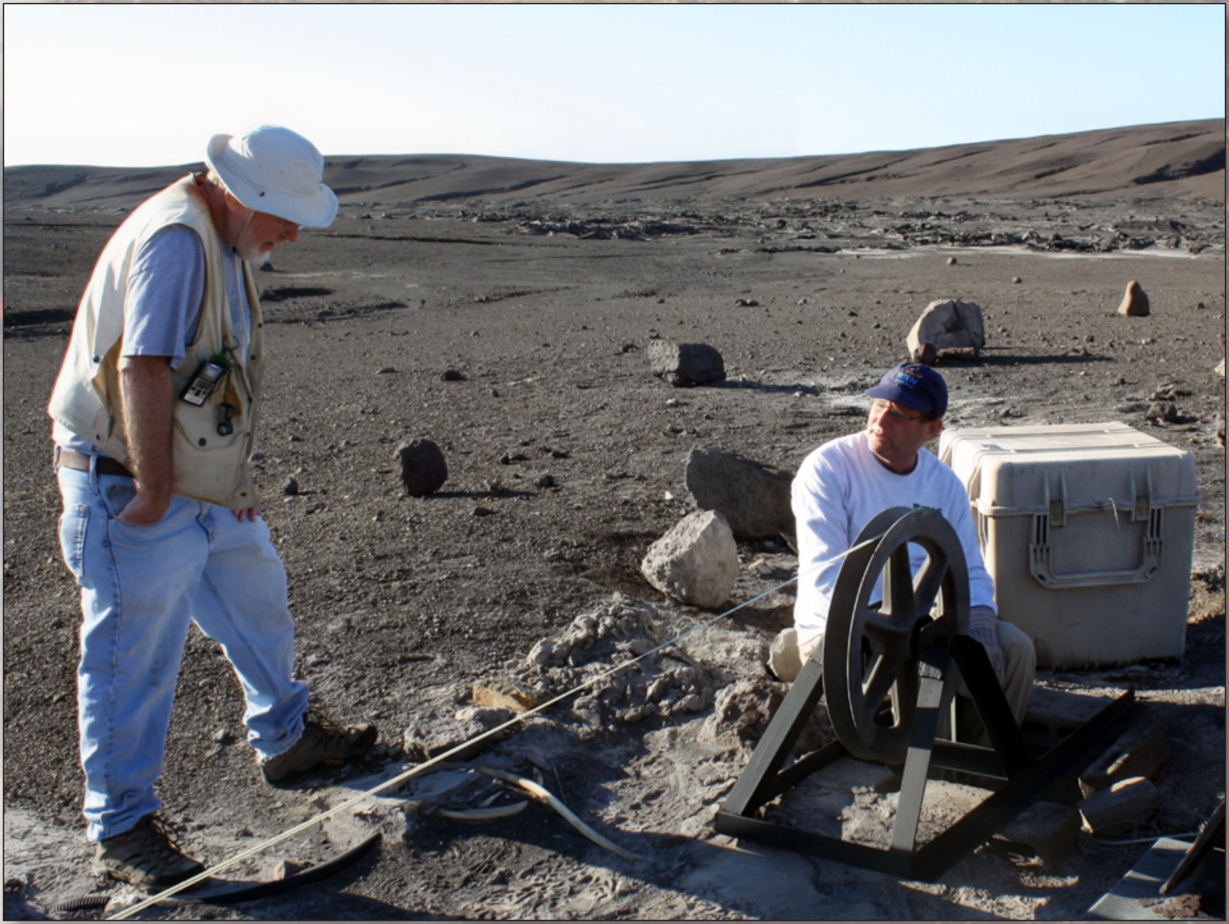
Special Topic—Boreholes

Chapter K of
Recommended Capabilities and Instrumentation for Volcano Monitoring in the United States



Scientific Investigations Report 2024–5062

U.S. Department of the Interior
U.S. Geological Survey

Cover. U.S. Geological Survey scientists D. Swanson and S. Hurwitz measure the depth to the water table at the 1,262 meter-deep National Science Foundation borehole (commonly referred to as the “Keller Well”) within the summit caldera of Kīlauea, Hawaiʻi. Campaign measurements of water-table depth following the 2018 summit caldera collapse and Lower East Rift Zone eruption enabled scientists to better understand the mechanisms for explosive summit eruptions and summit recharge. Photograph by S. Peek, U.S. Geological Survey, December 18, 2018. Background image shows a typical view of the 2008–2018 lava lake in the Overlook crater within Halemaʻumaʻu, Kīlauea. Photograph taken from a helicopter by Tim Orr, U.S. Geological Survey, on August 16, 2013.

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By Shaul Hurwitz and Jacob B. Lowenstern

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Edited by Ashton F. Flinders, Jacob B. Lowenstern, Michelle L. Coombs, and Michael P. Poland

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Abbreviations

CALIPSO	Caribbean Andesite Lava Island-volcano Precision Seismo-geodetic Observatory
LVEW	Long Valley Exploratory Well
PBO	Plate Boundary Observatory
USD	U.S. dollar

Chapter K

Special Topic—Boreholes

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Introduction

Installation of instrument packages in deep (several hundred to several thousand meters) boreholes near volcanoes is relatively expensive (a few million to tens of millions of U.S. dollars), but can provide a low-noise, high-quality source of geophysical (seismic, strain, tilt, and pore pressure), physical (temperature and water level), and geochemical data. Observations from instruments at depth have the potential to provide insights into processes associated with magma intrusion, unrest, and eruption that would not otherwise be possible (Lowenstern and others, 2017; Eichelberger, 2020). Examples of instrumented boreholes in volcanic areas include the 3-kilometer (km)-deep Long Valley Exploratory Well (LVEW) in California (for example, Priest and others, 1998; Prejean and Ellsworth, 2001; Fischer and others, 2003; Roeloffs and others, 2003; Sorey and others, 2003), the 1,262 meter-deep NSF Well (commonly referred to as the “Keller Well”) within the summit caldera of Kīlauea, Hawai‘i (Keller and others, 1979; Myren and others, 2006), and the Caribbean Andesite Lava Island-volcano Precision Seismo-geodetic Observatory (CALIPSO) project at Soufrière Hills, Montserrat, which includes a series of four 200-meter (m)-deep holes (for example, Mattioli and others, 2004; Voight and others, 2006). The Plate Boundary Observatory (PBO) of the National Science Foundation’s Earthscope project placed seismometers, tiltmeters, strainmeters, and pore-pressure sensors at depths of 100 to 250 m in more than 100 boreholes scattered in western North America, including at Mount St. Helens, Washington, and Yellowstone Caldera, Wyoming. The total cost for an instrumented PBO borehole ranged from $250,000 to $270,000 U.S. dollars (USD) and a few thousand USD are required annually for maintenance (David Mencin, UNAVCO, written commun., October 2020).

Capabilities Provided

High-Quality Seismic and Geodetic Recordings

When deployed within boreholes, seismometers, strainmeters, and tiltmeters are insulated from the noise created at the surface by wind, rain, rivers, animals, machinery, and general temperature and pressure variations. These factors commonly degrade the quality of data obtained from surface-based instruments. For example, seismometers at high-altitude and (or) high-latitude sites on the flanks of volcanoes are particularly susceptible to noise associated with strong storm systems. Borehole seismometers have demonstrably higher signal-to-noise ratios of seismic and strain recordings than surface-based instruments (for example, Prejean and Ellsworth, 2001). Thus, from a practical perspective, the consistently high signal-to-noise ratio of borehole seismometers provides a reliable record of seismicity regardless of surface noise levels. Likewise, strainmeters offer the most sensitive means of monitoring deformation associated with magmatic activity. In Iceland, strainmeter records provided the only detected transient deformation immediately prior (by tens of minutes) to the 1991 and 2000 eruptions of Hekla (Linde and others, 1993). Luttrell and others (2013) used strain signals from seiche waves in Yellowstone Lake as input for modeling the depth and extent of partially molten magma in the upper crust beneath Yellowstone Caldera.

An indirect source of noise on seismic records is the uppermost several tens to hundreds of meters of the crust, which generally is highly fractured and, thus, highly attenuative and subject to fluctuations in surface temperatures. Comparison of earthquakes recorded by surface seismometers near Long Valley Caldera and LVEW borehole seismometers indicates that borehole records contain more impulsive P- and S-wave arrivals and much higher frequency content (Prejean and Ellsworth, 2001). The records from the borehole seismometer were also less affected by scattering and attenuation. Because a primary goal of volcano seismology is to determine the nature of a seismic source, it is ideal to avoid scattering and attenuation as much as possible (Prevedel and others, 2015). Thus, borehole seismometers would likely increase a network’s ability to detect changes in seismic sources (see chapter B of this volume; Thelen and others, 2024), as well as to determine the processes that generate various types of seismicity. Indeed, Shelly and others (2013) and Shelly and Hardebeck (2019) relied on PBO borehole data for use in relocating hypocenters in Yellowstone earthquake swarms.

Direct and Indirect Measurements of Subsurface Geology and Hydrology

Boreholes provide a window into subsurface geologic, hydrologic, and thermal regimes that are largely hidden from instrumental measurements at the ground surface. Core samples from the LVEW borehole, for example, provided a continuous stratigraphic section to a depth of 2.3 km below Long Valley Caldera’s resurgent dome. Samples from this core led to the discovery of numerous rhyolitic dikes and sills that intruded the Bishop Tuff (McConnell and others, 1995), providing direct evidence for post-caldera intrusions in the area of the resurgent dome. Several drilling programs have unexpectedly intersected molten magma bodies, for example, in Hawaiʻi, Kenya, and Iceland, providing important insights about the geometry of the magmatic system as well as a direct test of the geophysical models that guided the drilling programs (Larsen and others, 1979; Teplow and others, 2009; Elders and others, 2011; Rooyakkers and others, 2021). Borehole instruments have also yielded important insights into the hydrothermal systems associated with volcanic areas (Pribnow and others, 2003; Hurwitz and others, 2010; Brown and others, 2013; Hurwitz and Anderson, 2019). For example, Roeloffs and others (2003) used borehole-pressure-transducer recordings from the LVEW and four other boreholes in Long Valley Caldera to investigate earthquake-induced, groundwater-level changes that persisted for days to weeks. They inferred that such changes are caused by accelerated inflation of Long Valley Caldera's resurgent dome—inflation too small to be detected by surface-based deformation monitoring.

Boreholes on steep stratovolcanoes are rare but could provide crucial information on time-dependent water saturation and rock alteration within the edifice. These parameters are particularly important to measure because hydrothermal alteration can result in elevated pore-fluid pressures and strength reduction of rocks within a volcanic edifice, which can in turn lead to edifice flank collapse and lahar formation (Finn and others, 2001; Hurwitz and others, 2003; Reid, 2004; Ball and others, 2018). Among Cascade Range stratovolcanoes, Mount Hood, Oregon, is relatively rich in drill-hole information owing to geothermal reconnaissance in the 1970s and early 1980s. However, even at Mount Hood, all the drill holes are at least 5 km laterally away from the summit, and the highest wellhead is nearly 2 km vertically below the summit. The Pucci drill hole, completed in 1980, reached a depth of 1,130 m from an elevation of 1,628 m (1,800 m below the summit) and revealed that the standing water level was 573 m below the land surface and the bottom-hole temperature was 76 degrees Celsius (°C) (Robison and others, 1981). These data suggest that the water table beneath the volcano is relatively deep or that the vertical fluid-potential gradient is near unity—information that could not be recovered from any other type of measurement.

An example of the utility of water-level measurements, water chemistry and water isotopic composition is provided by samples from and measurements within the NSF Well ("Keller Well") at Kīlauea (fig. K1). A 6-centimeter, water-level (pressure) decrease in May 2001 was coincident with a rapid and large increase in compressional strain, recorded by the strainmeter that was installed in the well, and indicated that surface deformation at Kīlauea is not triggered by pressurization of the hydrothermal system (Hurwitz and Johnston, 2003). Analysis of water samples collected between 2003 and 2011 showed that the chemical and stable isotope compositions of groundwater were modified by magmatic gas condensation. Temporal variations of dissolved sulfate and chloride in the water coincided with changes in volcanic activity and indicate that magmatic gases were being absorbed (scrubbed) by groundwater, thus leading to underestimates of gas released from magma and magma volumes (Hurwitz and Anderson, 2019). The water level in the well measured a few months before the 2018 Kīlauea eruption (Hurwitz and others, 2019) guided interpretations of possible explosive magma-water interactions and hazards assessment during the 2018 eruption, when magma was draining from the summit lava lake (Hsieh and Ingebritsen, 2019; Cahalan and others, 2023).

Temperature sensors installed in boreholes enable continuous thermal profiling of the crust, for example, in Well CH-10B in Long Valley Caldera (Clor and others, 2018).

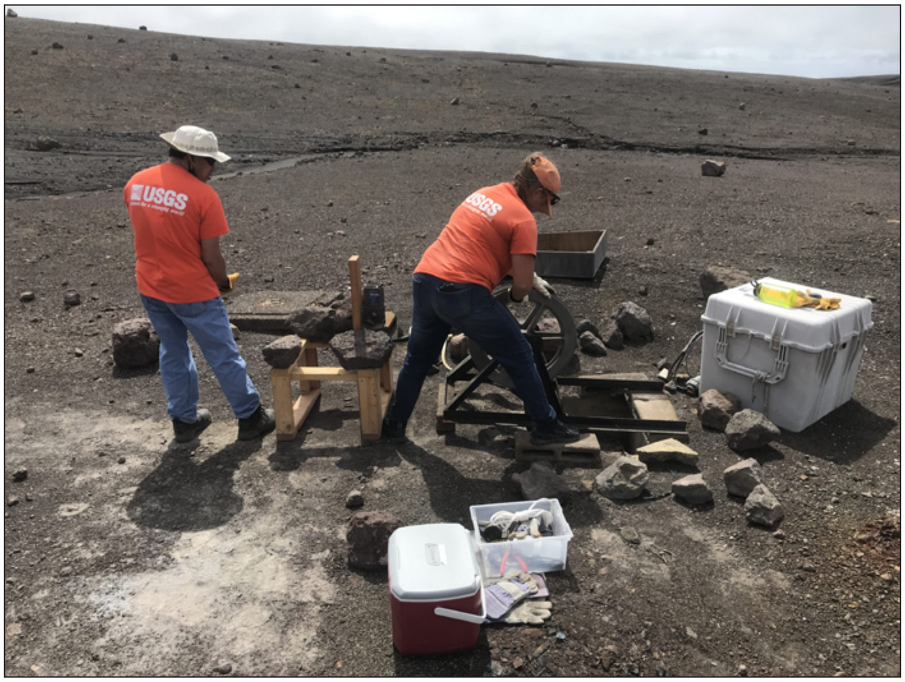

Figure K1. Photograph showing U.S. Geological Survey Hawaiian Volcano Observatory staff measuring water-table depth and collecting water samples for analysis from the 1,262-meter-deep NSF Well in the summit caldera of Kīlauea, Hawaiʻi. Photograph by F. Younger, U.S. Geological Survey, March 22, 2022.

Temperature-depth data from shallow boreholes document conditions in hydrothermal systems, where phreatic eruptions might originate. Temperature data in deeper boreholes place constraints both on the position of the brittle-ductile transition (an important control on earthquake occurrence) and on the potential location of magma. For example, temperatures at a depth of 3 km in the LVEW borehole were unexpectedly low (about 100 °C) (Hurwitz and others, 2010), calling into question the previous assumption that a magma reservoir hotter than 800 °C resided at 4- to 5-km depths (Rundle and others, 1986).

General Recommendations and Considerations

Despite clear advantages for producing noise-free geophysical data close to magma and direct samples of geologic and hydrologic conditions at depth, boreholes are rarely a part of routine volcano monitoring, primarily because they are expensive to drill and maintain (for example, Mattioli and others, 2004). However, in some situations—for example, at a particularly active and hazardous volcano located in an area where the logistics of installation and maintenance are feasible—boreholes could be considered. These boreholes should (1) be at least 200 to 300 m deep, (2) include core recovery to better characterize the volcano's subsurface structure and eruptive history, and (3) be equipped with appropriate instrumentation. Instrumentation could include some combination of seismometers, tiltmeters, strainmeters, pore-pressure sensors, temperature sensors, and geochemical sensors. The data acquired from geologic and hydrologic sampling and geophysical instrument packages should be made available to the research community to maximize their utility. Drilling deeper boreholes (for example, more than 1 km) in active volcanoes and installing instrumentation is substantially more expensive and therefore may require partnerships with other academic and government agencies, which, in the United States, might include the Department of Energy or National Science Foundation.

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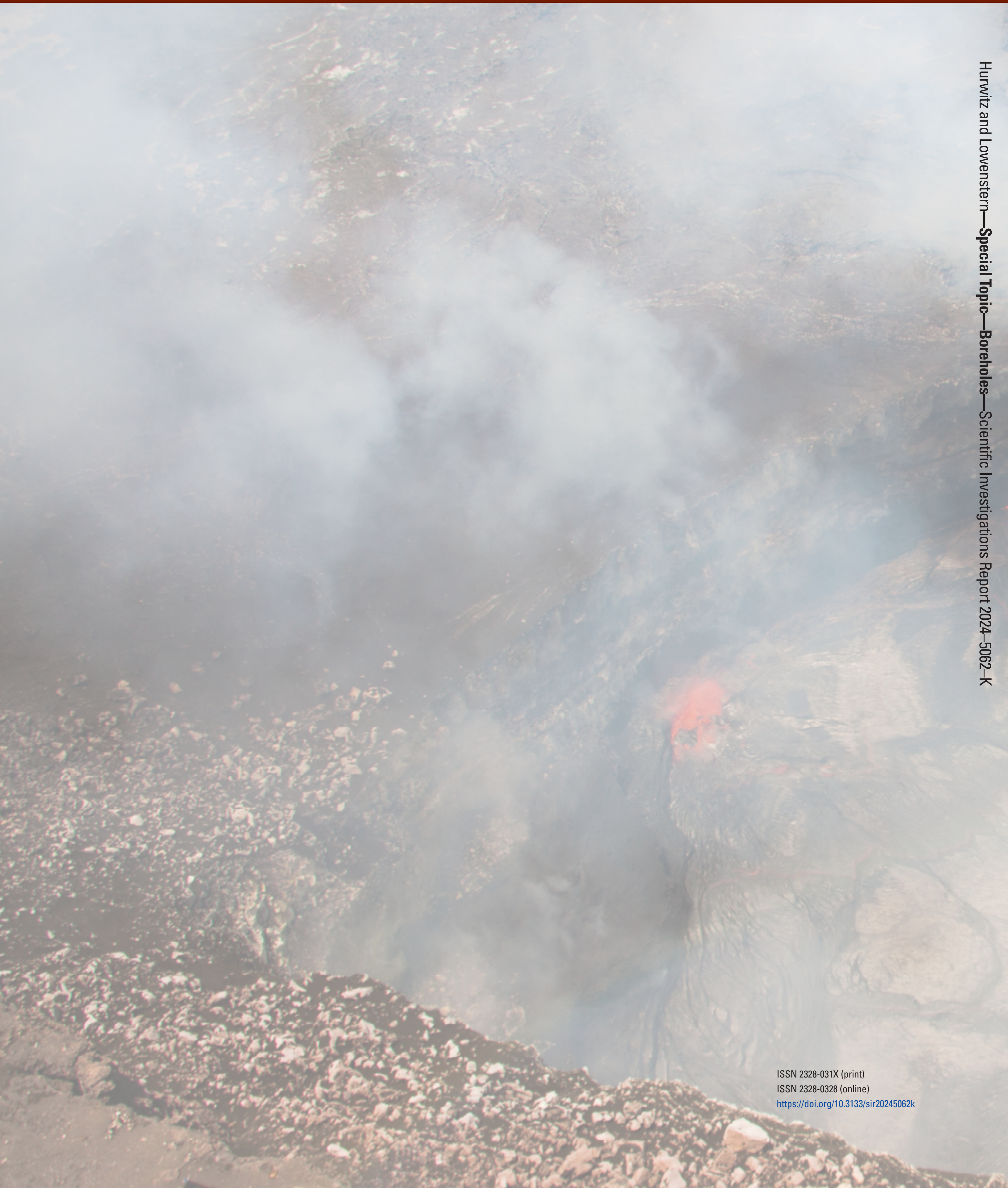

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