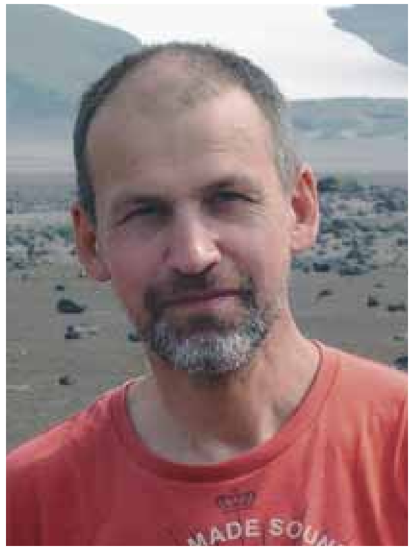
# Seismic «PULSE» OF A VOLCANO

## An Expedition to Gorelyi

I. KOULAKOV

*Volcanos have always been the focus of interest and sometimes even worship. The spellbinding beauty and might of volcanic eruptions inspired legends and myths, which were nothing else but attempts to interpret these astonishing natural phenomena. Even at present, the interest in volcanos is no weaker: the humanity is still vulnerable to the natural disasters caused by major eruptions. Scientists strive to understand the volcanic machinery. Such studies not only provide insight into the geodynamic processes taking place in the Earth's bowels but also improve the predictions of volcanic events*



Ivan KOULAKOV, Doctor of Geology and Mineralogy; Head of the Laboratory of Seismic Tomography, Trofimuk Institute of Petroleum Geology and Geophysics, Novosibirsk, Russia.
Author and co-author of over 70 scientific publications

White clouds above the Gorelyi Volcano (1829 m) are its hallmark. They are formed by the gases and water vapor ejected from vast depths

*Key words:* volcanoes, seismic stations, tomography, earthquakes

One of the ways to look inside a volcano and get a peep of its structure is seismic tomography. It is a young geophysical method, which is now extensively used for the investigation of various geologic bodies. Seismic waves produced by eruptions propagate in the Earth's interior and illuminate it like X-rays. The task of seismic tomography is to decipher this information and construct a 3D model of elastic parameters, e.g., seismic velocities. Such a model, in turn, provides insight into the geologic processes occurring deep in the Earth.

A good-quality tomographic pattern requires the accumulation of a great deal of precise information. For this purpose, it is necessary to establish seismic networks and maintain them for long. This demands a lot of money, because a modern seismic station costs as much as a new low-cost car, and a meaningful experiment involves dozens of such stations. Another problem is to deliver heavy equipment to hard-to-access areas and install it on a volcano.

It is no surprise therefore that, in spite of the great interest in seismic tomography methods, there are few examples of satisfactorily established networks suitable for obtaining good quality seismic images of a volcano interior.

In 2013, the Laboratory of Seismic Tomography (Trofimuk Institute of Petroleum Geology and Geophysics, Novosibirsk, Russia) started an expedition to the Gorelyi Volcano in Kamchatka. Its goal was to establish a sufficiently dense network of seismic stations.

## The "breathing" volcano

Gorelyi is among the most active volcanos in Kamchatka. It may be dangerous, as evidenced by a large caldera (huge round cuphole) about 30 km in diameter, surrounding the present volcanic edifice. This caldera formed during a violent eruption of the proto-Gorelyi volcano about 40 ka BP, a geologic yesterday.

The volume of rocks ejected in that eruption is estimated to be about 100 km³; thus, it may have produced a global climatic effect, as the Tambora eruption did in 1815. Such explosive eruptions are associated with andesitic magmas, which are highly viscous matter saturated with fluids.

Presently, Gorelyi produces regular quiet eruptions of basaltic lavas. Owing to their low viscosity, they spread gently over a large area and form a shield volcano with gentle slopes. As a rule, this mode does not cause disastrous eruptions. Nevertheless, nobody can be sure that the volcano will not change its behavior, as it did repeatedly in its geologic history.

In the last century, Gorelyi erupted regularly, though not too potently, at 20–30-year intervals. The latest eruption occurred in 1980. Its ash reached Petropavlovsk-Kamchatsky, the city located 70 km away from the volcano.

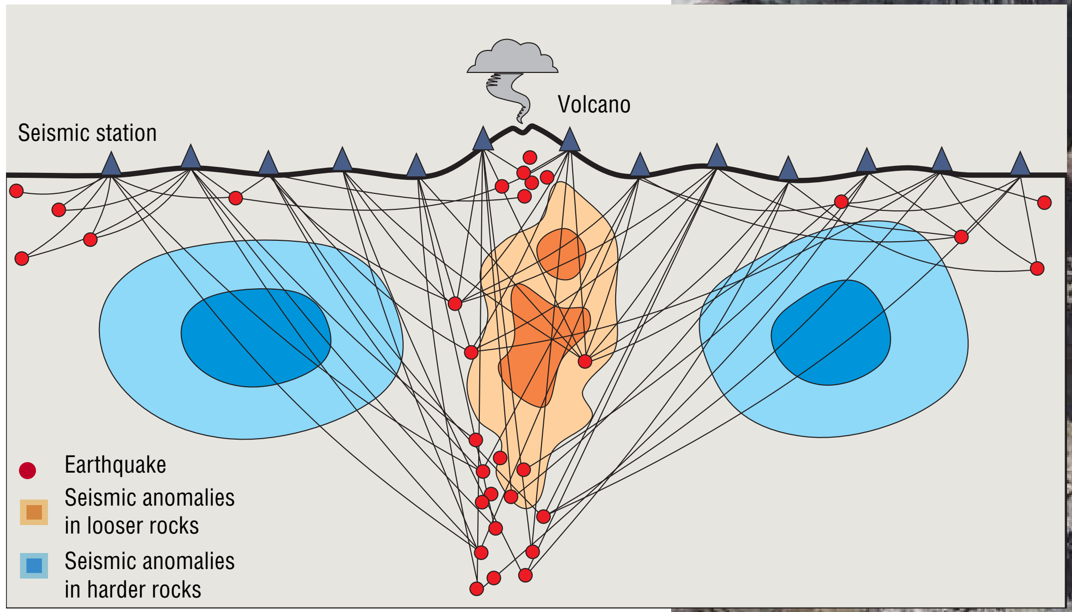
**Some of the largest volcano eruptions had global impacts on climate and human history. The disastrous eruption of the Huaynaputina volcano (South America) caused the Little Ice Age in Europe in 1601 and crop failure with famine in Russia in 1601–1603. The latter was one of the causes of the tragic Time of Trouble. The climatic consequences of the Tambora eruption in Indonesia, 1815, included crop failure, famine, epidemics and riots on all continents. Even the recent, relatively weak eruption of Eyjafjallajökull in Iceland caused an extensive air travel disruption, although the volume of its ejecta (0.01 km³) was incomparable with the known historical eruptions, such as Krakatau in 1883 (20 km³). Currents of hot gas and rocks (pyroclastic flows) constitute a tremendous threat. They move at great velocities and devastate everything. The most famous example is the Vesuvius eruption in 79, which wiped out the prosperous city of Pompeii**

Continued on Page 75

Only one permanent seismic station existed on Gorelyi before 2013. Two more operated on the Mutnovsky and Asacha Volcanos

Explorers at the edge of the active crater of Mutnovsky

In most cases, the deep structures of volcanos are examined by seismic tomography involving passive observation. A seismic signal generated by natural sources (earthquakes) is recorded by the seismic stations set on the surface. During propagation, seismic waves “accumulate” integral information on the spatial distribution of elasticity parameters between the source and the transducer. The role of tomography is to decipher this information and reconstruct the spatial distribution of seismic parameters




The Gorelyi Volcano is 75 km southwest of Petropavlovsk-Kamchatskii.
Gorelyi is a typical caldera volcano. Its present-day edifice is crowned by three fused large volcanic cones with dozens of side ruptures on their slopes. Atop the volcano there are eleven craters including the central crater, which ejects a powerful flow of gases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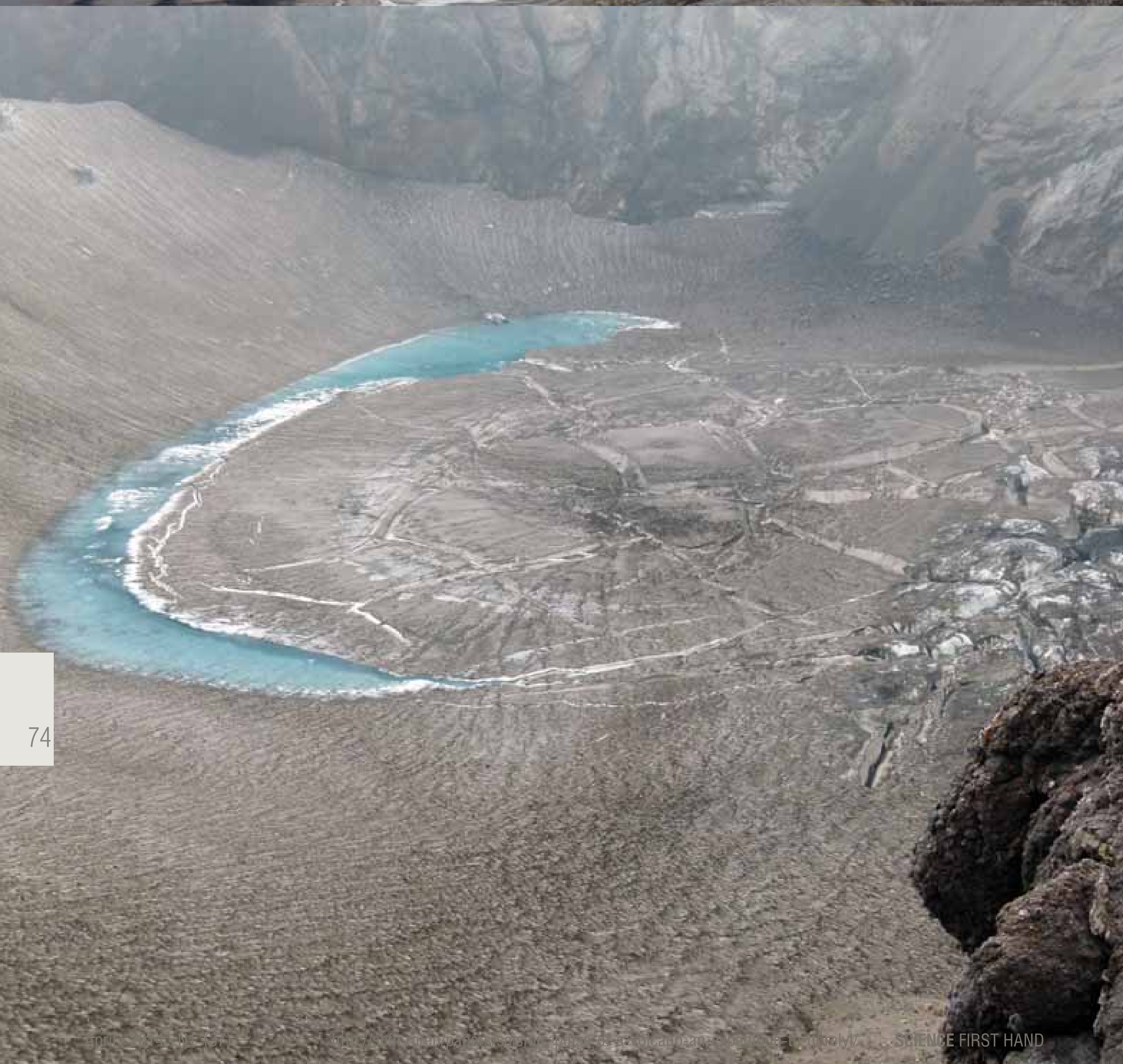
A sight from the summit of Gorelyi. *Left:* the nearly perfect cone of the Vilyuchik Volcano; *right:* Mutnovsky Volcano



This solidified lake is located in one of the craters of the Mutnovsky Volcano, which belongs to the same magma system as Gorelyi

Now Gorelyi is in its activation phase: the volcanic edifice daily experiences dozens of earthquakes and long-term seismic oscillations, or tremors, are recorded. These are generally thought to be associated with matter movement inside the magma chamber. The seismic activation phase may soon give way to the eruption phase, but no accurate prediction of the development of the processes occurring inside the volcano can yet be made.

Another feature of Gorelyi is constant gas emission through the central crater. It is a grand spectacle. Gases break forth from the glowing orifice at the crater bottom, and their hiss sounds like a rocket engine. The gases rise hundreds of meters high at astonishing velocity, condense, and form clouds seen dozens of kilometers off.

The daily amount of gases emitted from the central fumarole of Gorelyi is estimated to be 11,000 tons. This figure makes one think that probably the main product of volcanos is the constantly emitted gaseous fluids rather than effusive rocks, produced now and then. Obviously, in this regard, volcanic activity should contribute much to the atmospheric budget of the Earth. It is a different story, though.

## August in Kamchatka

In spite of the interesting structure and high activity of Gorelyi, until recently the volcano has attracted less attention from geophysicists than it deserved. Before our expedition, only one permanent station had been established there, which allowed the record of seismic activity on a real-time basis but not the determination of the earthquake coordinates inside the volcano. There were two more stations nearby Gorelyi, on the neighboring volcanos Mutnovsky and Asacha. However, this network was insufficient for the comprehensive investigation of the internal structure of Gorelyi.

The expedition started in the summer of 2013. The base camp was at the caldera bottom at the volcano foot. The site was a deserted windswept valley. The soil was highly porous there, and all water coming from glaciers immediately soaked in. So there was no water source near the camp, and drinking water was brought to us in barrels. To have a wash, we went to the bottom of snowfields, where small pools could be found. Hydrotherapeutic procedures taken in strong wind and at temperatures slightly above 0°C were highly exhilarating. Despite the uneasy living conditions, the previous broad experience of all the members of the team and proper housekeeping made the camp quite livable.

Stations were set both on the volcano slopes and outside the caldera regardless of the weather: strong winds, fog, rain, dust storms, and other delights of August in Kamchatka were ignored.

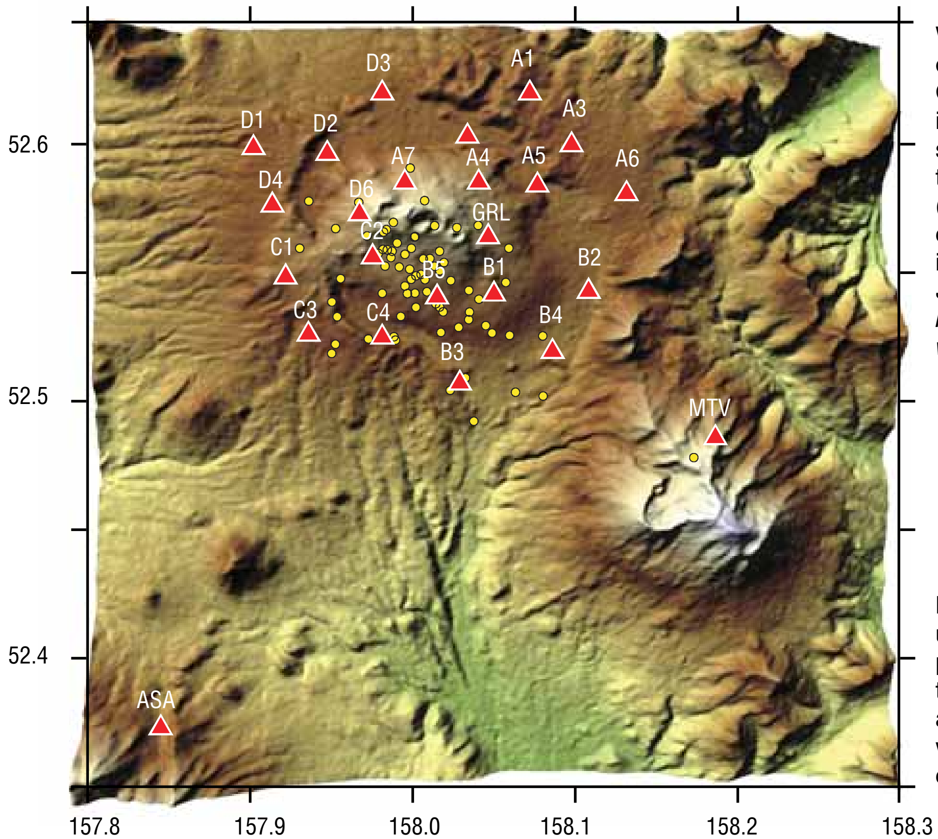

## EXPEDITION MEMBERS

The field work on the installation of seismic stations was done in August, 2013, by a team of ten people. Six of them were employees and student apprentices of the Laboratory of Seismic Tomography, Trofimuk Institute of Petroleum Geology and Geophysics, Novosibirsk, Russia. Every year they conduct field work on the seismic investigation of various Kamchatka volcanos. The team included two foreign scientists, who joined it as volunteers. One of them was Alejandro Dias, a postgraduate of the University of Granada, Spain, with which our laboratory has had a long-term cooperation. His purpose was to accumulate valuable experience of work under severe field conditions. The other was Prof. N. Shapiro, Vice Director of the Paris Institute of Earth Physics (Institut de Physique du Globe de Paris), known worldwide as the pioneer of field of inquiry in seismology. He gave us very valuable advice on the improvement of network installation. Ilyas Abkadyrov, a young researcher of the Institute of Volcanology and Seismology, Petropavlovsk-Kamchatsky, helped us out in trouble thanks to his experience in field work in Kamchatka. Finally, the skill and dedicated service of Sergey, the driver of our expedition, contributed much to the success of the work. Kamchatka drivers, who work miracles, deserve special mention. For example, in order to approach some parts of the volcano and thus to reduce walking, vast snowfields had to be crossed. Beneath the snow occur concealed ponds of melt water. If a heavily loaded GAZ-66 falls into such a pond, it is extremely difficult to release it. Sergey's phenomenal intuition allowed us to overcome all obstacles and reach by car the sites where even walking was difficult. A geophysical expedition working in the same area and at the same time failed to fulfill its task because they did not manage to cross the snow fields

The Spanish colleague Alejandro Dias and Pavel Kuznetsov treading a path to a new station on Gorelyi slope

Snow fields are full of concealed obstacles. Crossing them requires from the driver a great skill and intuition

A lodge for the team was erected in the caldera at the bottom of the present edifice of Gorelyi




Within the first few hours of operation, the seismic net set on Gorelyi in the summer of 2013, in addition to the three operating stations of the Kamchatka branch of the Geophysical Survey of the RAS (ASA, MTV, and GRL), recorded the coordinates of several seismic events indicative of volcano activation. *Station locations are indicated with red triangles, and earthquakes, with yellow dots*

In August, Kamchatka weather is unpredictable. At times, it pampers people with bright sun, and at other times, it meets them with gale, rain, and fog. Whatever the weather, walks to Gorelyi were never cancelled



The caldera bottom was passable by a vehicle, but we had to continue on foot for 3–4 km across broken country with heavy weights aback. The backpacks contained all the components of a seismic station plus a computer, digging tools, heat-insulating oakum, and other stuff required for installing stations.

A seismic station consists of three main modules. First, a sensor. To put it simply, it is a very sensitive microphone, which receives the vibrations of the Earth's surface at low frequencies, e.g., with periods up to 50 s. Second, a recorder. It digitizes signals from the sensor and records them to a memory card. Third, power supply units. Abroad they often use solar or wind generators, but they do not work in Kamchatka because of strong wind



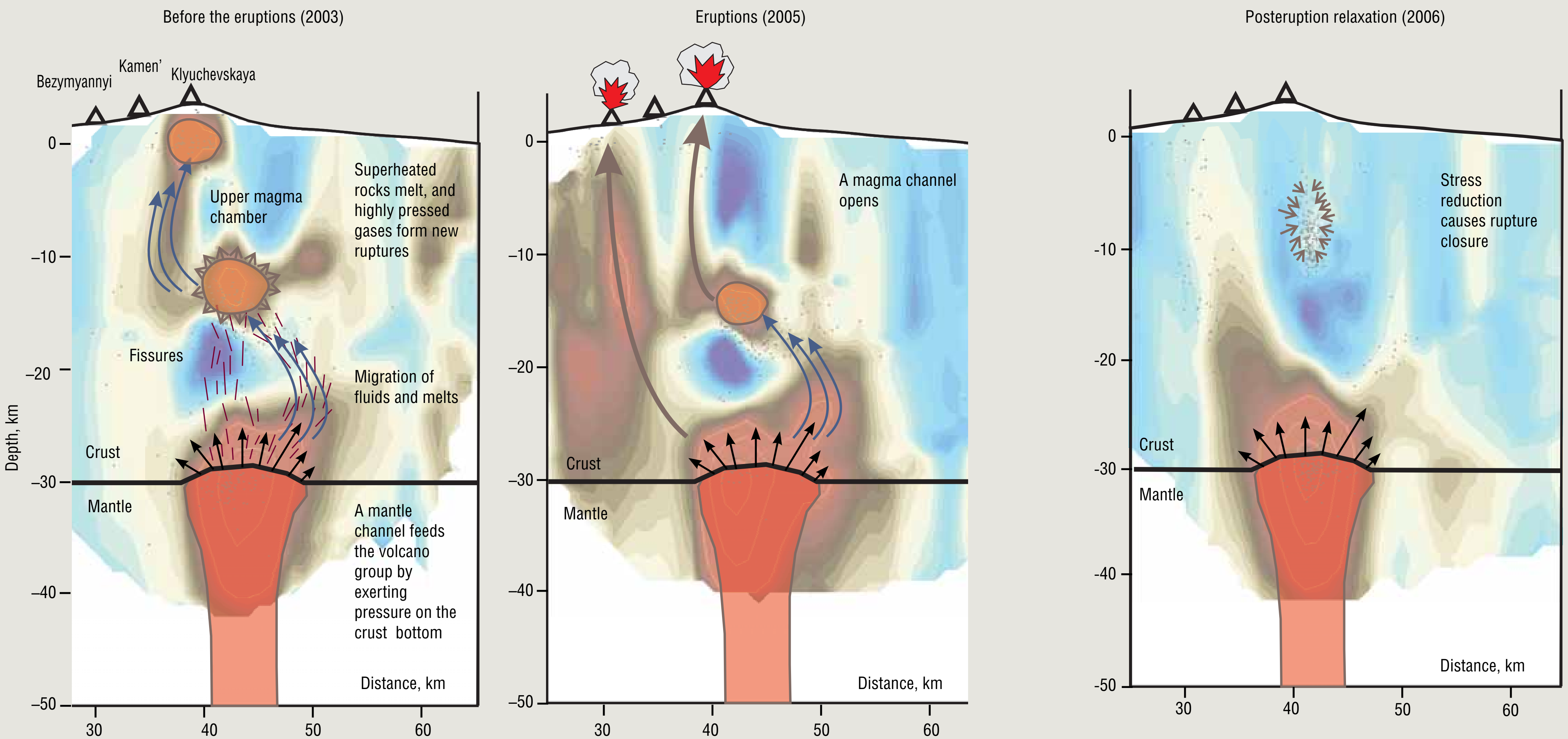
Fumaroles on the Mutnovsky Volcano emitting hot, disgustingly smelling gas



Kamchatka Peninsula is the habitat of the Anadyr red fox

and abundant snowfall. For this reason, we used special high-capacity batteries. Forty kilograms of batteries is sufficient for one year of the station operation.

The equipment was buried deep to protect it from frost, which was hard given the stony ground of the volcano. However, the devices were even more endangered by vandals, both two- and four-legged. A few permanent geophysical stations set in hardly accessible places were




In the various time projections of the tomographic images beneath the Klyuchevskaya volcano group, including Bezymyannyi, Kamen', and Klyuchevskaya Volcanos, high ratios of longitudinal and transverse wave velocities ($V_P/V_S$) are shown in brown. This ratio is a reliable indicator of fluids and melts in rocks. Dots indicate earthquake hypocenters

## VOLCANIC METAMORPHOSES

Siberian scientists were among the first to prove that the structure of volcano interiors could change substantially in the various phases of volcanic activity (Koulakov *et al*., 2013).

Long-term seismic observations allowed the construction of a 4D tomographic image of the crust beneath the volcanos of the Klyuchevskaya group in the central area of Kamchatka and tracing of its alteration at various eruption steps. It was found that the main magma provenance beneath Klyuchevskaya, located below 24 km, remained unchanged throughout the observation time. The above formations were notably modified by migrating fluids and melts.

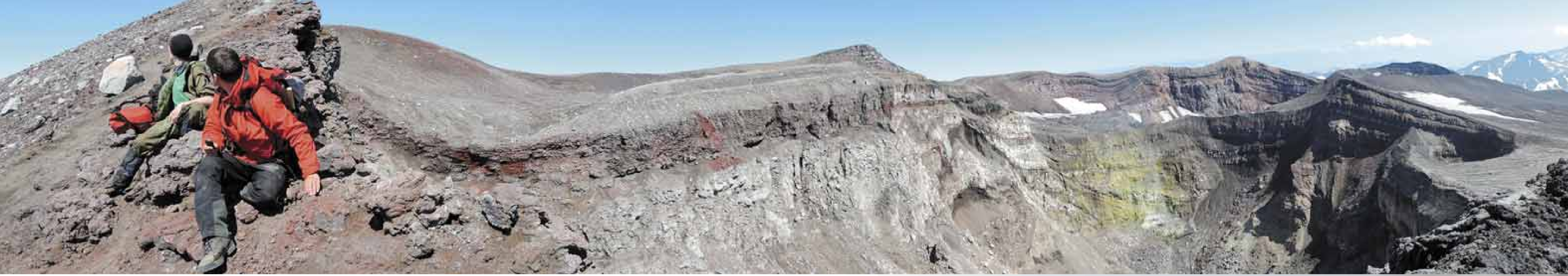
Before the major eruptions of the Klyuchevskaya and Bezymyannyi Volcanos, there were two bodies beneath them showing abnormally high ratios of the velocities of longitudinal and transverse waves ($V_P/V_S$). They were located one above the other, at the depths of 1 and 12 km, respectively. These anomalies reflect the presence of intermediate magma chambers. Their existence is proven by the petrological data on the diversity of compositions and modes of the eruptions of Klyuchevskaya group volcanos.

The eruption altered profoundly the crust structure beneath the volcanos. The pattern of seismic anomalies changed, and the mean $V_P/V_S$ value increased. This observation suggested that the eruption was accompanied by an enhancing migration of fluids and melts, which saturated rocks beneath the volcanos.

The mean $V_P/V_S$ value decreased within three years after the eruptions, and the anomalies in the upper part of the crust vanished. This points to the relaxation phase of the volcano, when the amount of fluids in the system is insufficient to form magma chambers.

The results show that magma chambers are dynamic systems. Probably, they consist of porous matter with superheated rocks close to the melting point. The influx of fluids from the mantle decreases their melting temperature, resulting in partial melting and magma chamber formation. However, if the fluids come to the surface during volcanic activity, the molten substance can rapidly disappear from the magma chambers

The main components of seismic stations installed on Gorelyi are a Baikal recorder and a CME 4111 detector (*bottom*), manufactured in Russia. These tools are buried for a year. The constant operation of one seismic station during a year demands several batteries weighing 40 kg in total



Young geologists at the edge of the Gorelyi crater. Regrettably, the image does not convey the deafening roar of gases belched from orifices below

completely crushed despite the concrete walls and armored doors. The malefactors utilized autogenous welders brought across roadless areas. As a rule, nothing was stolen, but costly research instruments not applicable in ordinary life were broken to pieces.

Bears, abundant in Kamchatka, are another hazard. They evince great curiosity and interest in humans. Sometimes, bears devastated stations immediately after they had been set up, and a full repair was required. It is for this reason that it is recommended to refrain from eating, easing oneself, or leaving any traces that would point to  human presence at the site. Fortunately, in August bears kept aloof from people, although we always felt that they were somewhere nearby.

It took us ten days of hard work to put into operation all the new stations, but the departure was postponed. On the last day of the installation, we received information that seismic activation of the volcano began, which appeared as hundreds of subtle but discernible earthquakes per day. The opportunity to obtain unique data rapidly was not to be missed, so we spent a  three-day holiday at the volcano bottom, while all the stations were simultaneously recording seismic processes.

During field work, Novosibirsk scientists, supported by the Institute of Volcanology and Seismology, Far East Branch of the RAS, set 21 seismic stations in addition to the older one. In terms of its location and tooling, the seismic network covering the volcano is among the world's best.

The new network has already produced information on hundreds of seismic events on the volcano, which will be used to localize the magma chamber. Based on these data, of a tentative tomographic image of the volcano is to be constructed in the nearest future.

The bulk of the data will be obtained in August 2014, and then the equipment will be withdrawn. It is believed that the records obtained during the year of the network operation will provide comprehensive information on the functioning of the magmatic system and allow estimation of the probability of its activation in the future.

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