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Fire & ice

Volcanoes and frozen lands make an explosive combo

By Alexandra Witze

SVEIFLUHÁLS, Iceland — High atop an Icelandic mountain one magnificent summer day, with blankets of soft moss underfoot and a translucent lake shimmering in the valley below, geologist Emily Constantine Mercurio is conjuring up an image of hell.

Tens of thousands of years ago, says Mercurio, a graduate student at the University of Pittsburgh, this place was the heart of a roiling volcanic eruption. Molten rock bubbled up from a fissure in the Earth's crust. On top of that lay hundreds of meters of ice. Lava met ice, and the result was an inferno.

Heat from the eruption instantly boiled ice to steam, which ramped up the eruptive power like a pressure cooker blowing its top. Magma hitting the steam exploded into tiny fragmented bits, sending pillars of fine-grained ash billowing overhead. It would have resembled the scene many people heard about on the news this spring — a volcano that erupted an hour's drive to the east, known as Eyjafjallajökull (pronounced "AY-ya-FYAT-la-yo-kult").

Eyjafjallajökull began erupting on March 20, but few people other than volcanologists and Icelanders took notice at first. For weeks, all it did was spurt lava gently out of an exposed ridge. On April 14, though, the eruption suddenly shifted a few kilometers west — no longer on open land, but beneath an ice cap. Just as happened at Sveifluháls, magma met ice and turned it to steam, throwing ash into the stratosphere. European airline flights shut down for days over worries about how the ash might affect jet engines.

What a difference a little ice makes. Had the second phase of the eruption not shifted westward, the volcano would not have closed down much of Europe's air traffic. "In the absence of ice, Eyjafjallajökull would have been a much less disruptive volcano," says Dave McGarvie, a volcanologist at the Open University's campus in Edinburgh.

Eyjafjallajökull's eruption has refocused attention on a small but rapidly growing subset of volcanology: the study of volcano-ice interactions. Ice-covered volcanoes, or "glaciovolcanoes," are not fundamentally different from other volcanoes in terms of plumbing or eruptive style. But they distinguish themselves the moment magma breaks through the crust and meets ice.

One reason to study icy volcanoes is to better understand their risks. Nobody died in the Eyjafjallajökull eruption,

Iceland's Eyjafjallajökull volcano erupted quietly at first this spring (shown) —until magma shifted directly beneath a glacier.

but in 1985 an eruption beneath an icy mountain in the Colombian Andes sent massive mudflows coursing downstream, killing more than 20,000 people. Dozens of volcanoes mantled with ice are scattered around the world, each posing a distinct hazard (see Page 18).

Scientists are also studying volcano-ice interactions to learn more about the past. By chronicling geologic signs that volcanoes like Sveifluháls once erupted under ice, researchers can build up a picture of how far ice extended over the planet, and when.

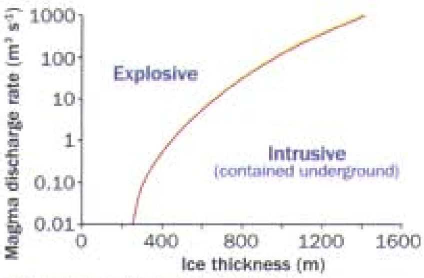
Icy volcanoes might even be a key to answering a vexing question – whether a warming climate could trigger more eruptions by lifting the heavy mantle of ice above volcanoes. As glaciers retreated from Iceland at the end of the last ice age, about 12,000 years ago, volcanic activity increased 10- to 30-fold. Some researchers speculate that the ongoing melting of ice caps worldwide could have a similar effect.

Land of ice volcanoes

Iceland is an ideal place to see icy volcanoes and for scientists to figure out how such volcanoes work. The country has some two dozen active volcanoes, of which Eyjafjallajökull is relatively puny. The island is so volcanically active because it is the above-water manifestation of the Mid-Atlantic Ridge, the chain of mountains that runs down the center of the Atlantic like an underwater backbone. Here Earth's crust pulls apart, and upwelling magma cools and forms new crust that spreads away from the ridge in the great recycling process known as plate tectonics. Iceland is geology in action; a one-hour flight from Reykjavik skims over steaming geothermal areas, the great crustal rift and some of the country's most famous volcanoes.

Many of those volcanoes are mantled in ice, including several under the 1,000-meter-thick Vatnajökull ice cap.

Thin ice, more explosions Computer modeling of volcanic eruptions under ice suggests that thin ice plus even a little magma equals hazardous explosive eruptions.



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Glaciovolcanoes around the world

Volcanoes capped with ice pose distinct hazards in different countries. Researchers are trying to better understand these mountains to prevent future disasters.

Iceland: Land of fire and ice

1. Sveifluháls
An eruption thousands of years ago created this volcanic ridge.

2. Eyjafjallajökull
This small volcano shut down much of Europe's airspace this spring.

3. Katla
This neighboring volcano has erupted in tandem with Eyjafjallajökull before.

4. Hekla
One of Iceland's most active volcanoes, it has erupted five times since 1947.

5. Gjálp
Its 1996 eruption spurred pioneering studies of glaciovolcanism in Iceland.

6. Grímsvötn
It last erupted in 2004, and many scientists think it will be Iceland's next to go.

WORLD MAP: CARTESIA, ADAPTED BY E. FELICIANO

Sometimes, thick ice can muffle a volcanic eruption entirely. At Eyjafjallajökull, though, the ice is only a couple of hundred meters thick at most. That's not enough to keep the eruption from breaking through ice, though it is enough to generate lots of meltwater and steam when magma hits. "What the ice did was provide the trigger, the catalyst for the production of very fine ash," says McGarvie. Surprisingly, and for reasons volcanologists don't yet understand, Eyjafjallajökull kept churning out fine-grained ash for longer than expected.

Still, ice wasn't the only thing that made the volcano produce so much ash. Another factor was the chemical makeup of the magma during the second phase of the eruption. In March, the magma that poured out was primarily basalt, a common lava type that makes up 90 percent of the volcanoes in Iceland. Magma in the April eruption, however, suddenly had more silica in it. Silica makes magma more viscous or sticky; gas bubbles can't escape as quickly as they can in more fluid magma, and the whole mess rapidly becomes more prone to exploding.

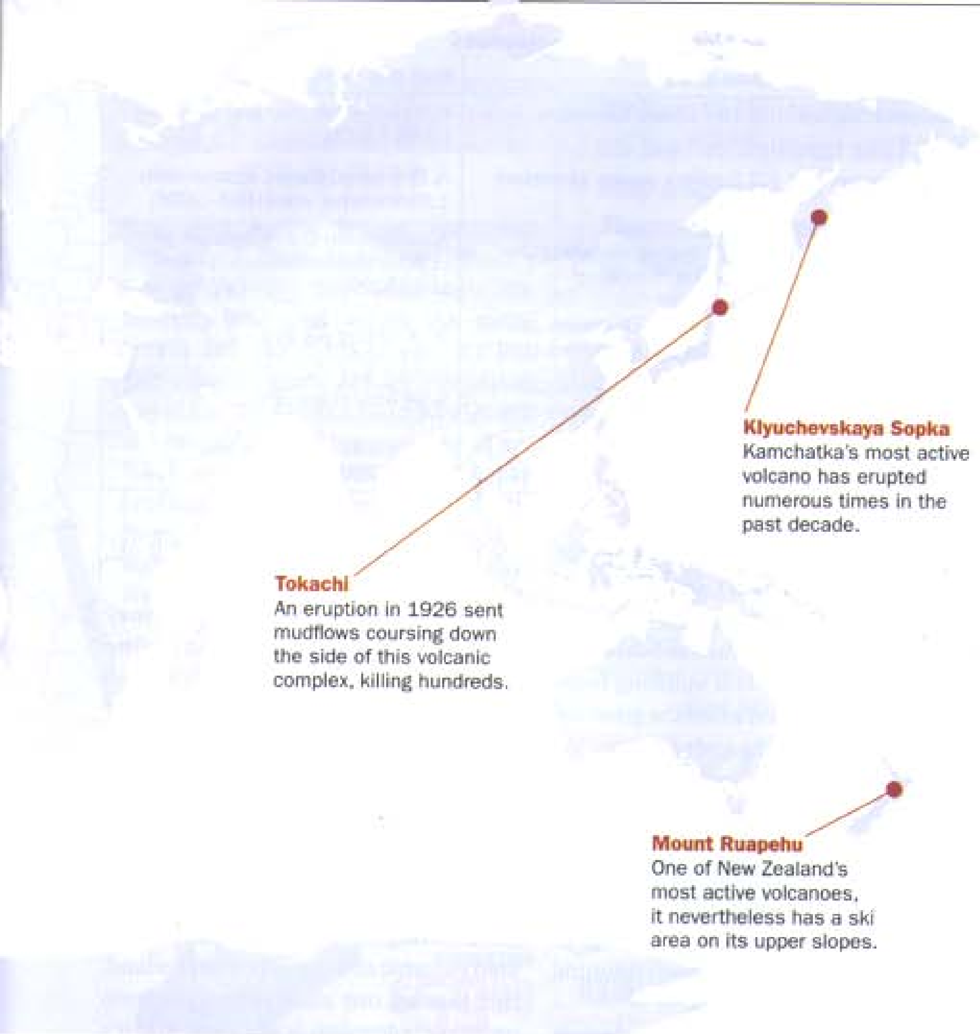
Scientists are not sure why the magma composition changed from eruption to eruption, but one possibility is that Eyjafjallajökull began to tap a separate magma chamber. Another idea, says McGarvie, is that basalt erupting from deep within the volcano suddenly encountered a chamber of more silica-rich magma, and the two mixed before erupting under the ice.

It's hard to untangle how much of Eyjafjallajökull's power came from erupting under ice, and how much from the chemical composition of its magma. Volcanologists may eventually get a handle on that question by analyzing lavas from various stages of the eruption. Researchers led by Magnús Tumi Guðmundsson of the University of Iceland in Reykjavik have launched a full-out assault on the mountain to gather such information.

Like the 1996 eruption of the Icelandic volcano Gjálp, whose study pioneered the field of glaciovolcanism, Eyjafjallajökull may end up as a linchpin in understanding these types of eruptions. "We will learn a great deal from this volcano," McGarvie says.

Frozen past

Farther west, at Sveifluháls, Mercurio is doing her best to push such knowledge back in time, to create a window to glimpse the glaciovolcanic past. She is



BOBBIE MYERS AND STEVEN R. BRANTLEY/U.S. GEOLOGICAL SURVEY, ADAPTED BY E. FELICIANO

part of a new effort to study what tracks icy eruptions make in the geologic record.

When magma cools, it leaves distinctive textures in the resulting rocks, revealing the conditions under which they formed. Lava that is chilled quickly contains only small crystals; lava that takes longer to cool has time for larger crystals to grow. Fractures along the cooling edge can also indicate how dramatic the temperature difference was between the magma and whatever it encountered to cool it — air, water, ice or snow.

"It would be great if you can find lavas and say they must have cooled in contact with snow or ice or some other environment," says volcanologist Hugh Tuffen of Lancaster University in England. "You could reconstruct changing ice and snow, and understand the way the behavior of the volcano has been coupled to that."

Icelandic volcanoes can also be used to tackle important paleoclimatological questions, like how thick ice sheets got during the last ice age. While some measurements, such as the ratios of oxygen isotopes in trapped air bubbles, can tell scientists how cold temperatures were, that information can't be translated directly into ice thickness. The only way to find out is through shoe-leather geology — mapping structures in the field and untangling the story of what transpired thousands of years ago.

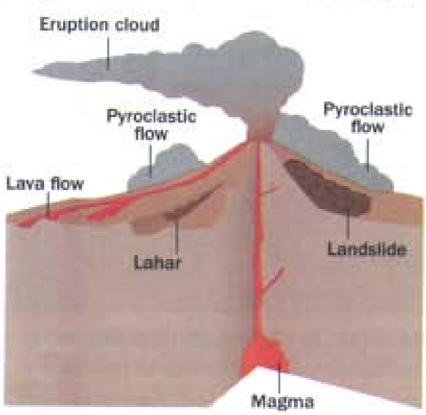
That question is what brings Mercurio to Sveifluháls this gorgeous summer day. Her backup troops include her adviser, University of Pittsburgh volcanologist Ian Skilling; master's student Holly Kagy; and a field assistant, Mercurio's cousin Kathy Zollinger.

At first, Sveifluháls looks too huge to ever comprehend: a massive ridge of black rock, some 21 kilometers long. The barren landscape lies about a 40-minute drive south of Reykjavik. The gravel roads that run down either side of the ridge are usually empty of other cars, save for fishermen trying their luck in Lake Kleifarvatn or the occasional tourist heading to the mud pots at the local geothermal field.

But hiking up into the lunarlike terrain, Mercurio and Skilling start to point out geologic details that tell the story of the past inferno. Here in an outcrop amid a steep pile of scree lie pillow basalts — the billowy-looking rocks that form when lava erupts underwater. There, lower down the ridge, stretch the remnants of an ephemeral lake, its ancient coastlines marked along the edges. Such features mean water, and water means ice melted by lava. "We're looking for evidence of drainage, all the way down the ridge," Skilling says.

Summer after summer, Mercurio has been building up a history of what happened at Sveifluháls. She can't be sure exactly when it erupted; the rocks here are too young for typical radioactive dating techniques. But at some point, probably between about 40,000 and 13,000 years ago, magma came bursting up through ice. Months later, when the eruption subsided, the ridge remained. More than 1,000 of these erupted ridges, called "tindar," dot Iceland's countryside.

Special hazards All volcanoes can be hazardous, but when magma hits ice as it emerges, the resulting mudflows (called lahars) and high-flying ash can be especially dangerous for nearby residents and airplanes.



In some places the researchers spot physical evidence of where ice used to be. Atop one section of the ridge, Skilling points out a place where thick layers of cooled magma slump down and then are truncated abruptly at one end. The magma must have run into a wall of ice here, he says — cooling and stopping before the ice melted away.

Mercurio's fieldwork suggests that the ice at Sveifluháls was some 400 meters thick at the end of the last ice age. Puzzlingly, models of Iceland's ice cover suggest that it should have been 1,500 to 2,000 meters thick. Asked why the difference, Mercurio shrugs. Only more studies of glaciovolcanism can answer these kinds of questions.

Ice thinning at selected ice sheets and volcanoes

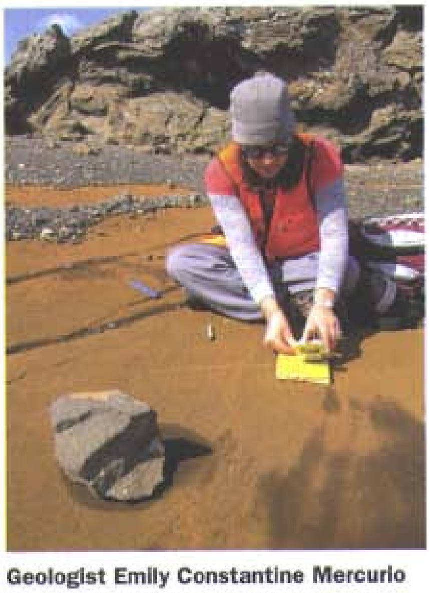
Location	Area of ice	Rate of thinning
Vatnajökull ice cap, Iceland	8,100 square kilometers (2000)	0.8 meters per year average (1995–2008)
West Antarctic Ice Sheet	2.2 million square kilometers (2009)	At Pine Island Glacier, approximately 1.6 meters per year (1995–2006)
Popocatépetl, Mexico	0.729 square kilometers (1958); zero today	Approximately 0.2 meters per year (1996); approximately 4 meters per year (1999)
Cotopaxi, Ecuador	19.2 square kilometers (1976); 13.4 square kilometers (1997)	3–4 meters per year
Kilimanjaro, Tanzania	2.5 square kilometers (2000); 1.85 square kilometers (2007)	0.54 meters per year
Villarrica, Chile	30.3 square kilometers	0.81 ± 0.45 meters per year (1961–2004)

SOURCE: H. TUFFEN/*PHIL. TRANS. R. SOC. A* 2010

Melting future

Northwest of Mercurio's field site, a low gleaming office building in Reykjavik houses the earth science department of the University of Iceland — ground zero for probing the links between volcanoes past and present. Volcanologist Freysteinn Sigmundsson spends his days digging through data from Eyjafjallajökull and wondering what other eruptions are yet to come. "What will be the influence on volcanic activity if all the ice caps shrink?" he asks.

The disappearance of ice sheets lifts weight off the land, he says, and great pieces of Earth's crust can rise with their backs unburdened. Many regions in northern latitudes, such as Scandinavia and Canada, are still uplifting from the pressure released when the great ice sheets retreated at the end of the last ice age. In Iceland, where an ice sheet some 300 kilometers wide has mostly disappeared, this "glacial rebound" is as much as 20 millimeters per year. In addition, glaciers worldwide are retreating because of rising global temperatures. Ice caps in Iceland, for example, have been thinning since around the year 1890.



Geologist Emily Constantine Mercurio measures the orientation of ripples frozen in rock atop Sveifluháls in Iceland.

Glacial rebound and thinning glaciers together can affect volcanic activity in multiple ways, Sigmundsson says.

For one, reducing pressure at the surface causes more magma to be produced at depth. "This is sort of excess magma," Sigmundsson says. "If the conditions in the crust remain the same, you would expect more magma to make it to the surface." The thinning of the Vatnajökull ice sheet, for instance, may have caused a 10 to 15 percent increase in magma production over the past century.

Ice loss also shifts areas of stress on buried magma chambers. Volcanologists know that ice loss can affect eruptions; in 2004, half a cubic kilometer of meltwater suddenly drained from a lake beneath Vatnajökull, and the nearby Grímsvötn volcano erupted. In cases where a volcano was about to erupt anyway, like Grímsvötn, a change in surface stress could provide the final trigger necessary to set it off, Sigmundsson says.

Finally, taking ice away also may open new channels for magma to find its way to the surface, via new fractures or fault lines.

Still, volcanologists argue about exactly what effect shrinking ice will have. At the end of the last ice age, volcanic activity in Iceland experienced a big pulse; activity was more than 10 times that seen today. Some have argued that the thinning of Vatnajökull has accelerated volcanic activity in central Iceland. But teasing out such processes from ordinary volcanism is not easy. And it's not clear whether more volcanic activity might mean a greater number of eruptions, or the same number but with more magma volume in them.

Back atop Sveifluháls, such concerns seem remote. At 63° N latitude the sunlight has that rarefied Arctic feel, and the city of Reykjavik sparkles in the distance. An eruption amid the serenity seems a far-off possibility.

Yet as Mercurio will tell anyone who listens, the peace is deceiving. There's no doubt that the geological demons driving Iceland's volcanoes will be back. ■

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- Eyjafjallajökull webcam: http://eldgos.mila.is/english/eyjafjallajokull-fra-thorolfsfelli
- View a photo slide show of research at Eyjafjallajökull at www.sciencenews.org/icyvolcano

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