conditions in which the deposition of electrons into the ETC exceeds the capacity of the ETC to reduce oxygen. Absorbing a few electrons onto fumarate might enable cells to avoid uncontrolled electron leakage that generates damaging reactive oxygen species. Such scavenging could be particularly advantageous in tissues such as liver and kidney that are major sites of metabolite detoxification. Larger reverse fluxes through complex II might enable cells to sustain oxidative pathways such as amino acid and nucleotide biosynthesis and thus maintain cell proliferation under otherwise hostile conditions. Understanding the function of complex II reversal in normal physiology will thus require quantifying the net flux of fumarate reduction relative to succinate oxidation.

The ability of complex II to provide a valve for excess electrons also has important implications for pathological conditions such as ischemia and cancer. Complex II reversal has been linked to ischemia-reperfusion injury (*6*), but whether it is required for tissue adaptation to low oxygen is unknown. Likewise, tumor cells frequently experience hypoxic microenvironments in vivo. Given that complex II reversal supports the ETC to a lesser extent than oxygen, it is unknown whether complex II can meet the biosynthetic demands of tumor cells growing in hypoxic microenvironments. The potential of fumarate to absorb electrons to combat oxidative stress is especially intriguing in the context of human tumors with mutations in fumarate hydratase (FH). The current findings suggest that fumarate accumulation, characteristic of FH-mutant tumors (*7*), may provide a metabolic advantage under mitochondrial stress. Conversely, mutations in complex II are also observed in human tumors (*7*), raising the question of whether these cells engage alternative electron acceptors during hypoxic stress or whether the absence of fumarate reduction exposes a targetable weakness in these tumors. Counterintuitively, complex II and FH mutations would be predicted to have opposite effects on fumarate-mediated ubiquinol reduction, but both occur in renal cell carcinoma. These tumors may therefore represent a valuable system for future studies to understand the pathological implications of reverse complex II activity. ■

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VOLCANOLOGY

Reactivation of Cumbre Vieja volcano

A long-quiescent volcano's behavior requires rethinking about forecasting and hazards

By Marc-Antoine Longpré[1,2,3]

After 50 years of repose, Cumbre Vieja volcano—historically the most active of the Canary Islands—entered an eruptive episode on 19 September 2021, forcing the evacuation of ~6400 residents and destroying infrastructure worth more than 400 million euros. The volcanic unrest began in 2017 but accelerated only 8 days before the onset of the eruption. This behavior, characterized by comparatively protracted periods of quiescence and unrest, is at odds with global systematics for basaltic volcanoes (*1*).

Close monitoring of persistently active volcanoes, such as Kīlauea (Hawai'i) and Mount Etna (Sicily), allows for the identification of patterns in precursory unrest that help in the forecasting of eruptions (*1*). However, this strategy is not possible at volcanoes characterized by much longer quiescence periods, for which the most recent eruptive events predate the monitoring record. Cumbre Vieja volcano, on the island of La Palma in the Canary Archipelago, produced six eruptions between 1500 and 2020 CE, with repose periods ranging from 24 to 237 years (*2*). Before September 2021, it had last erupted in 1971, when a single seismic station installed on the island of Tenerife served the entire archipelago. In the past two decades, Spain's Instituto Geográfico Nacional (IGN) and the Instituto Volcanológico de Canarias (INVOLCAN) greatly expanded their monitoring networks on Cumbre Vieja and elsewhere in the Canary Islands, which allowed for the capture of the details of volcanic unrest in the run-up to the 2021 eruption. A preliminary evaluation of this unrest, and of the style and impact of the ensuing and ongoing eruption, offers valuable lessons for eruption forecasting, hazard assessment, and risk management in the Canaries and similar volcanic islands.

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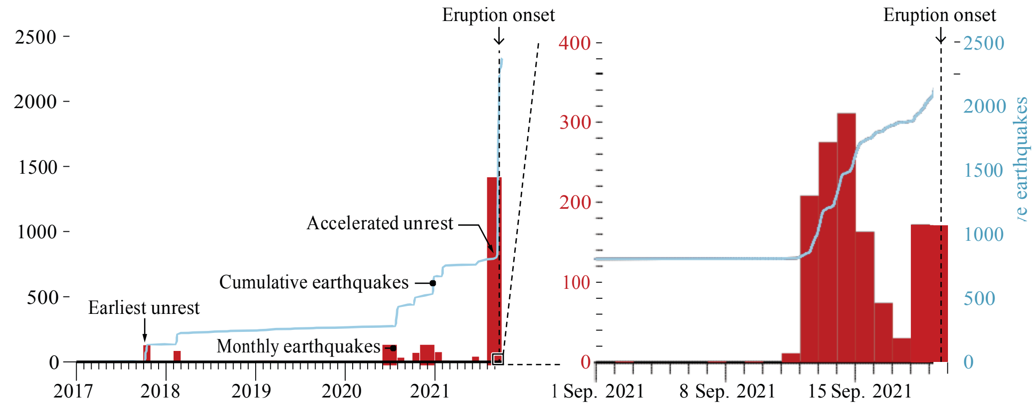
The IGN earthquake catalog (*3*) indicates very low background seismicity beneath La Palma in the interval from 2000 to 2016, with only six low-magnitude events. In October 2017, however, an earthquake swarm was detected, comprising 128 events over 8 days, and a similar cluster of 84 earthquakes recurred in February 2018 (see the figure). Most of these events and subsequent pre-eruptive earthquakes ranged in magnitude from 1 to 2. In hindsight, these discrete, 15- to 30-km-deep seismic swarms likely mark the earliest sign of volcanic unrest (*4*, *5*)—although some have placed it even earlier (*6*)—and they may represent forerunner magma intrusions at mantle depth. Seismic activity returned to comparatively low levels for the following 2.5 years, with only 53 located events from March 2018 to June 2020, but picked up again in late July 2020. Six distinct swarms, ranging from 14 to 160 events, occurred between July 2020 and February 2021. Nevertheless, the next 6 months were relatively quiet, with minor clusters of 39 and 14 earthquakes occurring in June and August 2021, respectively. Notably, hypocenter modes show a deepening trend from October 2017 (20 to 25 km) to June 2021 (30 to 35 km) but return to 20 to 25 km in August 2021, possibly reflecting magma plumbing dynamics.

Beginning on 11 September 2021, the patterns in precursory unrest changed substantially. The number of detected earthquakes rapidly increased to several hundred daily, of which only a subset have been located. These events clustered at much shallower depths (<12 km) and were of greater mean magnitude than previous seismicity. Notably, and in contrast to earlier swarms, this activity was accompanied by marked ground deformation recorded by GPS and interferometric synthetic aperture radar (InSAR) (*7*), presumably caused by shallow magma migration. This accelerated run-up provided only 8 days of warning for an imminent eruption, which started at 14:10 UTC on 19 September 2021. Relocated earthquakes of the 11 to 19 September sequence reported by IGN show a remarkable shallowing trend and migra-

Cumbre Vieja reactivates

After 50 years of quiescence, sporadic and low-magnitude seismicity beneath the volcano started up in 2017. However, a sudden increase in the number of earthquakes occurred only 8 days before the eruption began. Data from (*3*).



tion to the northwest—toward the eventual eruption site.

Two eruptive fissures about 200-m long broke out on the northwestern flank of the ridge-shaped volcano, at 1 km above sea level and 2 km east of the village of El Paraíso. Timely evacuation of the residents living downslope of the vents proceeded smoothly. From the beginning, the eruption was both explosive and effusive, and pyroclastic activity of Strombolian style rapidly built a main cone and fed lava flows, initially traveling at 700 m/h (*7*). Lava bulldozed through densely settled areas and had destroyed ~2600 buildings, >70 km of road, and 2.3 km^2 of crops within 6 weeks. In comparison, the 2018 eruption of Kīlauea volcano destroyed 723 buildings over 3 months (*8*). By the end of the ninth day of eruptive activity, the lava reached the coast, adding ~0.4 km^2 of land leading up to the Atlantic Ocean (*7*). The rapid and steady growth of the lava flow field, reaching 9.9 km^2 by 3 November, along with the associated destruction were captured by Sentinel-2 satellite data and reported frequently by the Copernicus Emergency Mapping Service (EMS).

The substantial explosivity of the Cumbre Vieja eruption is somewhat surprising because the extent of this behavior was not clear from the historical records of previous Canary Island eruptions (*2*). Violent Strombolian explosions at the main vent produced sustained, ash-rich eruption columns rising 3 to 6 km above sea level (*9*). This led to widespread volcanic ash fall in various parts of the island, even reaching Tenerife, covering >65 km^2 with thicknesses greater than several millimeters according to Copernicus EMS data. Within 4 weeks, up to 60 cm of ash and lapilli had accumulated at proximal locations, ~1 km southwest of the new cone. Ash fall and accumulation caused sporadic closure of La Palma airport and the cancellation of more than 300 flights (*10*), negatively affecting tourism, a major economic sector of the island. In addition to volcanic ash, the eruption column contained copious amounts of gases. Emissions of sulfur dioxide ranged from 3200 to 53,600 metric tons per day (*7*). Sulfur dioxide clouds remained in the troposphere but drifted thousands of kilometers over parts of Europe, Africa, Asia, and the Atlantic Ocean (*9*, *11*).

Behind images of wreckage in the lava's path hides tragedy for thousands of islanders who have lost their homes. Fortunately, this natural disaster has yet to directly claim human lives, thanks to the coordinated emergency response of local authorities who were well prepared, having gained experience with volcanic crisis management during the 2011 to 2012 submarine eruption near the neighboring island of El Hierro.

With disaster come opportunities. Identifying and dissecting the reactivation of Cumbre Vieja, from its very inception, after five decades of quiescence has tremendous value. The preliminary analysis outlined here suggests that the eruption had been preparing for 4 years. However, unrest accelerated to the point where an eruption seemed likely only 8 days before magma broke the surface. This scenario contrasts with the precursory run-up to the 2011 to 2012 eruption that lasted 96 days and increased more progressively (*12*). More broadly, Canary Island volcanoes defy global relationships between repose and eruption run-up times, both of which are typically shorter at more commonly pictured basaltic volcanoes (*1*). This represents crucial information for eruption forecasting at quiescent volcanoes.

The 2021 eruption of Cumbre Vieja is also a telling example of how basaltic volcanoes may simultaneously produce lava flows and considerable explosive activity. This can cause wide dispersal of potentially harmful volcanic ash that goes well beyond the immediate vicinity of the vent. This presents an opportunity to reassess past eruptions in the Canaries along with related hazards.

Another bright light among dark ash clouds is the international scientific cooperation effort coordinated largely by INVOLCAN. Multi-disciplinary teams on and off the ground are sharing data in near-real time, particularly by means of Twitter (*13*), which allows for rapid knowledge buildup and efficient dissemination to the public.

The eruption currently shows no sign of waning, which is expected because historical eruptions have lasted between 3 weeks and 3 months (*2*). When it does end, the resilient people of La Palma will recover and rebuild their communities. But someday, perhaps in a future distant enough as to challenge collective memory, the volcano will erupt again, in a different location. A similar social dilemma arises as that which has been described at Kīlauea volcano (*8*): Will the stakeholders do the necessary long-term planning to permanently reduce risk associated to urban development on the flanks of Cumbre Vieja?

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Marc-Antoine Longpré

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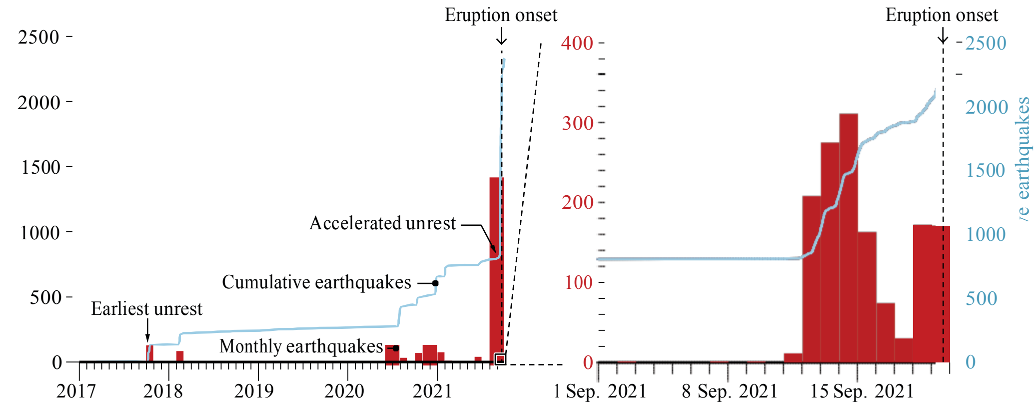

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