Biennial report for Permanent Supersite/Natural Laboratory

Icelandic Volcanoes Supersite 2018-2019

History	*http://geo-gsnl.org/supersites/permanent-supersites/iceland-volcanoes-supersite/*
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1. Abstract

The Icelandic Volcanoes Supersite initiative has continued to provide important results in the 2018-2019 period, both with new scientific results as well as societal benefits. Results have been communicated actively to the Iceland Civil Protection, including information on unrest at Öræfajökull volcano 2016-2019, where re-tasking of COSMO-SkyMed satellites allowed 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 plate spreading, glacial isostatic adjustment, use of InSAR and SAR data for operational response during eruptions, and studies of volcanic and geothermal deformation. The most important satellite data used by the science teams in the reporting period are from Sentinel-1, COSMO-SkyMed and TerraSAR-X satellites (several hundred images from each). Pléiades optical stereo images were also important; delivered for the first time through the Icelandic Volcanoes supersite project in the reporting period. The Pléiades data were used to constrain elevation at Iceland's icecaps in locations of subglacial geothermal activity on volcanoes, contributing to societal benefits as they were used to evaluate the likelihood of floods associated with ice cauldron drainage. 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.

2. Scientists/science teams

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Scientists/science teams issues

The Science team as listed in the table above includes researchers 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, Iceland GeoSurvey, University of Leeds, UK, University of Beira Interior, Portugal, University of Hokkaido, Japan, University of Alaska, USA, University of Edinburgh, UK, University of Geneva, Switzerland, and KAUST University of Science & Technology, Saudi Arabia.

Freysteinn Sigmundsson (University of Iceland) and Kristín Vogfjörð (Icelandic Meteorological Office) work effectively as joint point-of-contacts. Kristín Vogfjörð is the key contact at Icelandic Meteorological Office providing access to in-situ data. She is also the coordinator of EC project EUROVOLC 2018-2021; work within the Icelandic supersite project has been aligned with relevant EUROVOLC activities during the reporting period.

No significant obstacles are reported regarding the science team or regarding the organization of scientific research.

1. 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://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/ http://hraun.vedur.is/ja/hekla http://hraun.vedur.is/ja/vatnajokulsvoktun	public
GPS	IMO	http://brunnur.vedur.is/gps/time.html	GSNL scientists
Seismicity	IMO	http://en.vedur.is/earthquakes-and-volcanism/earthquakes	public
Seismicity	IMO	https://skjalftalisa.vedur.is/#/page/map	public
Gas	IMO	http://brunnur.vedur.is/gas/time.html	public

Additional data is being made available through EPOS: https://docs.vedur.is/api/epos/
This currently includes access to GNSS data and dispersion models, and other data sets will also be made available there.

Automated interferometric processing of Sentinel-1 images over Iceland is available at: http://icelandsupersite.hi.is/s1/monitoring.html

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.

2. Satellite data

Type of data	Data provider	How to access	Type of access
Sentinel-1A and 1B	ESA	https://scihub.copernicus.eu/	registered public
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
ALOS-2	JAXA	https://auig2.jaxa.jp/ips/home	successful proposers
Pleiades	CNES	Available after Data Request submission to, and acceptance by, Airbus and CNES	GSNL scientists

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		461	179	69	15
2015		353	174	22	368
2016		355	153	42	361
2017		262	112		848
2018		356	104		1108
2019		646	110		1015
Total:	**742**	**2565**	**1195**	**165**	**3715**

Additional images:
Pléiades optical stereo images were provided by CNES in 2019, including ~4500 km^2 of images

Satellite data issues

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

Sentinel-1 data has now become a very important resource for interferometry over Iceland, complementing other SAR satellite data. The average time between acquisition time and download time is about 4.5 hours (for October-November 2019). Downloading Sentinel-1 data has been working well, but an image takes about 30 minutes to download which is relatively slow compared e.g. to TerraSAR-X data.

COSMO-SkyMed: The data continues to be important for monitoring deformation processes in Iceland and invaluable in some cases. Data can be acquired and processed soon after acquisition, and timely presented at monitoring meetings with the Icelandic Civil Protection, to facilitate the assessment of potential hazards. The use of COSMO-SkyMed data increased in the reporting period following quota increase by the Italian Space Agency, with main volcanoes being systematically covered now. Most important have been images covering Öræfajökull volcano following the onset of unrest that began there in 2016, and the possibility to form one-day interferograms has been critical in some cases.

No Radarsat-2 data were ordered in the reporting period.

TerraSAR-X: In 2019 124 TerraSAR-X images were ordered, and a total of 110 were received. The number of TSX imaged to study and monitor the main active volcanic areas of Iceland are shown in the Figure 1. Ordering the images is a fairly clear and simple process.
The ordered images for the TerraSAR-X satellite may not be delivered if their scheduled acquisition time conflicts with the TanDEM-X mission (TDX). This overlap between mission may also lead to few processing changes, e.g. a part of our data in 2019 was delivered with a slight frequency shift (1dB). This, however, does not seem to have affected InSAR results.

Pléiades data have been delivered smoothly about 2-3 days after images have been acquired.

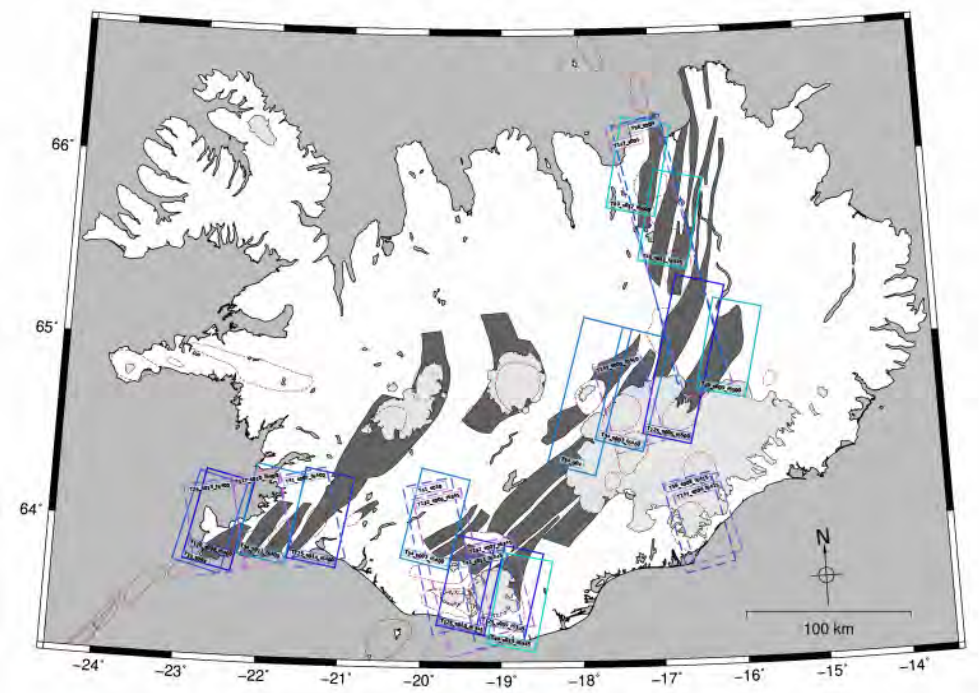

Fig. 1. Overview of the 11 TerraSAR-X tracks that cover the main active volcanic systems in Iceland. Fissure swarms are shown as shaded; central volcanoes with oval outline.

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 who would be responsible for this task rather than research/monitoring staff. However, funding has not been available for this.

3. Research results

In the following we provide examples of some recent research results from use of supersite data. A country-wide study of ground deformation based on Sentinel-1A and 1B data is the first example. The following examples show studies in the following areas: Öræfajökull volcano, Bárðarbunga volcanic system, Hengill triple junction in South Iceland, and Askja caldera north of the Vatnajökull ice cap (Fig. 2). These use Cosmo-SkyMED and TerraSAR-X data. Final example demonstrates the use of Pléiades data for detecting elevation changes on Icelandic ice caps. In the following, the name of areas studied are followed by the lead person for each study.

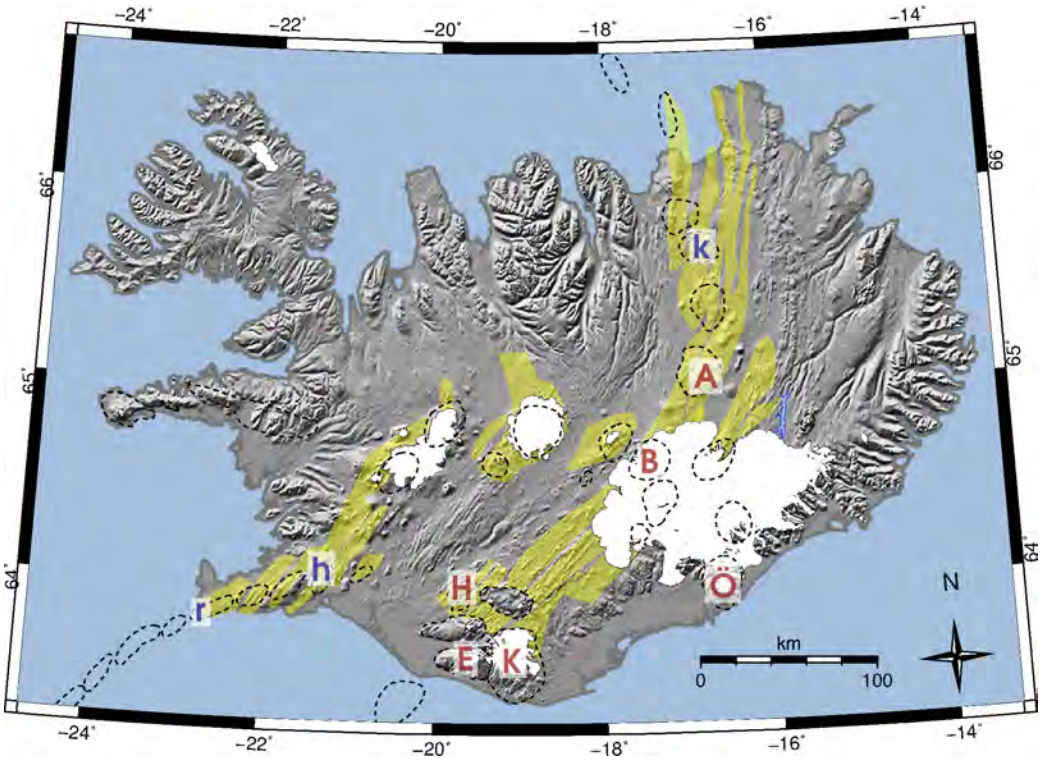

Fig. 2. *Map of Iceland with fissure swarms (yellow), central volcanoes (hatched outlines), glaciers in white and areas studied and/or mentioned in this report. These include the following volcanoes: Öræfajökull (Ö), Bárðarbunga (B), Hekla (H), Eyjafjallajökull (E), Katla (K), Askja (A), Krafla (k), Reykjanes (r), and Hengill (h). The last three (blue letters on map) represent area where geothermal processes have been studied. The biggest glacier is Vatnajökull, and the one covering the Katla volcano is the Mýrdalsjökull glacier.*

Country-wide observations of plate spreading and glacial isostatic adjustment (V. Drouin)

East-west and vertical ground velocities for 2015–2018 are retrieved over 81% of Iceland from Sentinel-1 radar interferometry (Drouin and Sigmundsson, 2019), using satellite images from six different tracks. Only summertime images are considered, to avoid snow cover. Average line-of-sight velocity fields for 2015–2018 for each track are estimated using a simple approach: single master interferometry time series together with a linear component estimation for each pixel. The line-of-sight velocity fields are combined, and their signal is decomposed to extract approximate east (near-East) and approximate vertical (near-Up) velocities. Only pixels passing a coherence and outlier criteria are considered, resulting in 81% coverage of Iceland. The 19%

of missing coverage is mostly glaciers and farmland. We find a general agreement between the near-East velocity field and a revised plate spreading model, and the near-Up velocity field and a glacial isostatic adjustment model. Models and their residuals suggest a difference in rheology between the rift zones in Iceland.

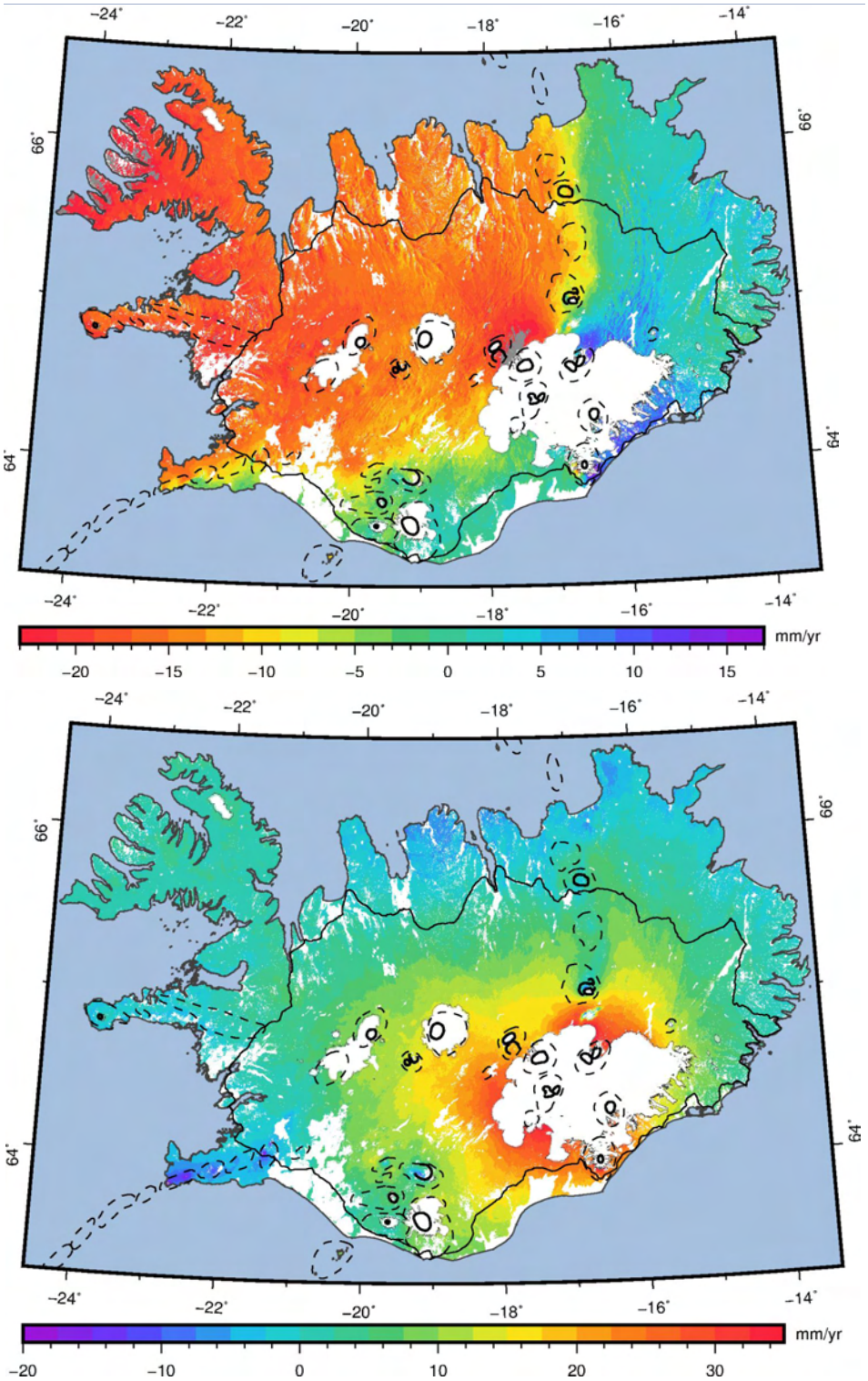

Fig. 3. *Near-East (approximate East) and near-Up (approximate vertical) velocity fields shown in upper and lower panels, respectively. The velocity fields are derived from the decomposition of line-of-sight velocities from interferometric analysis of six synthetic aperture radar tracks (Drouin and Sigmundsson, 2019).*

Öræfajökull (M. Parks)

Öræfajökull is an ice-capped stratovolcano in SE-Iceland within close proximity to settlements and tourist sites. It is capable of producing large ash-rich eruptions, which may trigger devastating pyroclastic flows and jökulhlaups. There are two reported eruptions in the last 1000 years: A major Plinian event in 1362, inundating nearby areas by pyroclastic flows, with major tephra fallout, ballistic ejecta and jökulhlaups, and a smaller flank eruption in 1727 with a volcano explosivity index of 3-4, but nonetheless damaging earthquakes, tephra fallout and jökulhlaups (Catalogue of Icelandic Volcanoes, http://icelandicvolcanos.is).

At the end of 2016, Öræfajökull volcano entered a phase of increased activity. This was initially characterized by elevated seismicity, followed by heightened geothermal activity, gas emissions, and inflation. Geodetic analysis of GPS and InSAR observations (both COSMO-SkyMed and Sentinel-1 data) spanning the period of unrest indicates inflation of the volcano (example of CSK analysis displayed in Fig. 4). The geodetic and seismic observations suggest the most likely cause of cauldron deepening and unrest is the intrusion of magma. These results were presented to Civil Protection and were key for distinguishing uplift related to magma inflow rather than that caused by glacial isostatic adjustment. The modeled source depth (using different source geometries) is located between 2.4-5.4 km. The associated volume change range is between 7-24 million m^3 (Parks et al., 2019 – see conference presentations). This is comparable to the intrusions beneath Eyjafjallajökull during the 1990s. Since the end of 2018 both seismicity and deformation at Öræfajökull have decreased (Fig. 5), however the volcano continues to be closely monitored.

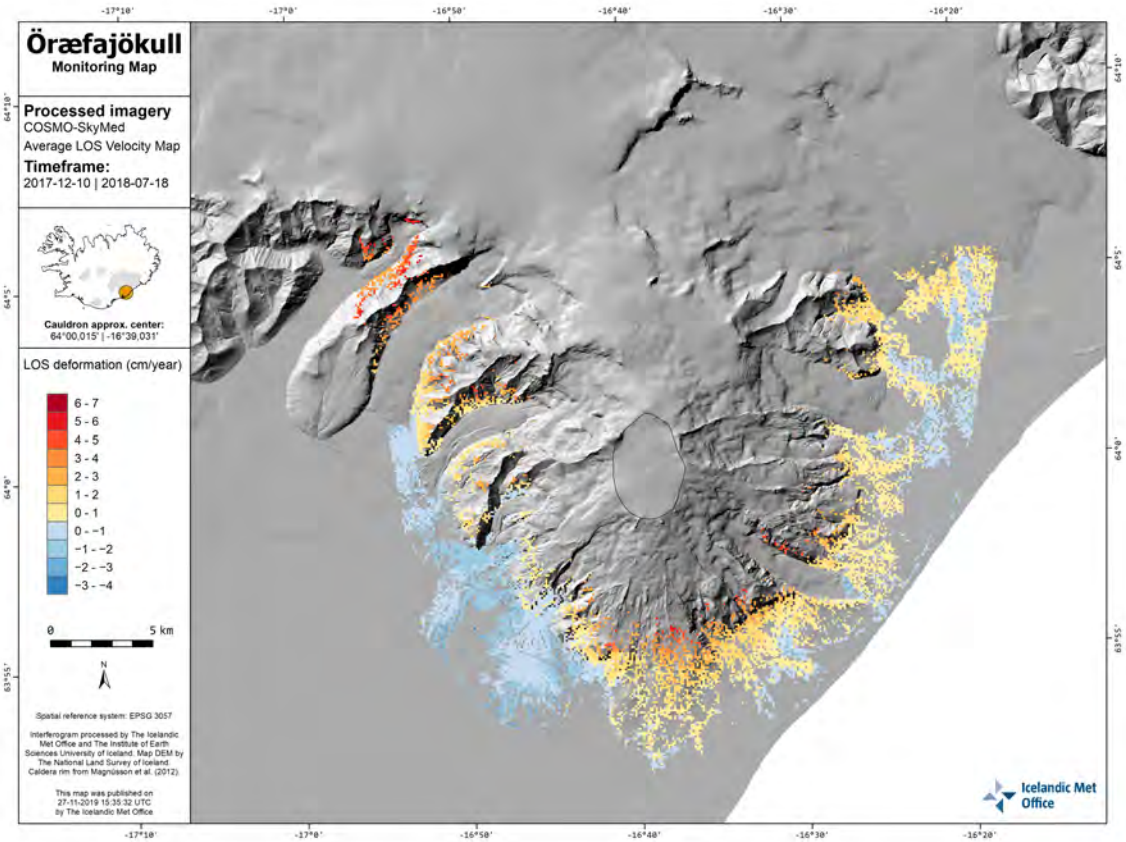

Fig. 4. *Results of PS-InSAR analysis of COSMO-SkyMed data spanning 10 December 2017 to 16 June 2018, showing inflation (red signal) on the southern flank of Öræfajökull.*

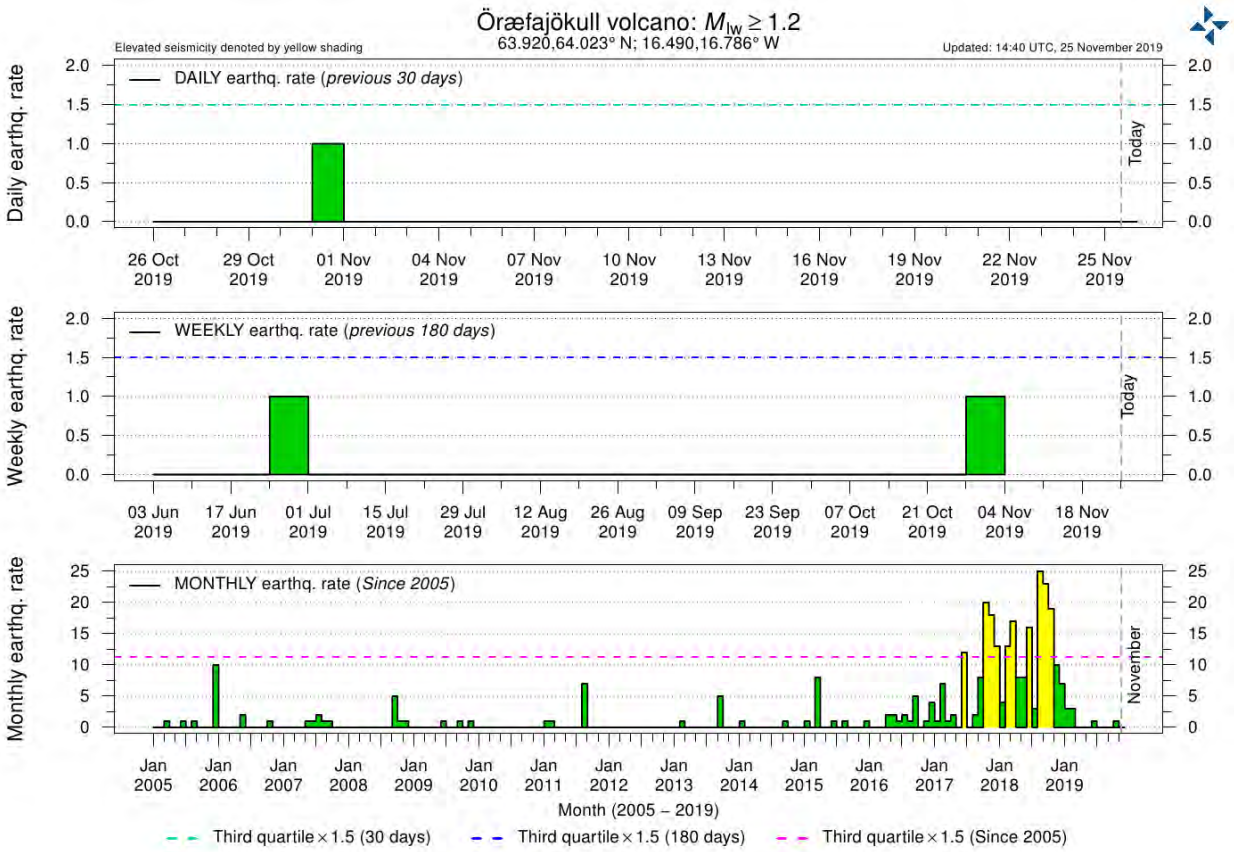

Fig. 5. *Seismicity at Öræfajökull volcano between 2005 to 2019 (Icelandic Meteorological Office).*

Bárðarbunga

<u>Evaluation of role of SAR and InSAR for operational response to eruptions</u> **(S. Dumont)**

Three studies have been undertaken at the Bárðarbunga volcanic system in 2018-2019 in relation to the Icelandic Volcanoes Supersite. One of them considers the role of SAR amplitude and phase information for operational response to the major 6-month-long effusive eruption that occurred in in Holuhraun, Bárðarbunga volcanic systems in Iceland, in 2014-2015, as evaluated in a publication by Dumont *et al*. (2018). Collaborative work led by University of Iceland and Icelandic Meteorological Office to integrate satellite and aerial synthetic aperture radar (SAR) observations into eruption monitoring and operational response was described, and the role of FutureVolc and the Icelandic Volcanoes Supersite projects in this context specifically addressed. TerraSAR-X and CosmoSky-Med SAR data were found to be very important.

SAR amplitude and inSAR interferometric observations were used throughout the whole duration of the volcano-tectonic event, and in the following months, to quantify and track the evolution of volcanic processes at Holuhraun and the geothermal activity at Bárðarbunga volcano as illustrated in Fig. 6. Information provided to civil protection as soon as it became available, based on SAR and InSAR observations, included for example maps of surface displacement or topographical changes, and the temporal evolution of the lava field. The role of

FutureVolc and the Icelandic Volcanoes Supersite Projects was found to be important for delivering advice to civil protection authorities.

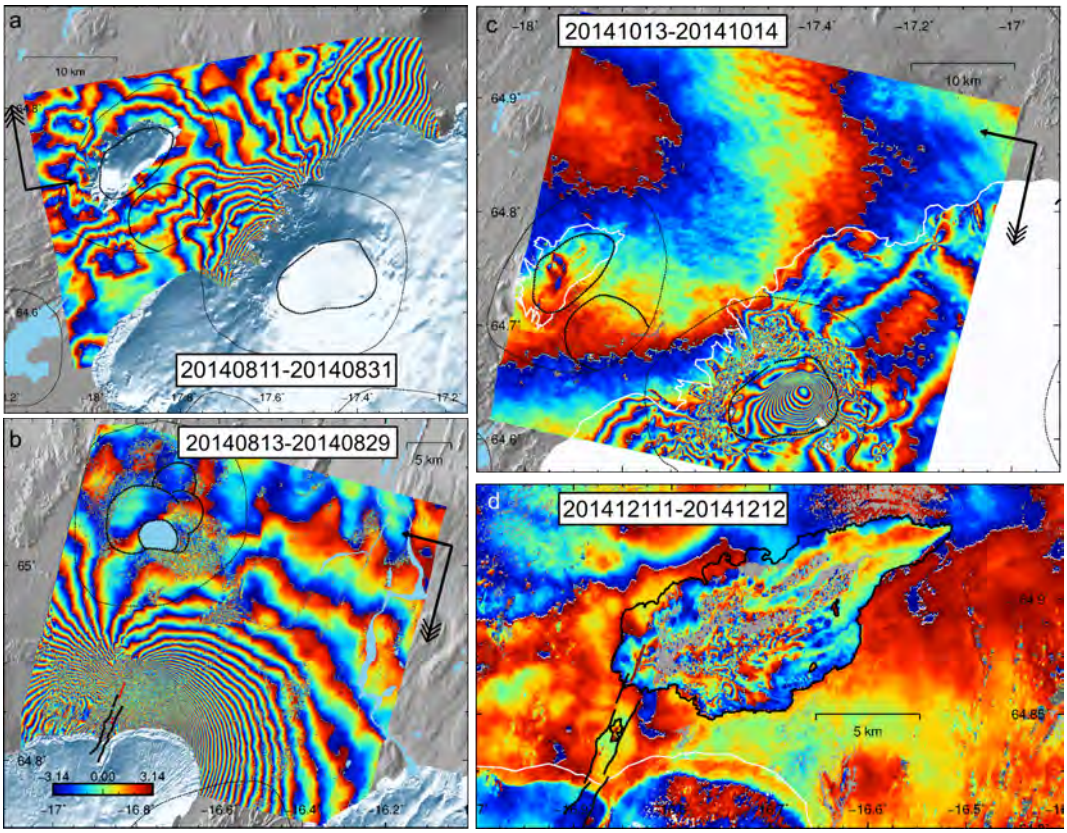

Fig. 6. *Surface deformation using SAR interferometry at Bárðarbunga caldera and Holuhraun eruption site, revealed as wrapped interferograms formed using CosmoSky-Med images. Central volcanoes are shown with black dotted lines, calderas using dashed lines, graben borders and eruptive fissure using black and red lines respectively, and the glacier in white. Simple black arrow indicates the line-of-sight direction, the triple arrows the satellite flight direction. Different surface deformation patterns include: (a) fringe pattern outside the Vatnajökull ice cap related to deflation and subsidence of the Bárðarbunga caldera caused by the withdrawal of the magma body into a propagating dike that induced a horizontal dominated surface displacement north of the caldera, (b) Northern tip of the dyke propagation where the effusive eruption initiated, (c) Subsidence of the ice-capped Bárðarbunga caldera captured by 1-day interferogram revealing caldera collapse. (d) 1-day descending interferogram over the lava field reveal the most active lava channels (decorrelating areas) and those where lava continued flow or inflate at slower rate (area of coherent signal).*

<u>SAR pixel tracking at ice covered volcanoes to reveal subglacial deformation</u> (**Y. Himematsu**)

The 2014-2015 events at Bárðarbunga have been studied extensively with InSAR. However, ice/snow cover on volcanoes impedes the mapping of crustal deformation because of decorrelation problems. Previous geodetic observations have reported deformation signals at ice-free regions of the major dike formed in 2014 in the Bárðarbunga volcanic system, but direct observations of the subglacial crustal deformation associated with the dike intrusion have been limited. A pixel tracking approach to various satellite synthetic aperture radar (SAR)

data over the northern part of the Vatnajökull icecap and the Holuhraun plain has now been applied and results published by Himematsu et al. (2019). The pixel tracking data revealed not only crustal deformation fields in the ice-free region of the magma intrusion, which covers only about 20% of the entire length of dike, but also icecap surface movements over the subglacial part of the dike in the ablation area of the Vatnajökull icecap. Signals above the icecap, suggesting subsidence due to subglacial graben formation, are consistent with the dike propagation path inferred from seismicity during the episode. By subtracting the scaled pre-diking signals from the co-diking signals, we corrected for the steady-state icecap flow signals to derive the subglacial crustal deformations. The inferred subglacial crustal deformation signals can significantly contribute to the improvement of dike opening/faulting distributions. Applying the pixel tracking to satellite images will enable mapping subglacial crustal deformation in the case of subglacial volcanic activity (Fig. 7).

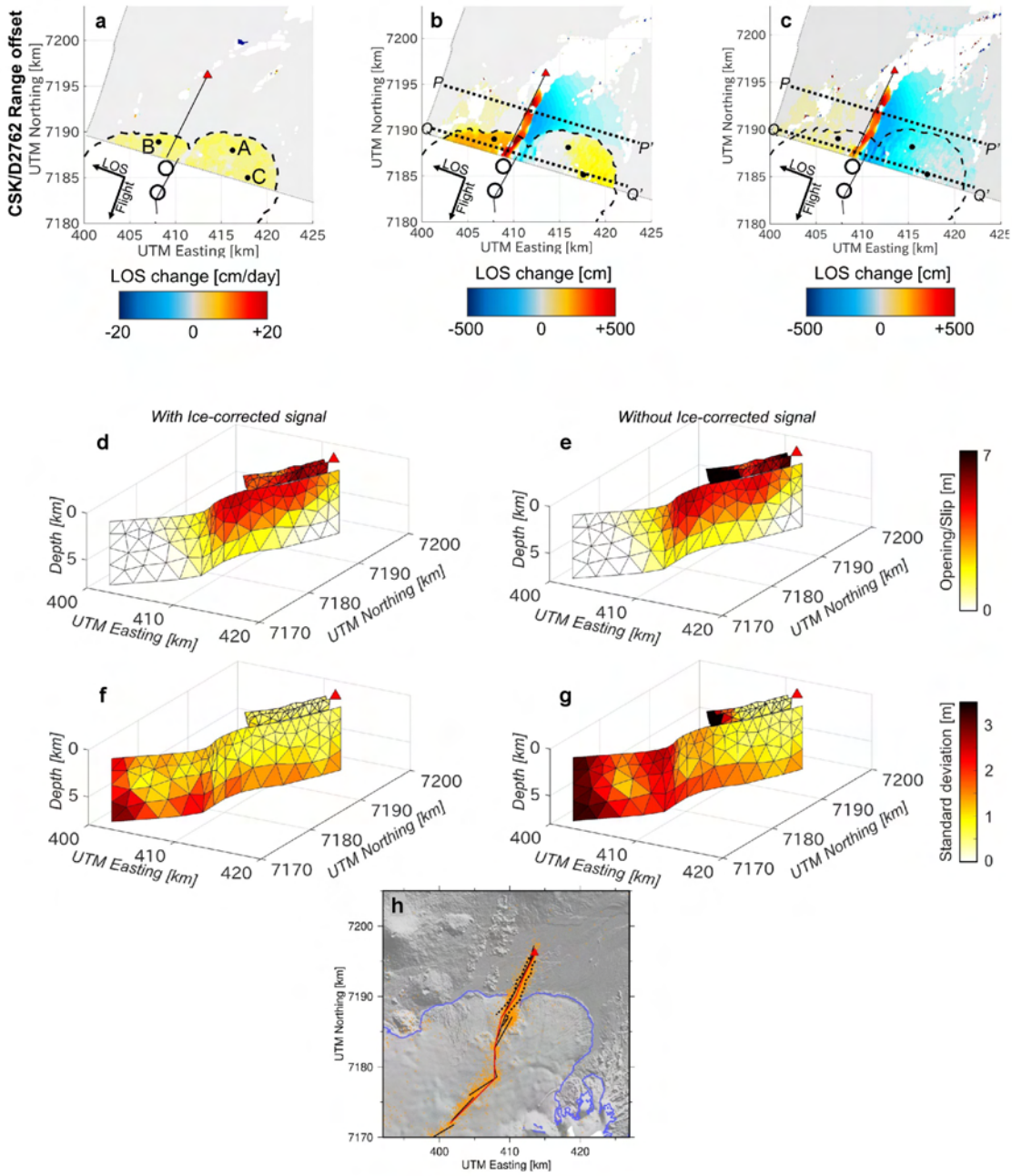

Fig. 7. See caption on the following page.

Fig. 7 caption. *Pre- and co-diking COSMO-SkyMed (CSK) pixel tracking results and ice-corrected signals. (a-c) CSK range offset (line-of-sight: LOS) from descending track (pre-diking: 28 July-12 August 2014, co-diking12 August-23 September 2014, ice-corrected). A positive value indicates LOS changes away from the satellite direction. Coordinates are in UTM zone N28. (d) Inferred opening and normal faulting distributions constrained using the ice-corrected signals, and (e) their standard deviations. (f) Inferred opening and normal faulting distributions without using the ice-corrected signals, and (g) their standard deviations. The three-dimensional view is from the northeast. (h) Map showing the top location of dike (red solid lines) and graben bounding faults (dashed black lines), the outline of the icecap (light blue line), dike segment (black lines) and seismicity during the episode (orange dots).*

<u>InSAR contribution to study of post-eruptive volcanic unrest</u> (**S. Li**)

Unrest in the Bárðarbunga volcanic system after the 2014-2015 activity is also being addressed in a specific study utilizing InSAR and other data sets. the 2015-2018 period is characterized by elevated seismicity within the caldera, ground deformation indicating inflation of the volcano, and continuing development of ice caldrons on the caldera rim of Bárðarbunga. Together these observations show that the volcano continues to be in a state of unrest.

InSAR and Global Positioning System (GPS) analysis are applied to calculate the average ground deformation velocity between 2015 and 2018, when the deformation rates were relatively steady. The two complementary geodetic techniques are important for this study of post-eruptive process at Bárðarbunga, in particular considering the limitations posed by the ice over of the caldera and steep topographic slopes. The nearest GPS station and coherent pixels in interferograms are about 2-3 km from the rim of the Bárðarbunga caldera. After correcting the observed deformation for glacial isostatic adjustment and plate spreading, the remaining average horizontal velocity at the nearest GPS site is 110 mm/yr, radially away from the co-eruptive subsidence center at the caldera.

Modelling is aimed to explain GPS and InSAR detected deformation by evaluating the role of three potential processes: i) viscoelastic response to changes in surface topography due to caldera collapse in the co-eruptive period, ii) viscoelastic response to magma withdrawal in the co-eruptive period, and 3) deformation caused by magma inflow in the post-eruptive period. Results have been presented at conferences (Li et al., conference presentations in 2018 and 2019).

Hengill, SW-Iceland (C. Ducrocq)

The Hengill area in southwest Iceland is at a triple junction between the Eurasian and North American plates, and the Hreppar microplate. The area contains two active volcanic systems, Hrómundartindur and Hengill, and two high-temperature geothermal power plants, Nesjavellir and Hellisheiði. It is an example of an area where deformation of tectonic, volcanic and geothermal origin overlap, that all need to be evaluated to understand processes and hazards involved. A ten-year data set from 2009-2019 of images from the TerraSAR-X satellite, and its excellent resolution, is important for this purpose. The mean line-of-sight (LOS) velocity related to ground deformation 2009-2019, based on images from ascending track T41 of the TerraSAR-X satellite, is shown in Fig. 8.

The tectonic motion and deep processes result in a broad deformation field, visible by a gradual increase, from negative values to the south of the Hengill area, to positive values in the North. The extraction of geothermal fluids causes localized subsidence near the power plants. Deviation from the average deformation field have been documented. In 2011-2012 ground deformation related to the beginning of the water injection process in Hellisheiði in 2011-2012 has been studied and reported by Juncu et al. 2018. Uplift of significant amplitude, up to 2cm over the injection area was observed and interpreted. From autumn 2017 to spring 2018 another deviation occurred. The Hengill area was the locus of an uplift episode which may have been associated with a deep source, due to magmatic and/or hydrothermal process. Evaluation of this period of uplift is being further studied (Ducrocq et al., presentation at American Geophysical Fall meeting 2019).

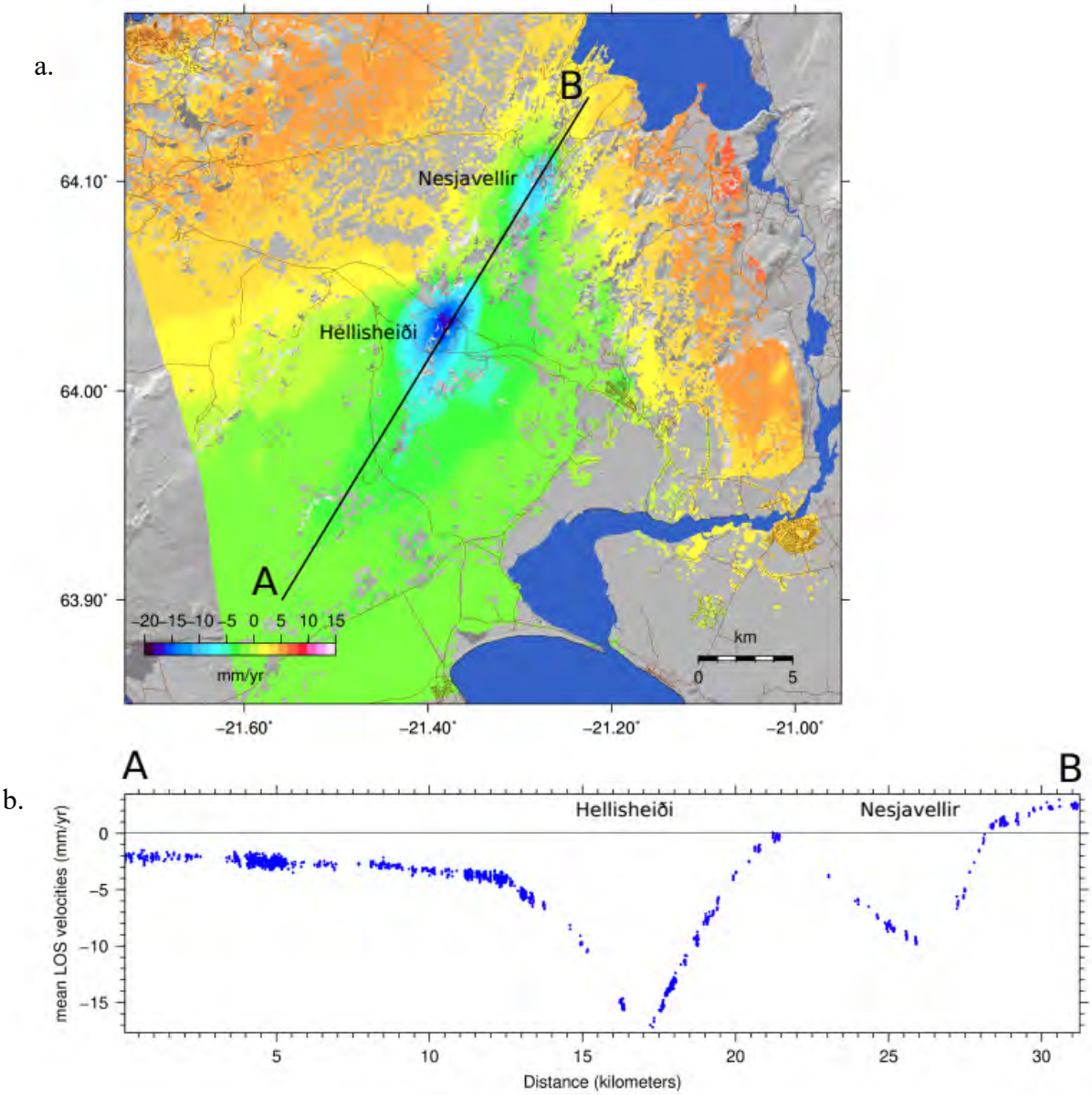

Fig. 8. *a) TerraSAR-X mean line-of-sight (LOS) velocities for 2009-2019 over the Hengill area, SW-Iceland. Negative values correspond to motions away from the satellite, and positive values, towards the satellite. Date analyzed by the DORIS and StaMPS software. The reference for the velocities is the mean of the whole area. b) Mean LOS velocities projected onto the profile shown in (a), showing pixel values in 100 wide zone along the profile.*

Subsidence of the Askja caldera 2002-2017 (J. Giniaux)

The long-term deformation trend of the Askja caldera was revealed by Giniaux (2019) using 15-years of InSAR data, from six tracks and four different satellites (Fig. 9). The GBIS software for inferring best fit models from geodetic observations developed at University of Leeds (Bagnardi and Hooper, 2018) was modified to consider a time-variant magmatic source. It was found that a single process causes all the deformation at the caldera, declining slowly at an exponential rate. A point pressure source embedded in an elastic half-space medium with an exponential decay model can fit the observations in the 2002-2017 period. Assuming the model is appropriate to reproduce the pressure conditions responsible for the bowl-shape subsidence at Askja, there is 95% confidence that the centre of pressure decrease is located at 3±0.1 km depth, and that the volume decrease between 2002 and 2017 was 0.07 km^3. This translates into volume change rates of -0.0016 km^3/yr in 1983 decreasing to -0.0008 km^3/yr in 2017 (Fig. 9).

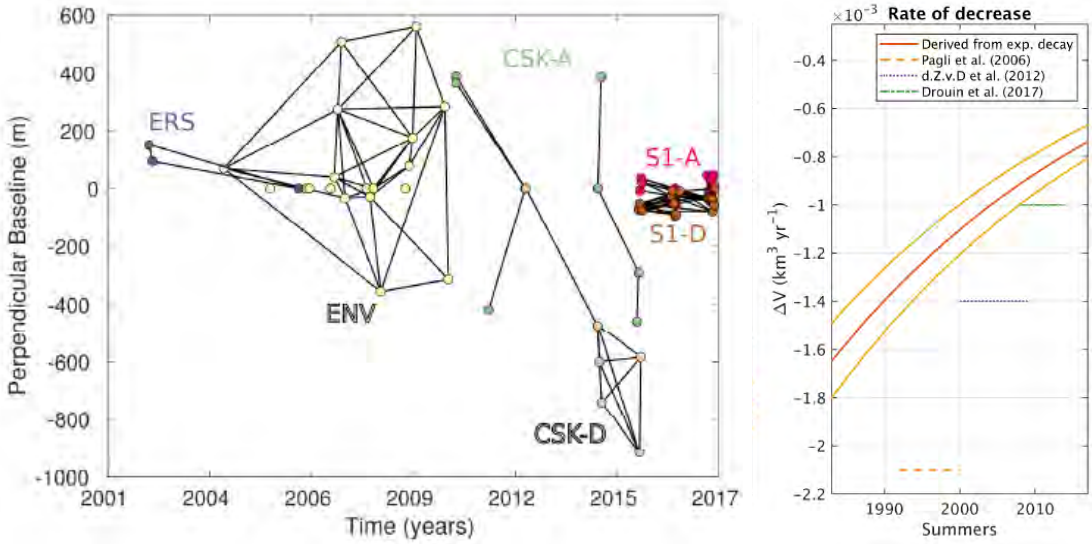

Fig. 9. *Interferogram baselines and time spans used to constrain deformation at Askja caldera 2002-2017, and the inferred rate of volume decrease per year at the caldera center.*

Recorded gravity changes between 2015-2017 along a profile crossing the caldera were also interpreted. It was found that gravity changes and deformation are uncorrelated in time, and that the volume change constrained from InSAR does not agree with the volume of magma loss predicted by the measured gravity changes. These results suggest that the hypothesis of magma draining down to deeper levels is not responsible for the volume change occurring beneath Askja, and that the gravity changes are due predominantly to other unconnected processes.

Digital elevation models from Pléiades data (E. Magnússon)

Pléiades optical stereo images were provided by CNES in 2019, including ~4500 km^2 of images (~2250 km^2 of stereo images), which could be used to obtain digital elevation models (DEMs) of four ice covered volcanic areas (Figure X). This included Öræfajökull ice cap (260 km^2) on 2-3 September, Bárðarbunga and the Skaftár cauldrons (~400 km^2) on 3 September, Grímsvötn and vicinity (~500 km^2) on 1 October, and finally the center part Mýrdalsjökull ice cap (280 km^2) covering Katla at four different dates: 8 August, 10 August, 27 September and 23 October.

The data from Mýrdalsjökull was particularly useful. It has: a) enabled quantification of elevation change and motion of unstable mountain side adjacent to one of Mýrdalsjökull outlet glacier (the unstable mountain side was discovered this summer) and b) helped revealing ice cauldron activity during the summer (Fig. 10) due to subglacial geothermal activity. Cauldrons K10 and K11 were of specific concern due to a warning issued to local authorities and civil protection, based on field observations, of a substantial flood likely to originate from beneath these cauldrons during the summer; typically water bodies beneath the two cauldrons drain in a single flood during the peak of the summer. The data, however, reveal that K10 leaked throughout the summer (minor subsidence observed in K10 for all periods shown in Fig. 10, while a flood from K11 did not occur until October (Fig. 10d), when the drainage in river affected by the flood was much lower than in the summer. The persistent leakage from K10 and the autumn flood from K11 resulted in much smaller flood peak than otherwise was expected.

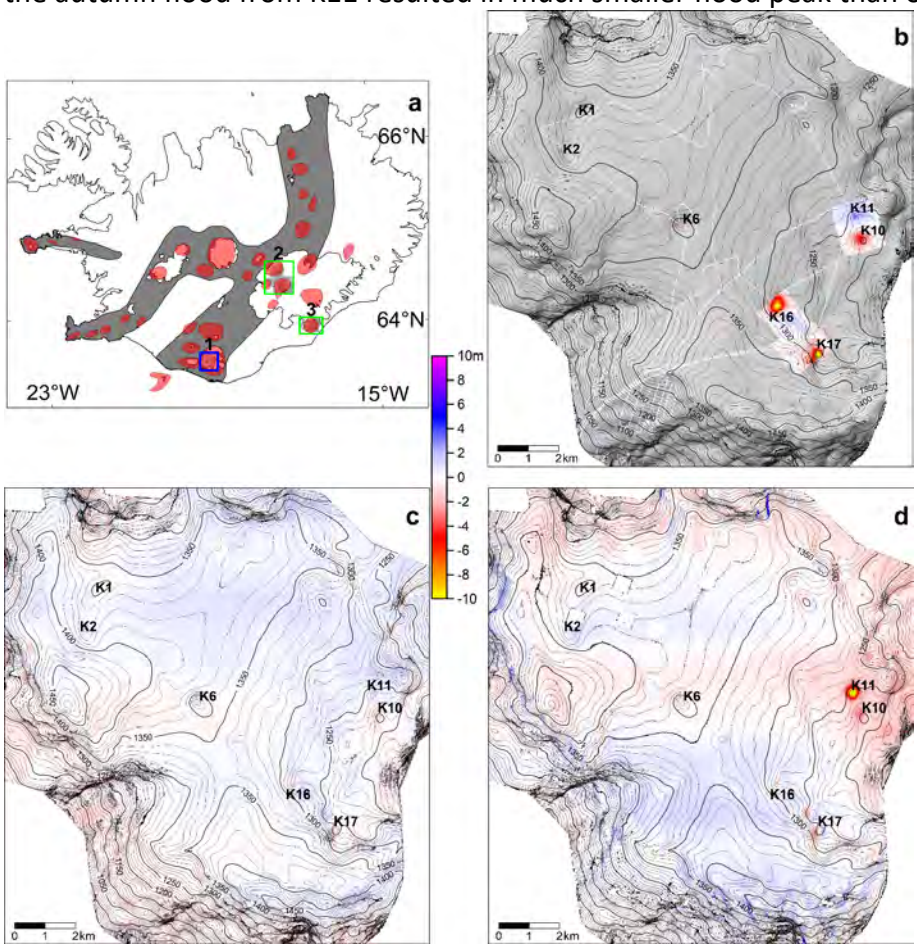

Fig. 10. *a) Map of Iceland showing its ice caps, volcanic belts (grey), central volcanoes (red) and areas of Pléiades stereo acquisitions in 2019 on Mýrdalsjökull (blue box signed 1), Grímsvötn, Bárðarbunga and Skaftá Cauldrons (green box signed 2) and Öræfajökull (green box signed 3). b-d) Elevation changes on Mýrdalsjökull (blue box on a) from Pléiades DEMs and GPS profile data from 20 May (GPS profiles) to 10 August (b), 10 August to 27 September (c) and 27 September to 23 October (d). The posted labels show the names of the most active ice cauldrons and contours reveal elevation from the latter DEM, from which the elevation changes is calculated. The mean elevation change outside the cauldrons has been subtracted from the absolute elevation change for each period to highlight anomalies in surface elevation changes differing from the ordinary.*

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Ducrocq C., Geirsson H., Árnadóttir T., Drouin V., Juncu D., Kristjánsson B. R., Gunnarsson G. (2018), **The 2017-2018 uplift episode in the Hengill area, SW Iceland, from geodetic data,** Oral presentation, GEORG Geothermal workshop, Reykjavík, Iceland, November 14-15th 2018.

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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, available at the website of the Icelandic Metorological Office:

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.

Other research product available is “Sentinel-1 velocity fields 2015-2018” provided by University of Iceland at:

https://osf.io/7uxzt/?view_only=2fff37806033465385c92219c2c4a6ae

Type of product	Product provider	How to access	Type of access
Catalogue of Icelandic Volcanoes	Icelandic Met Office	http://icelandicvolcanos.is/	Public
Sentinel-1 velocity fields 2015-2018	University of Iceland	See link above the table.	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 EUROVOLC project.

4. 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 have greatly benefitted from the supersite project, as that has provided an important component of understanding of volcano situation and unrest.

An important additional outreach is through development of an online course on volcano monitoring and magma movements, where supersite data has been used and CEOS, GEO and GSNL are acknowledged. The course is freely available or everyone and was designed to share knowledge gained e.g. through the Icelandic Volcanoes supersite project. It is at the edX education platform and can be found at:

https://www.edx.org/course/monitoring-volcanoes-and-magma-movements

More than 2000 persons in 94 countries have signed up for the course.

5. Funding

During the reporting period, each research team involved provided in-kind contributions in various forms through other related external projects, 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 three-year EUROVOLC project (1 February 2018 – 31 January 2021), funded by the H2020 program of the European Commission, helps 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.

6. Stakeholders interaction and societal benefits

Stakeholders include civil protection authorities, local authorities, Icelandic and international authorities, as well as civil aviation authorities. Stakeholders include also the general public in Iceland as well as population in other parts of the world in case of major eruptive activity in

Iceland that can influence air traffic and living conditions in large parts of the world.

InSAR analysis for monitoring of ground deformation has continued to provide social benefits in the form of better understanding of ongoing deformation and the status of Icelandic volcanoes.

This information is communicated most importantly to the 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 the 2016-2091 unrest period at ice-capped Öræfajökull. Evaluation of ground deformation from COSMO-SkyMed and Sentinel interferometry for the unrest period has been incorporated into deformation models, and one-day Cosmo-SkyMed interferogram provides constraints on effects of ice flow within the subglacial Öræfajökull caldera. The CSK interferograms 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.

The interaction of the supersite scientist with the Icelandic civil protection authorities is a direct contribution to the *GEO Disasters Resilience Benefit Area.* Once the information is provided to the civil protection authorities in Iceland, the information spreads from there to other stakeholders.

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.

7. Conclusive remarks and suggestions for improvement

The achievements of this GSNL initiative continue to be considerable in 2018-2019 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: Plate spreading, glacial isostatic adjustment in response to warming climate, dyke injection, graben formation, 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 importance of SAR and InSAR data in operational response to volcanic eruption has been evaluated, with reference to the Icelandic Volcanoes Supersite project. Technological advances include the development of a method to detect subglacial ground deformation by SAR pixel tracking, taking into consideration an estimate of ice cap changes and ice flow in a period prior to magmatic activity.

The interaction with the space agencies contribution data has been excellent during the reporting period.

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 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 suggested at a similar level as before.