

GSNL - Geohazard Supersites and Natural Laboratories

Biennial report for Candidate/Permanent Supersite

Hawai'i Supersite

Status	<i>Permanent</i>
Proposal documents	http://www.earthobservations.org/documents/gsnl/proposals/Hawaii_proposal.pdf
Acceptance letter(s)	http://www.earthobservations.org/documents/gsnl/proposals/Hawaii_notification_letter.pdf
Previous reviews	http://www.earthobservations.org/documents/gsnl/proposals/Hawaii_biennial_review_report_2012_2014.pdf
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Science team issues

- *The science team has remained static since the last biennial report. A goal for the next reporting period is to refresh the roster of science teams working on the project by identifying those groups that continue to actively research Hawaiian volcanism and attracting new teams to the Supersite. There is also a need to improve communication between the PoC and the science teams, perhaps through a listserv or some regular group email (for example, to share results or recent relevant publications). There has been little anomalous volcanic activity in Hawaii during the past 2 years (not including the lava flow crisis in Pahoia during 2014-2015, which, with a few exceptions, was more germane to geological and sociological studies than geophysical research), and work on Hawaiian volcanism will increase significantly during the next eruption of Mauna Loa, or during the next intrusion or change in the current eruption at Kīlauea. Such activity is likely during 2017–2018, given the high levels of inflation and seismicity at both volcanoes.*
- *The science teams behave independently, and there is no mechanism in place to facilitate communication between teams. A potential solution to this issue would be to hold a workshop or coordination meeting, or to propose a formal project along the lines of the Icelandic and Italian volcano supersites (Futurevolc and MED_SUV, respectively). There is little funding available for such a project, so it may be that electronic communications or side meetings during other events (for example, the Fall AGU meeting) are the best ways to ensure improved collaboration between science teams. Any new volcanic activity in Hawai'i will also certainly stimulate a desire for data (both space- and ground-based) and bring the community together to better understand the change in volcanism.*

In situ data

Type of data	Data provider	How to access	Type of access
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GPS	USGS – HVO	UNAVCO	Unregistered public
Seismic	USGS – HVO	IRIS	Unregistered public
Gas emissions	USGS – HVO	Published USGS Open-File Reports*	Unregistered public
Gravity	USGS – HVO	Published manuscripts*	Unregistered public
Tilt	USGS – HVO	Contact USGS – HVO**	GSNL scientists
Camera	USGS – HVO	Contact USGS – HVO**	GSNL scientists
Strain	USGS – HVO	Contact USGS – HVO**	GSNL scientists

* Denotes data that are only released when published because significant data processing is necessary to achieve useable results. Peer review is necessary to assure the quality of the processed data.

** Denotes data that are not made publically available due to lack of a suitable archive, but that can be obtained through collaboration with scientists at the USGS Hawaiian Volcano Observatory

In situ data issues

A few datasets, like gas emissions and gravity, require significant post-processing. Because of the need for stringent quality control, such data are not made publically available until they have been through the peer review process and published (either in academic journals or USGS Open-File Reports). Other datasets, including tilt, visual/thermal camera, and strain, are only available by contacting the data provider, since there are no established archives or agreed-upon formats for storing such data. The data may also be difficult to understand, requiring the provider to offer guidance on processing and interpretation to ensure that the user can meet their objectives.

Satellite data

Type of data	Data provider	How to access	Type of access
ENVISAT	ESA	http://eo-virtual-archive4.esa.int/?q=Hawaii	Registered public
RADARSAT-1	CSA	Supersites web page *	Registered public
ALOS-1	JAXA	Supersites web page *	Registered public
TerraSAR-X	DLR	Available after acceptance of PI proposal by DLR	GSNL scientists
Cosmo-SkyMed	ASI	POC requests access from ASI for individual users, data then accessible via UNAVCO	GSNL scientists
RADARSAT-2	CSA	POC requests access from CSA for individual users, data then accessible via UNAVCO	GSNL scientists
ALOS-2	JAXA	https://auiq2.jaxa.jp/ips/home	GSNL scientists
Sentinel-1 a/b	ESA	https://scihub.copernicus.eu/	Registered public

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NOTE: This list only includes SAR data, which typically require payment or approval of a research proposal. Freely available data (e.g., MODIS, Landsat) are not listed.

** Interface for downloading Radarsat-1 and ALOS-1 data does list available scenes, but clicking the link for a given image results in an error.*

Satellite data issues

The same issues that existed during the previous reporting period (2012–2014) still exist during the current reporting period (2014–2016), namely:

- Links to RADARSAT-1 and ALOS-1 data on the Supersite website do not work. That there have been no complaints about this, however, suggests that the page is not being used to download data.*
- There is no streamlined method for requesting user access to SAR data; each space agency has a different access policy, some of which require PoC approval (e.g., ASI and CSA), others of which do not (e.g., DLR). A single method for “joining” a Supersite and accessing restricted data (mostly SAR imagery) would be preferable, but would obviously be difficult to implement.*
- There is no Supersite-specific archive for non-SAR satellite data, like EO-1, Landsat, MODIS, ASTER, and other usually free datasets (although the USGS Hazards Data Distribution System has been stockpiling some imagery of Kīlauea since 2014). This imagery constitutes an important source of information for synergistic studies using SAR and ground-based data. Developing an archive for visual and thermal remote sensing data, as well as other relevant resources (e.g., DEMs), would be an important next step in growing the Hawai‘i Supersite to a new level of capability and utility.*

Research results

The Hawai‘i Supersite proposal emphasized the complementary nature of space-based, airborne, and ground-based data as a tool for investigating large-scale research questions related to Hawaiian volcanism—namely, the nature of magma supply to Hawaiian volcanoes; the best indicators of an impending change in eruptive activity; improving predictions of the timing, magnitude, and location of eruptions; and the relation between volcanic and tectonic activity. After four years as a permanent Supersite, all of these questions have received considerable attention. For example, magma supply to Kīlauea has been found to fluctuate on timescales of just a few years, and changes in supply have a direct impact on eruptive activity. Inflation of Kīlauea was found to promote failure of nearby faults, triggering M4+ earthquakes. Deformation and seismicity have been used to construct a map of magma storage and transport at both Kīlauea and Mauna Loa volcanoes, providing a basis upon which to interpret past, present, and future monitoring data. Many of these insights may not have been achievable without the support of the numerous space agencies and research institutions that have contributed data to the Hawai‘i Supersite.

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In addition to these “big picture” questions, the wealth of available data opened a number of additional, smaller-scale processes for scrutiny, and also promoted the development of non-traditional uses of SAR data. For example, in September 2015, a small (~30-m-diameter) pit crater opened without warning within ~1 km of the summit access road on the south flank of Mauna Kea volcano (which has not erupted in over 4000 years). RADARSAT-2 was the only SAR satellite acquiring data over the region at sufficiently high resolution to image the new crater, and examining RADARSAT-2 SAR amplitude imagery helped to narrow the formation time of the feature. Further, interferometry using RADARSAT-2 data revealed a small amount of subsidence at the site of the pit crater in the months prior to its formation. This result suggests that it may be possible to detect the impending formation of pit craters by looking for small-scale subsidence features in high-resolution SAR data.

RADARSAT-2 data also helped to develop a means of mapping lava flows over time. In 2014, when a lava flow from Kīlauea invaded a forested area on its way towards the village of Pāhoā, the usual means of identifying lava flow activity using InSAR—coherence—was no longer useful because the forest was also incoherent. Co-polarized amplitude imagery was also not helpful, since lava and vegetation had the same backscatter characteristics. The two surfaces were easily distinguishable in cross-polarized images, however. By combining the cross-polarized amplitude data from acquisitions on two different dates with the interferometric coherence between those dates in a three-band image (band1=date1_HV_amplitude; band2=date2_HV_amplitude; band3=date1-date2_coherence), it is possible to identify areas of lava flow activity regardless of where that activity occurs (in both vegetated and unvegetated areas). After being proven using RADARSAT-2 imagery, this procedure has been put into operational practice using regularly acquired Sentinel-1a/b data, thereby providing a new means of mapping lava flow activity at any time of day and during any type of weather. This is especially important in an era of shrinking budgets, when helicopter visits for observing remote lava flow activity are not always possible. Tracking lava flows can also be accomplished using data from the TanDEM-X mission, which is capable of mapping topographic changes over time. By summing these topographic changes, it is possible to derive the lava discharge rate—one of the most fundamental parameters of interest for forecasting lava flow hazards.

More “traditional” use of SAR data also yielded insights into the dynamics of Hawaiian volcanism. For example, in May 2015, a small intrusion of magma occurred beneath the south part of Kīlauea Caldera. The intrusion was preceded by several weeks of surface inflation and rising lava level within the summit eruptive vent. Inflation was tracked by tilt, GPS, and InSAR, and was associated with abundant seismicity, changes in gas emissions, and increases in gravity, while visual and thermal cameras monitored the rising lava lake, which eventually overtopped the vent rim and began spreading lava onto the floor of Halema‘ūma‘u Crater. Cosmo-SkyMed and Sentinel-1a data proved especially valuable in tracking the activity, as images were acquired during the transition from inflation to intrusion. These data were available very soon after they were acquired, which aided with hazards assessments by the Hawaiian Volcano Observatory during the intrusion. Subsequent modeling of the deformation has helped to elucidate aspects of Kīlauea’s magma plumbing system.

Despite these success stories, synergistic exploitation of Supersite data is still in a nascent stage. For example, SAR and other thermal/visual data acquired from space are rarely combined to better

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understand volcanic processes. In addition, the large SAR dataset—probably the largest for any volcanic area in the world—has only begun to be used for development of new techniques (a noteworthy success in this regard is mapping 3D displacements via multiple-aperture interferometry). Continued operation of the Hawai‘i Supersite, however, should lead to more work in these areas by providing the means for aiding technological developments and stimulating innovative usage of the vast catalog of available data.

MORE INFORMATION ON RESEARCH RESULTS IS AVAILABLE IN THE ANNEX TO THIS REPORT

Publications

Peer reviewed journal articles

- Wauthier, C., Roman, D.C., and Poland, M.P., 2016, Joint analysis of geodetic and earthquake fault-plane solution data to constrain magmatic sources: A case study from Kīlauea Volcano: *Earth and Planetary Science Letters*, v. 455, p. 38–48, doi:10.1016/j.epsl.2016.09.011.
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- Baker, S., and Amelung, F., 2015, Pressurized magma reservoir within the east rift zone of Kīlauea Volcano, Hawai‘i; Evidence for relaxed stress changes from the 1975 Kalapana earthquake: *Geophysical Research Letters*, v. 42, no. 6, p. 1758–1765, doi:10.1002/2015GL063161.
- Jo, M.-J., Jung, H.-S., and Won, J.-S., 2015, Detecting the Source Location of Recent Summit Inflation via Three-Dimensional InSAR Observation of Kīlauea Volcano: *Remote Sensing*, v. 7, no. 11, p. 14,386–14,402, doi:10.3390/rs71114386.
- Lin, G., Amelung, F., Shearer, P.M., and Okubo, P.G., 2015, Location and size of the shallow magma reservoir beneath Kīlauea caldera, constraints from near-source Vp/Vs ratios: *Geophysical Research Letters*, v. 42, no. 20, p. 8349–8357, doi:10.1002/2015GL065802.
- Jo, M.-J., Jung, H.-S., Won, J.-S., and Lundgren, P., 2015, Measurement of three-dimensional surface deformation by Cosmo-SkyMed X-band radar interferometry: Application to the March 2011 Kamoamoa fissure eruption, Kīlauea Volcano, Hawai‘i: *Remote Sensing of Environment*, v. 169, p. 176–191, doi:10.1016/j.rse.2015.08.003.
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Conference presentations/proceedings

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NOTE: It would be impossible to list all presentations that make use of Hawai'i Supersite data (there would be several dozen), especially without direct input from science team members; therefore, the table has been left blank. The most important research results are contained within the publication list.

Research products

In a strict sense, the Hawai'i Supersite has yet to directly produce any formal community research products. The data have been used by individual investigators to develop products, however, which are having an impact on the overall field. Chief among these are:

- new methods for extracting three-dimensional displacement data from SAR imagery
- deformation maps and time series generated by numerous investigators, but particularly by the Jet Propulsion Laboratory's ARIA (Advanced Rapid Imaging and Analysis) project
- schemes for mapping change due to active volcanism, particularly associated with the emplacement of lava flows (via coherence, amplitude, and topographic data)
- strategies for modeling atmospheric delay based on GPS and UAVSAR data collected in October 2016

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Because these products are either in development for release as part of InSAR processing software (for example, Multiple Aperture Interferometry methods) or are primary research results or operational tools with specific applications (for example, interferometry time series, topographic change due to lava flow emplacement, and atmospheric modeling strategies), they should not yet be considered research products, and the table below has been left blank.

Type of product	Product provider	How to access	Type of access
<i>e.g. ground deformation time series, source model, etc.</i>	<i>Name of scientist(s)</i>	<i>Link to publication, research product repository or description of procedure for access</i>	<i>E.g. public, registered, limited to GSNL scientists, etc.</i>
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Research product issues

There are currently few publically available research products for the Hawai'i Supersite. Deformation maps and time series generated by the JPL ARIA project are still in development, and so are only open to JPL scientists and their collaborators. The WInSAR consortium of UNAVCO provides a portal for users to upload and assign DOI numbers to products, like interferograms and time series (<https://winsar.unavco.org/portal/insar/>), but users have yet to take widespread advantage of this resource. Several investigators have provided links to time series and deformation maps on their personal websites. Most Supersite researchers, however, have yet to make products available beyond their own publications (although published data are, in most respects, considered open source, and so should be available in manuscript supplements or by contacting the authors). Funding, staff, and other assistance are needed to assist with the dissemination of research products. Few organizations have the funding to develop a resource to its full potential, especially once the research has been published (the “end game” for many scientists). The only exceptions include projects that have been created to specifically develop a resource—for example, the GMTSAR software from the Scripps Oceanographic Institution (the code was tested using data from the Hawai'i Supersite) and the JPL ARIA project (which will eventually provide research products to the scientific community; this happens regularly for events, like earthquakes, but not yet for ongoing processes, like eruptions and unrest episodes at Hawaiian volcanoes)—but these are few in number.

Dissemination and outreach

The primary means of informing the public of the existence and benefits of the Hawai'i Supersite are outreach efforts, including newspaper articles and lectures. For example, public presentations on the Island of Hawai'i as part of “Volcano Awareness Month” (every January) and weekly “Volcano Watch” newspaper articles have highlighted the benefit of the Supersite for the assessment and mitigation of volcanic hazards in Hawai'i, and also the greater understanding of Hawaiian volcanoes that the

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Supersite makes possible (through better access to data and by attracting scientific innovators to work on those data). Outreach to the scientific community has done via conference presentations (highlighting the available datasets and encouraging their exploitation) and personal visits to research institutions and universities around the world, where Supersite researchers share their results and encourage new users to participate in the work. These efforts have yielded fruit. For example, researchers at the GFZ German Research Center for Geosciences are interested in examining localized deformation of actively erupting volcanic vents using GPS and high-resolution X-band SAR data, and researchers at the University of Leeds (U.K.) have advertised for a Ph.D. student to study SAR amplitude imagery as a tool for better understanding volcanism in Hawai'i (and elsewhere by extension).

Funding

There is no dedicated nor specific funding for the Hawai'i Supersite. The Volcano Hazards Program of the U.S. Geological Survey, however, supports the Supersite by directing the PoC (who is a USGS employee) to manage the effort and cultivate a user community. This includes the use of funds from the Volcano Hazards Program's InSAR project to archive and manage SAR data from Hawai'i and to build computing resources for SAR data processing and analysis. Individual project scientists have obtained research funding from various organizations—like the U.S. National Science Foundation—and have leveraged the availability of Supersite data in their proposals, but no proposals that were specifically targeted to exploit the Hawai'i Supersite have been submitted.

Societal benefits

The most direct beneficiary of the Hawai'i Supersite is the U.S. Geological Survey's Hawaiian Volcano Observatory (HVO). Founded, in 1912, HVO maintains a dense network of geophysical stations around the island (which have been made available to the Supersite) and also collects geochemical and geological data on volcanic and seismic activity. These measurements fulfill a US Congressional mandate (the Stafford Act) to provide volcano and earthquake hazard warnings, supported by research, to local populations, emergency managers, and land-use planners. SAR data constitute a critical resource for this monitoring and research, but would be cost-prohibitive if not for the Supersite.

HVO communicates hazards information, much of which is aided by Supersite data, to a number of other organizations—primarily the National Park Service and Hawai'i County Civil Defense. These agencies are tasked with managing responses to volcanic and earthquake crises in the lands they oversee, while HVO is responsible for providing the information needed by responders to make decisions. This level of cooperative interaction was on display in 2014–2015 during the Pāhoā lava flow crisis, when lava nearly inundated a community on the Island of Hawai'i. Supersite data helped to assess the changing state of summit deformation, which was directly tied to lava effusion rate (and therefore lava flow advance rate), and also to map lava flow activity during periods of inclement

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weather, when direct observations were not possible. When a new phase of lava flow activity began in mid-2016, Supersite data (specifically, TanDEM-X results) were used to build a new topographic map of the lava flow field (accounting for recent lava flows that modified the landscape since the last whole-island Digital Elevation Model was acquired in 2005). This new map was used to chart the likely path of the new lava flow and was communicated to Hawai'i Volcanoes National Park, Hawai'i County Civil Defense, and the general public (via HVO's website) to keep all land managers and Park visitors aware of lava flow hazards.

Supersite data also contribute to the development of interpretations that are communicated to the public as part of daily volcanic activity updates, weekly newspaper articles, online content, and community outreach events (presentations, open houses, exhibits, etc.).

Conclusive remarks and suggestions for improvement

As demonstrated by the publications list, the Hawai'i Supersite continues to generate high-quality scientific products that have had a profound impact on understanding of Hawaiian volcanism and have also contributed critical input to hazards assessments and mitigation efforts in Hawai'i. Chief among the success stories are:

- understanding of magma supply variations to Kīlauea Volcano and the impact of these variations on eruptive activity*
- elucidation of the magma plumbing systems at Kīlauea and Mauna Loa volcanoes, which provide an essential framework for interpreting past, present, and future unrest*
- investigations into interactions between magmatism and tectonism at Hawaiian volcanoes*
- tracking of geophysical changes—especially deformation and seismicity—at Kīlauea and Mauna Loa, which provides situational awareness of potential future eruptions or changes to ongoing eruptions*
- development of new tools for tracking lava flow emplacement, including both areal coverage and effusion rate, and implementation of these tools in an operational framework to aid volcano monitoring efforts*
- testing of new algorithms for determining 3D displacements from InSAR data*
- high-resolution views of small-scale processes, including the formation and evolution of pit craters (at both Kīlauea and Mauna Kea)*

Despite these successes, a few issues continue to prevent the full realization of the Hawai'i Supersite:

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- *The scientific teams operate independently, and so there is no organized effort to promote any specific scientific goals. Improved coordination between investigators could generate better exploitation of research opportunities and collaboration between scientists.*
- *There is no specific funding for the Hawai'i Supersite, outside of that provided in-kind by the U.S. Geological Survey to support the efforts of the PoC. If funding were available, it could be used to better organize the user community and support collaborations and better dissemination of results.*
- *The website for the Hawai'i Supersite is static and has not been updated in some time (in addition, a number of links are broken, including those pointing to RADARSAT-1 and ALOS-1 data). A more dynamic web presence would allow for posting of research results and products, and it could also be used for dissemination and outreach efforts aimed at not only scientific users and agencies, but also stakeholders and the general public.*

A few operational challenges also exist:

- *The quota of RADARSAT-2 data for the Hawai'i Supersite has been exhausted.*
- *The relationship between the PoC's TanDEM-X PI proposal and the Supersite is not clear—are TanDEM-X data obtained by the PoC available for distribution to registered Supersite users, or should interested scientists order the data using separate PI accounts, as is the case with TerraSAR-X requests?*
- *Non-SAR satellite data from Hawai'i are not archived anywhere. Such an archive would facilitate data fusion efforts that would merge SAR, visual, and thermal remote sensing imagery to gain new insights into Hawaiian volcanism.*
- *There is no archive for supporting data, like DEMs, which could be useful to Hawai'i Supersite investigators, as well as the general public and stakeholders.*

These challenges should not dissuade support for the continued operation of the Hawai'i Supersite, however, given the great weight of the successes and the certainty that future efforts will build on the extensive record of work completed thus far. Insights from Supersite data have become invaluable to stakeholders on the Island of Hawai'i, and results provide exceptional fodder for scientific research into how volcanoes work. Future exploitation of the Supersite will open new avenues for investigating Hawaiian volcanism, as well as how the synergy between space-, air-, and ground-based datasets can be optimized to provide insights into assessing, forecasting, and mitigating volcanic hazards.

DATA REQUESTS FOR FUTURE OPERATIONS

Based on the record of success presented above, the Hawai'i Supersite requests continued allocation of SAR data from international space agencies for research into volcanic processes and hazards. This would include:

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- *TerraSAR-X acquisitions every 11 days on 2 tracks (one ascending and one descending) covering the summit of Kīlauea Volcano.*
- *Cosmo-SkyMed acquisitions as frequently as possible on two tracks (one ascending and one descending), with Mauna Loa imaged every 16 days on each track and Kīlauea's summit imaged 2–3 times per 16 days on each track.*
- *A new allocation of RADARSAT-2 scenes, which will be used to investigate past (since 2015) and future deformation of both Kīlauea and Mauna Loa. An additional 200 scenes would bring the Supersite “up to date” on several key viewing angles, providing a continuous set of C-band observations since 2008 (a unique dataset, and one capable of providing a long-term perspective of several important episodes of activity, including the onset of inflation at Mauna Loa in 2014, and the transition from deflation to inflation of Kilauea in the early 2010s.*
- *Sentinel-1a/b data are freely available, and a limited number of ALOS-2 scenes is available to the PoC and selected members of the scientific team via “Research Announcement” projects, so no specific requests for those data are necessary.*

GSNL - Geohazard Supersites and Natural Laboratories**Biennial report for Candidate/Permanent Supersite***Hawai'i Supersite****Annex to 2015–2016 report***Introduction

During 2014–2016, the Hawai'i Supersite achieved a number of noteworthy results. This annex details some of the more unique of those results in an effort to highlight how remote sensing data, particularly SAR, have been used to elucidate volcanic processes that might otherwise be obscured. For example, cross-polarized SAR amplitude imagery were critical for tracking lava flow activity in forested areas (co-polarized imagery could not distinguish forest from lava) and, when combined with coherence information, provided a means of mapping lava flow activity during the 2014–2015 Pāhoā lava flow crisis. Mauna Loa volcano—the largest active volcano in the world—began to inflate in 2014, with the locus of inflation changing over time (a variation that was identified by GPS but required InSAR to map fully). In September 2015, a pit crater formed unexpectedly near the summit access road of Mauna Kea volcano (which is not typically monitored by SAR and has few ground-based instruments), and opportunistic SAR acquisitions helped to constrain the crater's formation time and also detect pre-collapse subsidence. An intrusion of magma into the south part of Kīlauea Volcano in May 2015 was imaged in exceptional spatial and temporal detail thanks to ground-based continuous tilt and GPS coupled with InSAR results from several satellites. Finally, the combination of lava effusion rates derived from TanDEM-X and subsurface magma storage rates from multiple SAR satellites suggests that magma supply to Kīlauea increased in 2016, implying increased potential for future changes in eruptive activity as the volcano becomes engorged with magma.

Based on this record of achievement, the Hawai'i Supersite requests continued support with similar quotas of TerraSAR-X and Cosmo-SkyMed imagery (roughly 60 scenes/year and 150 scenes/year, respectively). In addition, a new allocation of RADARSAT-2 data is requested. The RADARSAT-2 quota was expended in 2015. Because those data are the longest current continuous C-band record of surface change of Hawaiian volcanoes and have quad-pol and very high resolution modes, they provide a unique perspective on deformation and lava flow emplacement in Hawai'i. The opportunistic RADARSAT-2 acquisitions also cover portions of the island not imaged by other SAR satellites, and therefore can be used to investigate processes occurring away from the summits and rift zones of Kīlauea and Mauna Loa volcanoes.

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Lava flow mapping

Surface change due to the emplacement of volcanic deposits in unvegetated areas can be tracked with ease via interferometric coherence between SAR images acquired at different times. Vegetation is typically also incoherent (except in L-band SAR imagery), however, so change detection in forested areas using coherence is not possible. Amplitude imagery offers a potential means of overcoming this challenge, but backscatter differences between volcanic deposits and vegetation are small in co-polarized data (Figure 1, left), which is unfortunately the default acquisition mode for most SAR satellites. This challenge can be overcome by using cross-polarized SAR amplitude, as these images emphasize difference between vegetation and, for example, lava flows (Figure 1, right). RADARSAT-2 data are frequently acquired in high-resolution quad-pol modes, providing exceptional views of lava flow emplacement in forested areas—for example, during the 2014–2015 Pāhoā lava flow crisis at Kīlauea Volcano, when lava nearly overran a village on the eastern tip of the Island of Hawai‘i. By combining cross-polarized amplitude imagery from two different dates with the interferometric coherence across these dates in a 3-band (R-G-B) image, it is possible to achieve a high-spatial-resolution map of surface change due to volcanism regardless of ground cover (Figure 2). Such maps can be made regularly using cross-pol SAR data from both RADARSAT-2 and Sentinel-1a/b (Figure 3), and they are an invaluable complement to ground- and air-based mapping by the U.S. Geological Survey’s Hawaiian Volcano Observatory. In fact, operational use of this method provides a new, all-weather, day/night tool for mapping volcanic deposits and assessing their hazards and impacts.

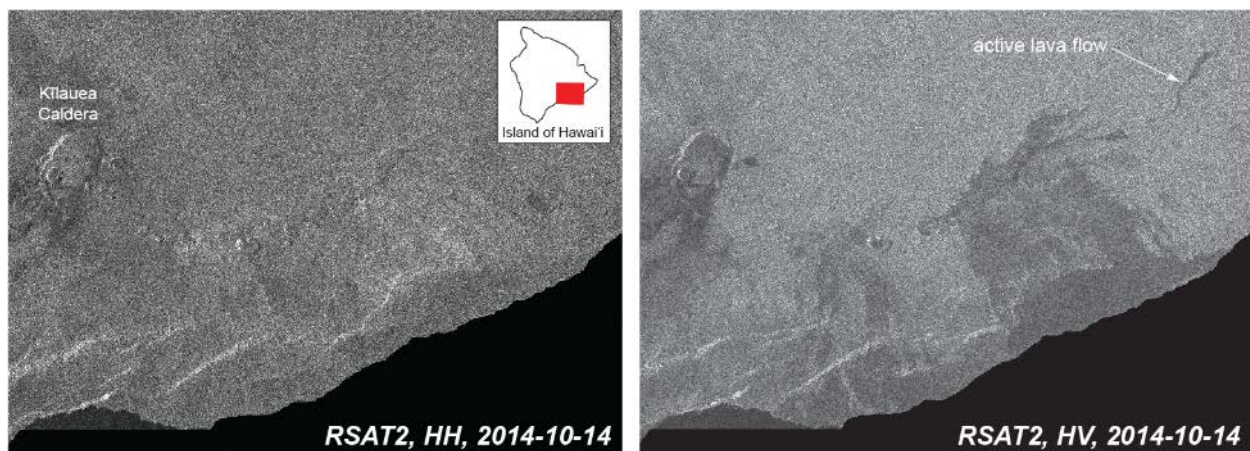


Figure 1. RADARSAT-2 co-polarized (left) and cross-polarized (right) backscatter images from Kīlauea Volcano. Both images are from the same acquisition. The active lava flow on the volcano’s East Rift Zone can only be distinguished in the cross-polarized data.

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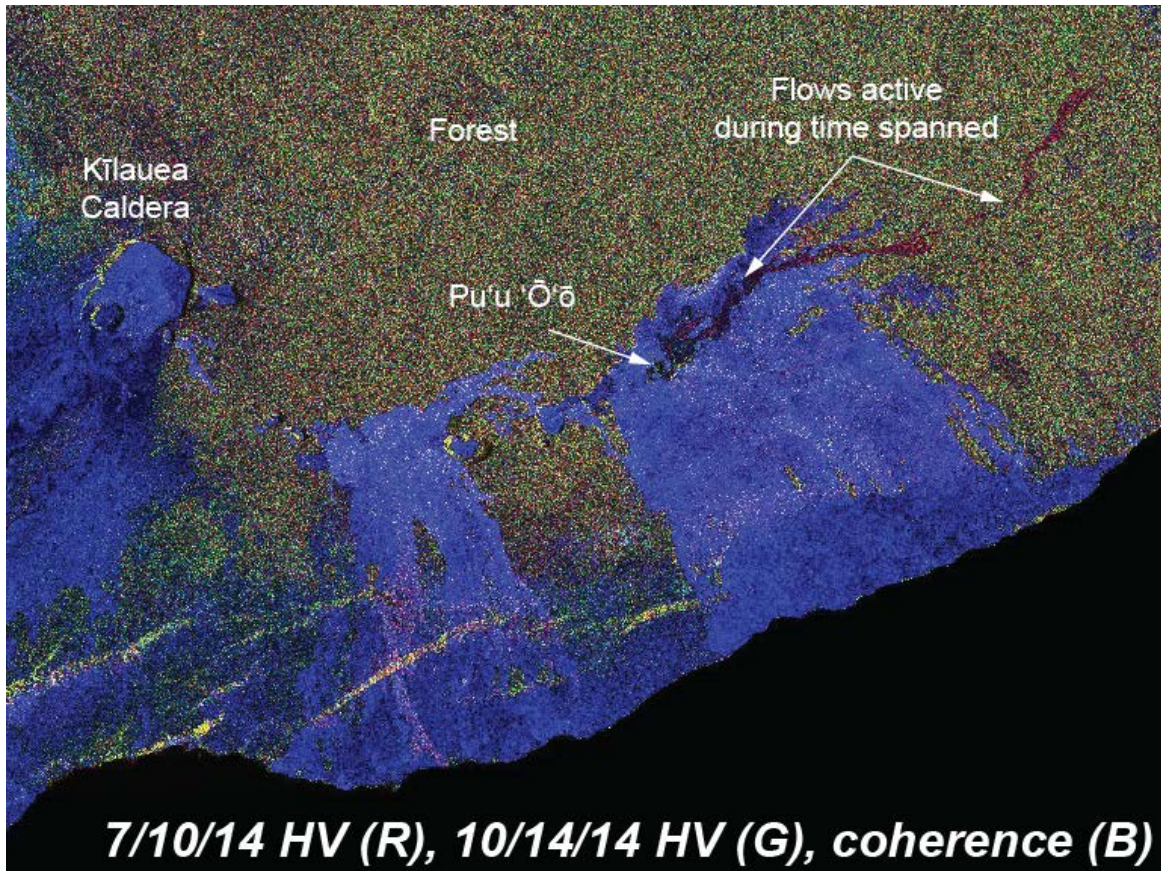


Figure 2. This false-color image integrates RADARSAT-2 cross-polarized (HV) data from July 10, 2014 (red), and October 14, 2014 (green), with a coherence map spanning the two time periods (blue). Flows that were active in forested areas during the time spanned appear red, while lava that covered older, unvegetated flows between the two time periods appears black. The combined cross-polarized and coherence imagery provides a complete view of lava flow activity over the time spanned, regardless of the type of ground that was covered by the lava. At the time the second image was acquired, this flow was threatening the village of Pāhoā.

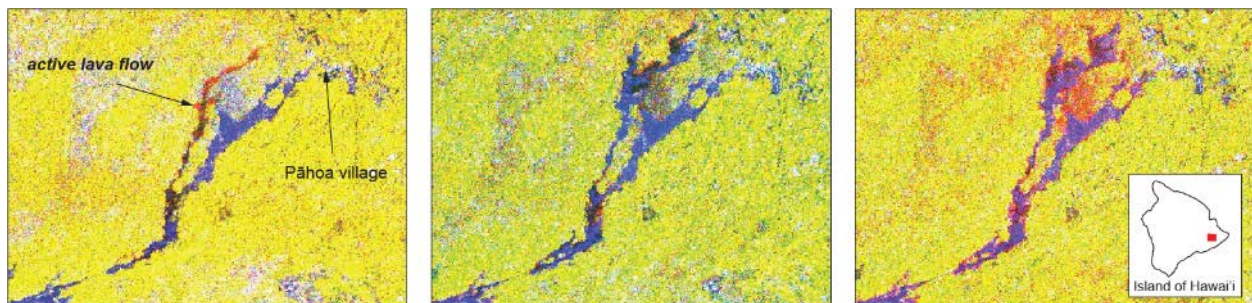


Figure 3. Sequential false-color images (R=earlier HV, G=later HV, B=coherence) from Sentinel-1a showing development of the Pāhoā lava flow field at Kīlauea Volcano, Hawai'i, during late 2014 and early 2015. Each image is approximately 10 km across. New lava flow activity appears reddish.

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Deformation of Mauna Loa volcano

Mauna Loa—the largest active volcano on Earth—is currently experiencing the longest period of repose in the past ~200 years, having last erupted in 1984. The volcano is far from quiescent, however, with episodes of inflation and heightened seismicity testifying to the accumulation of magma beneath the volcano’s summit. The most recent episode of inflation began in mid-2014, as indicated by continuous GPS data from the volcano’s summit region (Figure 4, top). The deformation has been well-characterized by InSAR—especially Cosmo-SkyMed data—and through late 2014 and early 2015 resembled the previous period of inflation (Figure 5, upper left), which occurred during 2002–2009 and was centered on the southwest part of Mauna Loa’s summit caldera. The deformation pattern suggested magma accumulation in a reservoir that was elongated along the length of the caldera and upper part of the volcano’s south rift zone. In late 2015, GPS stations to the southeast of the summit began recording accelerated rates of deformation (Figure 4, bottom), while summit GPS stations showed a stalling in the inflation (Figure 4, top). Examination of InSAR results from Cosmo-SkyMed revealed that the inflation pattern had shifted to the southwest, suggesting that magma accumulation was occurring beneath the south rift zone only, and not beneath the summit (Figure 5, upper right and lower left). Such a pattern had never before been observed. By late 2016, however, the original pattern of inflation had reestablished itself, with deformation centered on the southwest part of the caldera (Figure 5, lower right). The mechanism and consequences of this shift on the locus of deformation is not clear, but suggests a complex magma plumbing system that is composed of compartments that can become isolated from one another.

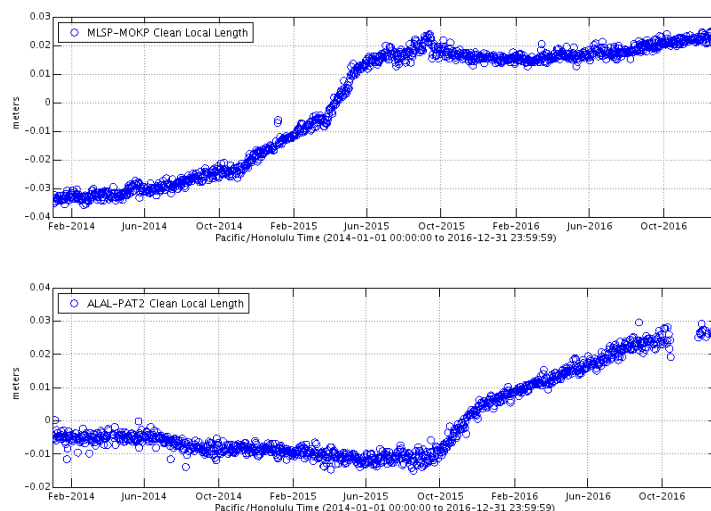


Figure 4. Distance change between GPS stations spanning the summit (top) and south rift zone (bottom) of Mauna Loa. Positive change is an increase in distance between stations, implying inflation due to subsurface magma accumulation. Inflation began at the summit in mid-2014, shifted to the southwest in late 2015, and returned to the summit area in late 2016.

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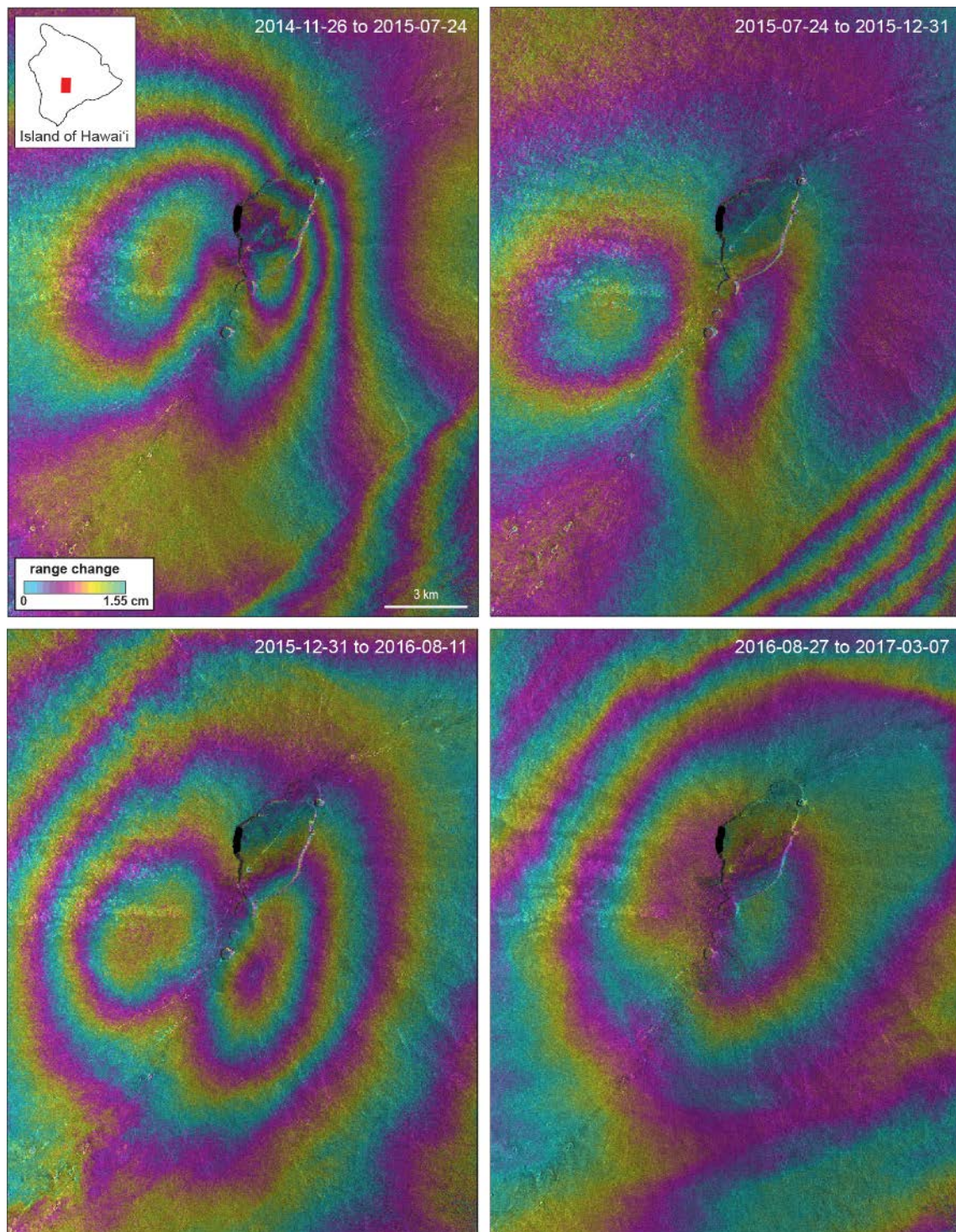


Figure 5. Cosmo_Skymed interferograms showing inflation of Mauna Loa's summit region during 2014-2017. Note that the locus inflation, defined by the two lobes of line-of-sight inflation, shifts to the southwest during mid-2015 to mid-2016 (upper right and lower left) relatively to early 2015 and late 2016 (upper left and lower right).

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Formation of a pit crater on Mauna Kea

On October 16, 2015, a helicopter pilot flying over the south flank of Mauna Kea volcano—which has not erupted in over 4000 years—noticed a new crater within about 1 km of the road accessing the summit of the mountain. Subsequent ground-based observations constrained the new crater to be 24 x 20 m with a depth of 20-35 m (Figure 6). This is the first pit crater known to have formed on Mauna Kea in the past several hundred years.



Figure 6. Worldview images from September 3, 2015 (top) and September 30, 2015 (bottom) showing the new pit crater, which must have formed sometime between the acquisition of the two images. The road to access the summit of Mauna Kea is in the upper left of both images.

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RADARSAT-2 data were being automatically acquired over this area and were the only SAR data from any satellite that covered the region and time period of crater formation. The crater was clearly visible in high-resolution of RADARSAT-2 imagery acquired after September 29, 2015, which further constrained the crater's formation time to be between September 5 and 29, 2015 (Figure 7).

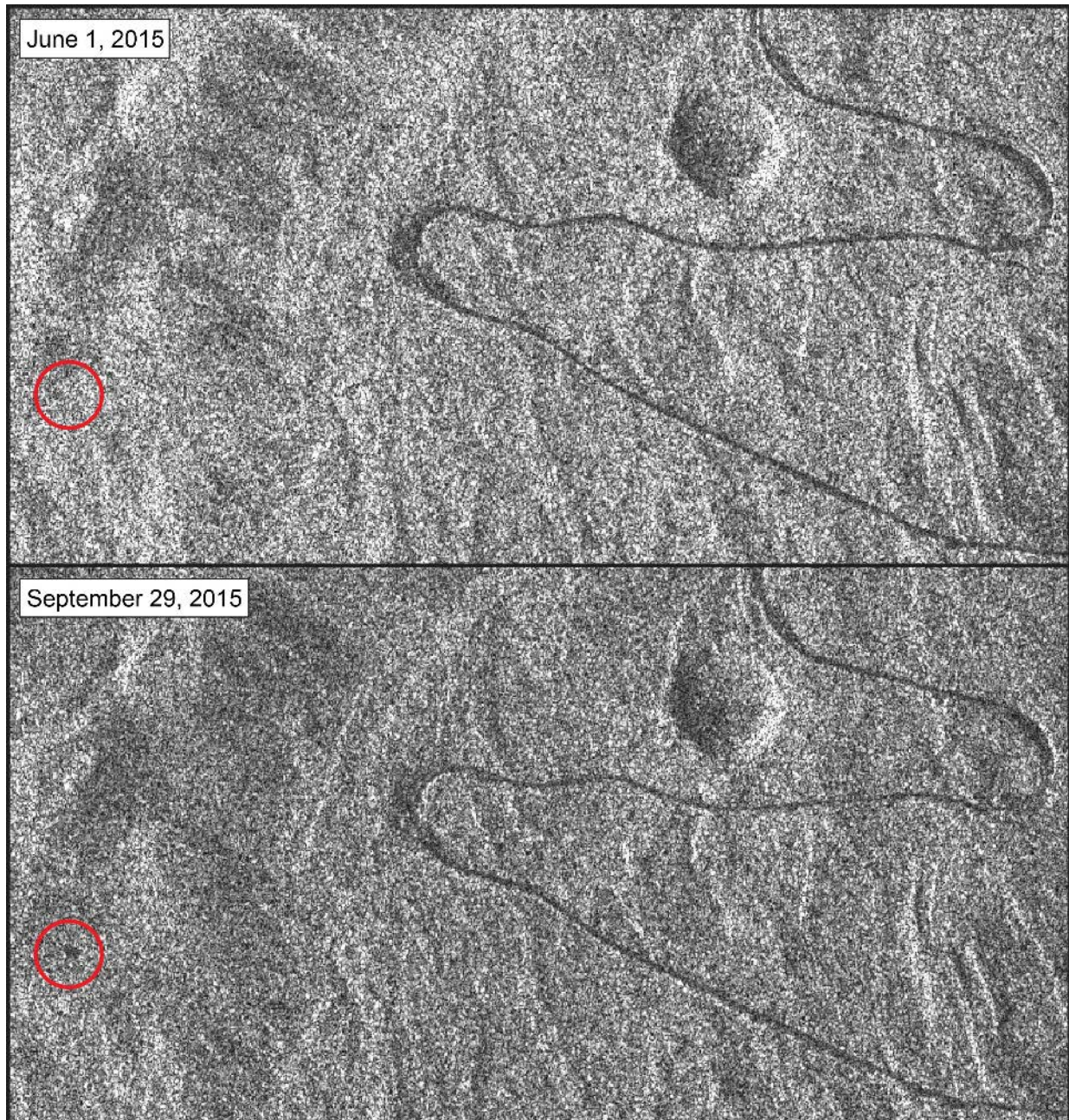


Figure 7. Amplitude imagery from RADARSAT-2 in radar coordinates (i.e., east and west are flipped). Red circle denotes crater location. Dark ribbon in center-left of image is summit access road. Crater is approximately 20 m in diameter.

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In addition to constraining the timing of the crater's formation, RADARSAT-2 data suggest the existence of pre-collapse deformation. An examination of the georeferenced interferometric phase for June 1–September 5, 2015 reveals a small area of anomalous phase (Figure 8, top), consistent with about 1 cm of subsidence relative to the surrounding area in the days to weeks before the crater formed. Interferometric phase during September 5–29, 2015, is not coherent at the site of the crater (Figure 8, bottom), as would be expected due to a major change in the scattering properties of the surface. Investigation of this event using satellite SAR would not have been possible without opportunistic RADARSAT-2 acquisitions.

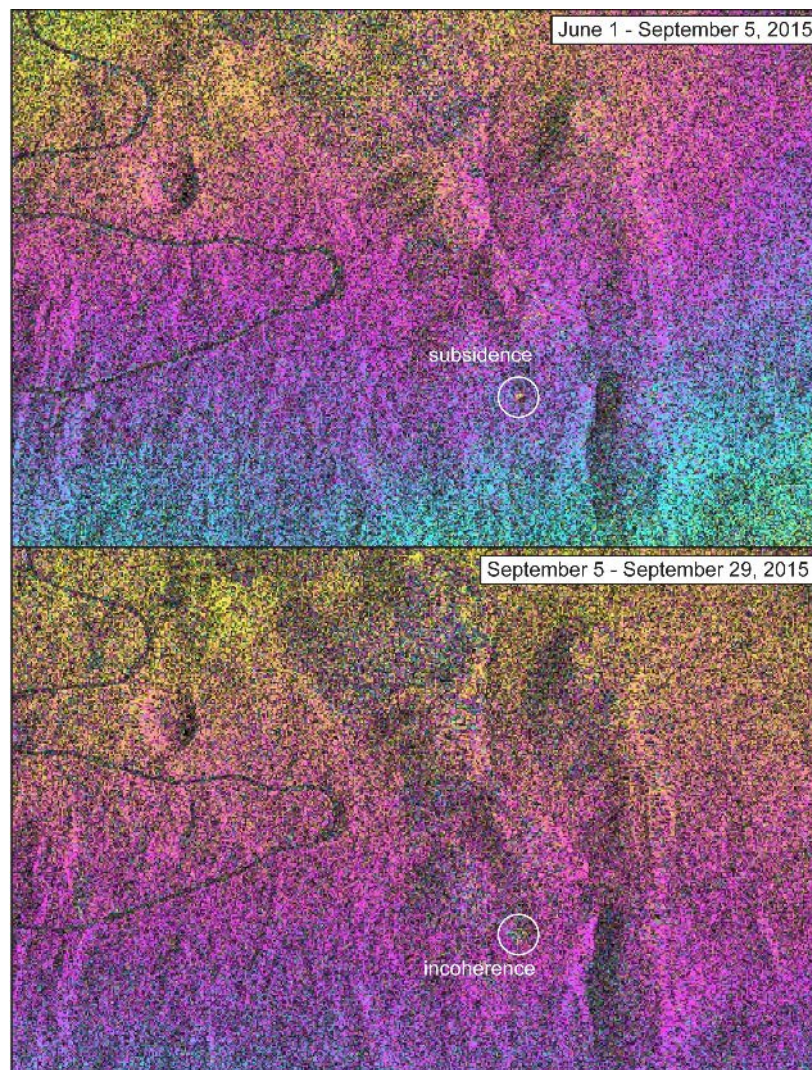


Figure 8. Interferometric phase before (top) and spanning (bottom) formation of the pit crater on the south flank of Mauna Kea. In the images, one fringe is equivalent to 2.8 cm of range change. The pre-collapse interferogram suggests about 1 cm of subsidence at the site of eventual crater formation, while the co-collapse interferogram is incoherent.

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May 2015 intrusion at Kīlauea Volcano

A sequence of magmatic events in April-May 2015 at Kīlauea Volcano produced a complex deformation pattern that can be described by multiple deforming sources, active simultaneously. The series of events began on April 22, with rapid inflation of the shallow (~1.5 km below the surface) magma reservoir near Halema'uma'u Crater in Kīlauea Caldera (Figure 9). Inflation continued at an exponentially decaying rate for more than a week, while the lava lake within the Halema'uma'u eruptive vent rose about 40 m, overtopping its rim and spilling onto the crater floor. Inflation was accompanied by elevated seismicity in the caldera and especially in the upper East Rift Zone. On May 11, borehole tiltmeters began recording rapid deflation of the Halema'uma'u reservoir (Figure 10), accompanied by a drop in the level of the lava lake drop and an increase in the rate and magnitude of earthquakes in the south caldera. Within a day, inflation in the south caldera was clear from tilt, GPS and InSAR data. The visual pattern of deformation from InSAR (Figure 11) and simple inverse modeling are consistent with magma accumulation in the south caldera magma reservoir—a complex feature often imaged in the past, especially by leveling and InSAR. Inflation in the south caldera occurred for about 5 days. During this time, the lava lake level continued to drop to about 20 m below pre-April 22 levels. Preliminary modeling suggests that the volume lost from the HMM reservoir and lava lake is comparable to that gained in the south caldera.

This event provides a rare glimpse of rapid magma transfer between two subcaldera magma storage bodies, raising new questions about how these reservoirs are connected and offering the potential to further elucidate the geometry of Kilauea's summit magma storage system.

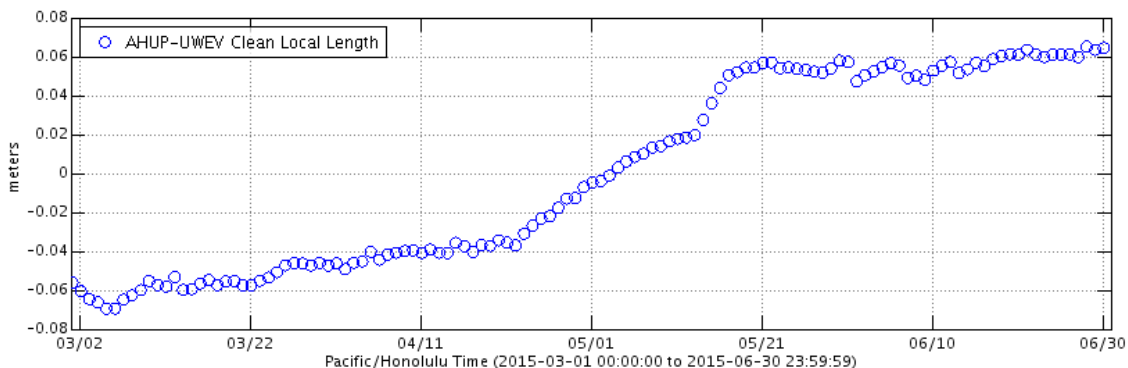


Figure 9. Distance between two GPS stations spanning the summit of Kīlauea Caldera. Positive change is increasing distance, which implies inflation due to subsurface magma accumulation.

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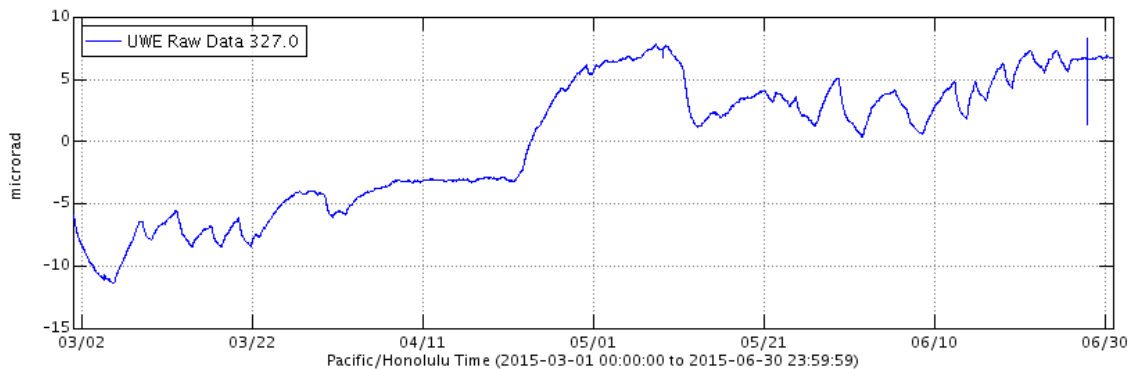


Figure 10. Ground tilt recorded by a borehole instrument located about 2 km northwest of the Halema'uma'u lava lake. Positive tilt is away from the caldera (inflation) and negative is toward the caldera (deflation). Rapid deflation on May 11, accompanied by inflation of the south caldera at the same time (Figure 9), indicates drainage of magma from a shallow reservoir beneath Halema'uma'u Crater and accumulation of magma in the south caldera.

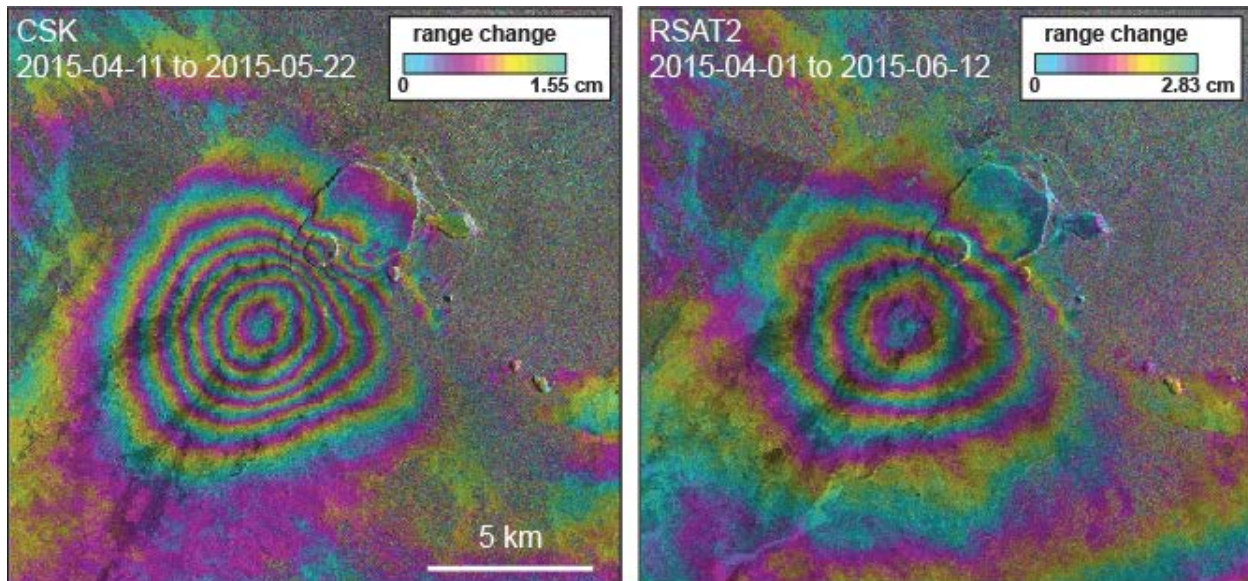


Figure 11. Representative interferograms spanning the April 2015 inflation and May 2015 intrusion at the summit of Kīlauea Volcano from Cosmo-SkyMed (left) and RADARSAT-2 (right).

Increased magma supply to Kīlauea Volcano

A significant recent research result at Kīlauea is documentation of changes in magma supply to the volcano over timescales of years. Magma supply, determined as the combined volume of magma that accumulated beneath the surface and also erupted at the surface, controls the eruptive activity of a given volcano. A surge in supply at Kīlauea during 2003–2007 was associated with the formation of new eruptive vents, while a lull in supply during 2012–2015 was accompanied by sluggish lava flow activity

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(which was fortunate, as this may have prevented lava flows from overrunning the village of Pāhoa in late 2014). The changes in magma supply were documented by a combination of datasets, but relied heavily on SAR data. Interferograms were used to assess volumes of magma storage beneath the surface, while changes in surface topography over time derived from TanDEM-X data provided an estimate of eruptive volumes.

A change in eruptive activity in 2016 appears to be associated with the end of the 2012–2015 lull in magma supply. During the lull, eruption rates were on the order of 1-2 m³/s, and magma storage beneath the surface was negligible (based on models of interferograms). In May-July, 2016, the eruption rate determined from TanDEM-X topographic differences increased to about 4 m³/s, and interferograms indicated extensive inflation of the summit region (Figure 12), suggesting magma storage—a result that is corroborated by GPS (Figure 13). The inflation plus the increase in lava eruption rates suggests that the magma supply to Kīlauea in 2016 was elevated compared to that of 2012–2015, perhaps suggesting that a change in eruptive activity (e.g., an intrusion or formation of a new eruptive vent) within the coming months is likely.

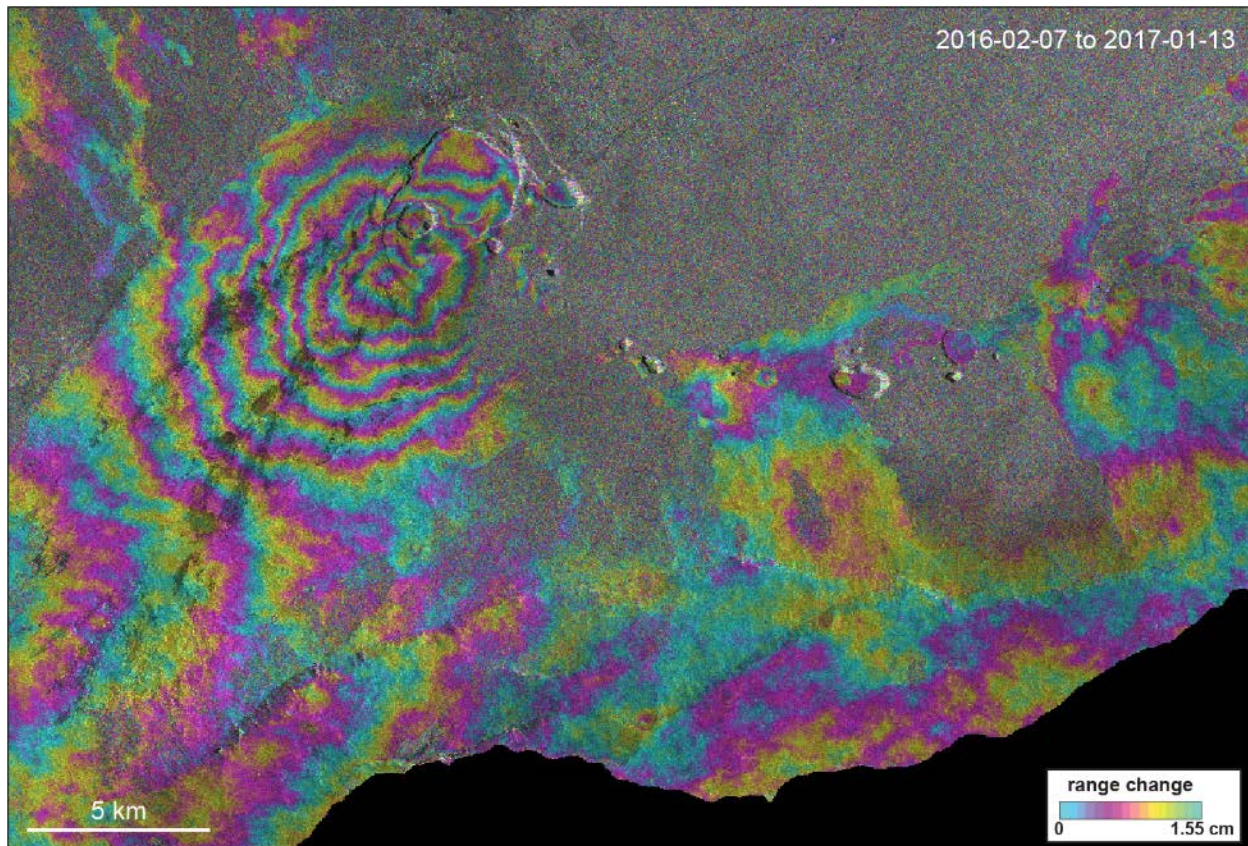


Figure 12. TerraSAR-X interferogram spanning February 7, 2016 to January 13, 2017 and indicating inflation centered in the south part of Kīlauea Caldera.

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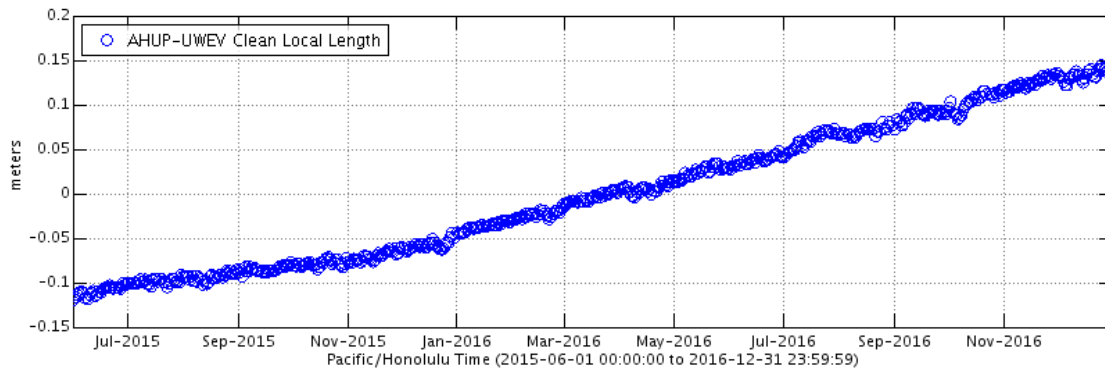


Figure 13. Distance between two GPS stations spanning the summit of Kīlauea Caldera. Positive change is increasing distance, which implies inflation due to subsurface magma accumulation. Inflation of Kīlauea’s summit occurred at a relatively steady rate from the May 2015 intrusion through the end of 2016.