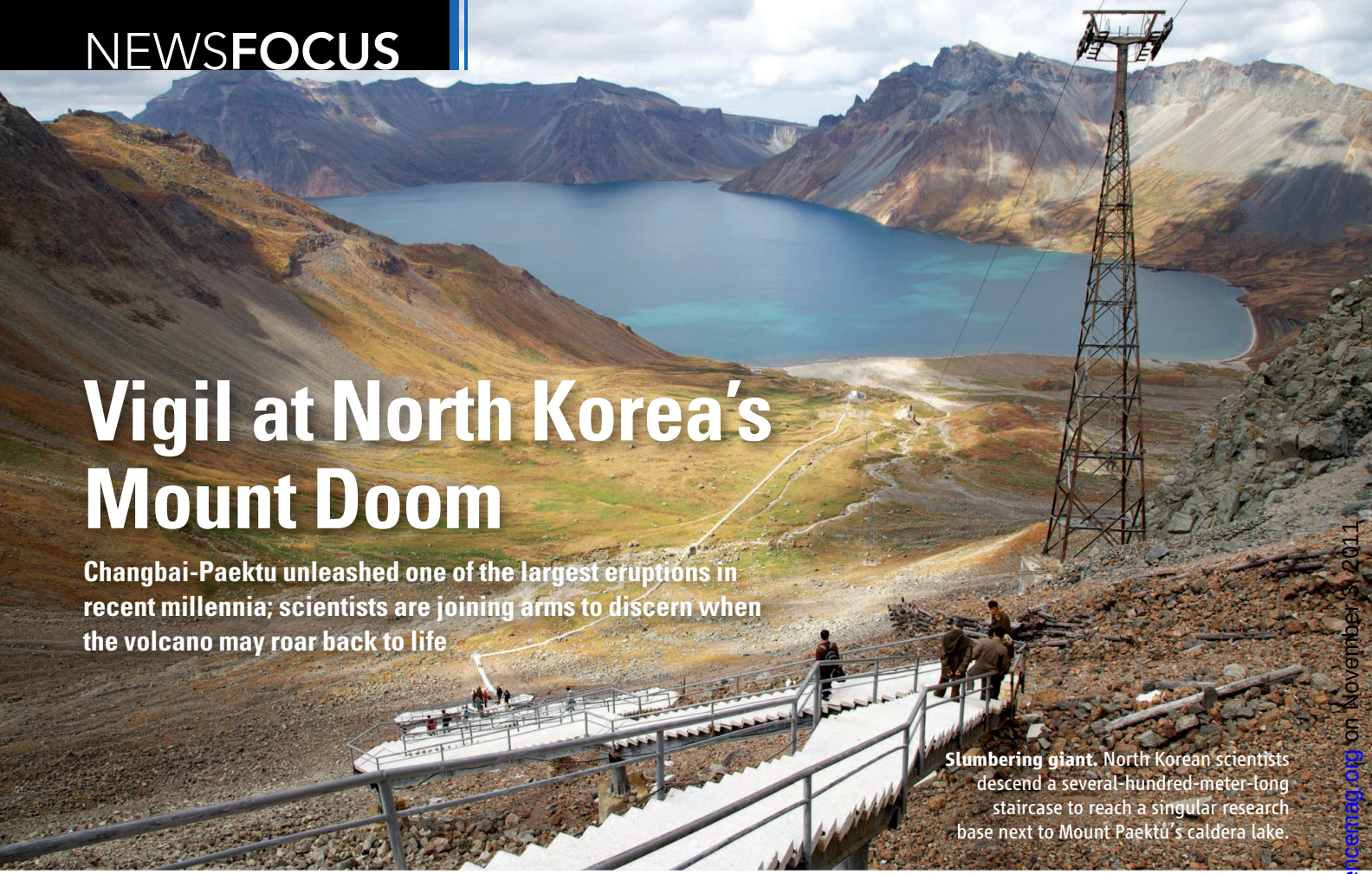
Vigil at North Korea's Mount Doom

Changbai-Paektu unleashed one of the largest eruptions in recent millennia; scientists are joining arms to discern when the volcano may roar back to life



Slumbering giant. North Korean scientists descend a several-hundred-meter-long staircase to reach a singular research base next to Mount Paektu's caldera lake.

CREDIT: CLIVE OPPENHEIMER

MOUNT PAEKTU, NORTH KOREA—James Hammond's tan fedora pokes out of the tiny log cabin, followed by the rest of the 30-year-old seismologist. He crouches at the entryway and types commands into a laptop to activate a steel cylinder on a shelf inside the shelter. "Give us a stomp," he asks a bemused colleague, who then figures out what he should do. Hammond frowns and fiddles with the wiring. "Another one!" Seconds later, he grins. "That was a magnitude 4.2," he says, beaming. Then the moment's significance sinks in. "We've just deployed the first broadband seismometer in DPRK," Hammond says, referring to North Korea by its formal name, the Democratic People's Republic of Korea.

Hammond, a researcher with Imperial College London, knew it would be a miracle if the seismometer were to record a major tremor. The instrument stayed in place on a steep slope above Paektu Bridge Volcano Research Station near DPRK's northern border for just one night in September, after which Hammond boxed it up and hauled it back to the United Kingdom. The "training exercise," Hammond says, gave the North Korean researchers hands-on experience with Western instrumentation. The fleeting deployment also has a powerful symbolic value: It demonstrates North Korea's openness to collaborate on a project of vital importance to the region.

Paektu Bridge is one of several North Korean stations monitoring Mount Paektu, a volcano that straddles the border with China. (Two-thirds of the mountain is in China, where it is called Changbai.*) Historical records and ash layers indicate that Changbai explodes to life every 100 years or so, the last time in 1903. One eruption in particular mesmerizes scientists. Around 1000 years ago, the volcano rained tephra—pumice and ash—across 33,000 square kilometers of northeast China and Korea, dumping 5 centimeters of ash as far away as Japan. The so-called millennium eruption was one of the largest of the past few thousand years, rivaling the 1815 Tambora eruption in Indonesia.

Scientists are keeping a wary vigil. "The hazard is huge," says Xu Jiandong, a volcanologist at the Institute of Geology of the China Earthquake Administration (CEA) in Beijing. Because Changbai's silica-rich magma is viscous and gassy, allowing pressure to build, the next eruption should be explosive, Xu says. In recent months, Chinese researchers have observed geophysical anomalies, including elevated temperatures of hot springs and deflation of the caldera rim. But most concur that there is no evidence of magma rising toward the surface, which would signal an imminent eruption.

When Changbai next stirs to life, an immediate concern will be the fate of Tianchi caldera's deep lake. The only outlet is a narrow valley on the volcano's north flank, in Chinese territory. A moderate-sized eruption could send a lahar—vegetation, water, rocks, and mud—hurtling down the valley, threatening 60,000 residents and expensive infrastructure such as hydropower stations. A millennium-scale eruption, says CEA volcanologist Wei Haiquan, "would be catastrophic." Some 100,000 people would be vulnerable to avalanches of superheated gas and tephra called pyroclastic flows. Ash would ruin crops throughout the region and affect transpacific flights. "The damage would be unimaginable," says Kim Hang Myong, former director of the Institute of Volcanology of the Earthquake Administration of DPRK in Pyongyang.

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Slides and podcast interview with author Richard Stone.

*Because most of the volcano is in China, this article refers to it as Changbai, except when describing work in DPRK.

Chinese scientists have ringed their side of the mountain with broadband seismometers and other monitoring instruments. Over the next 5 years, CEA plans to spend $24 million to upgrade its facilities. But the part of the mountain in North Korea has been mostly beyond the reach of foreigners and modern equipment—until now.

In September, Hammond, volcanologist Clive Oppenheimer of the University of Cambridge in the United Kingdom, and I were the first westerners to visit North Korea's volcano field stations. The unprecedented encounter was facilitated by two nongovernmental organizations: Pyongyang International Information Center on New Technology and Economy, or PIINTEC, based in Pyongyang, and the Environmental Education Media Project in Beijing. The British duo came away impressed with the North Korean scientists, who have had to make do with antiquated equipment or fashion their own. And DPRK's seven Paektu observatories will pave the way for fieldwork. "The infrastructure is fantastic. They're ready for state-of-the-art equipment," Oppenheimer says. He and Hammond plan to return to Paektu next summer for research and hope to catalyze an ambitious campaign of cross-border measurements as early as 2013.

In another sign of glasnost, Chinese scientists may also conduct research at Paektu next summer. Although geologists on both sides have made forays, this would mark the first geophysics fieldwork between the countries.

The main aim is heightened vigilance. "We hope to build up our capability to monitor the volcano and forecast eruption scenarios," says Yun Yong Kun, deputy director general of DPRK's Earthquake Administration. Toward that end, he says, "we welcome scientists with open arms." Studies in North Korea could also help penetrate scientific conundrums, including the true scale of the millennium eruption.

Deep scars

The golden leaves of Changbai larch, a species unique to the region, glow in the pale afternoon light. A few meters ahead, one tree leans precariously over a precipice. The valley below looks as if it were coated with chocolate meringue. Clinging to the sheer walls are wispy, gravity-defying spires straight out of a Dr. Seuss story, hollow ignimbrite structures formed by escaping gas. A 120-meter-deep scar, some 30 kilometers from Changbai's west flank in Chinese territory, was carved by a pyroclastic flow that barreled down the mountain, incinerating everything in its path. A deeper, longer gash runs north.

Seismic shift. Breaking new ground, James Hammond (*top left*) and Clive Oppenheimer prepare to install a broadband seismometer. North Korea welcomes cooperation at Paektu, says Institute of Volcanology Director Kim Myong Song.

Volcanic eruptions are rated on a scale that depends on the volume or mass of lava and tephra they disgorge. It's comparable to the Richter scale for earthquakes. Anything above magnitude 8 rates as a supereruption. These gargantuan blasts spew more than 1000 cubic kilometers of ejecta, such as those hundreds of thousands of years ago that formed the calderas at Yellowstone in Wyoming. The most recent supereruption was New Zealand's Lake Taupo volcano about 26,500 years ago. Only a few 7s have occurred during the last 11,500 years; the millennium eruption was one of them.

On the North Korean side of the volcano, the wounds from that titanic blast are only slowly healing. "Stop here!" Oppenheimer commands. The minibus pulls over near a bone-white ridge on Paektu's treeless east flank. Oppenheimer scrambles down an embankment and examines a few-meter-thick layer of exposed pumice. The friable rock crumbles in his hand. "This must be from the millennium eruption," he says. Embedded in it are chunks of harder rock. "These lithics were part of the vent. They were ripped out by the ascending magma," Oppenheimer says. The fragments have their own story to tell. From their size and distribution, for instance, scientists can reconstruct the plume's height; models suggest that it reached 25 kilometers.

There's a more fundamental question, Oppenheimer says. "Why is Changbai here in the first place?" he asks. "We don't know much about what's going on inside the Earth that leads to the kinds of lava and pumice you see there." Most active volcanoes lie at tectonic-plate boundaries, like the Ring of Fire girdling the Pacific Ocean. Subduction churns magma into their conduits, like a stoker shoveling coal in a steam locomotive. Other volcanoes are fed by mantle plumes that funnel magma to the surface; prime examples are the volcanoes that continue to shape the Hawaiian Islands. Changbai is one of a handful of big volcanoes that defy easy categorization. Although it sits about 1200 kilometers west of the Ring of Fire, it seems to be fueled by deep subduction of the West Pacific Plate, says CEA seismologist Lei Jianshe. Some experts, however, reject the notion that subduction is the driving force.

Scientists have pieced together a timeline of the baffling volcano's history. Changbai began to form about 1 million years ago, after trachyte became the dominant composition of

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A Very Big Bang

Changbai's millennium eruption, one of the biggest in recorded history, is an enduring riddle. Piecing together what happened 1000 years ago could help scientists gauge the volcano's modern-day risk.

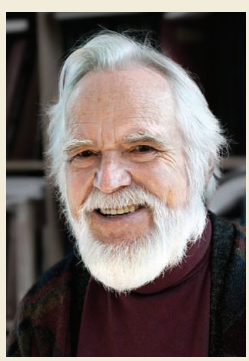
One major uncertainty is how much material, or tephra, was ejected during the eruption. Estimates range from 30 to 172 cubic kilometers. Prevailing winds swept much of the ash eastward, blanketing the northern Korean Peninsula with the thickest millennium layers. A true picture of the eruption will come only from mapping deposits on the Korean side of the border.

Witness to catastrophe. Trees buried in pumice on Paektu's east slope point to an early date of the millennium eruption.

An intrepid German researcher, Hans-Ulrich Schmincke, was the first to take a stab at that. After the 1991 eruption of Mount Pinatubo in the Philippines shot ash into the stratosphere, causing a brief global cooling, Schmincke, a volcanologist with the Leibniz Institute of Marine Science in Kiel, grew interested in probing the climate effects of past eruptions. For 2 years, he tried to get a visa to North Korea so he could study Paektu and failed. So in the summer of 1993, he and graduate student Susanne Horn set out for China for fieldwork at Changbai. Back in Beijing, Schmincke dropped in on the North Korean Embassy. "I'm a person who never gives up, he says. He gave an impassioned spiel on Paektu's threat, and they got their visas.

Arriving at Paektu a few days later, Schmincke was struck by "the huge layers of pumice." He persuaded their guides to allow them to sample from a wide area. "We got lots of data," he says. They calculated that the tephra volume was 96 cubic kilometers and that the eruption would have triggered a marked cooling effect.

North Korean volcanologists are attempting to refine estimates of tephra volume by mapping the millennium ash layer. So far, they've drilled 170 boreholes, 127 millimeters in diameter, on the volcano's east flank and the surrounding countryside. "Their drilling work is fabulous," says Clive Oppenheimer, a volcanologist at University of Cambridge in the United Kingdom. Korean researchers will begin analyzing the data over the winter.



Trailblazer. Hans-Ulrich Schmincke's fieldwork in North Korea in 1993 yielded insights into Paektu's potent past.

Another question is when did the millennium eruption happen? "There's no agreement on the date," says Xu Jiandong of the China Earthquake Administration (CEA). In the early 1990s, CEA volcanologist Liu Ruoxin collected chunks of carbonized wood from the volcano's north flank. Using radiocarbon analysis, he put the date at 1205 C.E.

Schmincke and Horn turned back the clock. On Paektu's east flank in 1993, they sawed off wood from a larch buried in 8 meters of millennium ash and brought it back to Kiel for radiocarbon dating. They pegged the eruption to the year 969 C.E. Other radiocarbon studies suggest it could have occurred a few decades earlier.

Although most experts put stock in the earlier dates, Xu says the matter isn't settled. He argues that the eruption might have been two or more events spread over a few centuries. Historical documents shed little light; one Korean text from 1199 C.E. refers to "white-hair rain," perhaps an oblique reference to the millennium eruption. The mute record is not surprising, says Cho Moonsup, a petrologist at Seoul National University. Long ago in Korea, he explains, scholars risked execution if they chronicled bad omens. Chinese and Japanese annals are silent.

Xu hopes to have the last word on the millennium eruption's timing. A few months ago, he shipped several dozen samples from four trees buried under millennium deposits on the three Chinese flanks, including the charred wood that Liu dated, to Switzerland for high-precision radiocarbon analysis using accelerated mass spectrometry. Results are due next month. **–R.S.**

the magma spilling across the region. "The lava grew more viscous and piled up," says geologist Song Gung Ho of DPRK's Institute of Volcanology. Then about 170,000 years ago, lava disgorged from smaller cones cooled into blood-red scoriae or cinders.

An explosive new phase started with a bang 4000 years ago when a massive eruption scattered gray ash over northeastern China and Korea. Later, the millennium eruption left a similar mark: deposits of pale comenditic pumice studded with black fragments ripped from the cone. Scribes recorded minor eruptions in 1668, 1702, and 1903. The story may not end there. The "most worrisome" scenario is that we are in the midst of a cycle of millennium-scale eruptions, says Cho Moonsup, a petrologist at Seoul National University.

Changbai's history and possibly its future could be revealed in the panoply of colors and textures of pumice scattered around the caldera rim. "These rocks tell so much about the volcano's past behavior," says Oppenheimer, who spends several weeks a year at Mount Erebus in Antarctica and other volcanic hot spots. "By looking at deposits of different ages, you can begin to understand the cycles." For example, the amounts of CO_2 and other volatiles in melt inclusions can reveal how much gas might have been expelled from the magma when the volcano erupted. Such information, Oppenheimer says, "enables us to build a model of a volcano's plumbing system just before it erupts."

It won't be easy. Even at volcanoes like Etna, Vesuvius, and Kilauea that have been observed for hundreds of years, Oppenheimer says, "we still don't understand everything about how they work."

Strange signs

Hoping to find clues to Changbai's next move, CEA aims to build one of the world's most ambitious volcano observatories. Plans call for installing real-time gas sensor arrays, adding to a network of 11 digital seismic stations and 16 GPS stations, and drilling a deep borehole in the volcano's flank for a suite of instruments. "Our goal is to create a network that's capable of forecasting an eruption," says Xu, who leads a CEA group that monitors six of China's 14 known active volcanoes, defined as those that have erupted in the past 10,000 years.

They have a solid foundation. Around 15 years ago, Chinese researchers established Tianchi Volcano Observatory on Changbai's north flank. The station is acutely vulnerable: It sits on the Erdaobaihe River—the outlet from the caldera lake—and could eas-

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Sizing it up. The millennium eruption was one of the biggest in the past several thousand years, as thick pumice layers in North Korea attest. Chinese scientists sample deposits (*right*) near the caldera rim on Changbai's south flank.

ily be demolished by a lahar. Several years ago, CEA built a second, safer perch, Changbaishan Volcano Observatory, 50 kilometers northwest of the caldera.

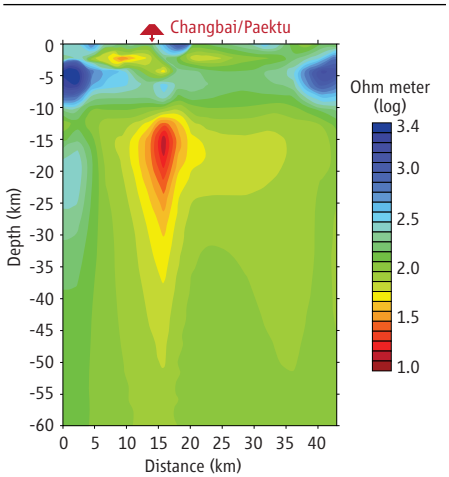
But Tianchi observatory, still staffed, has a hidden asset. A short hike behind the station is a massive steel door in the side of a hill. A technician unlocks it and leads Xu and me inside. It's pitch-black; we use our cell phone display screens to find our way. Built in the mid-1990s, the 65-meter-long chamber has a shaft at the end holding a broadband seismometer and, intriguingly, two 10-meter-long quartz tubes. Geophysicists monitor minute changes in conductivity in the crystal instruments, each a tiltmeter and tensometer, to track the mountain's deformation.

CEA's surveillance indicates that Changbai is biding its time. There was a flurry of excitement in June 2002 when swarms of tremors racked the mountain. CEA traced the epicenter to 5 kilometers beneath the volcano's cone, where the main magma chamber is thought to lie. Over the next 3 years Changbai shuddered, sometimes experiencing more than 200 spasms in a month; the background rate is fewer than 10 per month. Activity crested on 19 March 2003, when more than 500 tremors were recorded. CEA observations showed that the mountain rose about 68 millimeters over that period—five times the rate before the shaking started. Some scientists argued that the tremors were due to gas bubbles: volcanic indigestion. Others believed magma was rising toward the cone and braced for a blast. But after a swarm in May 2005, Changbai's seismicity receded to background levels.

However quiet the ground may be now, there are curious changes underfoot. Over the past 2 years, the CEA team has determined that the caldera rim has slumped a few centimeters even as the surrounding land continues to rise. The deflation has left researchers scratching their heads, as has last year's 90-degree twist in the predominant land motion, from southwesterly to southeasterly.

There are other anomalies. In 2008, Korean scientists discovered a new fumarole, or gas vent, near the east flank, 40 kilometers from the caldera. CEA scientists, meanwhile, observed an odd burst of sulfur dioxide last November and measured fluctuations in hot springs on the north flank. Two years ago, temperatures suddenly shot up 2° to 3°C on average, then went back down.

FIRE IN THE HOLE



Belly of the beast. Using magnetotelluric soundings, Chinese scientists have imaged what they presume is Changbai's main magma chamber. North Korean MT data suggest magma is ascending.

What these phenomena augur is a matter of debate. "The new evidence shows that the volcano will soon enter an active phase," argues Liu Guo Ming, deputy director of Changbaishan Volcano Observatory. Geologist Yun Sung-hyo of Pusan National University in South Korea agrees. "We urgently need emergency response plan," he says. Others insist that fears about a looming eruption are overblown.

Terra nova

A detailed probe of the magma chamber might provide some answers. But no matter how many instruments the Chinese put on their side of the volcano, a definitive view of its plumbing will only come after the North Koreans wire up their side as well.

There are two main methods of penetrating the interior. One is to track the speed of seismic waves from controlled explosions, revealing the composition and consistency of the rock. A low-velocity anomaly is usually interpreted as a magma chamber, for example. A second method is to survey the area with magnetotelluric (MT) sensors, which map subsurface variations in conductivity.

Changbai's underbelly is complex. Seismic scans have revealed globs of magma, 100 kilometers wide, lined up "like a string of beads" around 1000 kilometers below the surface, Wei says. As this magma ascends, he says, it mixes and changes composition. The volcano's main magma chamber appears to lie several kilometers below the surface, although as Hammond notes, "it's likely that magma pools at many depths in the crust." Finer imaging is needed, Lei says. The findings so far, he says, "are rough."

North Korean scientists have taken a stab at mapping Paektu's main magma chamber. In 2003, they built their own MT machine. "I'm very impressed," Hammond says. "It's a complicated technique." While the approach is widely used in oil exploration and other subsurface mapping, few geophysicists are familiar with the complex devices. Asked to explain their resourcefulness, one North Korean volcanologist

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Lasting impression. Gravity-defying spires, formed by escaping gas, cling to the walls of a pyroclastic valley gouged during the millennium eruption.

responds, simply, "*Juche*!"—North Korea's credo of self-reliance.

Using their machine, the North Korean team has discerned what they believe is a magma chamber at a depth of 6 kilometers. Their MT data indicate that since 2007, "the depth of magma is getting shallower. We believe it is ascending," says Kim Hang Myong. But he acknowledges that their MT device has wide error bars. "We wonder about the reliability of our data," Kim says. "He's right to be cautious," Oppenheimer says. "The spatial resolution of MT is very coarse."

A complete picture of Changbai's plumbing would only come from seismic and MT surveys traversing the whole volcano. That would require installing on the North Korean side as many as eight broadband seismometers to zero in on tremors, Hammond says. Cross-border surveys would also require explicit agreements from both governments, scientists say. China and North Korea are allies but wary of monitoring. Last July, North Korea adopted a law requiring foreigners who want to carry out volcanological or seismic research to get permission from the Earthquake Administration, and North Korean scientists must accompany them in the field. (China has similar regulations.) Seismic measurements are sensitive for another reason. In September 2006, several days before its first nuclear test, North Korea asked China to turn off its seismometers near the border. They repeated the request before their second test in 2009.

Good vibrations. Ri Gyong Song is hoping for broadband seismometers.

Caldera duty

In the summer of 1999, Kim Myong Song, director of DPRK's Institute of Volcanology, conducted an arduous survey of the steep hillside behind Paektu Bridge station. The institute had been founded 3 years earlier. Among other urgent tasks in setting up a network of observatories, Kim was searching for a patch of land with bedrock near the surface, where his team could install a seismometer. "We found the perfect spot, with little background noise," he says. He and a colleague hauled logs up the hill and built a shelter for the instrument.

It also worked well for the British broadband seismometer during its brief run in September. As Hammond installed it, Oppenheimer used duct tape to attach a white plastic GPS receiver to a pine tree branch to provide a time stamp for the seismic signals, which are recorded when an earthquake rattles the extremely sensitive seismometer. Ri Gyong Song, a seismologist at DPRK's Institute of Volcanology, who like Director Kim studied theoretical physics at DPRK's elite Kim Il Sung University, took careful notes. "We urgently need this kind of seismometer," he says.

North Korea has deployed six seismometers at Paektu, but only one is digital; the rest are modified Chinese analog seismometers. The researchers use solar panels and car batteries to power their instruments and a transmitter that sends data to Pyongyang via a national intranet. There are frequent outages in winter, when snow covers the panels, Kim Hang Myong says.

Despite the hardships, the 200 North Korean researchers who study the volcano have a jaw-dropping asset: a station operated year-round on the shore of the caldera lake. "It's unbelievable. I can't think of anyplace else that has a manned station inside a crater," Oppenheimer says. If the volcano were to awaken in summertime, the sentinels at Lake Chon Research Station could flee up a stone staircase that zigzags several hundred meters to the caldera rim. By mid-October, snow and ice make the steps too treacherous to navigate. Four men overwinter in the three-room warren. If the staircase were impassable in an emergency, they would rely on their compatriots to put an Austrian-built gondola, shuttered in winter, into service.

The team's main task is to track gases percolating up from the volcano's vent, which is 384 meters below Tianchi's surface, on the Chinese side, and two underwater springs to the south. They head out on Tianchi by boat to take samples every 5 days until December, when the lake freezes over. From then until the thaw, they strike out on the ice on foot, sampling from all three springs, including the vent on the Chinese side. "The lake is common area," a technician explains.

Researchers analyze samples in a cozy room with heated linoleum floors. On the wall, a long wooden board, painted red with white Korean characters, offers encouragement: "Great Leader Kim Il Sung lives together with us." With several gas sensors out of commission, technicians are only able to measure chloride and pH, fluctuations of which may presage an eruption. With the volcano in a quiet phase, Chinese researchers are content to measure gases wafting from hot springs in their territory every 3 months.

Volcanologists in arms

The Chinese and Koreans devote great attention to the volcano not only because it poses a serious threat but also because it resonates deeply with their cultural identities. The Chinese consider Changbai the birthplace of the Manchu people. Koreans revere the mountain. "Paektu represents our nation's soul. It's our ancestral home," Kim Myong Song says.

Oppenheimer and Hammond realize that getting an international research program at this iconic mountain off the ground will require more than their expertise—it will take science diplomacy, too. "There are many conflicts that can arise when a foreign team of scientists comes to a volcano. They arrive, collect data, write papers, and go home," Oppenheimer says. "It's important that the Koreans do this on their terms." The Koreans say they are ready. "We can ensure conditions for data sharing and making joint measurements," says Pak Kwang Pam, head of foreign technical cooperation with DPRK's Seismological Bureau.

All signs suggest things are off to a promising start, Oppenheimer says: "I hope very much this is just the beginning."

–RICHARD STONE

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