Eos

An Unprecedented Experiment to Map Kīlauea's Summit Magma System

Dozens of researchers deployed nearly 2,000 seismic stations—and a T-Rex—to better illuminate subsurface structure and magma storage below the summit of the highly active volcano.

By **Roger Denlinger**, **Daniel R. H. O'Connell**, **Guoqing Lin**, **Steve Roecker,** and **Ninfa Bennington**
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Kīlauea volcano, on the island of Hawai'i, erupts on 13 June 2023. Credit: Janice Wei/National Park Service

Kīlauea volcano, on the island of Hawai'i, is fed by the Hawaiian hot spot, a plume of buoyant rock and magma that rises through Earth's mantle and crust. As one of the most active volcanoes in the world, it has for centuries drawn scientific observers to the island, which became the site of one of the earliest volcano observatories.

Kīlauea has been probed, interpreted, and **studied intensively**, revealing much about the **inner workings** of basaltic volcanoes. Nevertheless, despite comprehensive research on nearly every aspect of this volcano, a clear picture of the size and configuration of Kīlauea's magmatic plumbing system has proved elusive.

Past efforts to estimate or indirectly image the extent of Kīlauea's magmatic system have yielded broad ranges of possibilities. The volume of the magma system from geodetic, seismic, geologic, and petrologic data has been estimated to be anywhere from 0.2 to 240 cubic kilometers [*Decker*, 1987; ***Denlinger***, 1997; ***Fiske and Kinoshita***, 1969; ***Pietruszka et al.***, 2015; *Poland et al.*, 2014]. Storage systems interpreted from diverse data have varied from a plexus of dikes and sills with little connectivity among them to several large, subterranean bodies with well-established connections. No dominant consensus emerged from these studies.

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Then a catastrophic change occurred. In early May 2018, a huge dike propagated 20 kilometers eastward from the volcano's active Puʻu ʻŌʻō vent on the East Rift Zone to Leilani Estates, followed soon by a magnitude 6.9 earthquake as the massive south flank of the volcano suddenly lurched seaward [***Neal et al.***, 2019]. The dike and flank movement opened a continuous conduit from Leilani Estates to the summit, and from May to August this conduit drained 15 years of magma supply (1.5 cubic kilometers) from the East Rift Zone and summit magma storage systems.

This drainage was driven by a **piston-like collapse of the caldera** within Kīlauea's summit region (Figures 1 and 2) [***Anderson et al.***, 2019]. The resulting voluminous lava flows damaged major infrastructure and destroyed **nearly 2,000 homes**. Scientists' ability to forecast the volume and duration of both the major summit collapse and accompanying eruptions was inhibited by the lack of a definitive understanding of Kīlauea's subsurface structure and how it could operate.

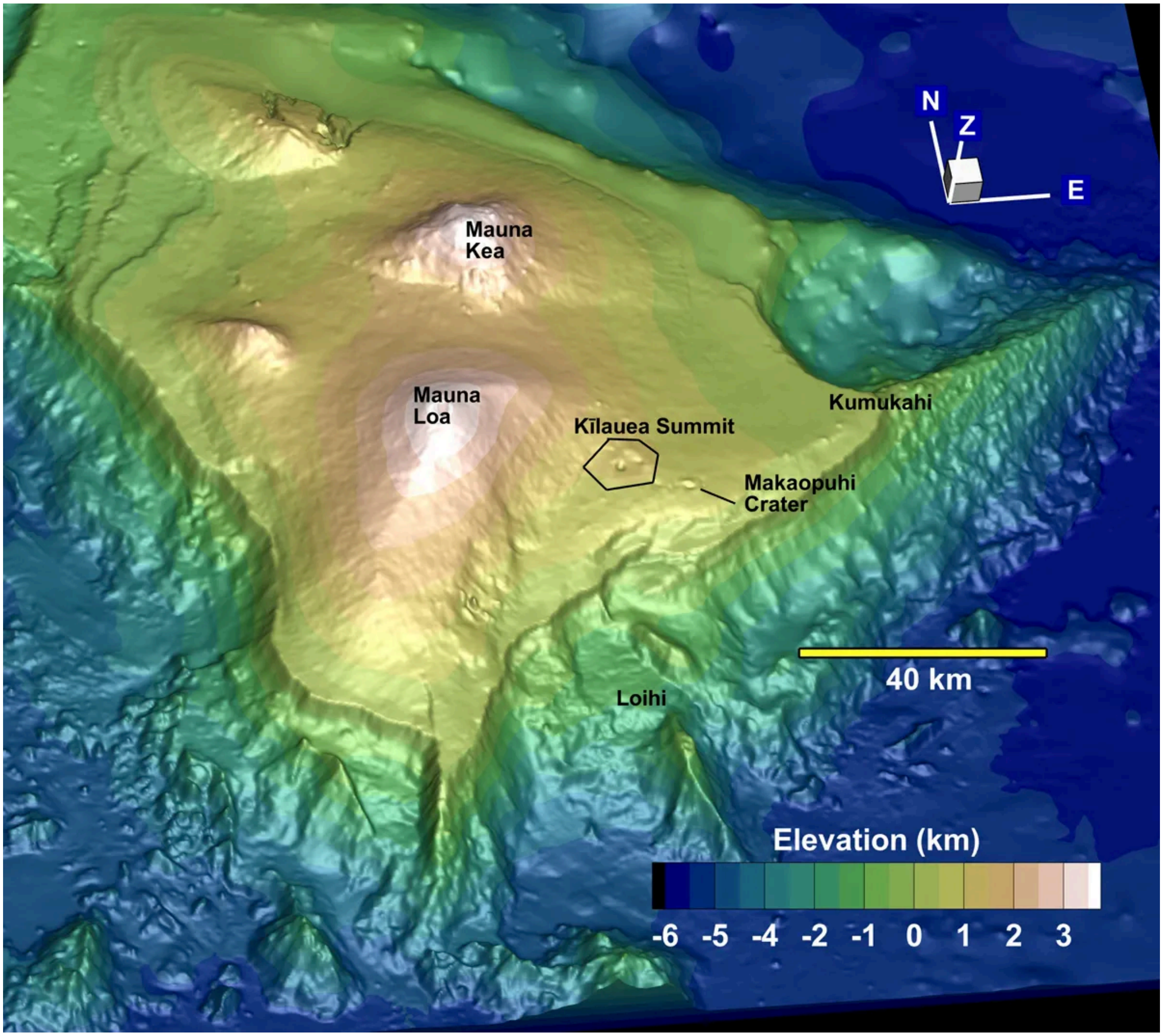

Fig. 1. The summit of Kīlauea and its proximity to the active volcanoes modifying the growing southern half of the island of Hawai'i are seen in this topographic perspective view. As Kīlauea grows, it pushes its south flank seaward over the underlying seafloor, forming an offshore bench and growing the prominent ridge shown extending east offshore Kumukahi. The recent imaging survey focused on the summit of Kīlauea, outlined in black here. Credit: [*Denlinger and Okubo*](#) [1995]

The 2018 eruption was the most catastrophic event on Hawaiian volcanoes in the past 200 years and fundamentally changed our understanding of the volume of magma stored in Kīlauea's summit region. The storage volume is much larger than previously accepted, but we are still in the dark as to exactly how this magma is distributed within the volcano. This distribution has implications for geologic hazards on the volcano.

In recent geologic history Kīlauea's summit eruptions have mostly been effusive, or nonexplosive. This behavior stands in contrast to geologic evidence for the formation of Kaluapele (Kīlauea's caldera) around 1500 CE, which was followed by **about 3 centuries of explosive volcanism**. Although additional eruptions since 2018 have shown that a more explosive future is highly unlikely for Kīlauea, flow and faulting hazards persist. Having accurate subsurface information about magma storage is crucial to improving our forecast capabilities and responses to volcanic events as the volcano evolves.

Following the 2018 eruption, Congress provided supplemental funding under the Disaster Relief Act of 2019 (see Acknowledgments) to the U.S. Geological Survey (USGS) to replace the instruments and facilities of the Hawaiian Volcano Observatory (HVO) lost in the eruption and to support research to better understand Kīlauea and its hazards. USGS scientists (including three of the authors) proposed a passive imaging experiment to help provide key information and also joined with academic colleagues (the remaining authors) to obtain additional support from the National Science Foundation for active source seismic imaging.

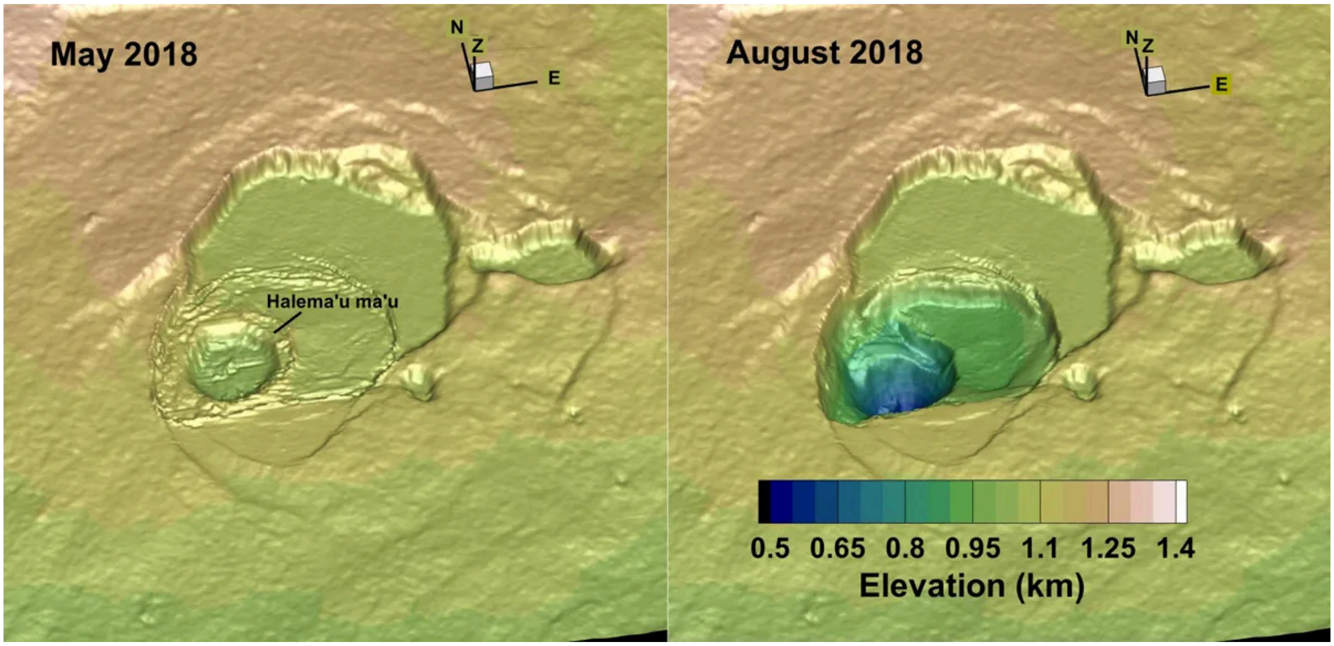

Fig. 2. Detailed topography from lidar imaging at the summit of Kīlauea shows the dramatic collapse of Halemaʻumaʻu that occurred between May and August 2018, when a massive amount of magma drained from beneath the summit and erupted more than 33 kilometers away along the lower East Rift Zone. The elevation scale at right applies for both images.

The **ensuing project**—one of the largest and most ambitious ever conducted at the summit of an active volcano—required years of planning and a strong partnership with the National Park Service (almost all of the survey area is within Hawaiʻi Volcanoes National Park). Damage related to the 2018 summit collapse along with other technical and logistical hurdles associated with the exercise of deploying a massive amount of equipment and marshaling support from numerous participants from multiple institutions complicated this effort. Nonetheless, the deployment and data acquisition for the study were smoothly and successfully completed in April–June 2023. Ongoing analysis of the enormous trove of data acquired (almost 200 million waveforms) will provide the sharpest look yet into the core of this iconic volcano.

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Thinking Big

Our plan for the array called for procuring nearly 2,000 self-contained seismic stations, or nodes, deploying them across the summit (Figure 3), and then retrieving them following the data collection. Each node included a three-component seismometer with an onboard power supply, data storage, and GPS locator. Networked together, the seismic imaging they provide is identical in concept to CT (computed tomography) scans that image the interior anatomy of the human body. However, instead of studying penetrating X-rays we used variations in penetrating seismic wavefronts to illuminate Kīlauea's internal summit structure.

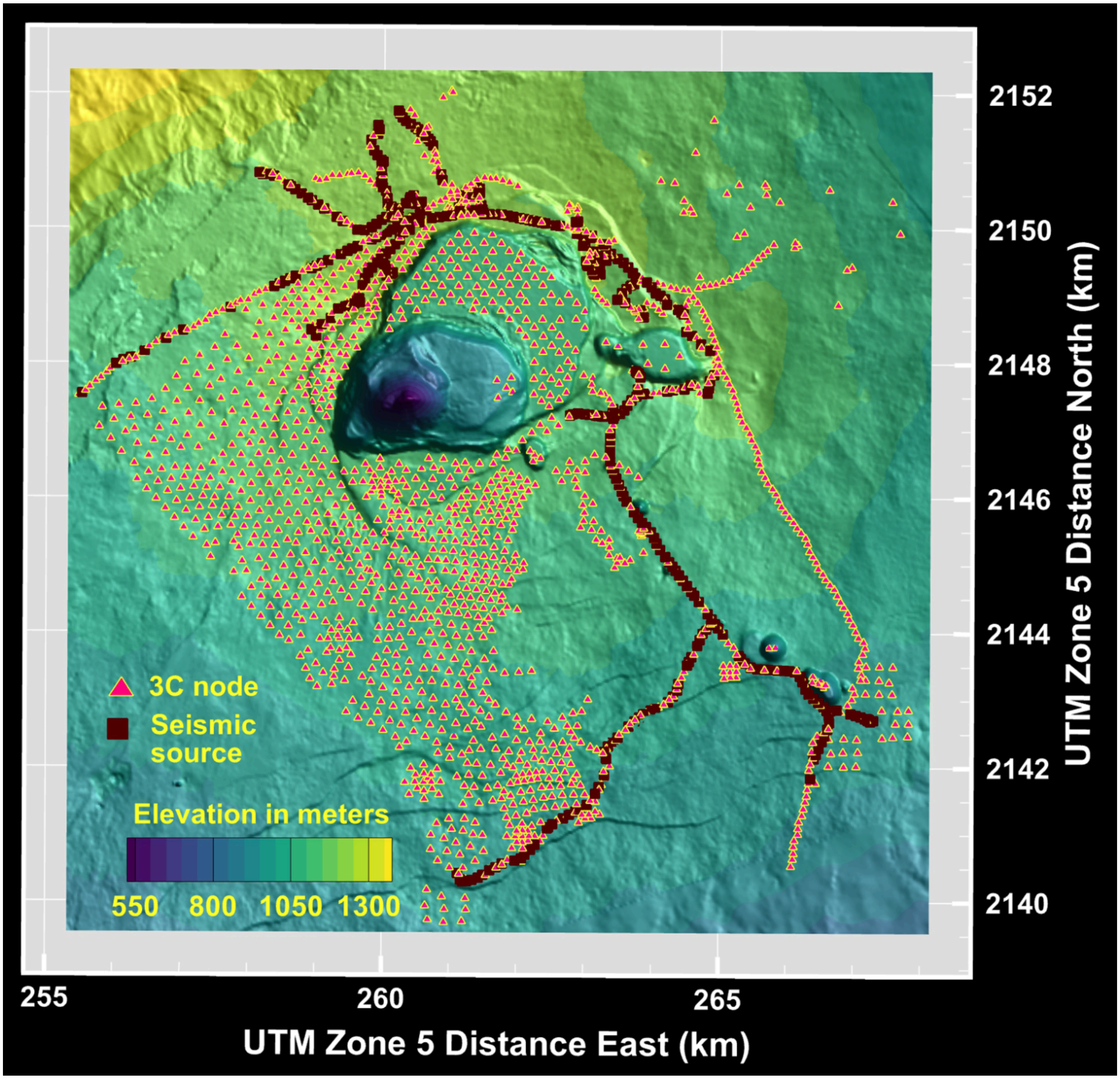

Fig. 3. The seismic network deployed around the summit of Kīlauea was composed of 1,815 three-component (3C) self-contained seismic stations, called nodes. All node locations are shown here. The locations where the seismic source truck T-Rex was deployed are also shown. Fully 3C data were collected from only about a third of these sites because the ability to apply shear waves was limited by the integrity of the pavement and its underlayment. UTM = Universal Transverse Mercator.

HVO had only a limited number of seismic nodes available, so we borrowed an additional 1,580 from the Incorporated Research Institutions for Seismology (IRIS) Consortium's Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL) Instrument Center to build the dense array needed for our survey.

For active (controlled source) seismic surveying, we used a 34-ton triaxial vibroseis shaker truck called [T-Rex] that is managed by the Natural Hazards Engineering Research Infrastructure (NHERI) at the University of Texas at Austin (UT-Austin). This massive beast had to be shipped from Texas to Hawaii, stored at a special facility in the park, and then driven each day to predetermined locations to generate ground vibrations using a roughly 6-square-meter baseplate mounted to its underbelly. These vibrations propagated through the volcano, providing the seismic signals necessary to image the interior.

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Such an experiment, involving thousands of seismic nodes spread across an active volcanic summit like Kīlauea’s, not only is expensive but also requires a large, expert workforce as well as vehicle and helicopter support. Furthermore, because the PASSCAL nodes used can operate for only 30 days at a time, the entire surveying effort had to be completed in that short time frame. Redeployment for longer was not possible because we lacked accessible infrastructure for retrieving, recharging, and quickly downloading tens of terabytes of data from the nodes. Even with a single deployment, the process of deploying and retrieving the nodes, operating T-Rex, and coordinating helicopter flights, all within 30 days, required a well-orchestrated, collaborative effort among the team of USGS and academic scientists with collective experience in both passive and active seismic imaging.

In terms of scale and complexity, this project is the largest field experiment ever carried out on an active volcano, involving far more seismic nodes, a larger active source component, and tighter logistical constraints than earlier experiments such as a 2020 deployment [at Yellowstone caldera](#) or the 2014–2016 [Imaging Magma Under St. Helens](#) (iMUSH). Given its size and complexity, park officials were rightfully concerned about the potential physical impacts of our experiment on the region, which hosts multiple endangered species and which had already been rattled by more than 60,000 earthquakes during the 2018 collapse sequence that significantly damaged park roads and other infrastructure.

The T-Rex vibroseis source operates along Crater Rim Drive just northeast of the abandoned U.S. Geological Survey (USGS) Hawaiian Volcano Observatory (HVO) building and the closed National Park Service Jaggar Museum. T-Rex and its USGS support vehicle (foreground) are flanked by two vehicles for traffic control. Roger Denlinger of USGS walks toward T-Rex after placing accelerometers on the pavement to monitor the intensity of the shaking. If the local ground vibration exceeded a threshold recommended by Hawaii Highway Division engineers, shaking was immediately stopped. Credit: Janice Wei/National Park Service

Team members thus worked closely with the National Park Service to develop a plan to minimize damage from our seismic surveying activities. For example, on the basis of results from preliminary ground-penetrating radar (GPR) surveys done for this project, which revealed features such as shallow underground cavities, we greatly reduced the number of locations where we had originally planned to use T-Rex to generate shaking. Specifically, we eliminated sampling sites on road sections near or over lava tubes, known faults, and natural or human-made voids to avoid causing further damage. With input from the Hawaii Department of Transportation, we also defined a threshold for excessive ground vibrations (2.5 centimeters per second) on their engineered roads. During the project, we deployed accelerometers at each sourcing site so that we could monitor the shaking and shut down immediately when this threshold was approached.

To reduce the impact on visitors to Hawai'i Volcanoes National Park, we also significantly reduced the amount of helicopter flight time we'd planned to reach remote sites inside the park. Instead, we made more use of existing four-wheel-drive-accessible roads in closed areas, and we enlisted additional people and vehicles to increase the number of survey sites located adjacent to both paved and unpaved roads.

As the project was underway, we kept the public informed about our progress with interpretive signs and we stationed scientists at key visitor sites in the summit area. Further, we coordinated with the park to hold on-site training for scientists involved in the fieldwork to ensure their awareness of the cultural sensitivities and endangered species in the park, and we timed the experiment so it would not interfere with the nesting season for nēnē, the Hawaiian state bird.

So Many Nodes, So Little Time

With permissions secured and our plan in place, ground crews deployed the nodes across the volcano's summit. In addition to 1,580 PASSCAL nodes, we used two other kinds of nodes: eighty-three 0.2-hertz nodes from SmartSolo and one hundred fifty-two 2-hertz nodes from Geophysical Technology, Inc. (GTI). As the latter two types have longer-lasting batteries than the PASSCAL nodes, we set them up first. These nodes were first distributed in caches via helicopter in a single morning and then deployed to specific sites by a skeleton crew over about a week's time.

Whereas this initial week of deployments was fairly relaxed, the next stage of setting up the PASSCAL nodes was decidedly unrelaxed. Timing was critical to our strategy, and we had to coordinate road crews, off-road vehicle crews, and helicopter crews simultaneously to keep to the schedule. Once these nodes arrived in Hawaii in a large sea container and were transported to the park, we had just 5 days budgeted to deploy them before we began surveying with T-Rex.

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And there was another wrinkle. The PASSCAL nodes have removable spikes for anchoring them in the ground. Although we used most as is, we had requested that PASSCAL remove spikes from more than 100 nodes so we could deploy them in buckets of sand to be placed on hard surfaces (lava flows) that the spikes wouldn't easily penetrate. Because of the weight and size of the bucketed sensors—roughly 12 kilograms apiece versus 3 kilograms for the typical spiked sensors—we couldn't haul many of them at a time inside the helicopter. So we designed and tested a more efficient means to **sling load** the buckets to remote sites without them tipping, as well as a layout pattern facilitating deployment of these heavy sensors by field crews on foot.

Matt Patrick (left) and Mike Cappos (right) of USGS assemble a sling load to transport bucket nodes by helicopter. Credit: Janice Wei/National Park Service

We transported our assembled bucket nodes to a helicopter staging area, built the slings on site, and then transported them to where they would be deployed. In all other cases, multiple node caches could be transported inside the helicopter along with the person who would place the nodes at each cache site.

The node caches were distributed to nearly three dozen areas around Kīlauea's summit. Although a group of four to six people (the size varied day to day) was able to cache and deploy the 235 SmartSolo and GTI nodes within about a week, more than two dozen people were needed full-time to distribute and activate the 1,580 PASSCAL nodes in the 5 days we allocated for this work before surveying could begin. Retrieval of the nodes was roughly the reverse of the deployment operation, with the addition of a crew stationed at the sea container to facilitate cleaning and repacking of the PASSCAL nodes for shipment back to the U.S. mainland.

Thanks to our team's detailed planning and to superb logistical support from partners at the University of Hawai‘i at Hilo, USGS, and the University of Miami, all deployments and retrieval operations went smoothly and efficiently. All recovered nodes collected data for their full term. Only two nodes—each of which had been installed near lawns in residential areas—were lost. (One succumbed to a lawnmower shortly after being deployed.)

Traversing a Fractured, Faulted Summit

The 2018 caldera collapse that disrupted Kīlauea's summit infrastructure (Figure 2) created unique challenges for data acquisition. We could not drive T-Rex entirely around the summit, for example, because many roads that were destroyed had not been rebuilt. And although T-Rex is a multiply articulated off-road vehicle, we could not drive it across the Ka‘ū Desert south of Kīlauea's summit crater because it would damage sensitive ecosystems. Yet we knew from comprehensive advance testing that confining T-Rex to only the paved roads remaining after 2018 would leave gaping holes in our sampling of the subsurface magma system, complicating our ability to piece together images of this system from the seismic data we collected.

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To help fill these gaps, we relied on ambient seismicity recorded by the node array (Figures 3 and 4). The sensors recorded more than 8,500 shallow earthquakes that occurred within 5 kilometers of the center of Kaluapele and more than 25,000 earthquakes outside the caldera. The detections of these earthquakes provide additional illumination, particularly from the south and west, that we needed to image the upper crustal structure of the summit. This seismicity mitigated the lack of complete surface coverage with the T-Rex controlled source.

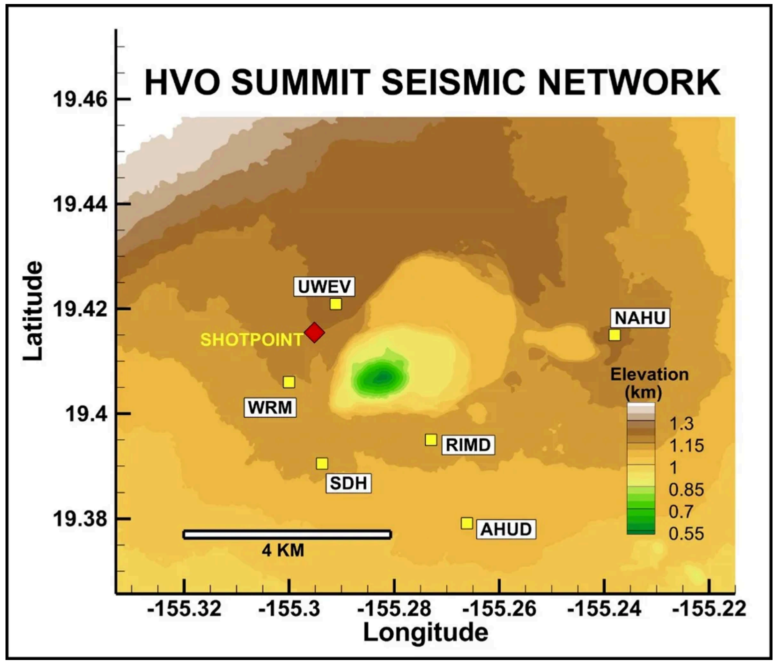

Fig. 4. Permanent USGS HVO seismic network stations (yellow squares) were operating during the survey and also recorded T-Rex vibroseis signals. This network layout spans all of the survey nodes shown in Figure 3 and provided monitoring of signal quality during the experiment. The red diamond represents T-Rex's location when the data in Figure 5 were collected. Click image for larger version.

Even when we could use T-Rex to produce active source seismicity (Figure 5), it was more difficult than expected. With the results of our preliminary GPR survey, we had located proposed sites where T-Rex would shake the ground or pavement, but in practice, many of these sites proved unusable.

Our initial foray with T-Rex was on unpaved roads over old pāhoehoe lava north of the park, in an area near the Volcano Winery just northwest of the town of Volcano. We presumed that solid coupling between T-Rex's steel baseplate and the pāhoehoe, with its relatively smooth, ropy surface texture, would work well for inducing shaking. In addition, weather forecasts predicted daytime winds strong enough to jostle vegetation and vibrate the ground but nighttime winds that were docile. Consequently, we initially chose to run T-Rex in this area at night.

Both of these plans proved untenable. Though the pāhoehoe on the unpaved road surface appeared to be nearly flat, it was not flat enough to keep from unevenly loading T-Rex's baseplate and punishing the truck's hydraulic drive systems. And the wind never did die down. So we adjusted our plan and started operating T-Rex at dawn, keeping it on pavement to maintain uniform loading of both the road surface and T-Rex's hydraulic and mechanical systems. Even so, we had to use care in operating the massive T-Rex machine on pavement. To avoid road damage, we coated T-Rex's steel baseplate with rubber, monitored the ground response during use, and immediately stopped shaking and moved to the next source position if the peak ground velocity approached the 2.5 centimeter-per-second threshold.

We found that the ground-shaking response was far more variable than we had expected from our GPR survey. In particular, we found that resonances induced by the shaking and signal attenuation with distance from the T-Rex conspired to limit our ability to collect usable data at many locations. Because of the unpredictable ground responses, we were able to gather useful data at fewer than 400 sites out of the more than 700 we initially proposed.

For some locations where we could achieve good coupling, we observed first arrivals of compressional seismic waves (*P* waves) from vertical shaking across the entire deployed network of nodes (Figures 3, 4, and 5). At many of those same sites, we saw that the velocities of compressional waves generated by T-Rex were persistently and astonishingly low in the first 100 meters of depth, possibly resulting from pervasive fractures and voids within the surface lava flows. This low near-surface *P* wave velocity proved to be the norm at most sites we surveyed, and we found that by using this information to modify the existing velocity structure beneath Kīlauea's summit, we could determine earthquake locations more accurately.

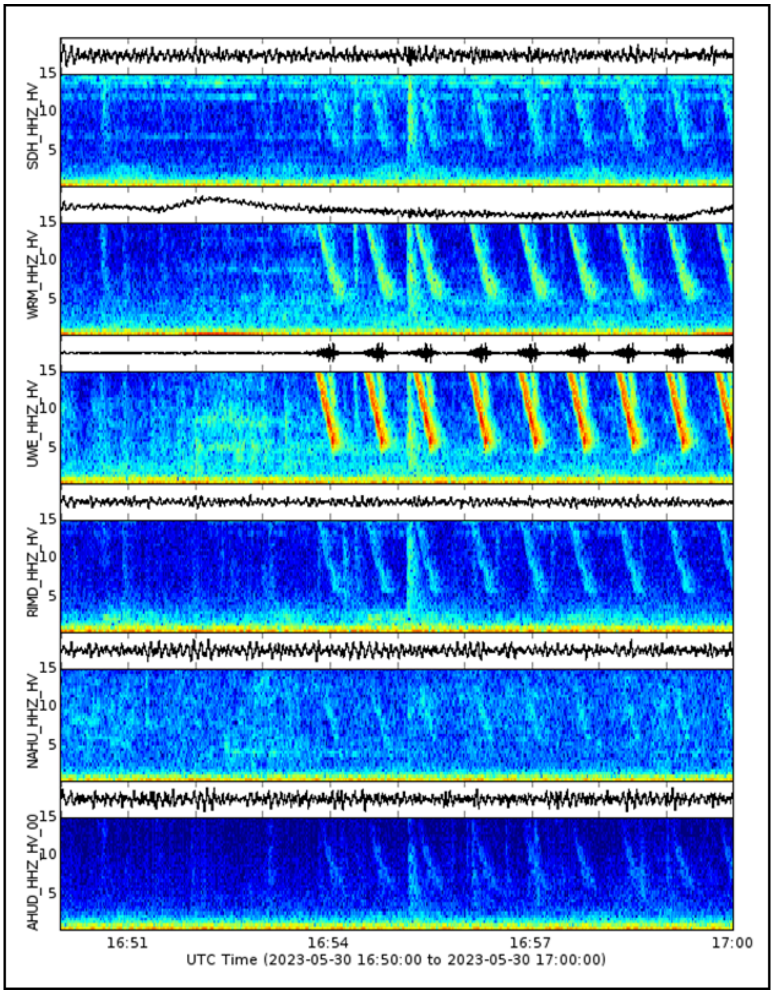

Fig. 5. Spectral signals from nine T-Rex vibroseis vertical sweeps (a sweep is a vibratory loading of the baseplate over a programmed frequency range) recorded by the HVO seismic stations identified in Figure 4 are shown here, with frequency in hertz on the vertical axis. In each sweep, the vibration frequency of T-Rex's baseplate was decreased from about 28 to 5 hertz. Click image for larger version. Credit: Wes Thelen/USGS

Imaging Kīlauea's Summit Structure Anew

Our imaging will have significant consequences for continued study of Kīlauea. Previous seismic and gravity studies yielded a basic framework of the volcano's magma system defined by seismicity and by accumulation of dense olivine in this system [*Denlinger and Flinders*, **2022**, **2024**; ***Flinders et al.***, 2013; ***Lin et al.***, 2014]. We used this earlier work and the results of numerous geodetic studies of eruptions to design this experiment, targeting areas in the upper 6 kilometers of the subsurface above a large, dense, high-velocity body (with the density and velocity of olivine) that underlies the summit and its caldera.

The 2018 summit collapse enlarged the caldera (as shown in Figure 2), portions of which subsided by as much as 500 meters [***Neal et al.***, 2019], and permanently altered at least the upper 2 kilometers of the summit structure [***Shelly and Thelen***, 2019]. Using local earthquakes and the active source T-Rex, we achieved unprecedented coverage from the 1,815 seismometers we packed into the summit area. Working with these data and the existing HVO seismic network, we have identified approximately 35,000 earthquakes that occurred within 30 kilometers of the center of Kaluapele during our experiment, giving us potentially 192 million waveforms to analyze across the network.

Within the next year, we anticipate using these seismic data to slice through the summit volume from the surface downward (Figure 6), much as in a medical CT scan, and use this information to create much sharper and more comprehensive tomographic pictures of the summit magma system. As of the publication of this article, we have sliced down to only an elevation of about 1 kilometer below sea level. These results provide unique information by illuminating the summit structure overlying the magma system. And as we continue to slice down and refine these data, these images will eventually reveal the transition to and the structure of the magma system itself.

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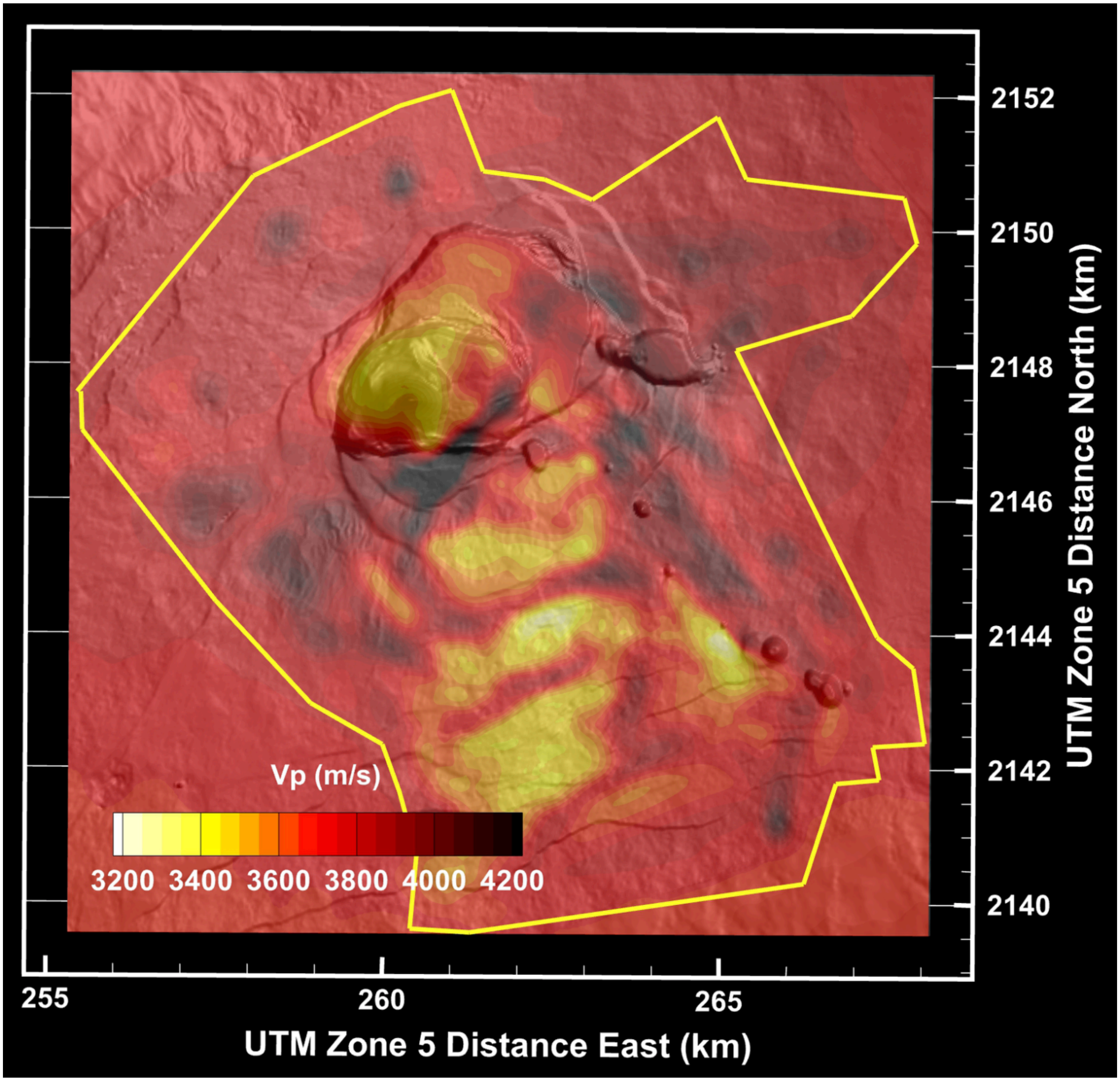

Fig. 6. This map view shows an example tomographic slice below Kīlauea at sea level produced using both earthquakes and controlled seismic source data; only *P*-wave velocities (Vp) within the yellow polygon are constrained by measurements. Variations in velocity in this preliminary image—which results from preliminary work by coauthor Dan O'Connell and Aaron Girard at the Colorado School of Mines—are suggestive of surface fault structure in the Koae Desert south of the caldera as well as of some of the Southwest Rift Zone extension into the caldera. Deeper slices will constrain the upper portion of the summit magma system. Such results will be built upon by more intensive 3D seismic tomography conducted at the University of Miami, by ambient noise tomography conducted at Rensselaer Polytechnic institute, and by joint inversions involving many of the authors and hundreds of gravity measurements in the summit area.

The expected new view of the magmatic plumbing structure of Kīlauea will enhance scientific understanding of one of the world's most active volcanoes: how it erupts, how and where it stores magma, and how it collapses at the summit while feeding voluminous lava flows erupting tens of kilometers away. Studying this structure will also ensure that we will more effectively inform emergency managers, policymakers, and the public about the hazards they face as we watch this volcanic system evolve.

Acknowledgments

This survey went smoothly and efficiently in large part because of the comradery and professionalism of staff members of HVO, the Alaska Volcano Observatory, the California Volcano Observatory, and the Cascades Volcano Observatory, all under the auspices of USGS's Volcano

Hazards Program. The teams quickly solved problems as they arose, coordinated well, and moved efficiently and intelligently over sometimes difficult, bushy, and/or deeply crevassed terrain. In addition to those working in the field, the remaining staff of Hawai‘i Volcanoes National Park went above and beyond to facilitate this operation, putting in additional radio links, providing maintenance space for T-Rex, granting access to closed areas, and helping us operate because the truck proved to be a big distraction for visitors to the park. These contributions from the observatories and the park were essential to our success, as was the knowledge and expertise of the NHERI engineers at UT-Austin, who helped us with T-Rex and kept it running during our survey. In particular, we acknowledge Steve Brantley (USGS emeritus) for leading permitting efforts and Lil DeSmither from the University of Hawai‘i at Hilo, Rebecca Kramer and Ashton Flinders from USGS, and Elizabeth Vinarski from the University of Miami for logistical support related to the instrument deployments. In addition, we acknowledge support from the 2019 congressional supplement to the USGS (Additional Supplemental Appropriations for Disaster Relief Act, 2019 (H.R. 2157)) and National Science Foundation grants EAR-2218645 (University of Miami), EAR-2218646 (Rensselaer Polytechnic Institute), and CMMI-2037900 (NHERI at UT-Austin) for use of T-Rex. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

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