# Messages in the Bubbles

Laacher See volcano is quiet, but gas bubbles rising through the overlying lake are a reminder of its potential hazard. Scientists took a close look at the bubbles to test eruption monitoring methods.

Scientists spent several days last August examining Laacher See, a volcanic caldera lake in western Germany, for evidence of connections between gas seeps, the surrounding sedimentary structures, and volcanic activity. Credit: iStock.com/bbsferrari

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Volcanic gases are the engine of volcanic eruptions. They determine whether volcanoes erupt effusively or explosively, and they can also affect volcanic plumbing systems during periods of quiescence [*Girona et al.* (https://doi.org/10.1038/srep18212), 2015]. During such quiet periods, passive (noneruptive) volcanic degassing can release substantial amounts of carbon dioxide ($CO_2$) into the air [*Carn et al.* (https://doi.org/10.1016/j.jvolgeores.2016.01.002), 2016], and these emissions can influence atmospheric and oceanic $CO_2$ levels over a much wider area [*Aiuppa et al.* (https://doi.org/10.1038/s41598-019-41901-y), 2019].

We sailed for 3 days, with as many as four boats at a time, on a lake surface that gave no indication of the large magma reservoir lying below the caldera.

Directly observing $CO_2$ emissions from subaerial volcanoes (those that are not submerged in water) is technically challenging because of the high $CO_2$ levels already present in the atmosphere, but detecting $CO_2$ emitted by volcanoes submerged in water using acoustic instruments is relatively straightforward.

Lake bed $CO_2$ seeps were the topic of an unusually focused experiment involving a large group of scientists from various disciplines that took place last August at Laacher See, a scenic lake in the Eifel region of Germany. The 2-kilometer-wide lake, surrounded by trees and hosting a peaceful 900-year-old Benedictine abbey on its shore, sits in the caldera of a volcano thought to have last erupted at the end of the Pleistocene. Our multinational team of 13 volcanologists, sedimentologists, oceanographers, and hydrogeophysicists set out to look for evidence of connections between these gas seeps, the surrounding sedimentary structures, and volcanic activity. We sailed for 3 days, with as many as four boats at a time, on a lake surface that gave no indication of the large magma reservoir lying below the caldera. During our fieldwork, we were disturbed only by fishermen and tourists on pedal boats.

## From Erupting to Bubbling

Gas seeps near submerged volcanoes in the ocean or in lakes can provide information that is not available for subaerial volcanoes. The lake bed of Laacher See contains numerous such gas seeps, making it an attractive candidate for our study.

Laacher See volcano produced a Plinian (https://volcanoes.usgs.gov/vsc/glossary/plinian.html) eruption about 12,900 years ago, spewing ash as far away as Greece. It erupted 20 cubic kilometers of the rocky fragments known as tephra, a dense-rock equivalent (https://en.wikipedia.org/wiki/Dense-rock_equivalent) of 6.3 cubic kilometers of magma [*Schmincke et al.* (https://doi.org/10.1016/S1040-6182(99)00017-8), 1999], making it similar in magnitude to the Pinatubo eruption (https://eos.org

/articles/pinatubo-25-years-later-eight-ways-the-eruption-broke-ground) of 1991. Since this large-scale eruption, a lake formed in the caldera, and the volcano has been quiet. In recent years, however, significant plumes of gas bubbles have been observed in the lake [*Goepel et al.* (https://doi.org/10.1007/s00531-014-1133-3), 2015], and high concentrations of dissolved $CO_2$ have been measured.

Although we did not study bubble compositions in the present work, according to recent geochemical analyses, the $CO_2$ contained within the lake appears to be of magmatic origin, and the $CO_2$ content of the soil gas ranges between atmospheric values (0.03%) and 100% [*Gal et al.* (https://doi.org/10.1016/j.ijggc.2011.04.004), 2011; *Giggenbach et al.* (https://doi.org/10.1016/0377-0273(91)90065-8), 1991]. A recent study documented deep and low-frequency earthquakes, inferred to have been caused by magma movements beneath the volcano [*Hensch et al.* (https://doi.org/10.1093/gji/ggy532), 2019], although there are presently no signs of upcoming volcanic activity in the near future.

## Sounds, Sediments, and Stratification

We divided our group of 13 scientists into several teams to study various aspects of the lake and its gas seeps. Two teams focused on the bottom of Laacher See and the degassing occurring in the water column, using iXblue Seapix 3-D and Norbit multibeam echo sounders to characterize bubble flares. Although echo sounders are typically used to map the contours of the underwater terrain [*Morgan et al.* (https://doi.org/10.1016/S0377-0273(02)00503-6), 2003], they can also map gas bubbles (https://eos.org/science-updates/gas-bubble-forensics-team-surveils-the-new-zealand-ocean) in water. Acoustic waves emitted by a sounder reflect off gas bubbles and are recorded in water column data as high acoustic backscatter (https://oceanservice.noaa.gov/facts/backscatter.html) values. This backscatter provides a means to track bubbles during their ascent [*Greinert et al.* (https://doi.org/10.1029/2009JC005381), 2010] and to quantify the gas flux involved [*Ostrovsky et al.* (https://doi.org/10.4319/lom.2008.6.105), 2008].

Team member Zakaria Ghazoui checks a hydrophone unit suspended beneath a raft in Laacher See. Credit: Corentin Caudron

Four scientific teams also investigated whether links exist between spots where degassing occurs and specific sedimentological structures in the lake bed, such as faults, small depressions, and pockmarks. Along with echo sounder profiles, we acquired seismic reflection profiles using the Innomar parametric echo sounder and the iXblue Echoes 10000 Chirp (https://link.springer.com/article/10.1023/A:1004349805280) subbottom profiler to image the upper 35 meters of sedimentary infill in the caldera lake with a vertical resolution of about 8 centimeters. Additionally, teams deployed a remotely operated vehicle to provide visual observations from the lake bottom. Preliminary results from these efforts show clear relations between locations of degassing and lake bottom morphologies, such as possible pockmarks and faults, providing information on how these morphologies influence volcanic degassing in this area.

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One team investigated new tools that, like seismic and infrasound instruments deployed on Earth's surface, could become part of volcano monitoring efforts in aqueous environments. For example, we deployed a hydrophone—essentially a microphone immersed in the water—for several hours to record noise created by the bubbles released at the lake floor. Similar to observations of bubbles in other volcanic lakes [*Vandemeulebrouck et al.* (https://doi.org/10.1016/S0377-0273(99)00176-6), 2000], the Laacher See gas bubbles radiated energy below 5 kilohertz; this consistency suggests the technique's potential use for monitoring in a variety of submerged volcano environments.

Another team looked for new ways to detect impending limnic eruptions—a hazard typically associated with volcanic lakes. These sudden gas eruptions, which are not necessarily volcanic in origin, can occur as a consequence of lake water stratification, in which a sequence of stable layers of water that grow progressively cooler from the surface to the lake bed remain unmixed. $CO_2$ seeping into cool, pressurized water near a lake bed is quickly dissolved, like carbonation in a chilled bottle of seltzer water, and can build up to high levels. If a disturbance such as a landslide stirs the water and disturbs the stratification (like shaking a sealed bottle of seltzer water), the $CO_2$ can bubble up to the surface and erupt to form an oxygen-poor atmospheric layer that can suffocate people and animals. Limnic eruptions have caused substantial casualties in the past—a 1986 eruption (https://eos.org/meeting-reports/cameroons-lake-nyos-gas-burst-30-years-later) of $CO_2$ at Lake Nyos in Cameroon claimed some 1,700 victims [*Kling et al.* (https://doi.org/10.1126/science.236.4798.169), 1987].

An instrument raft floats on the placid surface of Laacher See in August 2019. Credit: Corentin Caudron

This team tested the potential of electrical resistivity tomography (https://eos.org/research-spotlights/looking-inside-an-active-italian-volcano) and of transient electromagnetic methods to detect thermal lake stratification from the lake surface. Preliminary results show that these nonintrusive techniques unambiguously detected lake stratification in Laacher See. Thus, these methods hold great promise for future continuous monitoring efforts in lakes where limnic eruptions could endanger surrounding communities.

Understanding the intrinsic and spatial dynamics of volcanic gas bubbles is a cornerstone of efforts to develop a new generation of early-warning systems needed for volcanic risk assessment. The 2019 Laacher See fieldwork provided a snapshot of underwater volcanic degassing, its relation to sedimentary structures, and its potential for use in monitoring degassing and thermal stratification. Analysis of the data collected and future experiments will inform decisions about the role of multiproxy hydroacoustic data in ongoing global scientific efforts to increase the predictability of volcanic and limnic eruptions.

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