VOLCANOLOGY

Deep long-period earthquakes generated by second boiling beneath Mauna Kea volcano

Aaron G. Wech[1]*, Weston A. Thelen[2], Amanda M. Thomas[3]

Deep long-period earthquakes (DLPs) are an enigmatic type of volcanic seismicity that sometimes precedes eruptions but mostly occurs at quiescent volcanoes. These earthquakes are depleted in high-frequency content and typically occur near the base of the crust. We observed a near-periodic, long-lived sequence of more than one million DLPs in the past 19 years beneath the dormant postshield Mauna Kea volcano in Hawai'i. We argue that this DLP sequence was caused by repeated pressurization of volatiles exsolved through crystallization of cooling magma stalled beneath the crust. This "second boiling" of magma is a well-known process but has not previously been linked to DLP activity. Our observations suggest that, rather than portending eruptions, global DLP activity may more commonly be indicative of stagnant, cooling magma.

The exsolution of magmatic gases, or volatiles, plays a fundamental role in controlling eruption behavior and governing magma ascent beneath volcanoes. As magma ascends, the reduced confining pressure allows the dissolved gases to decompress. Bubbles nucleate and grow as they exsolve from the magma. This initial volatile exsolution occurs over time scales of seconds to minutes (*1*). Most magmas never reach the surface [e.g., (*2*)], but even stalled intrusions continue to degas. As the magma cools, it crystallizes, which gradually raises the volatile concentration in the residual liquid and results in continued exsolution over much longer time scales. This subsequent process, known as "second boiling," is often used to explain shallow volcanic activity [e.g., (*3*)], but little is known about its role at depth, and direct observations have been elusive.

We gain insight into the processes occurring beneath volcanoes by analyzing seismic signals, but we do not understand the origin of all of these signals. Many volcanoes produce occasional bursts of low-frequency earthquakes in the midcrust to upper mantle (*4*). These earthquakes are known as deep long-period earthquakes (DLPs) because of the dearth of high-frequency energy (>5 Hz) compared with normal earthquakes. These events sometimes provide the earliest indication of future volcanic unrest (*4*), but most occur in isolated bursts without any current or subsequent surface activity; inexplicably, many occur beneath dormant volcanoes. Despite numerous proposed models explaining the origin of DLPs, no consensus exists on what physical process is responsible for their generation. DLPs are often attributed to fluid movement at depth (*4*), which may signal a magmatic intrusion. We show that the long-dormant Mauna Kea volcano in Hawai'i exhibits repetitive DLP seismicity unlike anywhere else on Earth.

Mauna Kea volcano is the highest peak on the Island of Hawai'i (Fig. 1) and, when measured from the seafloor, is also the tallest mountain in the world. In addition to being culturally important for Hawaiians, Mauna Kea hosts a dozen astronomy research facilities at its 4205-m summit. This shield volcano formed over the Hawaiian hot spot 1 million years ago as part of the Hawaiian-Emperor seamount chain (*5*). Northwest motion of the Pacific Plate, however, has gradually decreased magma supply from the mantle to Mauna Kea as Hawaiian volcanism shifts to the younger Mauna Loa, Kīlauea, and Lō'ihi volcanoes. Mauna Kea erupted at least eight times during the past 41,000 years, with the most recent eruption occurring ~4500 years ago (*6*). The volcano is now in the postshield stage, as the reduced magma supply can no longer sustain shallow crustal reservoirs, and magma storage has shifted to deeper within the lower crust and upper mantle (*7*). DLPs beneath Mauna Kea provide a singular opportunity to probe deep magma storage and investigate the role of magma cooling in generating DLP seismicity.

Traditional earthquake detection algorithms routinely overlook DLPs. We initially recognized DLP activity through envelope cross-correlation (*8*) and visual inspection. We used a single-station template matching technique to identify 1,051,617 DLPs with magnitudes ranging from ~1.2 to 1.5 (*9*). These DLPs exhibited a variety of patterns on time scales spanning minutes to years (Fig. 2). The most notable feature of the time series was the near-periodicity of high-amplitude events on a decades-long time scale. Overall, events repeated with interevent times of 7 to 12 min, and this periodicity was punctuated, at times, with many smaller subevents between higher-amplitude events (Fig. 2A). We also saw both smooth fluctuations of interevent times on time scales of hours to days as well as abrupt shifts in interevent times on minutes-long time scales (Fig. 2E). Activity was occasionally irregular, but interevent times also rarely exceeded 12 min, even when activity was less periodic (Fig. 2D). Subevents had smaller magnitudes than periodic events (Fig. 2, A and G). Similarly, shorter periodicities resulted in smaller magnitudes (Fig. 2, A and E). The dependence of size on recurrence interval results in relatively constant total energy release (Fig. 2C), which suggests that a stable, continuous process controls activity.

The DLPs occurred 22 to 25 ± 3.3 (SD) km below sea level (*9*), directly above an anomalous low *P*-wave velocity (V_p) zone surrounded by a ring of tectonic earthquakes (Fig. 1). These tectonic earthquakes radiated higher frequencies and were likely caused by lithospheric flexure under the weight of the volcanic edifice (*10*). Regional tomography indicates the low V_p zone extends down from the base of the crust (*11*), although the exact location of the Mohorovicic Discontinuity (Moho) between the crust and the mantle is not well constrained in this location. Seismic refraction data show a dipping Moho discontinuity down to depths of ~18 km beneath neighboring Mauna Loa volcano (*12*). Whether the oceanic lithosphere is broken under the island load remains an open question (*13*). We argue for the existence of a hot, ductile zone on the basis of the low-velocity zone directly below the summit of Mauna Kea inside a halo of tectonic earthquakes. We interpreted the low V_p to mark partial melt ponding at the base of the crust, which is consistent with a decreased magma supply from the mantle hot spot.

We inverted *P*-wave first-motion polarities from stacked waveforms (*9*) that resulted in a mechanism composed of a positive tensile crack and a vertical compensated linear vector dipole (CLVD), suggesting a complex, volumetric source with very little double-couple faulting (Fig. 1A). Standard moment tensor decomposition yielded 24% positive isotropic, 61% CLVD, and 15% double-couple components. These values deviate markedly from tectonic faulting, which we interpreted as evidence of a volcanogenic source.

DLP amplitudes and interevent times were occasionally affected by the passing of seismic waves from local, regional, and teleseismic earthquakes (*9*). The triggered responses manifested in different ways but typically resulted in an increase in subevents (Fig. 3A and figs. S1 and S2). In most cases, DLP activity changes occurred on the order of one interevent cycle (7 to 12 min). Not all earthquakes triggered a DLP response. This likely indicated that the state of the DLP source region and properties of the passing seismic waves (e.g., amplitude, direction) were important factors in triggering. For teleseismic events, DLP activity became more regular after the passage of the surface waves,

[1]U.S. Geological Survey, Alaska Volcano Observatory, Anchorage, AK, USA. [2]U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, WA, USA. [3]Department of Earth Sciences, University of Oregon, Eugene, OR, USA.
*Corresponding author. Email: awech@usgs.gov

suggesting a potential frequency dependence as well (Fig. 3A and fig. S2). Associated dynamic stress perturbations that elicited a response ranged from hundreds down to a few kilopascals (*9*)—orders of magnitude below lithostatic stress and comparable to tidal stresses imparted at those depths. We calculated the stress field time series from ocean and solid earth tides and found that the DLP rate was suppressed during times of increased compressive stress (pressure) with >99% confidence (Fig. 3B) (*9*).

DLPs often have CLVD moment tensors (*14*), resulting from a variety of different mechanisms (*15*–*17*). Most of these mechanisms involve complex shear with no net volume change, but our observations require a positive isotropic component, which suggests that positive tensile faulting plays a role in the CLVD mechanism (Fig. 1A). For Mauna Kea, we prefer a mechanism that involves pressure-driven mass transfer between a nearly vertical cylinder and a horizontal crack (Fig. 4B). Mass flux in this geometry produces a vertical CLVD by the expansion of the crack together with a volume-compensated contraction of the cylinder (*18*).

This mechanism accounts for the moment tensor observations, but the exact crack geometry is unconstrained and ultimately depends on a structure specific to Mauna Kea. Far more important is the underlying process driving repeated DLP activity. Although the aforementioned mass flux could involve magma transport, we consider this unlikely. Mauna Kea is a dormant volcano in the postshield stage with no surficial signs of magma ascent. Increased separation from the Hawaiian hot spot has decreased Mauna Kea's magma supply and shifted magma storage deeper, leaving an abundant store of cooling magma ponded beneath the Moho. An attractive alternative is that volatiles exsolved via second boiling of these stalled magmas drive DLP seismicity. Unlike decompression-driven exsolution, which occurs on short time scales and requires magma ascent, second boiling relies on stalled intrusions and can take hundreds to thousands of years, providing a long-term, nearly continuous supply of volatiles as the cooling magma crystallizes. We propose that a continuous flux of volatiles exsolved from second boiling migrates upward through a matrix of fractures to repeatedly pressurize a complex reservoir system and generate DLP seismicity at Mauna Kea (Fig. 4B). This explanation accounts for the different moment tensor components, and it also elucidates the most interesting part of the DLP observations—the periodicity and longevity.

Our interpretation suggests that volatile exsolution from cooling magma drives Mauna Kea's DLP seismicity. Previous work has shown that shear failures driven by thermal stresses associated with contracting, cooling magma can produce DLP earthquakes with CLVD moment tensors (*17*). This mechanism may occur beneath some volcanoes, but it is inconsistent with the observed earthquake and tidal triggering of DLPs beneath Mauna Kea.

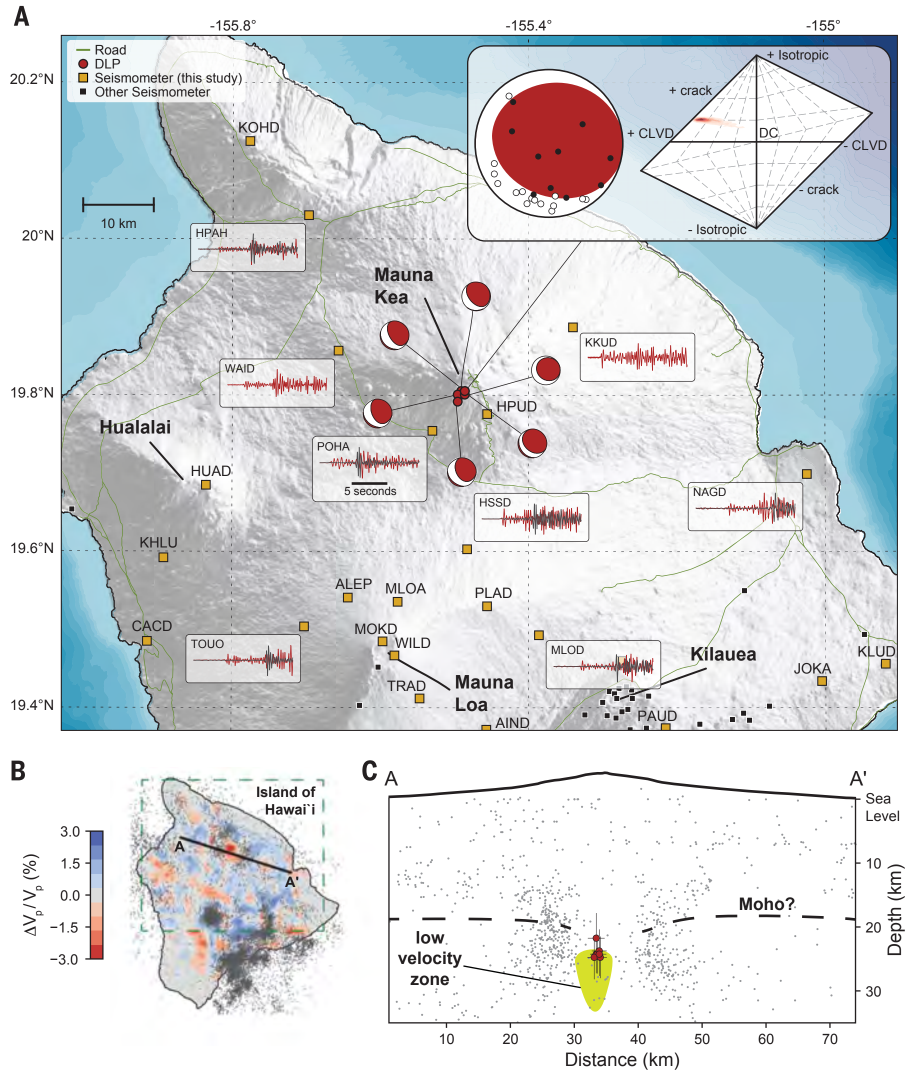

Fig. 1. Map and cross section of the study region. (**A**) Map of Mauna Kea volcano showing deep long-period (DLP) events (red circles) and seismic stations (squares), with station names labeled. Example waveforms show 15 s of vertical (red) and transverse (black) components. Inset shows focal mechanism for one event and its corresponding probability density function sampling the moment tensor space on a Hudson plot. (**B**) Overview map of the Island of Hawaiʻi. Colors show deviations in average *P*-wave velocity (V_p) (*11*) below the DLP source at a depth slice of 30 km. Gray dots indicate earthquakes deeper than 20 km. Boxed portion corresponds to area shown in (A). (**C**) Cross section showing all earthquakes (gray dots) and DLPs (red circles; mean ± SD) within 5 km of the A–A′ transect in (B). Dashed line depicts possible Moho location. Yellow feature depicts low-velocity zone from tomography.

We attribute DLP rate changes from stress perturbations to dynamic changes in permeability (*19*). Compressive stress from tidal loading would reduce pore space, temporarily decreasing permeability, and consequently restrict volatile flux. A decrease in flux to the DLP source crack will increase the time it takes to pressurize and subsequently fail, resulting in an increase in recurrence interval and decrease in overall DLP rate. Meanwhile, extensional stress would have the opposite effect. Similarly, stress oscillations from passing seismic waves can temporarily increase permeability and subsequent fluid flow (*19*), which explains our observed earthquake-triggering response.

The continuous deep activity does not mean that a Mauna Kea eruption is imminent. On the contrary, our interpretation suggests that these DLPs result from cooling magma, not ascending magma. Although DLPs can be harbingers of future eruptions—possibly reflecting decompression-driven exsolution—most are not. Second boiling provides an alternative explanation for background DLPs

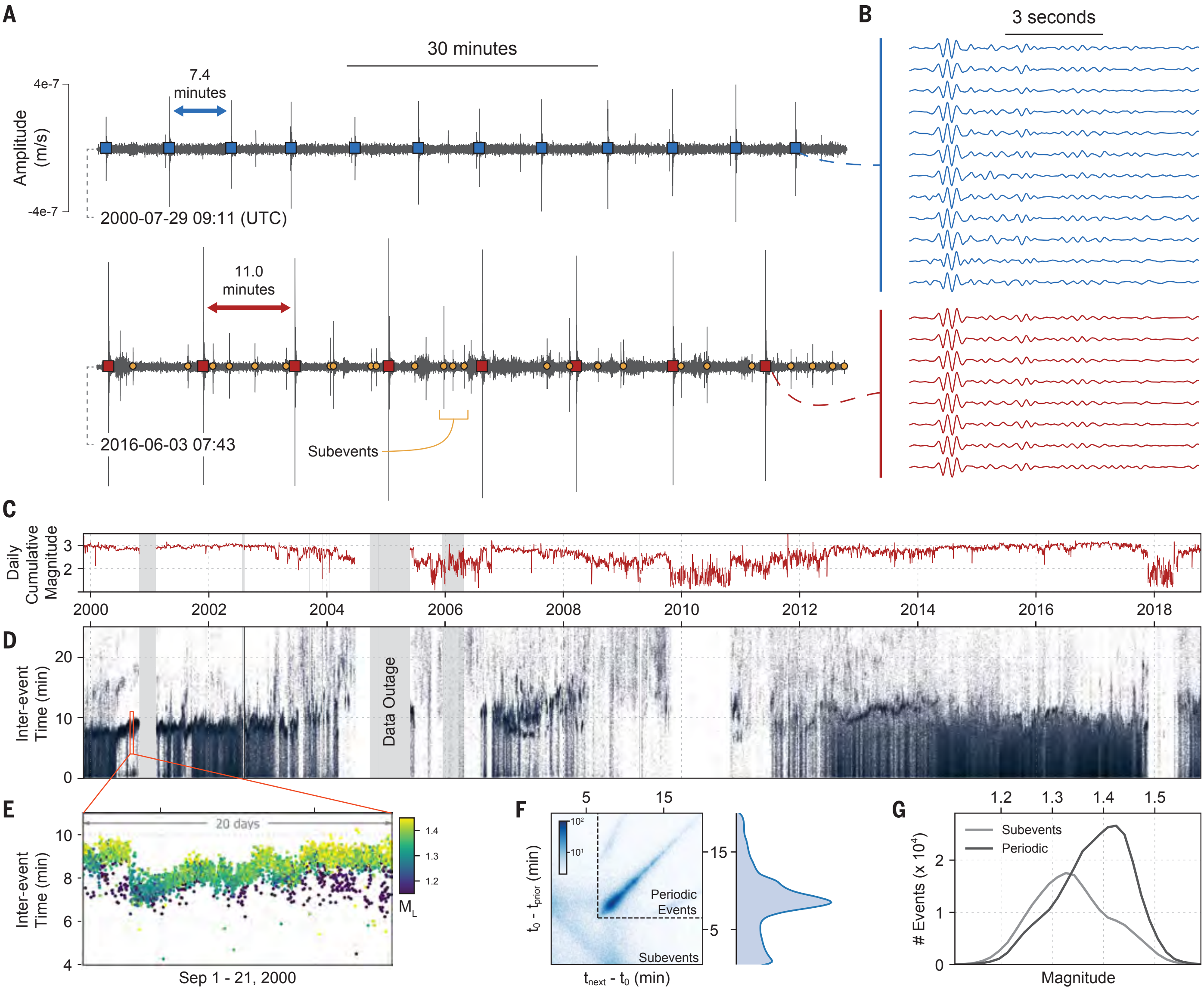

Fig. 2. DLP activity summary. (**A**) Example waveforms from seismic station POHA showing 90 min of 2 to 7 Hz horizontal (BHE) data recorded in July 2000 and June 2016. High-amplitude events are marked with squares corresponding to waveforms in (B). Small orange circles mark smaller subevents detected in 2016. (**B**) Normalized, time-aligned 9-s waveforms of high-amplitude events from (A). (**C**) Daily cumulative magnitude for all detected events. (**D**) Time versus interevent time (*y* axis) of all detected DLPs. (**E**) Expansion of axes indicated with red box in (D). Points are colored according to DLP magnitude. (**F**) Density map time plot comparing time to next event (*x* axis) with time since previous event (*y* axis) for all events correlating > 0.7. Lines at 6.5 min separate periodic events from subevents for distributions in (G). Corresponding kernel density estimation of time since previous event is shown on the right. (**G**) Magnitude distribution for periodic (dark gray) and subevents (gray).

that is applicable to volcanoes generally. Mauna Kea's DLP source mechanism results from a particular crack geometry, which will vary between volcanoes, but second boiling is ubiquitous. Many volcanoes have deep magma storage with a discontinuous magma supply, and most magmas never reach the surface. This means that second boiling may be a substantial source of DLPs worldwide and that the occurrence of most DLPs does not signal magma ascent or impending eruptive activity (Fig. 4A). Second boiling provides an explanation for why many DLPs concentrate near the base of the crust, as this is the discontinuity where magma is most likely to stall. Our hypothesis may also explain nonvolcanic DLPs (*20*) as the result of stalled deep intrusions.

We identified persistent, periodic earthquakes deep beneath Mauna Kea volcano that repeated every 7 to 12 min for decades. To put this observation into broader context, the cumulative energy release equates to a magnitude 3 earthquake every day (Fig. 2C). Activity of this magnitude under any volcano would be notable, but its presence beneath the dormant Mauna Kea volcano is even more surprising. Shallow repeating seismicity can occur at volcanoes, reflecting different physical processes [e.g., (*21*)], but deep earthquakes repeating with such regularity for so long have not been previously documented. Our waveform stacking provides high-fidelity waveforms that reflect the DLP source process, and the ongoing signal provides a tool for probing conditions deep beneath the dormant volcano. The range of behaviors we observed should change

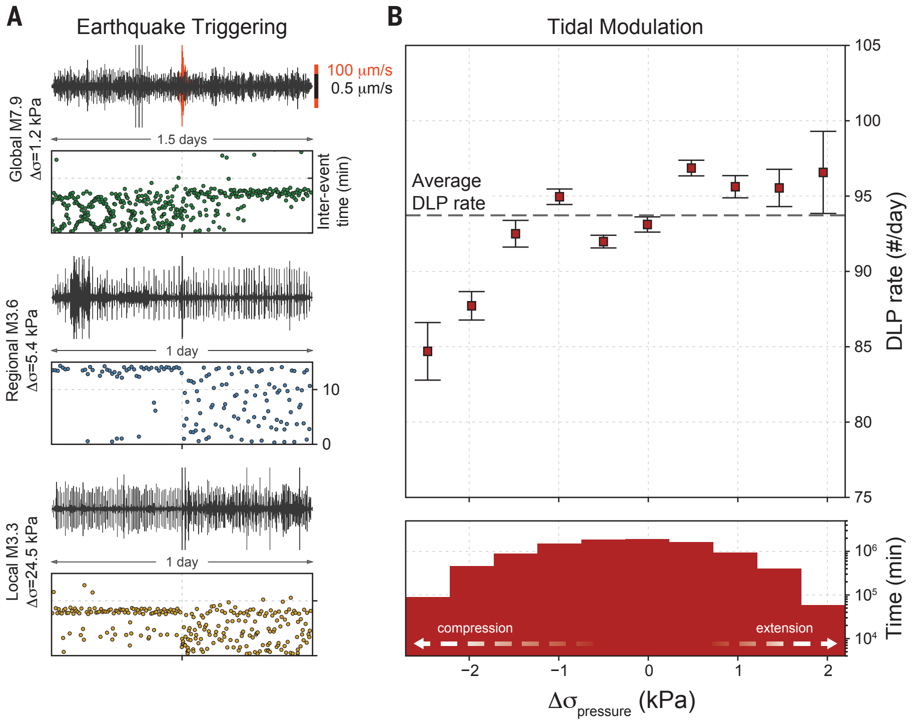

Fig. 3. DLPs affected by external stress. (**A**) Triggering examples from global (top, green), regional (middle, blue), and local (bottom, gold) earthquakes. Δσ is peak dynamic stress calculated for each earthquake (9). Black waveforms are 2 to 7 Hz bandpass filtered, and the red waveform is filtered from 0.02 to 0.2 Hz to capture teleseismic surface waves. Scatterplots show interevent times. (**B**) DLP rate in number of events per day calculated for each stress bin (top), where negative stress signifies compression, and the amount of time the tides induced the stresses in each bin (bottom).

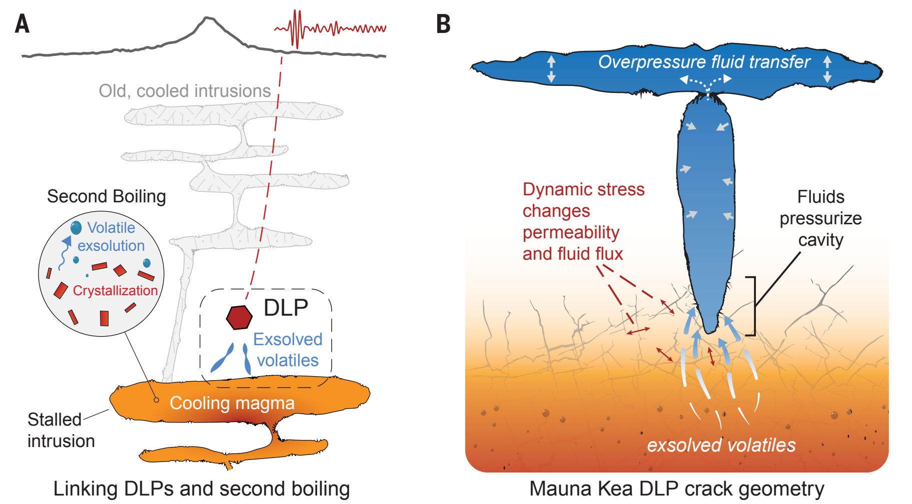

Fig. 4. Linking second boiling and DLPs. (**A**) Cartoon showing second boiling of stalled magma exsolving volatiles to generate DLPs. (**B**) Exsolved volatiles percolate through a matrix of fractures to pressurize a vertical cavity beneath Mauna Kea. Fluid transfer to the horizontal crack generates DLP seismicity. Dynamic stress from passing seismic waves or tidal loading causes changes in permeability, which affects the fluid flux into the cavity.

our understanding of the seismogenic role of deep volatiles and the interpretations of DLPs.

While underlying crystallization-driven exsolution may explain background DLPs generally, there is no analog for deep earthquakes behaving like they do beneath Mauna Kea, and we do not expect DLPs to manifest in this way in many places. Volatiles usually move through the lower crust aseismically. It may be that the long repose time at Mauna Kea has allowed for fluids to create more established, focused pathways in the lower crust, which would make longer-dormant volcanoes more likely candidates for abundant DLPs. Or perhaps Hawai‘i's thinner crust, relative to continental arcs, better facilitates the generation of seismic waves. Nevertheless, an important result of this discovery is that it underscores the possibility of unexpected signals hidden beneath other volcanoes, which may improve our understanding of volcanic processes. The Island of Hawai‘i is relatively well instrumented and has been heavily researched for many decades, yet more than a million periodic DLPs went unnoticed for almost two decades. This overlooked activity does not reflect negligence but instead highlights the limitations of routine processing and traditional monitoring techniques in volcano seismology. We expect careful, systematic searches to reveal DLP activity at many other volcanoes.

Our model provides a new framework for interpreting DLPs that does not imply an increased volcanic hazard. DLP swarms or DLPs at persistently erupting volcanoes still likely signal magmatic intrusions. But at volcanoes with low magma supply rates and/or long repose times, the occurrence of DLPs, in the absence of other anomalies, is likely just a reminder of the continuous, active processes associated with deep, cooling magma.

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SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/368/6492/775/suppl/DC1
Materials and Methods
Figs. S1 and S2
References (*23*–*39*)

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Deep long-period earthquakes generated by second boiling beneath Mauna Kea volcano

Aaron G. Wech, Weston A. Thelen and Amanda M. Thomas

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Rumblings of a dormant volcano

Earthquakes near volcanoes are often a warning sign of a future eruption. However, deep long-period earthquakes (DLPs) are a special type of seismicity tied most often to quiescent volcanoes. Wech *et al.* found more than a million of these DLPs under the inactive Mauna Kea volcano in Hawai'i over the past 19 years (see the Perspective by Matoza). Analysis of this large number of observations allowed the authors to conclude that the DLPs were connected to a deep, cooling magma body. Deep gas releases triggered by minerals crystallizing in the deep magma through the "second boiling" process may open cracks, triggering the DLPs.

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