GROUP ON EARTH OBSERVATIONS

GEO Disaster Resilience SBA

GSNL - Geohazard Supersites and Natural Laboratories

Biennial report for Candidate/Permanent Supersite

# *Icelandic Volcanoes Supersite: 2016 - January 2018*

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|---|---|
| **Status** | *Permanent Supersite* |
| **Proposal documents and previous reports** | *http://geo-gsnl.org/supersites/permanent-supersites/iceland-volcanoes-supersite/* |
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## Summary

The Icelandic Volcanoes Supersite initiative has continued to provide important results in the 2016 – January 2018 period, both with new scientific results as well as societal benefits. Results have been communicated actively to the Iceland Civil Protection, including information on new unrest at Öræfajökull volcano, where re-tasking of COSMO-SkyMed satellites has allow formation of one-day interferogram to constrain ice flow in an area of elevated subglacial geothermal activity. Numerous presentations at scientific meetings have used supersite data. Publications include a series of papers on the gradual collapse at Bárðarbunga volcano 2014-2015 and the associated eruption and rifting activity. The most important satellite data used by the science teams in the reporting period are from COSMO-SkyMed and TerraSAR-X satellites (several hundred images from each), in addition to Sentinel-1 data. A challenge for the science teams has been the end of the European FutureVolc project in early 2016. That project provided direct funding to work with the supersite data, but after its end the science teams have used alternate sources to carry out research and monitoring. Considerable efforts have been devoted to study geothermal processes during the reporting period, both natural and also the effects of geothermal utilization. The icelandicvolcanoes.is website operated by the Icelandic Meteorological Office provides access to online catalogue of Icelandic volcanoes, an important resource with information on geology and eruptive history of Icelandic volcanoes, as well as alert levels of volcanoes and activity status based on seismic activity. In-situ data is found at web sites and through contacts with individual scientists. A continuation of the Icelandic Volcanoes Supersite initiative, with commitment from space agencies and researchers involved at a minimum of similar level as before, including those contributing in situ data, has the potential to provide important social benefits and new findings in the future.

## Science teams

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|---|---|
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## ***Science team issues***

The Science team as listed in the table above includes the researchers (individuals) that have been actively working with satellite data provided by CEOS partners to the supersite and have signed appropriate agreements with the space agencies involved. It also includes scientists at the Icelandic Meteorological Office, leading access to in-situ data.

Individuals rather than institutions have led science activities within the supersite initiative. Accordingly each scientist is reported in the table above. The scientists are from ten institutions: University of Iceland, Icelandic Meteorological Office, National Land Survey of Iceland, University of Leeds, UK, KAUST University of Science & Technology, Saudi Arabia, University of Beira Interior, Portugal, Stanford University, USA, Canada Centre for Mapping and Earth Observation, University of Miami and New Mexico Tech, USA

In the beginning of the reporting period a part of the research was organized through a coordinated effort of the deformation team within the FUTUREVOLC research project (http://futurevolc.hi.is). This was a 26-partner project funded by FP7 Environment Programme of the European Commission, addressing topic “Long-term monitoring experiment in geologically active regions of Europe prone to natural hazards: the Supersite concept”. The project started on 1 October 2012 and finished on 31 March 2016.

The two main institutions involved in the scientific exploration of the satellite data provided by the supersite are the University of Iceland and University of Leeds. The point-of-contact (Freysteinn Sigmundsson) has coordinated extensively with the head of the Icelandic Volcanoes supersite team at University of Leeds (Andy Hooper). Their research teams have worked in close collaboration.

Data has been delivered to other institutions as requested by other scientists, following the procedures imposed by space agencies. Some researchers have worked independently on the SAR data provided and thereby advanced science. This shows the supersite has worked as planned, with data being delivered to other research groups after contact with the point-of-contact.

In summary, we report no major obstacles in the organization of scientific research. Compared to previous years, there is now more interest in the data provided through the Icelandic Volcanoes Supersite. Number of researchers actively working with the supersite data has increased.

## In situ data

The most important data sets used in joint interpretation of data are seismic observations and ground displacements inferred by GPS. See websites in the following table.

| Type of data | Data provider | How to access | Type of access |
|---|---|---|---|
| **Seismicity** | IMO | http://en.vedur.is/earthquakes-and-volcanism/earthquakes | public |
| **Seismicity** | IMO | http://hraun.vedur.is/ja/viku | public |
| **Seismicity** | IMO | http://hraun.vedur.is/ja/drumplot/drumplot/allarsort.php | public |
| **Seismicity** | IMO | http://hraun.vedur.is/ja/Katla/<br>http://hraun.vedur.is/ja/hekla<br>http://hraun.vedur.is/ja/vatnajokulsvoktun | public |
| **GPS** | IMO | http://brunnur.vedur.is/pub/gps/timeseries/ | GSNL scientists |
| **Webcams** | IMO | http://brunnur.vedur.is/myndir/webcam/ | public |

### *In situ data issues*

In addition to the web addresses, individual scientists at Icelandic Meteorological Office (IMO) can be contacted for in-situ data.

Extensive information on Icelandic volcanoes can be found at: http://www.icelandicvolcanoes.is

The web interface of this data hub provides at present information on Icelandic volcanoes to all users, including operational users, airlines and civil protection, on Icelandic volcanoes, via the catalogue of Icelandic Volcanoes (CIV). CIV is an open web resource in English and is composed of individual chapters on each of the volcanic systems. It is an official publication intended to serve as an accurate and up to date source of information about active volcanoes in Iceland and their characteristics.

Another aspect of the hub is data portal, where scientific users are able to download data and upload theirs studies and analyses. The data hub at icelandicvolcanoes.is has at present some data on previous eruptions in Iceland, but more work is needed to secure the operation of this data portal and access through it to real time data.

Some development in this respect is taking place through the EPOS-IP (European Plate Observing System Implementation Phase 2014 – 2019). This includes testing of streaming seismic data to ORFEUS, the official service for distribution of seismic data within EPOS-IP. Raw seismic data from previous eruptions has been compiled and work is ongoing to make the raw data sets accessible.

## Satellite data

| Type of data | Data provider | How to access | Type of access |
|---|---|---|---|
| **ERS-1/ERS-2** | ESA | http://eo-virtual-archive4.esa.int/?q=Iceland | registered public |
| **ENVISAT** | ESA | http://eo-virtual-archive4.esa.int/?q=Iceland | registered public |
| **TerraSAR-X (TSX)** | DLR | Available after proposal submission to and acceptance by DLR | GSNL scientists |
| **Cosmo-SkyMed (CSK)** | ASI | POC requests access from ASI for individual users, data then accessible via secure ftpsite: sftp://askja.rhi.hi.is | GSNL scientists |
| **RADARSAT-2** | CSA | POC requests access from CSA for individual users, data then made accessible by POC | GSNL scientists |
| **Sentinel-1** | ESA | https://scihub.esa.int/ | registered public |
| **ALOS-2** | JAXA | https://auig2.jaxa.jp/ips/home | successful proposers |

The following table lists images available:

| Year | Envisat | Cosmo-SkyMED | TerraSAR-X | Radarsat-2 | Sentinel-1 |
|---|---|---|---|---|---|
| 2003 | 21 | | | | |
| 2004 | 87 | | | | |
| 2005 | 116 | | | | |
| 2006 | 100 | | | | |
| 2007 | 134 | | | | |
| 2008 | 196 | | 2 | | |
| 2009 | 59 | | 45 | | |
| 2010 | 29 | 35 | 70 | | |
| 2011 | | 41 | 75 | | |
| 2012 | | 32 | 72 | 6 | |
| 2013 | | 24 | 99 | 26 | |
| 2014 | | 459 | 179 | 69 | 15 |
| 2015 | | 351 | 173 | 22 | 358 |
| 2016 | | 344 | 147 | 42 | 336 |
| 2017 | | 235 | 112 | | 801 |
| **Total:** | **742** | **1521** | **974** | **165** | **1510** |

## *Satellite data issues*

Interaction with the space agencies providing data has been excellent. Handling and use of satellite data has been in agreement with guidelines provided by each of the space agencies providing data.

Cosmo-SkyMed data are extremely important to monitor deformation processes in Iceland and were invaluable during the recent Bárðarbunga eruption. During this event the bulk of the data was received in near real-time – 6 hours after the acquisition – which enabled near real-time processing and timely presentation of results at monitoring meetings with the Icelandic Civil Protection, to facilitate the assessment of potential hazards. New acquisitions were also recently placed over Öræfajökull volcano following the onset of unrest, which commenced here at the start of 2017.

TerraSAR-X and Radarsat-2 data have been delivered according to agreed procedures. Ordering of TerraSAR-X data is fairly straightforward. However, during the TanDEM-X (TDX) mission many orders for TerraSAR-X were cancelled because of conflicts with TDX. Ordering archived Radarsat-2 data requires use of a Windows-only software, making the process somewhat tedious. Furthermore, the software itself is not particularly user-friendly. Having a website-based tool to order archived data would be welcome.

Sentinel-1 data has now become a very important resource for interferometry, complementing other satellite data. Downloading Sentinel-1 data works very well. We note, however, that the download speed is not has good as for TerraSAR-X and Radarsat-2 data, eventually because of a large number of users downloading data simultaneously.

Vincent Drouin has analyzed six Sentinel-1 tracks between summer 2015 and summer 2017 to achieve a full high-resolution coverage of the deformation over Iceland. Interferograms were generated with the ISCE software and multi-looked to have approximately a 100 m resolution. Tracks were selected so that each part of the country is covered with at least one ascending track and one descending track. The different satellite views from descending and ascending tracks allows the decomposition of observed LOS changes into estimates of the near-East (approximate east) and near-Up (approximate vertical) velocities everywhere in Iceland, with exception of low coherence areas like glaciers and farmland.

Managing large satellite based data sets takes a significant amount of time to order, download and organize, so unfortunately delays are inevitable uploading data to secure sites and filing the required space agency contracts during periods of volcanic unrest/eruption. This could be improved by assigning a dedicated IT person at the home institute of the point-of-contact, who would be responsible for this task rather than research/monitoring staff. Proposals have been written to contribute to such support.

## Research results

In the following we provide examples of some  recent research results from use of supersite data. Studies in the following areas are covered (see Fig. 1): Öræfajökull volcano, Bárðarbunga volcanic system, Hekla volcano, Eyjafjallajökull and Katla volcanoes, Northern Volcanic Zone, and Reykjanes and Hengill, South Iceland. Advances in methods for InSAR data analyzes are also presented

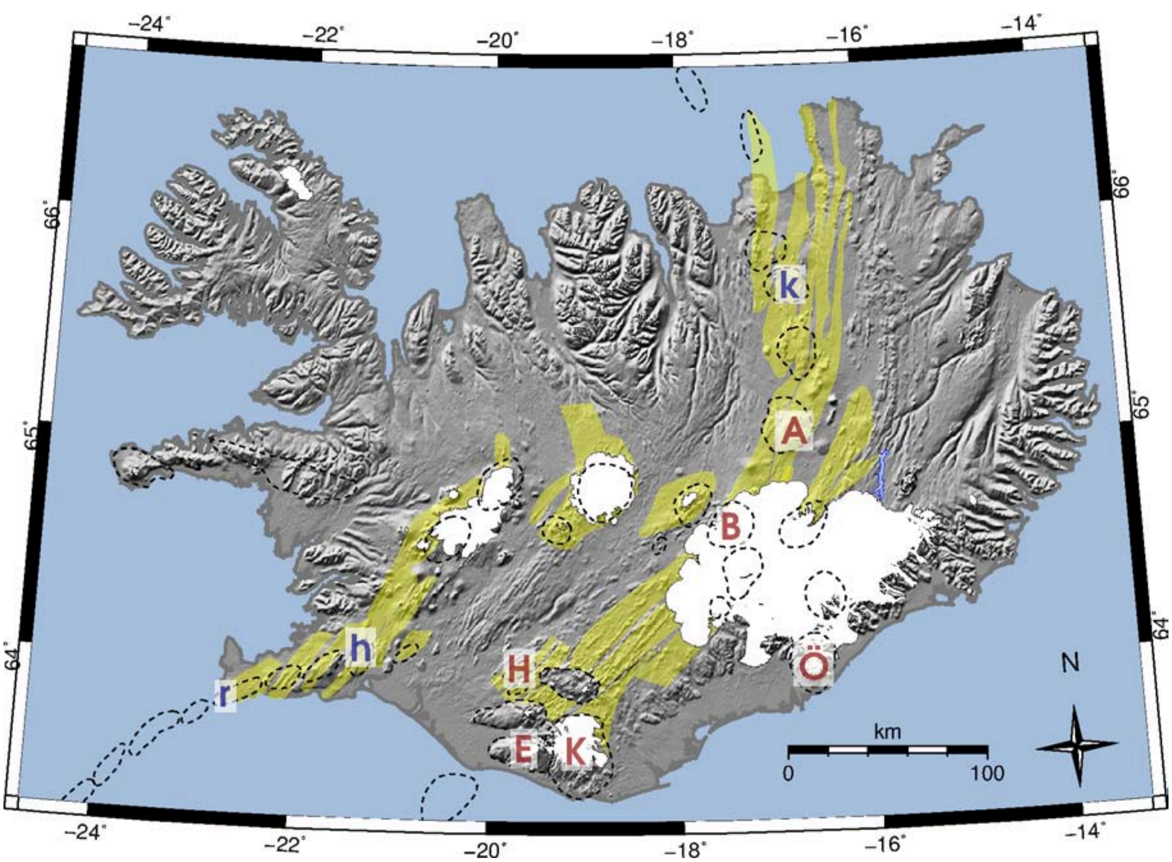


**Fig. 1**. *Map of Iceland with fissure swarms (yellow), central volcanoes (hatched outlines) and areas studied and mentioned in this report.  These include the following volcanoes: Öræfajökull (Ö), Bárðarbunga (B), Hekla (H), Eyjafjallajökull (E), Katla (K), Askja (A), Krafla (k), Reykjanes (r), and Hengill (h). The last three (blue letters on map) represent area where geothermal processes have been studied.*

**Öræfajökull volcano (M Parks and V Drouin)**

In December 2017 COSMO-SkyMed satellites were re-tasked over Öræfajökull volcano in response to a phase of unrest characterized by increased seismicity (Fig. 2) and the deepening of an ice cauldron within the caldera as a result of increased geothermal activity, possibly related to the influx of new magma beneath this volcano. At the time of writing (January 2018) the volcano remains at an elevated alert level (yellow), following analysis of geophysical/geochemical/hydrological parameters. Geothermal water leakage seems to be on-going at similar rate to that observed since the beginning of the unrest. Gas release is also reported in the area. Satellite images and the most recent overflights have revealed that the geothermal source is still evolving and that new areas have become active within the caldera. In light of these data the Icelandic Meteorological Office (IMO) assesses Öræfajökull to be experiencing a phase of unusual activity above the known background and the yellow color code is presently maintained. Supersite CSK satellite images are critical for detecting additional changes within the caldera in terms of crevasse development, cauldron deepening and associated ice flow, and potentially any rapid increases in surface deformation that may be precursory to an eruption.

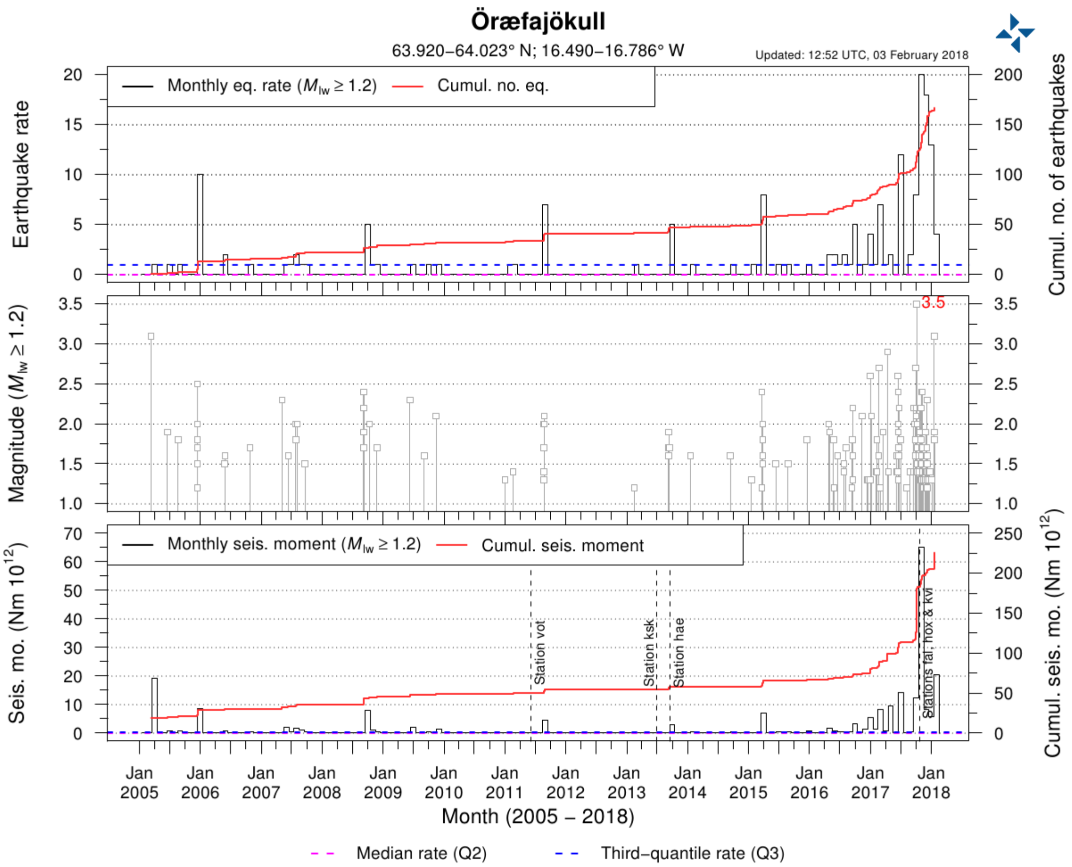


**Fig 2.** *Seismicity at Öræfajökull volcano. The seismicity at Öræfajökull became elevated at the beginning of 2017.*

The re-tasking of the CSK satellites allowed the formation of several one-day interfergrams by Michelle Parks over the unrest area. One of these was coherent over the ice cap surface covering the volcano (Fig. 3), showing fringes due to ice surface displacements, as expected due to ice flow.

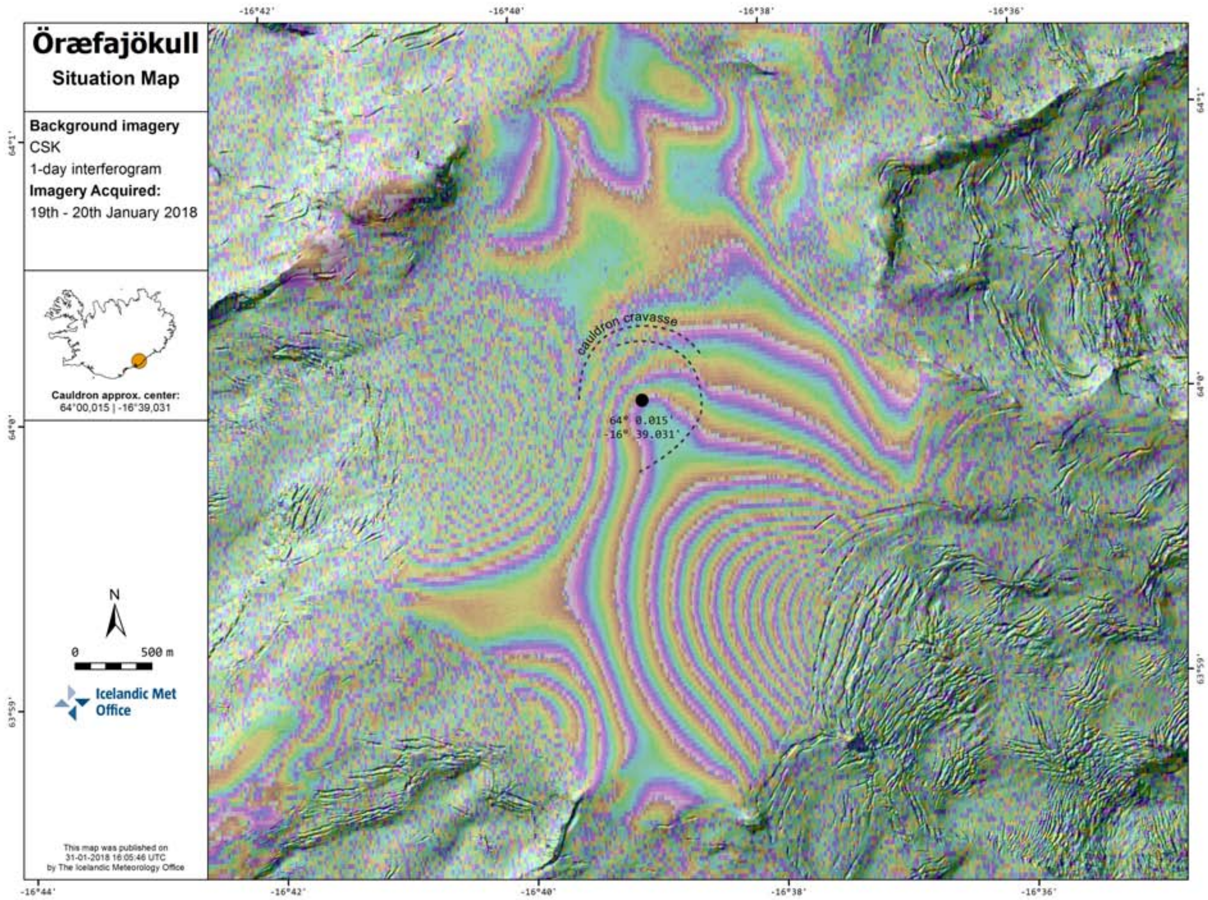


**Fig. 3**. *CSK geocoded, wrapped one-day interferogram covering the period 19-20 January 2018. The interferogram has maintained coherence on the ice-cap covering Öræfajökull volcano. The fringes display ice-motion away from the caldera.*

Vincent Drouin formed a series of ascending and descending Sentinel-1 interferograms, covering the period from 2015 to 2017. Following a correction for glacial isostatic adjustment (GIA), these data indicate a small inflation signal around the southern part of Öræfajokull volcano. The volcano is over 2000 m high, has steep slopes, is covered by a glacier, and is located next to the Atlantic Ocean and Vatnajökull, the largest ice cap of Europe. This causes extreme weather conditions around the volcano, which makes InSAR observations much more difficult than at other volcanoes in Iceland. Therefore the large number of images delivered by the Sentinel-1 mission is very valuable. It allowed creation of InSAR time-series of over 30 images, using only summer acquisitions from 2015 to 2017, and therefore improvement in the (deformation) signal to (atmospheric) noise ratio. In the end, four Sentinel-1 tracks have been used to observe and constrain an uplift signal on the southern flank of Öræfajökull between 2015 and 2017. Another significant uncertainty arises from uncertainties in the GIA model, and this complicates the interpretation. Confidence in these results will be improved following a longer acquisition period of both Sentinel-1 and CSK data in this region and by updating the current GIA model.

Since unrest started in Öræfajökull volcano, there have been regular Science Board meetings, called by the Department of Civil Protection and Emergency Management, with scientists from IMO (responsible for monitoring natural hazards) and the University of Iceland. IMO sends out weekly reports of the monitoring status and informs stakeholders more frequently when required. In addition to the Science Board meetings there have been meetings with the locals living in close proximity to the volcano, where the civil protection together with several scientists (experts in historical eruptions at Öræfajökull and monitoring experts) have given presentations and answered questions from the public. The civil protection has presented evacuation plans in the event of an impending eruption and potential glacial floods, and evaluated volcanic hazards. Meetings related specifically to the tourist industry have also been held for Icelandic companies operating in the field of travel and tourism. The goal of these meetings was to present the volcano monitoring status, evacuation plans and discuss volcanic hazards.

Deformation modeling incorporating both InSAR and GPS observations at this volcano is crucial for understanding the potential amount of new melt that has been intruded beneath the volcano within the last two years and also the depth range of any intrusion. Preliminary modeling results using a sill-like source suggest a magmatic intrusion may have occurred beneath Öræfajökull at a depth of approximately 5 km. These results have been presented to civil protection. Modeling will be updated following new satellite acquisitions in the coming months.

**Bárðarbunga volcanic system and the Holuhraun 2014-2015 eruption**

In the reporting period a series of papers has been published on the Bárðarbunga volcanic system and the Holuhraun 2014-2015 eruption that have benefitted from the Icelandic Volcanoes Supersite. These include the papers by Gudmundsson et al. (2016) on "Gradual caldera collapse at Bárdarbunga volcano, Iceland, regulated by lateral magma outflow" published in Science, a paper by Parks et al. (2017) on "Evolution of deformation and stress changes during the caldera collapse and dyking at Bárdarbunga, 2014-2015: Implication for triggering of seismicity at nearby Tungnafellsjökull volcano" published in Earth and Planetray Science letters, and a paper by Ruch et al. on "Oblique rift opening revealed by reoccurring magma injection in central Iceland" published in Nature Communications.

Supersite SAR data covering these events has thus continued to be a source of important information behind scientific advances. A fourth paper published also in 2017 by Pedersen et al. provides a detailed analyzes of the eruption that occurred (Lava field evolution and emplacement dynamics of the 2014–2015 basaltic fissure eruption at Holuhraun, Iceland) as explained below.

**Holuhraun eruption – emplacement of a major lava field (Gro B.M. Pedersen et al)**

The 6-month long eruption at Holuhraun (August 2014–February 2015) in the Bárðarbunga volcanic system was the largest effusive eruption in Iceland since the 1783–1784 CE Laki eruption. The lava flow field covered ~84 km$^2$ and has an estimated bulk (i.e., including vesicles) volume of ~1.44 km$^3$. The eruption had an average discharge rate of ~90 m$^3$/s making it the longest effusive eruption in modern times to sustain such high average flux. The size of the lava field made remote sensing data extremely important for monitoring the growth of the lava flow field, and aerial and satellite data (including TSX and CSK) provided important complementary observations throughout the eruption. A paper has been published (Pedersen et al., 2017) describing results on the emplacement of the lava field (Fig. 4). Both TSX and CSK data were radiometrically calibrated using the Sentinel-1 toolbox provided by ESA. Refined Lee speckle filtering was applied using a 5 × 5 window, and finally, a Doppler terrain correction was performed using the TanDEM–X intermediate digital elevation model. Airborne SAR data complement the SAR satellite images by providing a higher spatial resolution that resolves detailed internal lava morphologies such as lava channels, boulders, grooves, shear zones and plates. The SAR satellite images, on the other hand, only allow identification of lava channels and other large-scale internal structures.

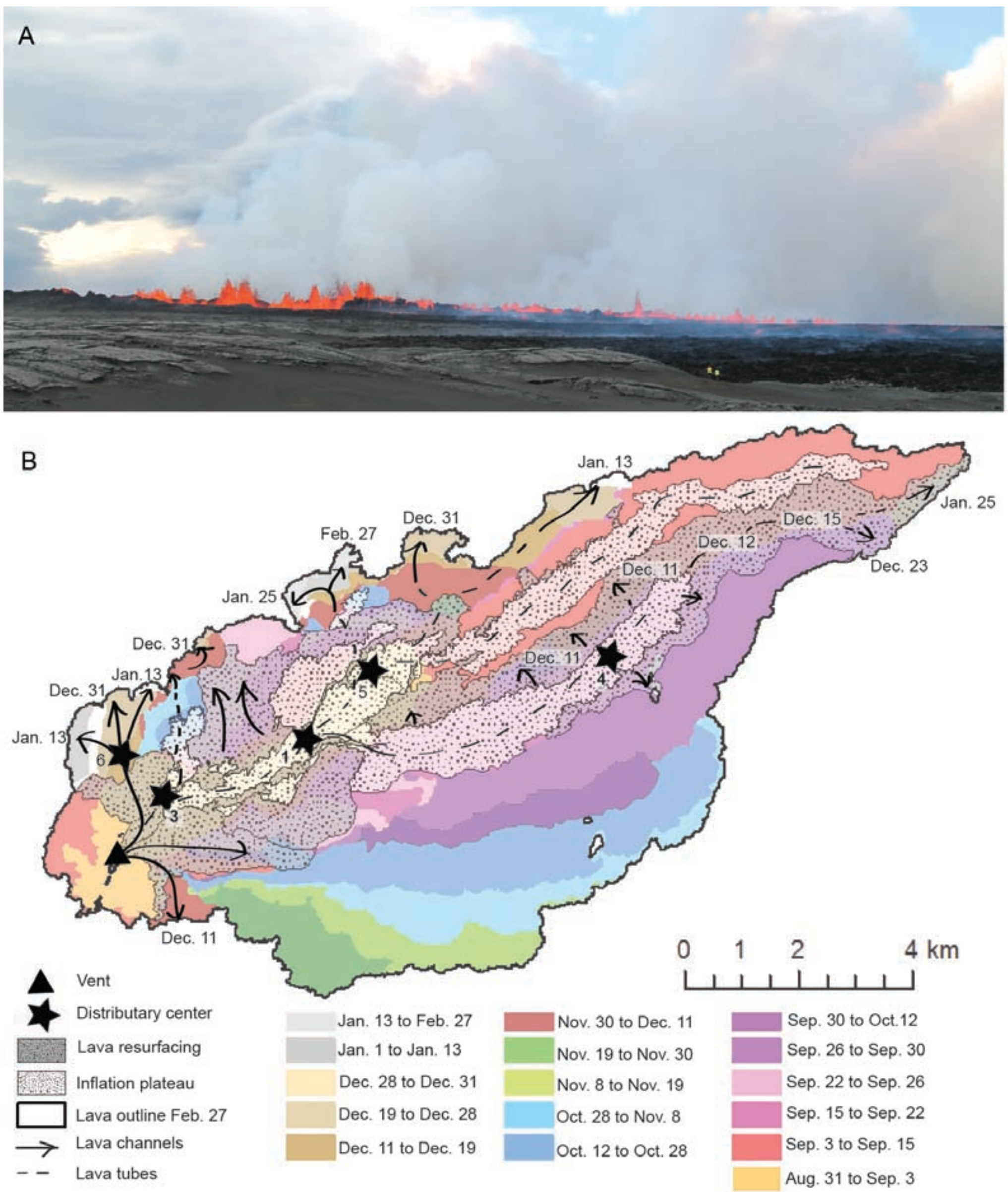


**Fig. 4.** *(A) The Holuhraun eruption; a view east of the vent on the first day eruption, 31 August, 2014 (photo: Gro B.M. Pedersen). The 2 km fissure can be seen in the background, while new lavas (middle ground) are emplaced on older lava fields (foreground). The 2 persons are assessing the extend of the lava field by foot, which already by the next day became so extensive that remote sensing data was essential for the flow field mapping. (B) Map showing the evolution of the Holuhraun lava field.*

**KAUST** scientists (Crustal Deformation and InSAR group leaded by Sigurjón Jónsson) have used both COSMO- SkyMed and TerraSAR-X data to study the deformation associated with the 2014-2015 Bárðarbunga intrusion. They used pixel-offset tracking and focused on the near-field deformation in the graben between the eruption site and the glacier. Combined with seismicity and fieldwork, the results provide information about the graben formation and its evolution. Along with the meter-scale extension, they observe significant left-lateral shear across the graben. Joël Ruch has presented the results at EGU in Vienna (April 2015), at the ILP conference in Potsdam in Germany (invited talk, Sept. 2015). The final results have been presented at AGU (Dec. 2015), at the Italian Geological Society conference in Naples (invited talk, September 2016) and at the CHAPMAN Conference on submarine volcanism in Hobart, Tasmania (January 2017). A paper has been published in Nature Communications in 2016.

Using the large SAR data set collected during the unrest at Bárðarbunga and Holuhraun eruption, Stéphanie Dumont and her colleagues from University of Iceland, IMO and other FutureVolc partners continue to investigate the active volcanic plumbing system feeding the eruption at Holuhraun using a multi-disciplinary approach. Their analysis relies on geodetic data including individual interferograms formed using TerraSAR-X, CosmoSky-Med and RADARSAT-2 SAR images over the eruption site. This data are complemented with three-dimensional displacements observed by GPS in the area. Using the series of interferograms, a joint inversion of interferometric SAR (InSAR) images and GPS has been performed using a Bayesian approach to characterize the time evolution of the dyke opening at depth as well as the slip along faults. These results have been then combined with analysis of seismic data (local earthquakes and tremor) as well as other parameters used as a proxy for eruptive activity (such as SO2 flux, effusion rate, morphological changes at the vents), to characterize the space-time changes associated with the plumbing system feeding the Holuhraun eruption. This approach allows them to study in detail three main phases: dyke emplacement, a transition period associated with the main conduit establishment and an effusive regime. Results have been presented at conferences.

**Hekla volcano (W Wittmann, S Dumont, M Bagnardi)**

Hekla is one of the most frequently erupting volcanoes in Iceland with 18 summit eruptions during the past 900 years, the last one in February-March 2000. Before 1970 the average repose period between eruptions was of ~60 years but since then Hekla has erupted four times, approximately every 10 years (in 1970, 1980-81, 1991 and 2000).

Werner Wittman and colleagues from University of Iceland and University of Liverpool have studied lava cooling processes at Hekla volcano using ERS (T52, T324, T359), ENVISAT (T324) and CSK (T2574, T2575) images. In their paper published in 2017 in Journal of Geophysical Research, Solid Earth, they present time-series from 1993 to 2014 and the associated LOS velocity maps that allow the characterization of the contraction/subsidence of lava fields formed in 1991 and 2000. Ascending and descending configurations were combined to retrieve the near-vertical and near-east components of the deformation field characterizing both periods, post 1991 and 2000 eruptions. Lava lobes formed in 1991 revealed both an exponential decay, with subsidence rates ranging from ~20 mm/yr, 5 years after emplacement to ~2 mm/yr, 15 years after emplacement (Fig. 5) . These data were combined with thermal parameters measured experimentally to investigate the subsidence induced by thermal contraction and to create a thermal model for evolution of the lava field.

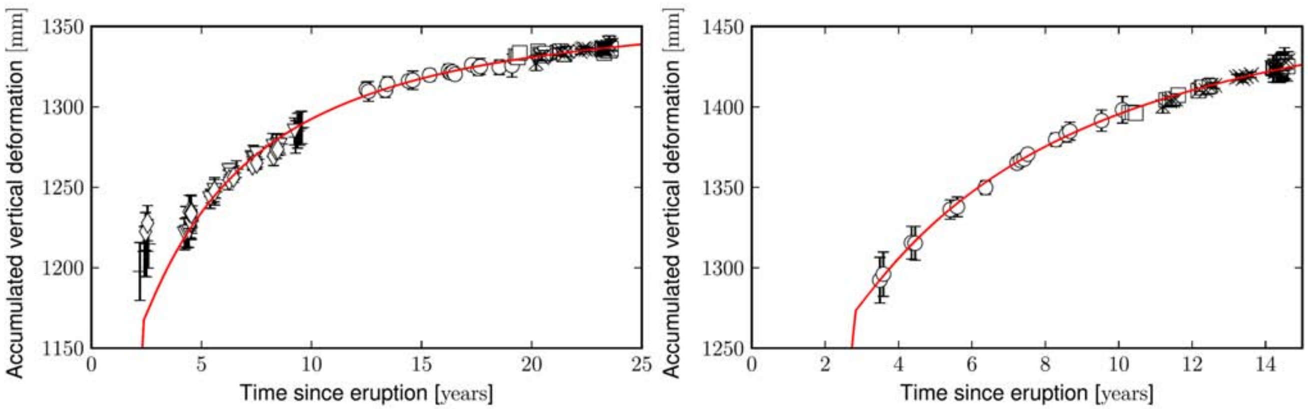


**Fig. 5.** *Best fitting thermal model (red) for accumulated vertical deformation of 1991 lava tongue (left) and a 2000 lava tongue (right). InSAR constrains relative changes from year to year, shown as symbols (for different satellites and tracks).*

While this volcano is one of the most active in Iceland, the structure of its plumbing system is still debated. To track magma movement beneath this volcano and investigate the evolution of its plumbing system/possible changes since the 2000 eruption, an extensive archive of SAR data has been used by Stéphanie Dumont to form time series to detect ground deformation due to pressure changes in the plumbing system.

**Eyjafjallajökull and Katla volcanoes (M Parks)**

PS-InSAR techniques have been used to generate a time series of high-resolution deformation measurements, in the vicinity of Eyjafjallajökull and Katla volcanoes using both TSX and CSK images. This study exploits the combination of InSAR and GPS derived ground deformation measurements, in order to advance our understanding of sub-volcanic processes at these neighbouring volcanoes. Both GPS and InSAR measurements undertaken since the Eyjafjallajökull 2010 eruption (closing the airspace) reveal inflation near the summit of the volcano until the summer of 2015. The location corresponds with the region of deflation identified during the explosive April 2010 eruption. The recent inflation is likely associated with renewed magma recharge to the shallow chamber that was tapped during the explosive phase of the eruption. Recent InSAR results have not detected any deformation outside the ice-cap, however this does not exclude the possibility of a shallow source beneath the volcano.

**Northern Volcanic Zone (V Drouin and J Giniaux)**

The Northern Volcanic Zone (NVZ) of Iceland is a subaerial part of the divergent boundary between the

North-American and Eurasian Plates. Therefore, it is subject to deformation from plate spreading but also from volcanic and geothermal activity. The NVZ is composed of several volcanic systems, the two main active ones in recent times being Krafla and Askja. At Askja, ongoing subsidence in the caldera, the landslide of July 2014 and the influence of the 2014-2015 Holuhraun eruption could all be observed thanks to the COSMO-Skymed and TerraSAR-X images acquired over that period of time.

For Krafla, Vincent Drouin has used ERS, Envisat, and TerraSAR-X satellite images to monitor deformation around two geothermal power plants since 1992 (Fig. 6). He used several TerraSAR-X images in the last few years as well as Radarsat-2 images, which large footprints enables monitoring the entire NVZ in one single process. The data allowed the observation of clear ground subsidence signals at geothermal
production areas, and show that responsible deformation sources have been stable through time. Modelling based on this deformation data suggest that thermal contraction within the geothermal reservoirs can explain the observed subsidence. The deformation data also shows that subsidence caused by a nearby magma source decayed exponentially in the 1990s until 2000.

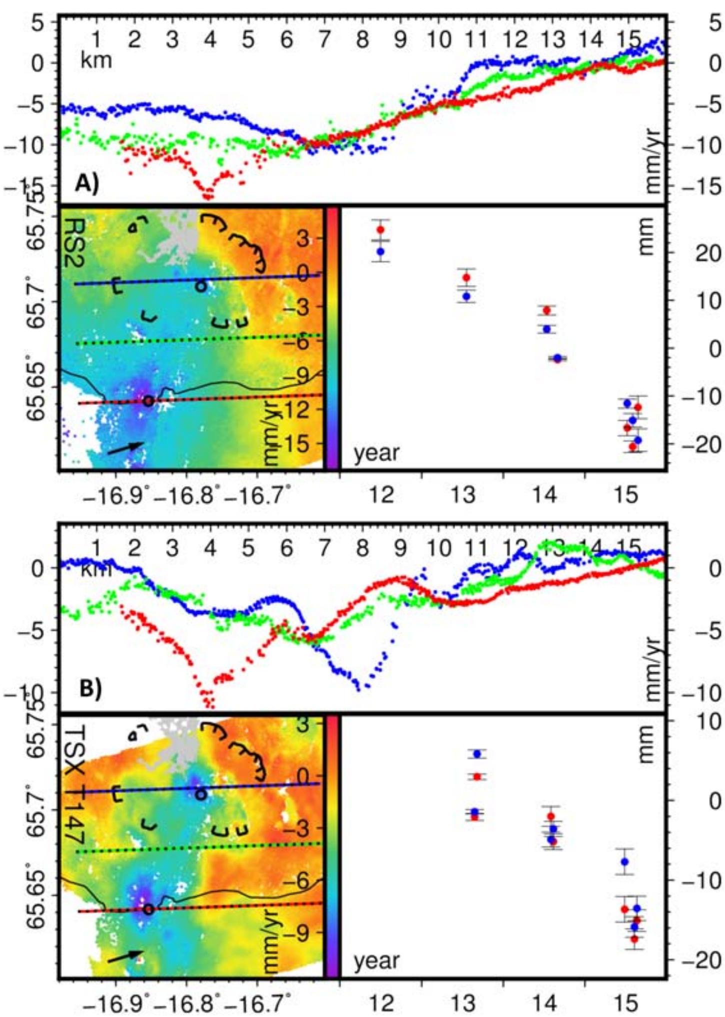


**Fig. 6** . *Overview of ground deformation measurements between 2012 and 2015 at Krafla. B) Radarsat-2 InSAR time series. Left: Average LOS velocity for each PS. Profiles (colored dotted lines), sampling area for time series (black circle), and satellite look direction (arrow) are indicated. Upper: profiles across the Krafla geothermal area (blue), the Bjarnarflag area (red), and between (green). Right: time series of average LOS displacement at Krafla (blue) and Bjarnarflag (red) sampling areas. C) TSX T147 InSAR time series. TerraSAR-X data were provided by the German Aerospace Center (DLR), and Radarsat-2 data were provided by the Canadian Space Agency (CSAS), both through the Icelandic Volcanoes Supersite project.*

Jeanne Giniaux is a PhD student studying deformation at Askja volcano (Fig. 7). To date she has used ERS data from 2002 to 2006 (track 273), ENVISAT data from 2004 to 2010 (track 273) and Sentinel-1 data from 2015 to 2016 (tracks 147 and 111). She is currently working on COSMO-SkyMed data from 2010 to 2015 (tracks 26550 and 24670) and on Sentinel-1 data from 2017 (tracks 147 and 111) to cover the entire period 2002-2017. Her aim is to precisely characterize the surface deformation at Askja and combine these InSAR observations with microgravity to determine the potential physical processes responsible for the on-going subsidence.

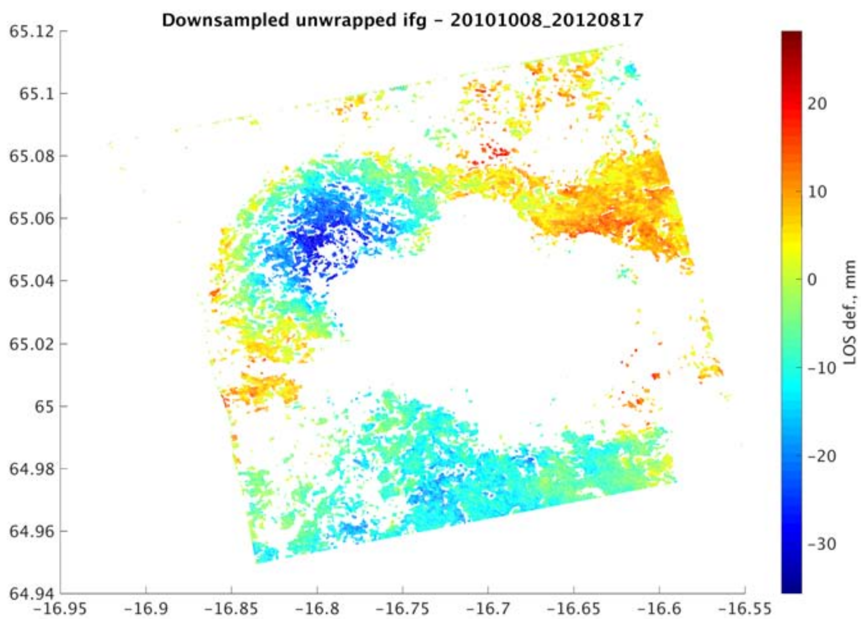


**Fig. 7.** *Askja CKS unwrapped interferogram from the ascending track 26550, covering the period 8 October 2010 to 17 August 2012.The blue elliptical signal in the NW corner of the interferogram represents subsidence (or movement away from the satellite).*

**Reykjanes and Hengill, South Iceland (M Parks and D Juncu)**

This work involves monitoring the ground deformation at geothermal sites related to both geothermal utilisation and volcano-tectonic processes. Michelle Parks used Envisat and TerraSAR-X satellite data, spanning 2003 to 2016, to derive constraints on the cumulative ground deformation at the Reykjanes geothermal area, Iceland, and compare these results to production data acquired from observation wells in this region. Persistent Scatterers interferometric analysis (PS-InSAR), was utilized to produce a time series of range change along line-of-sight (LOS) from the ground to the satellite to show the characteristics of on-going ground deflation in the vicinity of the Reykjanes power plant (Fig. 8). The average LOS velocities from ascending and descending tracks were decomposed into estimates of near-vertical and near-east displacements. Geodetic modeling was undertaken using sources of simple geometry within an elastic halfspace to determine the optimal sources for the observed contraction throughout 2005-2016. A scientific article has been written outlining this work, which is currently under review (Parks et al., 2018).

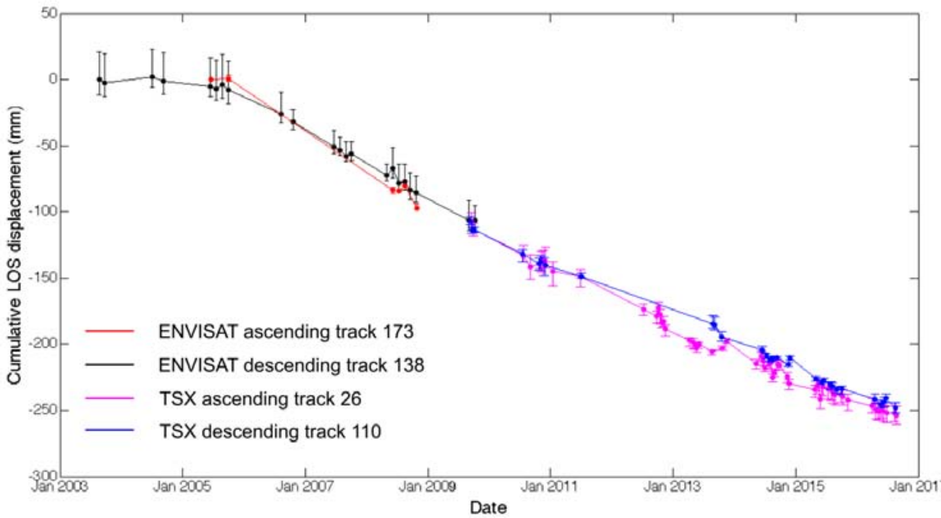


**Fig. 8.** Reykjanes *PS-InSAR time series. The red circles represent the time series derived using data from ENVISAT ascending track 173, black from ENVISAT descending track 138, magenta from TSX ascending track 26 and blue from TSX descending track 110. Figure from Parks et al., 2018 (under review).*

Daniel Juncu used a combination of Interferometric Synthetic Aperture Radar (InSAR) and Global Navigation Satellite System (GNSS) measurements to map ground deformation in the Hengill and Nesjavellir geothermal areas in SW Iceland related to geothermal utilization. The SAR data comprised ascending TSX images from track 41, acquired through the supersite, covering the period from 3 May 2012 to 24 July 2015. At Hengill (Fig. 9), up to ~20 mm/yr of subsidence over an approximately two kilometer wide deformation area has been attributed primarily to pressure drawdown within a geothermal reservoir (Juncu et al., 2017).

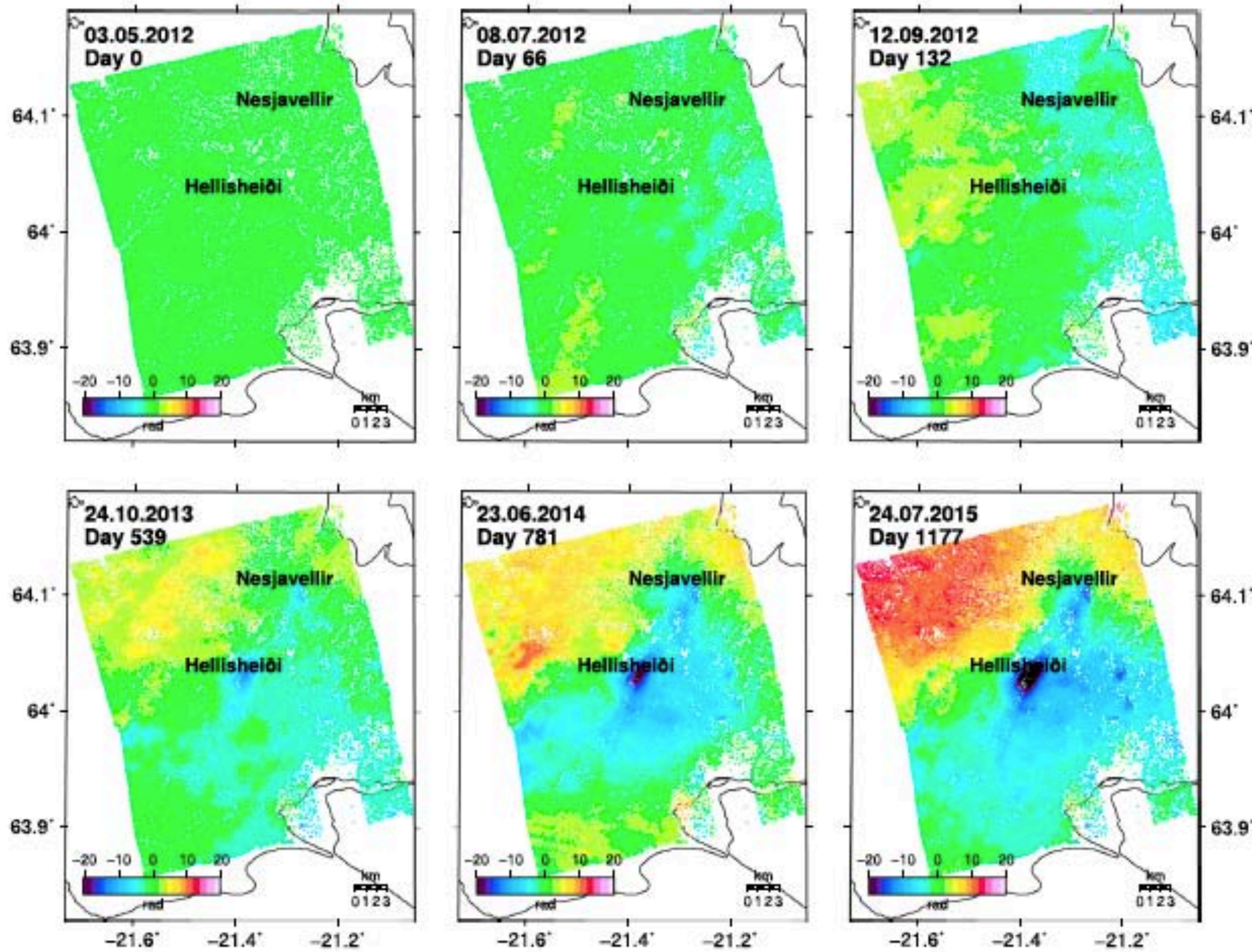


**Fig 9.** *TSX InSAR time series at Hellisheiði covering the period from 3 May 2012 to 24 July 2015. Negative LOS values represent motion away from the satellite. Figure from Juncu et al., 2017.*

Using InSAR data from the same track (TerraSAR-X, track 41, ascending), but from a different time interval (June 2011 – May 2012), in combination with GNSS data, Daniel Juncu analyzed ground deformation related to fluid injection and induced seismicity at the Hellisheidi geothermal field, SW Iceland. Around ~20 mm of expansive ground deformation was linked to fluid injection. The fluid injection, in turn, could be linked to the induced seismicity through the observed deformation (Fig. 10).

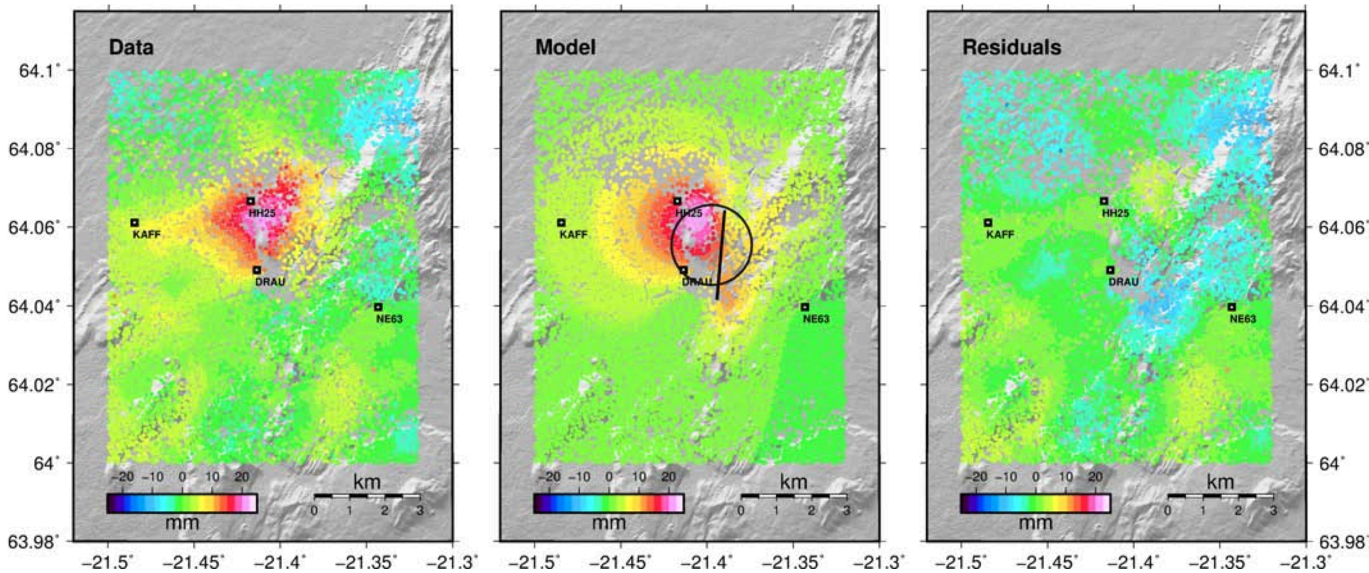


**Fig. 10.** *InSAR data, model and residuals in a study of the effects of fluid injection and induced seismicity at the Hellisheidi geothermal field.*

The study is a rare example where observations of significant ground deformation could be linked to induced seismicity and shows how such observations can help us to understand episodes of seismicity related to the injection of fluids into the crust.

**Development of methods (K. Spaans, A. Hopper, S. Dumont)**

Karsten Spaans and Andy Hooper developed a fast and flexible algorithm to estimate coherence and select points on an interferogram-by-interferogram basis, which overcomes limitations of the conventional boxcar ensemble method in areas of marginal coherence. Time series methods, which offer an alternative way to select coherent points, are typically slow, and do not allow for insertion of new data without reprocessing the entire data set. This new algorithm calculates the coherence for each point based on an ensemble of points with similar amplitude behavior throughout the data set. The points that behave similarly are selected prior to new images being acquired, on the assumption that the behavior of these nearby points does not change rapidly through time. The resulting coherence estimate is superior in resolution and noise level to the boxcar method. In contrast to most other time series methods, a different set of coherent points is selected for each interferogram, avoiding the selection compromise inherent to other time series methods. The method was developed using TerraSAR-X data from track 132, acquired between June 2009 and July 2013. This work was published in the Journal of Geophysical Research: Solid Earth (Spaans and Hooper, 2016).

Stéphanie Dumont and her colleagues have investigated the different decomposition methods that allow to retrieve the vertical and east component from a pair of interferograms, one from ascending satellite configuration and another one from descending configuration. Despite the increase in the number of SAR missions, an area is most frequently imaged by such a pair of interferograms. Such a pair defines an under-determined system with respect to the three-dimensional displacements and is not directly invertible, hence several approaches have been used. A new approach is proposed based on the Singular Value Decomposition. This approach has been compared to other approaches, e.g. using CSK data at the Bárðarbunga volcanic system. Results have been presented at meetings.

## *Publications*

The following publication and conference presentations all acknowledge the support from CEOS to the Icelandic Volcanoes Supersite.

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|---|
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## *Research products*

The primary research products of the Icelandic Volcanoes supersite are the scientific publications in the international literature (see list above) and advice to civil protection authorities. There is, however, an important research product that relates to the supersite, operated by the Icelandic Metorological Office, found online at:

http://www.icelandicvolcanoes.is

This is the online catalogue of Icelandic Volcanoes. It has an up-to-date information on geology and eruptive history of Icelandic volcanoes, as well as alert levels of volcanoes and activity status based on seismic activity. It is thus a very useful resource for all those working with supersite data.

| Type of product | Product provider | How to access | Type of access |
|---|---|---|---|
| **Catalogue of Icelandic Volcanoes** | Icelandic Met Office | http://icelandicvolcanos.is/ | Public |

## *Research product issues*

Additional information on scientific papers and presentations is provided by the lead-scientist of each contribution.

The catalogue of Icelandic Volcanoes has an appointed editor, who can approached with issues related to the catalogue.

Future development of research products, such as algorithms to analyze and interpret geodetic data, will take place within the new EUROVOLC project (see below).

## Dissemination and outreach

In addition to the publications and conference presentations above, there have been additional presentations in forms of invited lectures for the scientific community, public, and persons in the geothermal sector.

Supersite scientists (in particular the Icelandic Metorological Office and University of Iceland) have appeared on radio and TV interviews, as well as in TV documentaries, explaining the nature, behavior and unrest at Icelandic volcanoes.

Information has been provided on web pages of institutions involved, and in social media.

Dissemination and outreach activity on Icelandic volcanoes has greatly benefitted from the supersite project, as that has provided an important component of understanding of volcano situation and unrest.

## Funding

In the beginning of the reporting period, the Icelandic Volcanoes Supersite still benefitted from financial support of FUTUREVOLC project funded by European Commission 1 October 2012 – 31 March 2016. After the end of that, each research team involved has provided in-kind contributions in various forms through other related projects, external as well as internal funding. In particular, the Icelandic Metorological Office has continued the operation of the Icelandic Volcanoes data hub that is important for the supersite.

The end of FUTUREVOLC and the associated funding required some reorganization in personnel working with the satellite data provided by CEOS, as well is in other research activities. This was achieved in an acceptable manner during the reporting period, although resources have been limited.

Beginning of a new three year project on 1 February 2018, project EUROVOLC, funded by the H2020 program of the European Commission, may help with certain aspects of the supersite work, as the project is on integrating and opening research infrastructures of European interest. For example, University of Leeds, Icelandic Met Office, and University of Iceland have a leading role in the geodetic component of the project.

## Societal benefits

In this reporting period, 2016 – January 2018, SAR data have continued to be a critical resource for monitoring natural phenomena in Iceland. InSAR analysis for monitoring of ground deformation has importantly provided social benefits in the form of better understanding of ongoing deformation and the status of Icelandic volcanoes; information that has been communicated to Icelandic civil protection authorities and been used in their analysis of volcano unrest situations. The high spatial resolution of SAR data complements importantly other techniques to map ground deformation. Harsh climate and ever changing weather conditions often hamper the deployment of instruments on ground or aerial surveys. However, snow cover during winter causes loss of coherence in interferograms and limits to use of InSAR during wintertime.

InSAR analysis have been presented at many of the meetings of the science committee of Icelandic civil protection authorities. Most recent example is evaluation of new unrest period that began in 2017 at ice-capped Öræfajökull volcano and continues at time of writing (see annex). Evaluation of ground deformation from Sentinel interferometry for the 2015-2017 has been incorporated into deformation models, and one-day CSK interferogram provides constraints on effects of ice flow within the subglacial Öræfajökull caldera. The CSK interferogram used in this case is an example of product used in the evaluation of volcano situation, impossible to achieve without the Supersite support, as the Italian Space Agency scheduled the acquisition of images with one day spacing specifically to address the unrest at Öræfajökull.

Within this reporting period power companies in Iceland utilizing geothermal resources have also benefitted as stakeholders. Several studies of natural and man-made ground deformation (due to geothermal exploitation) have been carried out, in collaboration with the power companies that have provided complementary data.

Supersite scientists have also communicated directly to the public at various occasions on volcano unrest and behavior in Iceland, in the form of radio and TV news interviews, information on websites, TV documentaries, and newspaper articles.

## Conclusive remarks and suggestions for improvement

The achievements of this GSNL initiative continue to be considerable in the 2016 – January 2018 period. They include joint interpretation of satellite SAR data provided by CEOS and in-situ data, leading to important new understandings of deformation processes published in a series of papers in international journals (including an article in Science), and large number of conference presentations. A group of graduate students, junior and senior researchers, at a number of research institutions are working on various aspects of the SAR data provided by CEOS.

The published papers during the reporting period (see list above) provide important advances in our understanding of magmatic and geothermal processes, including:  Caldera formation, dyke injection, graben formation, formation and evolution of major lava fields during long lived eruptions as well as the subsequent contraction and cooling of lava fields, stress triggering due to magma intrusions and relation between activity in nearby volcanoes, deformation at geothermal processes due to natural processes as well as the effects of geothermal utilization. In many of these studies satellite data from CEOS has been combined with ground-based data such as seismicity and three-dimensional ground deformation mapped by GPS-geodesy.

The interaction with the space agencies contribution data has been excellent during the reporting period. A main issue in the reporting period was the end of the FUTUREVOLC project 31 March 2016. This project secured a formal consortium working with supersite data. However, in this reporting period the supersite team has succeeded in continuing to actively work with the data, although resources are more limited.

InSAR studies using Sentinel data have proven useful in Iceland and their role is anticipated to increase in coming years as time series utilizing these data become longer. They may eventually form the basis for routine mapping of deformation at Icelandic volcanoes. However, studies using other satellites will importantly complement studies based on Sentinel-1 data, and in some cases provide results impossible to receive with Sentinel-1. Examples include the higher resolution of X-band satellites (CSK and TSX) when compared to C-band (Sentinel), and the possibility to form one-day interferograms from CSK data if the COSMO-SkyMed constellation is programmed for that.

A continuation of the Icelandic Volcanoes Supersite initiative, with commitment from space agencies and researchers involved at a minimum of similar level as before, including those contributing in situ data, has the potential to provide important new findings in the future. In light of the considerable scientific achievements and societal benefits made to date, utilizing data provided through the Icelandic Volcanoes Supersite, a continuation of this initiative is requested at a similar level as before.