UNDERSTANDING KAMCHATKA'S EXTRAORDINARY VOLCANO CLUSTER

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Klyuchevskoy volcano, soaring 4750 meters above the Kamchatka Peninsula near the western shore of the Bering Sea, is one of the most active in the world. Many international flights connecting North America and Asia fly over the peninsula, where a group of active volcanoes, including Klyuchevskoy, occasionally fill the air with ash and dust. What drives the unusually high volcanic activity here? Do these volcanoes all feed from the same large pool of magma?

The Klyuchevskoy volcanic group (KVG), a part of the Kuril–Kamchatka volcanic belt, is located in a subduction

The Klyuchevskoy volcano in eastern Russia during a 2016 eruption. The photograph was taken in July; the eruption began in April and lasted about 6 months. To the right is the Kamen volcano. Both volcanoes are part of an especially active group on Russia's Kamchatka Peninsula, near the Bering Sea. Credit: Segrey Chirkov

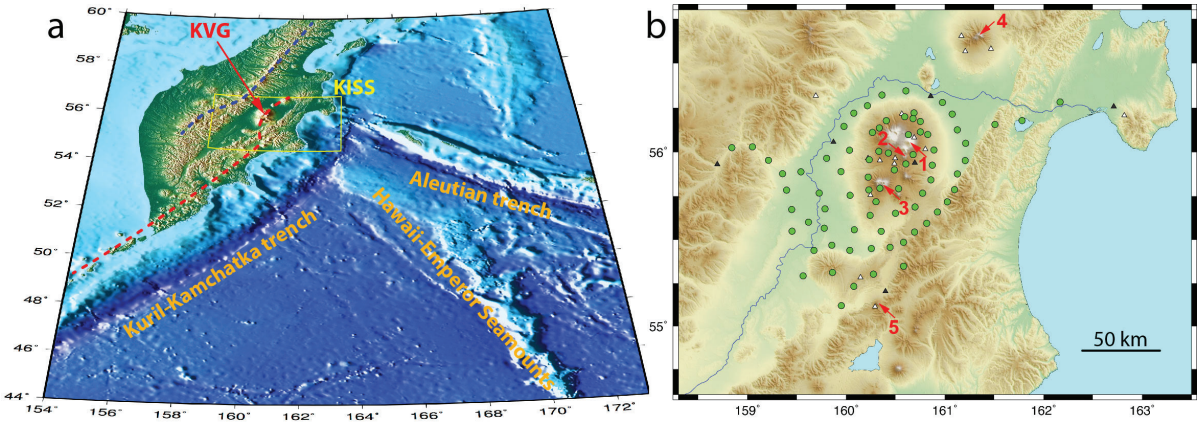


Fig. 1. KISS project setup. (a) Three-dimensional view of the Kamchatka–Aleutian tectonic plate junction. The red arrow indicates the location of the Klyuchevskoy volcanic group (KVG). The approximate positions of the active and extinct volcanic chains are indicated with red and blue dashed lines, respectively. (b) Region surrounding the KVG where the KISS seismic stations (green circles) collected data from July 2015 to July 2016. Broadband and short-period stations of the permanent seismic monitoring network are shown with black and white triangles, respectively. Red arrows show the locations of volcanoes that erupted during the past decade: 1, Klyuchevskoy; 2, Bezymianny; 3, Tolbachik; 4, Shiveluch; and 5, Kizimen.

zone where the Pacific oceanic plate plunges beneath the tectonic plate that carries the peninsula (Figure 1a). The strength and variety of volcanic activity in the region make it a natural laboratory to study where magma sits and how it moves in a subduction zone.

Previous surveys have been limited to the area around Klyuchevskoy. That changed in 2015–2016, when an international collaboration conducted the first geophysical survey of the entire KVG. The effort was named the Klyuchevskoy Investigation–Seismic Structure of an Extraordinary Volcanic System (KISS) experiment.

Data from KISS's instrument network offer an unprecedented look at one of Earth's most active volcanic regions and could reveal whether the underlying magma reservoirs are connected by one large volcanic supercomplex. The instruments also provided a real-time record of an unfolding eruption: They recorded the full sequence of events that preceded the most recent eruption of Klyuchevskoy, in April 2016.

KISS experiment fieldwork often took place in remote locations. Here, a Kamaz truck and Robinson helicopter transport equipment and field crews. Klyuchevskoy (erupting) and Kamen volcanoes are seen in the background. Credit: Sergey Chirkov

The Klyuchevskoy Volcanic Group

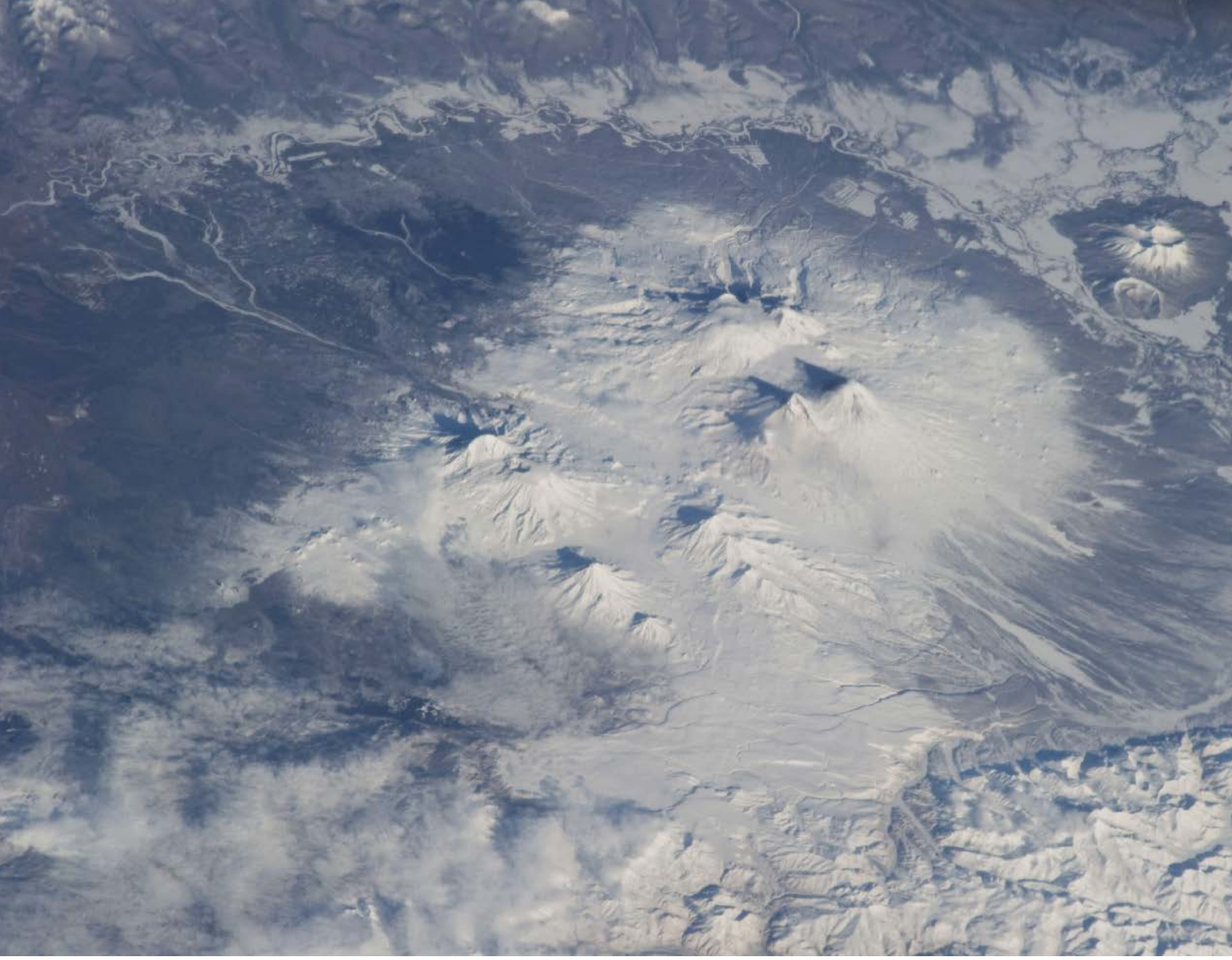
Over the past 10,000 years, Klyuchevskoy volcano has produced an average of 1 cubic meter of erupted rock every second [*Fedotov et al.*, 1987]. This eruption rate is much higher than that of most volcanoes associated with subduction and is comparable to the growth of the Hawaiian volcanic chain, often considered one of the most vigorous volcanic systems of modern Earth.

Besides Klyuchevskoy, the KVG contains 12 other large volcanoes. Two of them, Bezymianny and Tolbachik, have been very active in the past few decades. Two other active volcanoes, Shiveluch and Kizimen, are located only 60 kilometers north and south, respectively, of KVG (Figure 1b).

A whole spectrum of eruptive styles is present in the KVG, ranging from steady Hawaiian-type eruptions, as seen during the two most recent eruptions of Tolbachik, to the strongly explosive eruptions of Bezymianny in 1956, which were among the world's largest in the 20th century. (The word bezymianny means "unnamed" in Russian. Until the 1956 eruption, the volcano was considered to be extinct, so no one bothered to give it a name.)

The region's exceptional volcanic activity is related to the unique tectonic setting of the KVG, located at the sharp corner between the Kuril-Kamchatka and Aleutian trenches. This corner is where the Hawaiian–Emperor seamount chain, the underwater mountain range that stretches down to Hawaii, is subducted, and the KVG is perched above the edge of the subducted slab (Figure 1a).

Geodynamic models that attempt to explain the voluminous volcanism in the KVG are complex and include many factors. These include the release of fluids from the thick, highly hydrated Hawaiian–Emperor crust [*Dorendorf et al.*, 2000], the mantle flow around the corner of the Pacific plate [*Yogodzinski et al.*, 2001], and the recent detachment of a portion of the slab due to an eastward jump of the subduction zone beneath Kamchatka [*Levin et al.*, 2002]. The large variability of lavas and eruption styles reflects the complexity of the feeding system of magma sources and reservoirs in the upper mantle and the crust.



The Klyuchevskoy volcanic group in northeastern Russia, as seen from the International Space Station, viewed from the southeast. Credit: Earth Science and Remote Sensing Unit, NASA Johnson Space Center

A Unique Natural Laboratory

Because of its strong and variable activity, the KVG is a unique natural laboratory for studying volcanism in a subduction zone. Understanding how this zone functions requires detailed knowledge about the configuration of the subducted oceanic plates and about the distribution of magma conduits and reservoirs within the mantle wedge and the crust. A particularly important question is whether the individual KVG volcanoes are fed from independent magma sources or whether they form a single interconnected magmatic supersystem.

Gathering information about the deep KVG structure requires the use of geophysical methods. Past seismological studies [*Koulakov et al.*, 2011] have revealed possible pathways of melts ascending from the subducting slab and a multilevel system of magma reservoirs in the crust. However, the structures that these studies illuminated are restricted mainly to a few tens of kilometers surrounding Klyuchevskoy volcano, where most existing permanent seismic stations are located (Figure 1b). A full understanding of the behavior of the KVG magmatic system requires an investigation of subsurface structures at a much larger scale.

The KISS Project

To undertake such a large-scale seismological investigation of the KVG, we formed a consortium of institutions from Russia, France, and Germany and designed the KISS experiment. We operated a temporary network of 83 seismographs between August 2015 and July 2016.

The experiment took place in difficult terrain; helicopters and off-road trucks were needed to transport the equipment and field crews to the installation sites. An eruption-triggered mudflow destroyed one site, and a few others were wrecked by bears. Despite the harsh environment, the team recovered data from 77 instruments (Figure 1b).

Initial inspection of seismograms indicates that the network successfully recorded many tectonic and volcanic earthquakes and volcanic tremors. The collected data set, combined with records from permanent seismic stations, will be used to study various types of earthquakes associ-

The Klyuchevskoy volcano puffs gas during its 2016 eruption. Kamen and Bezymianny volcanoes are to the left. In 2015 and 2016, an international collaboration conducted a large-scale geophysical survey of the active group of volcanoes that includes Klyuchevskoy. Credit: Benoit Taisne

ated with the volcanic and magmatic activity and to image the crust and upper mantle with multiscale seismic tomography.

These results will help us understand why exceptionally large amounts of melts are generated in the upper mantle at the Kamchatka–Aleutian subduction corner and how these magmas are transformed during the ascent through the crust, producing the vigorous and very variable volcanism we see at the surface.

Monitoring the KVG for Hazardous Eruptions

Volcanic eruptions regularly affect a few small settlements located near the KVG, and they pose a significant threat to aviation because many international flights that connect North America and Asia pass over Kamchatka. Large explosive eruptions such as those of Bezymianny in 1956 and Shiveluch in 1964, when about 1 cubic kilometer of erupted material was ejected, might be particularly dangerous.

Moreover, Kamchatka has a well-established record of even larger caldera-forming eruptions in the Holocene [*Braitseva et al.*, 1995], with the largest of them forcibly ejecting about 150 cubic kilometers of rock fragments (tephra).

Considering that at present more than half of Kamchatka volcanic magmas are generated below the KVG, we cannot ignore the possibility of a future extreme explosive event in this region. We expect the results of the KISS experiment to help us evaluate such extreme event scenarios by improving our knowledge of the size of the KVG crustal magmatic reservoirs, along with the volume of potentially explosive magmas they might contain.

When the Klyuchevskoy volcano rumbled back to life and erupted in April 2016 (see http://bit.ly/Klyuchevskoy-eruption), the KISS network recorded the full sequence of reactivation leading up to the eruption. We will use this data set to improve our knowledge of how the rise of magma and the preeruptive buildup of pressure are expressed in the continuous seismic signals. The data will also help refine the routine monitoring of the KVG and other nearby volcanoes performed by the Kamchatka Branch of Russia's Geophysical Survey and by the Kamchatka Volcanic Eruption Response Team, which is operated by the Institute of Volcanology and Seismology.

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