Biennial report for Permanent Supersite/Natural Laboratory

Icelandic Volcanoes Supersite 2020-2021

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

The last two years has proved to be an exceptionally active period in Iceland – with a 14-month long volcano-tectonic unrest on the Reykjanes Peninsula (commencing in December 2019); which culminated in an effusive fissure eruption on the 19 March 2021 in Fagradalsfjall. In addition to this, Askja volcano entered a period of unrest at the start of August 2021, which at the time of writing (November 2021) is still ongoing. Throughout the 2020-2021 period the Icelandic Volcanoes Supersite initiative has continued to provide invaluable new information and scientific results, which have guided decision-making processes in Iceland and benefited society. Results have been communicated actively to the Iceland Civil Protection, including information on the dike intrusion and eruption at Fagradalsfjall, where re-tasking of COSMO-SkyMed satellites allowed the formation of long-term line-of-sight (LOS) timeseries, able to identify co-eruptive deflation and confirm renewed inflation following the end of eruptive activity on the 18th September 2021. A number of presentations at scientific meetings have used supersite data. Publications include a series of papers on use of Interferometric Synthetic Aperture Radar (InSAR) results for operational response during episodes of both unrest and eruption, and studies related to magmatic, hydrothermal and viscoelastic responses.

At Hengill the analysis of long-term InSAR timeseries has improved our understanding of the relationship between geothermal, tectonic and magmatic processes. Additional studies at Bárðarbunga have provided new information on distinguishing between inflation related to the inflow of new magma or viscoelastic effects, and at Krafla, new geodetic models will help constrain whether recent uplift is related to geothermal utilisation or magmatic processes.

The most important satellite data used by the science teams in the reporting period for InSAR analysis are from Sentinel-1, COSMO-SkyMed and TerraSAR-X satellites. Pléiades optical stereo images were used to obtain digital elevation models (DEMs) at four ice covered volcanic areas in addition to the 2021 eruption site on Reykjanes Peninsula. The icelandicvolcanoes.is website,

operated by the Icelandic Meteorological Office, provides access to the 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 or have contributed to research outlined in this report. It also includes scientists at the Icelandic Meteorological Office, leading access to in-situ data.

Freysteinn Sigmundsson (University of Iceland) and Kristín Vogfjörð (Icelandic Meteorological Office) have worked 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 organisation of scientific research.

1. In situ data

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/	public
Seismicity	IMO	http://hraun.vedur.is/ja/Katla/	public

		http://hraun.vedur.is/ja/hekla	
		http://hraun.vedur.is/ja/vatnajokulsvoktun	
Seismicity	IMO	https://en.vedur.is/earthquakes-and-volcanism/earthquakes	public
Seismicity	IMO	https://skjalftalisa.vedur.is/#/page/map	public
GPS	IMO	http://brunnur.vedur.is/gps/time.html	GSNL scientists
GPS	UI	https://notendur.hi.is/~hgeirs/iceland_gps/rnes/rnes_100p.html	public
Gas	IMO	http://brunnur.vedur.is/gas/time.html	GSNL scientists

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.

There is a GNSS service with metadata (station and site information) and 15s Rinex data are accessible from 16 GPS stations (FJOC, KISA, SKRO, VMEY, HAFS, GSIG, ISAK, KIDC, DYNC, RJUC, HUSM, HVEL, RHOF, THOC, HAUC and VONC).

There are 10 volcanological services; including access to hazard maps, volcano colour codes, weekly status volcanic reports and VONA reports (9 are under the Volcanoes menu and 1 is under Dispersion).

IMO is already transmitting seismic data to Orfeus EIDA from 6 seismic stations, since 2017 (these stations are GIL, ADA, SKR, FAG, ASB, GOD). Additional data from approximately 15 stations (covering the Bardarbunga eruption) should be made available in December 2021.

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*	*https://esar-ds.eo.esa.int/oads/access/*	*Registered public*
ENVISAT	*ESA*	*https://esar-ds.eo.esa.int/oads/access/*	*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 made accessible by POC*	*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://www.eorc.jaxa.jp/ALOS/en/alos-2/a2_data_e.htm*	*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
2020		695	176		1101
2021		733	198		1086
Total:	**742**	**3993**	**1569**	**165**	**5902**

Additional images:

Pléiades optical stereo images were provided by CNES, including ~3680 km^2 of images in 2020 (~1840 km^2 of stereo images) and ~4130 km^2 of images in 2021 (~1860 km^2 of stereo images and 137 km^2 in tristereo).

Satellite data issues

TerraSAR-X

As in previous years, the ordering of TerraSAR-X images is straightforward and done via the online portal. Downloading the acquired images can simply be done via secure file transfer (lftp); however, the images are ready for download ~5 days after the acquisition time, and longer delays can occur. Placed orders can sometimes not be delivered, due to, for example, conflict with other orders of the satellite or issues with ground stations. In 2020 a total of 201 images from the TerraSAR-X satellite were ordered and 176 delivered. In 2021, 232 orders have been placed and 198 images have been delivered (as of 10th of November 2021). The contact with the German Aerospace Center (DLR) has been excellent. For example, both DLR and Airbus agreed to a higher priority of images during the 2021 eruption in Fagradalsfjall, SW Iceland, thus helping the monitoring of the volcanic unrest and mitigation of hazards. Furthermore, the quota of images per year was increased in 2020 (and henceforward) from 180 to 250 to contribute to and facilitate the monitoring of the main volcanic systems in Iceland. This allowed us to closely study several occasions of volcanic unrest in the Reykjanes Peninsula (SW Iceland), Krafla and Askja volcanoes (North Iceland) and also order new images over the Grímsvötn ice-capped volcano (Mid-Iceland, Vatnajökull) and zones at risk of seismic activity in South Iceland.

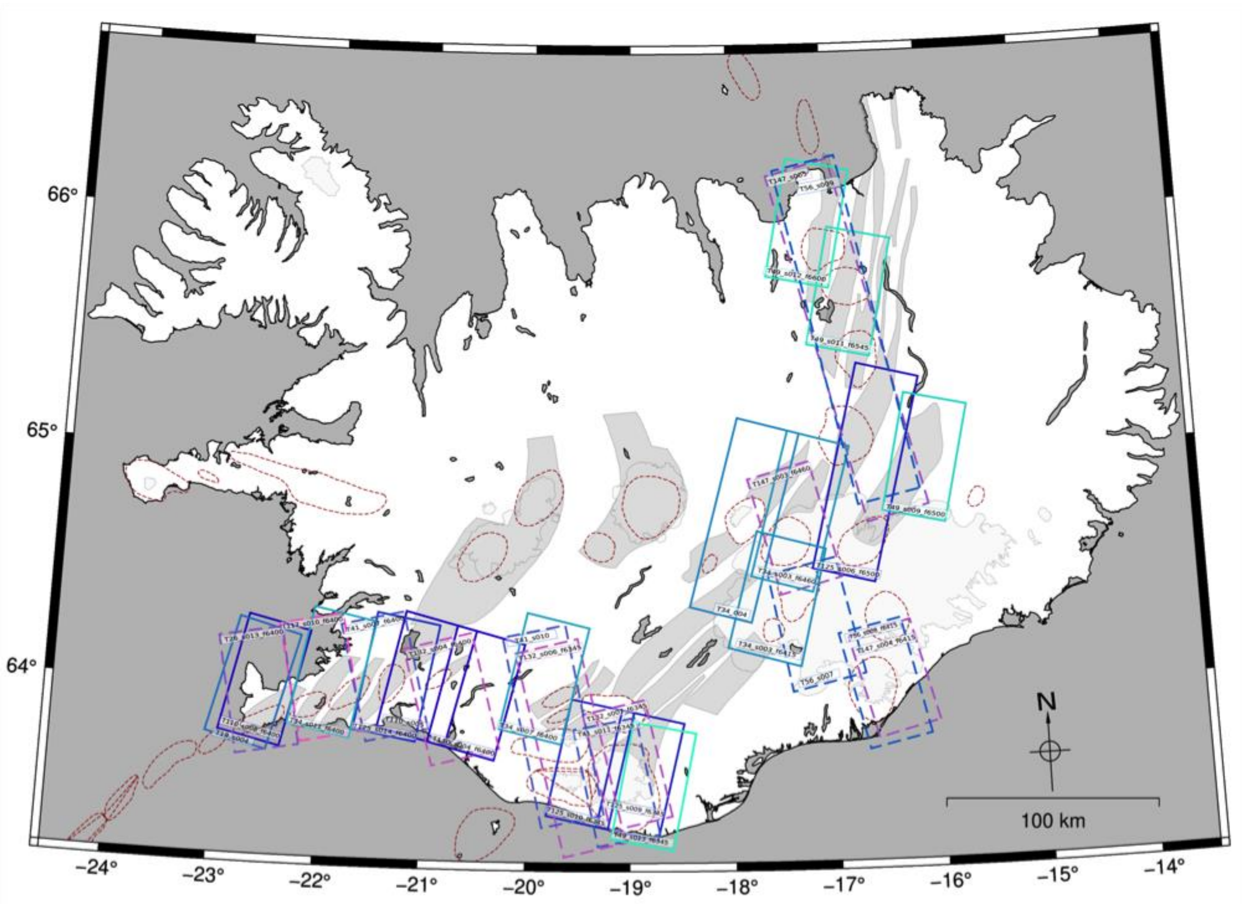

Figure 1. Boxes show the main TerraSAR-X tracks (dashed: ascending; continuous: descending) ordered in 2020 and 2021 over Iceland. The outline of the main glaciers (light grey), fissure swarms (dark grey) and central volcanoes (red dashed lines) are shown. This figure highlights that most of the monitored areas using TerraSAR-X images over Iceland are located at the plate boundary.

There are no issues to report concerning Pléiades or COSMO-SkyMed (CSK) data. A map showing the location of active CSK acquisitions is displayed in Figure 2.

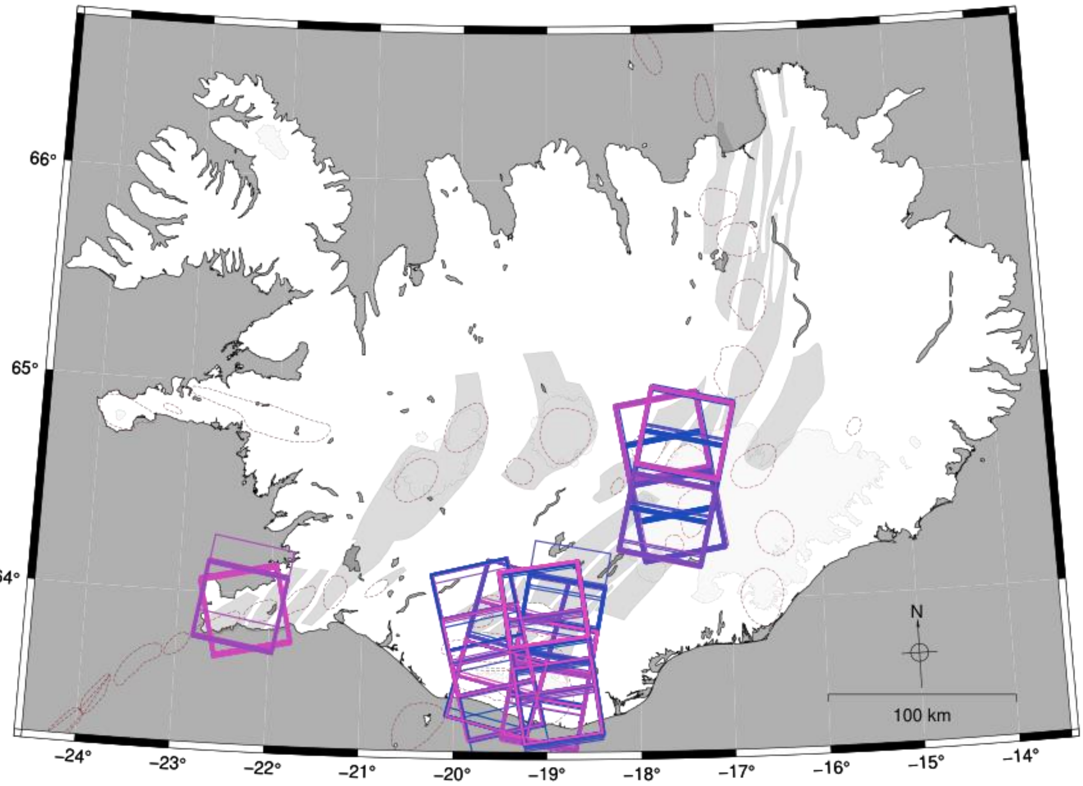

Figure 2. Outlines of current COSMO-SkyMed (CSK) acquisitions across Iceland.

3. Research results

Reykjanes Peninsula (SW Iceland) (Cécile Ducrocq, Michelle Parks and Halldór Geirsson)

In December 2019, the Reykjanes Peninsula entered a 14-month long phase of volcano-tectonic unrest, characterised by multiple magmatic intrusions and intense seismic activity. Between January to July 2020 three intrusions were detected in the vicinity of Mt. Thorbjörn and from July to August 2020 another near Krýsuvík. On the 24th February 2021, a dike intrusion was initiated in the crust beneath Fagradalsfjall. The intrusion continued until mid-March by which time the estimated length of the dike was 9 km and the associated volume change 34 million cubic meters. The intrusive event was accompanied by intense earthquake activity; several tens of thousands of earthquakes and eight events > M 5.0 were recorded along the plate boundary. About 300 events in this seismic sequence were reported as felt earthquakes. This volcano-tectonic unrest culminated in an effusive lava forming eruption, which commenced on the 19th March 2021 at 20.35 UTC. Deformation throughout both the unrest and eruption was detected using InSAR analysis (TerraSAR-X, CSK and Sentinel-1) and GNSS observations. Several projects (currently ongoing) are studying various aspects of the dynamics of the volcano-tectonic unrest and eruption. In a study currently in preparation, TerraSAR-X interferograms (e.g. Figure 3) are used to map the numerous active surface fractures important to infer tectonic implications, which may be used for hazard mitigation purposes concerning important infrastructures and nearby cities.

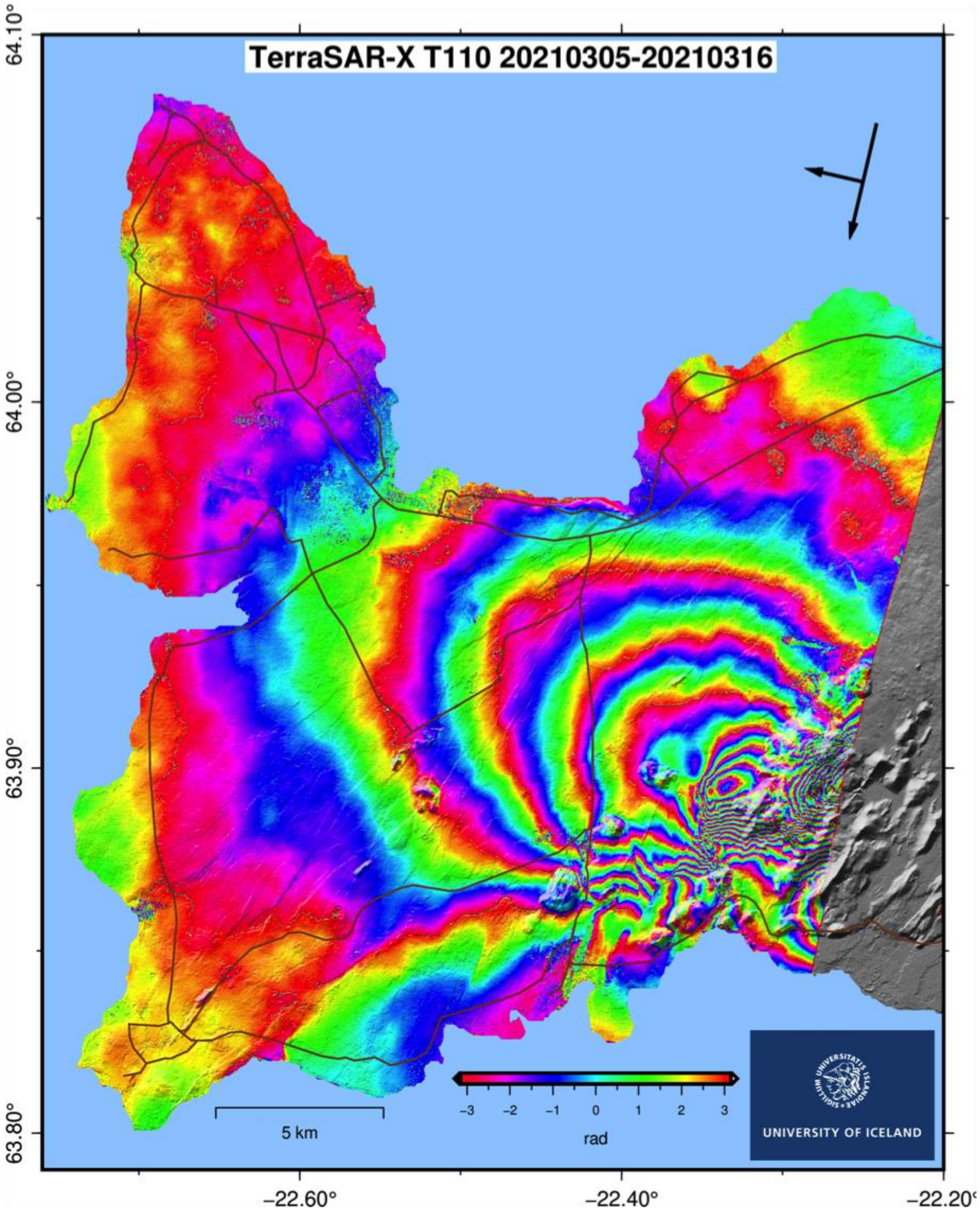

Figure 3. Example of wrapped interferogram generated from TerraSAR-X images during the 2020-2021 volcano-tectonic unrest of the Reykjanes Peninsula. This interferogram spanning March 5th to 16th 2021 shows ground motions, in the LOS of the satellite, associated with co-seismic (mainshock M5.4 -14th March 2021) earthquakes and a dike intrusion. Figure from Ducrocq et al. in prep.

In April 2021, CSK satellites were tasked over the eruption site by ASI, following a request by IMO. Persistent Scatter (PS) InSAR analysis of this data revealed a subtle long-term deflation signal most likely related to magma withdrawal from a deep source (around 14-16 km) during the eruption. Following the end of eruptive activity on the 18th September 2021, an inflation signal is observed which extends over a broad area from the southeast to northeast of the eruption site (Figure 4). This signal has also been observed on GNSS observations and Sentinel-1 interferograms. The signal is likely the result of renewed magma inflow at depth.

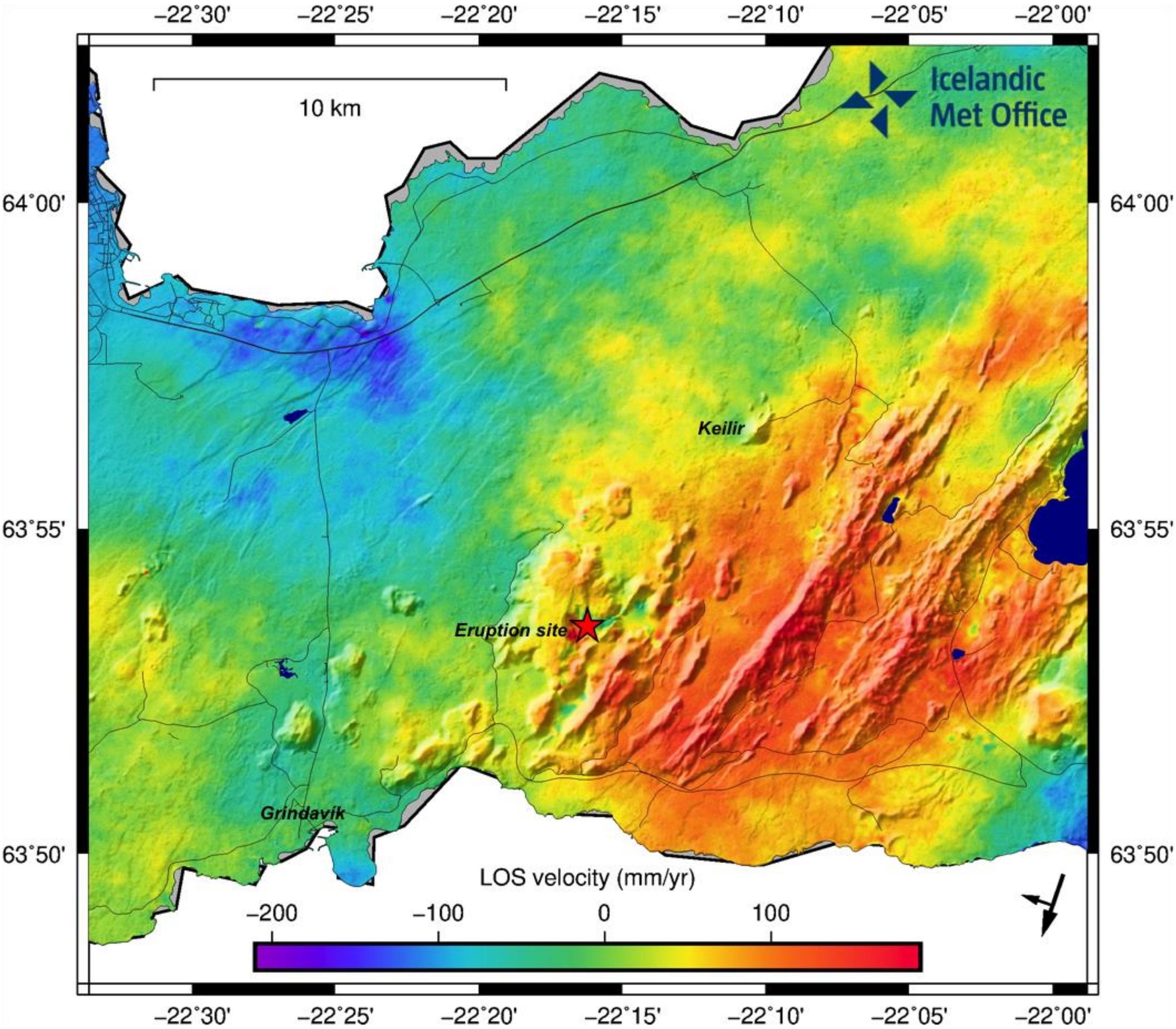

Figure 4. COSMO-SkyMed (CSK) line-of-sight (LOS) velocity map covering the post-eruptive period (24th September to 23rd October 2021).

Digital elevation models from Pléiades data (Eyjólfur Magnússon and Joaquin Belart)

Pléiades optical stereo images were provided by CNES, including ~3680 km^2 of images in 2020 (~1840 km^2 of stereo images) and ~4130 km^2 of images in 2021 (~1860 km^2 of stereo images and 137 km^2 in tristereo), which was used to obtain digital elevation models (DEMs) of four ice covered volcanic areas in addition to the 2021 eruption site of Reykjanes and vicinity (Figure 5). This included one DEM each year for Öræfajökull ice cap (2X260 km^2) and for Bárðarbunga and the Skaftár cauldrons (2X425 km^2), 2 each year for Grímsvötn and vicinity (304+217 km^2 in 2020 and 2X217 km^2 in 2021), and the central part of Mýrdalsjökull ice cap (183 km^2) covered 4 times in 2020 and 3 times in 2021. The eruption site of Reykjanes was covered twice in 2021 (100+137 km^2).

The data from Grímsvötn was particularly useful (Figure 5). It has in combination with the Pléiades DEM in 2019 (through CEOS) and other DEMs, enabled monitoring of water collection in the subglacial lake Grímsvötn, until the unset of a glacier outburst flood (jökulhlaup), which currently is ongoing. Based on this, we know that almost 1.0 km^3 of water was stored in the lake at the onset of the jökulhlaup, which potentially may all drain out during the ongoing jökulhlaup.

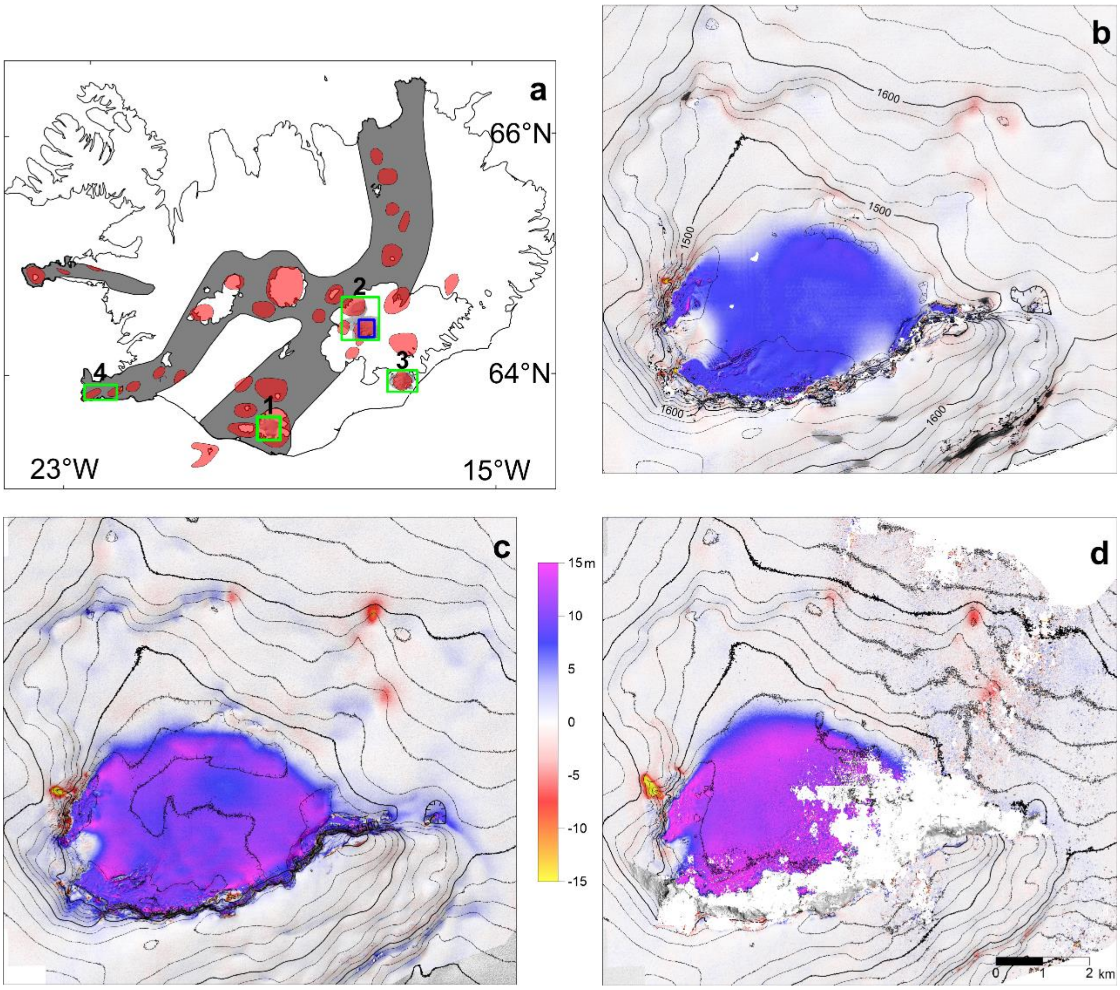

Figure 5. a) Map of Iceland showing its ice caps, volcanic belts (grey), central volcanoes (red) and areas of Pléiades stereo acquisitions in 2020-2021 on Mýrdalsjökull (green box signed 1), Grímsvötn, Bárðarbunga and Skaftá Cauldrons (green box signed 2), Öræfajökull (green box signed 3) and Reykjanes including the eruption site of Geldingadalur (green box signed 4). b-d) Elevation changes on Grímsvötn (blue box on a) from Pléiades DEMs and 18 June 2020 to 15 September 2020 (b), 15 September 2020 to 26 June 2021 (c) and 26 June to 20 November 2021 (d). 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.

Hengill, SW Iceland (Cécile Ducrocq and Halldór Geirsson)

The Hengill area hosts two active volcanic systems (Hengill and Hrómundartindur) and is located at the junction of the oblique rift zone of the Reykjanes Peninsula, the rift zone of the

Western Volcanic Zone and the transform zone of the South Iceland Seismic Zone. Within the last three decades, multiple seismic swarms, culminating in several earthquakes of magnitude 4.8-5.2, were recorded in the region. Some of the seismicity was associated with an intrusion and significant ground uplift (up to ~8 cm) between 1993-1999. Since 2006, InSAR and GNSS studies showed the eastern Hengill area to be subsiding (~1 cm/yr, Juncu et al. 2017), except for a 5-month period in 2017-2018, where the area showed uplift of ~1.2 cm (Ducrocq et al. 2021a). The nature (hydrothermal and/or magmatic) of the source is unknown. Figure 6 shows the 2017-2018 uplift over the Hengill area, as observed via InSAR (combined TerraSAR-X and Sentinel-1) and GNSS methods. This newly documented unrest in the Hengill-Hrómundartindur volcanic systems is crucial to understand inflation-deflation episodes in volcanic systems worldwide, as well as mitigation of hazards for the surrounding communities (~25 km of Reykjavík, capital city of Iceland).

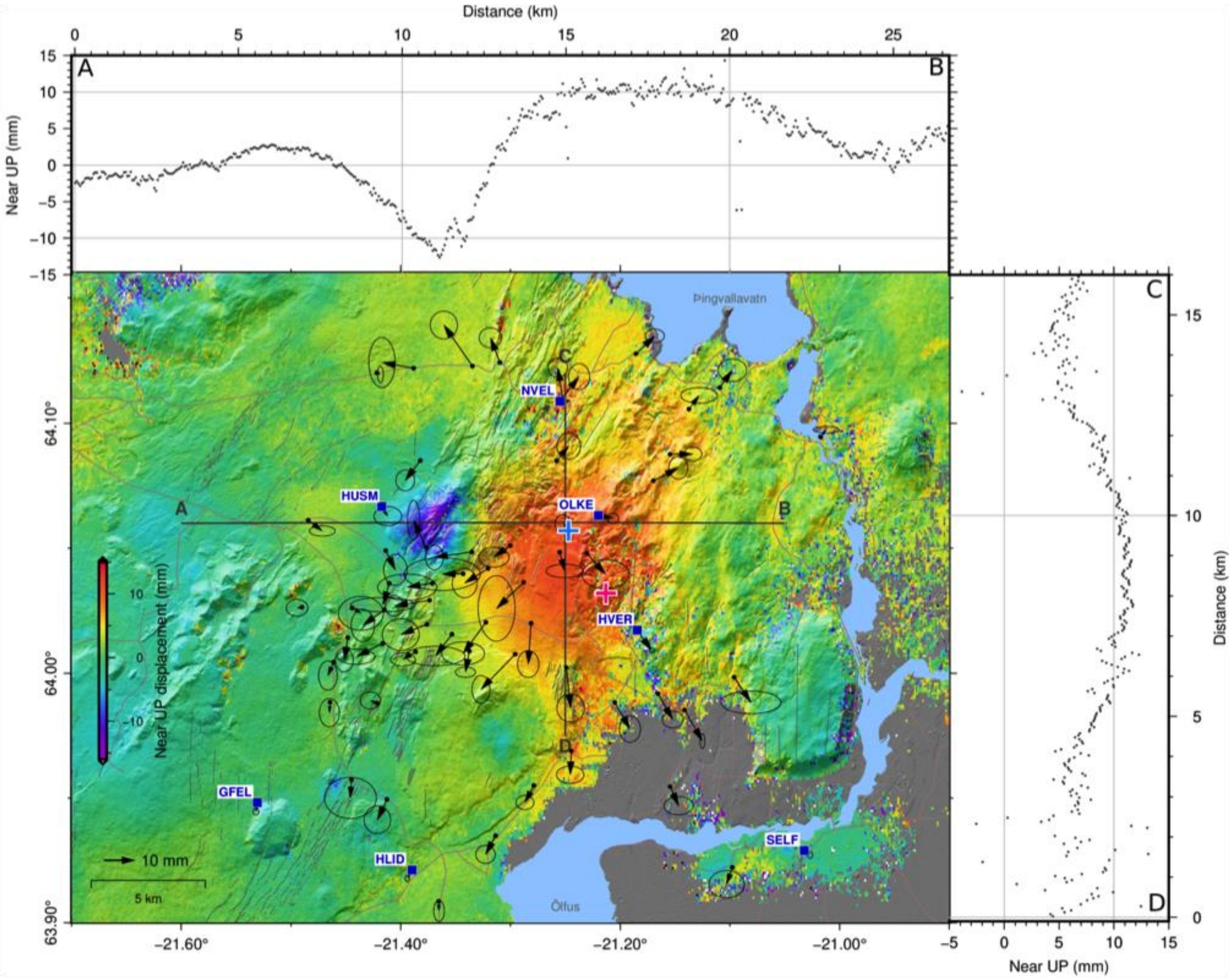

Figure 6. Near-vertical ground deformation (warm colours) over the Hengill area between 2017-2018 inferred from Sentinel-1 SAR interferometry. The localized subsidence (cool colours) is associated with geothermal injection and is the object of ongoing studies (Ducrocq et al. 2021b). Figure from Ducrocq et al. 2021a.

The Hengill area is also the locus of extraction and injection of geothermal fluids in two main locations (N and SW of Mt. Hengill). Several studies are ongoing (Ducrocq et al. 2021b), to understand localised subsidence and uplift motions in the Húsmúli area (cool colours in Figure 6) and its relation to earthquake swarms culminating in ~M4 earthquakes. Furthermore, large magnitude earthquakes from tectonic processes are recurrent in the Hengill area. Most recently, earthquakes ~ M6 occurred within the region in 2008 (Decriem et al. 2010) and the strain from long-term subsidence sources (anthropogenic and natural) affects the stress distribution in the region, which in turn brings some faults closer to failure (Árnadóttir et al. 2018, Geirsson et al. 2021). The long time series from TerraSAR-X in the Hengill area, and frequency of images of Sentinel-1 are thus key to understand the link between geothermal, tectonic and magmatic processes in the Hengill area.

Ongoing unrest within the Askja volcanic complex (Michelle Parks and Vincent Drouin)

At the beginning of August 2021, a sharp change from deflation to inflation was detected at Askja volcano. This signal was first detected on GNSS station OLAC, located to the west of Öskjuvatn and confirmed on Sentinel interferograms. Prior to the onset on this inflation, the volcano had been subsiding since at least 1983 – when regular levelling measurements resumed in this area. Geodetic modelling indicates the source of the inflation is located at a depth of approximately 2 km beneath the caldera, and as of the 18th November 2021, the estimated volume change was approximately 6 million cubic meters.

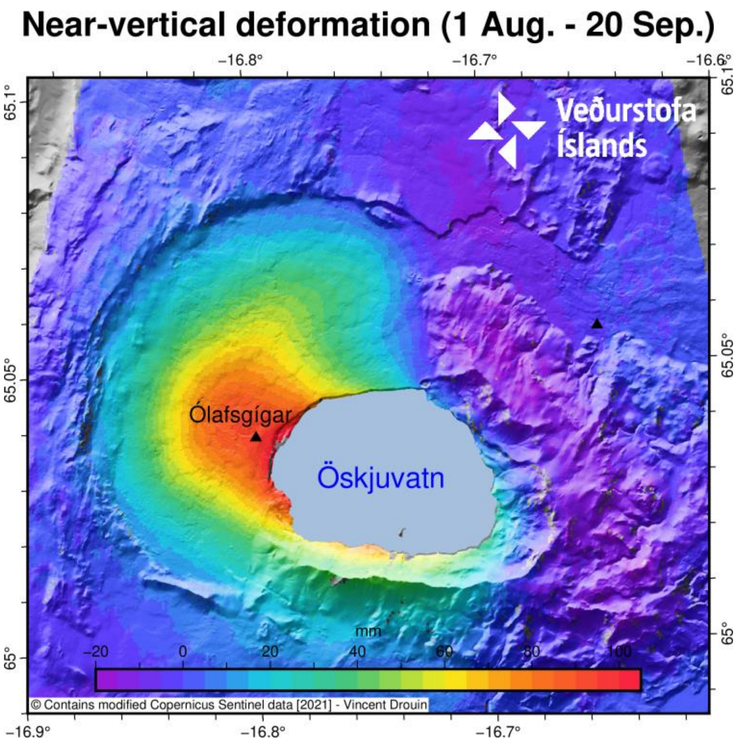

Figure 7. Near-vertical deformation at Askja, derived using decomposition of interferograms from four separate Sentinel tracks.

Post-rifting deformation around Bárðarbunga-Holuhraun dike (Siqi Li, Ronni Grapenthin and Freysteinn Sigmundsson)

The single dike intrusion of the 2014-2015 Bárðarbunga-Holuhraun eruption presents a unique opportunity for detailed study of post-rifting ground deformation processes without the complexity introduced by multiple intrusions. To study the post-rifting deformation, we use continuous GNSS and InSAR velocity fields from 2015-2020 (derived from Sentinel data), showing uplift on both sides of the dike and horizontal displacement away from the dike after correcting for the background signals. Two GNSS stations experience baseline lengthening at a rate of 21 mm/yr in the direction perpendicular to the strike of the dike.

A two-layer viscoelastic model with a 3.6×10^{19} Pa s viscoelastic half space overlain by a 4 km thick elastic layer (both layers with shear modulus 30 GPa) can explain the horizontal displacement. A thicker elastic layer and lower viscosity could also fit the displacement field well. While our model shows that viscoelastic relaxation explains broad horizontal displacements, other processes must be invoked to explain broad vertical deformation and horizontal residual motion near the dike.

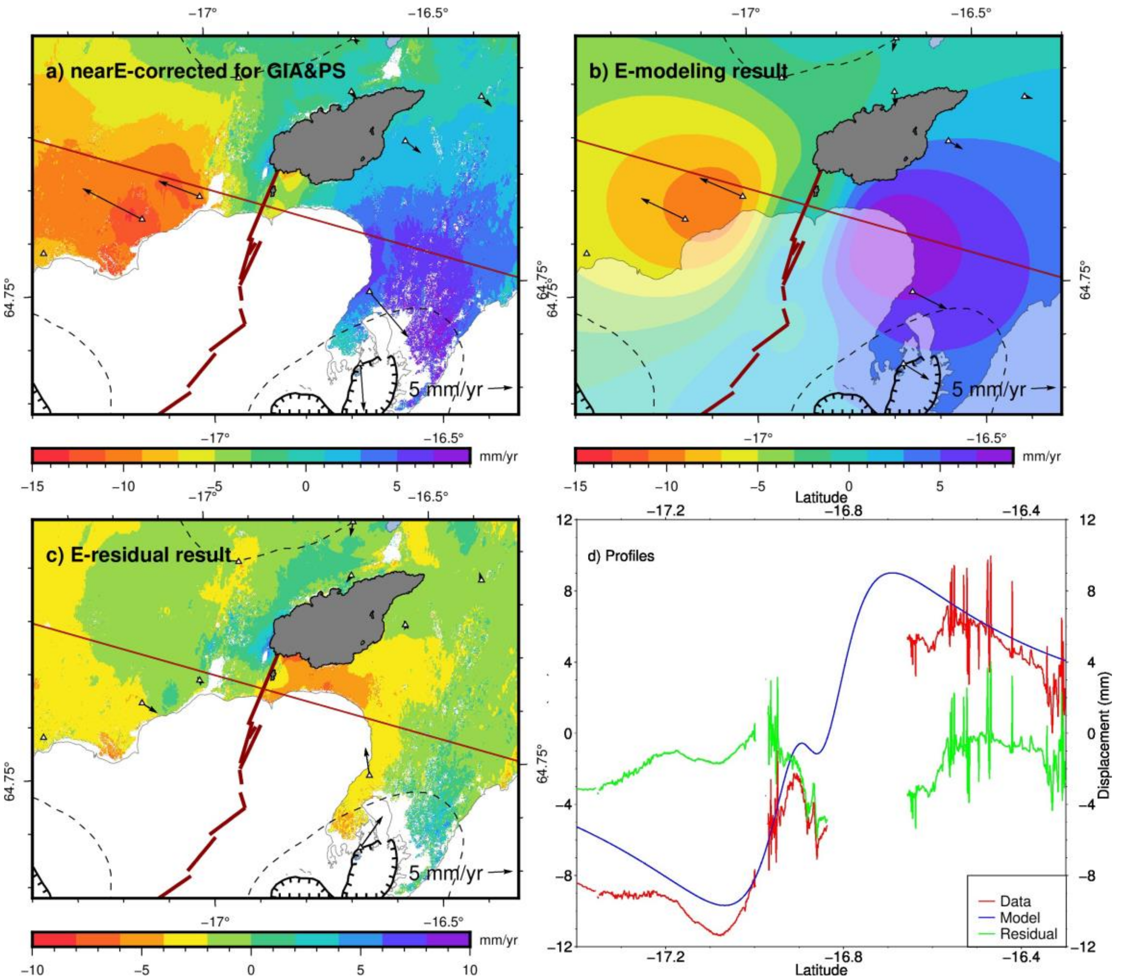

Figure 8. Corrected average velocity field in the east direction during 2015-2020 from InSAR (colour) and GNSS (black arrows). (a) The decomposed near-East InSAR average velocities after correcting glacial isostatic adjustment (GIA) and plate spreading. (b) Modelled East velocity from the viscoelastic model

with the optimal elastic layer thickness and viscosity. (c) Difference between a and b. (d) Velocity profile (red line in a, b, and c) in the east component across the study area.

Exploring tools to tell the difference between magma inflow and viscoelastic relaxation

Earlier studies on Bárðarbunga volcano suggest that viscoelastic relaxation and renewed magma inflow produce a similar average velocity in the post-eruptive period. We explore further if there are other constraints that can help distinguish between these two different processes.

Stress modelling is the first tool we explore. We first run a viscoelastic relaxation model, and explore the possibility of generating a similar stress field using an elastic magma inflow model. We consider a two-layer model with an elastic layer on top of the Maxwell viscoelastic material. Our modelling results suggest that one can produce a magma inflow model that generates similar stress fields as our proposed viscoelastic relaxation model. Therefore, by simply comparing the stresses, it’s hard to tell the difference between magma inflow and viscoelastic relaxation model.

Another tool we explored is the temporal variation; whether the temporal variation is different between the elastic magma inflow model and the viscoelastic relaxation model. The GNSS timeseries collected at different points shows different relaxation time around the Bárðarbunga volcano. Our model suggests that magma inflow should produce the same relaxation time in the observation area, while the viscoelastic relaxation model generates a different viscoelastic relaxation time. This can help to differentiate between different processes.

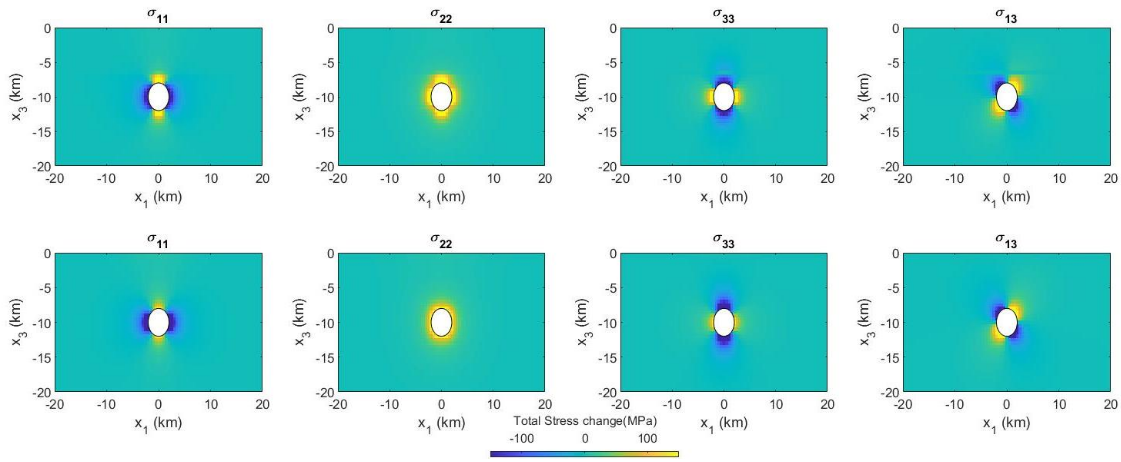

Figure 9. A comparison of the spatial pattern of the stress change caused by viscoelastic relaxation (upper) and magma inflow (lower). The panels shown are vertical cross-sections of four stress components in a plane across a magma body with a center depth of 10 km. The upper panel shows the stress change from the viscoelastic relaxation in the initial 6.3 years in the post-eruptive period, caused by a 0.4 km^3 point source. The lower panel is from a magma inflow model with the total inflow volume of 3.6 x 10^8 m^3. The four stress components are: σ_{11}, σ_{22}, σ_{33}, and σ_{13}. The unit for stress is MPa. The 1-axis is horizontal direction and the 3-axis is the vertical direction. The white circle indicates the source location.

Krafla Volcanic System (Chiara Lanzi and Freysteinn Sigmundsson)

The Krafla volcanic system in North Iceland is located at the divergent Eurasian North-American plate boundary. Due to its location, it is subjected to deformation from plate spreading but also volcanic and geothermal activity. The volcanic system consists of a central volcano with a 9 x 7 km caldera (Figure 10), and a transecting fissure swarm. In Krafla, geodetic monitoring carried out with Interferometric Synthetic Aperture Radar (InSAR) Sentinel-1 satellite images (by Vincent Drouin at Icelandic Meteorological Office) and Global Navigation Satellite System (GNSS) measurements allowed the detection of a change in the ground deformation pattern, which occurred in the summer of 2018, located in the middle of the caldera.

Geodetic modelling has been undertaken in two steps: 1) using a spherical source within an elastic half-space to determine the optimal source location for the observed signal and 2) finite element analysis considering different elastic material properties in a 3D domain enveloping a pressure spherical source. At the same time the deformation pattern changes, pressure variations have been observed at the magma-hydrothermal interface at well KJ-10, in the Leirbotnar geothermal field. The aim of the work is to evaluate if the change in the deformation pattern may be related to changes within the geothermal system, due to changes in geothermal utilisation strategy, or whether this is related to magmatic processes.

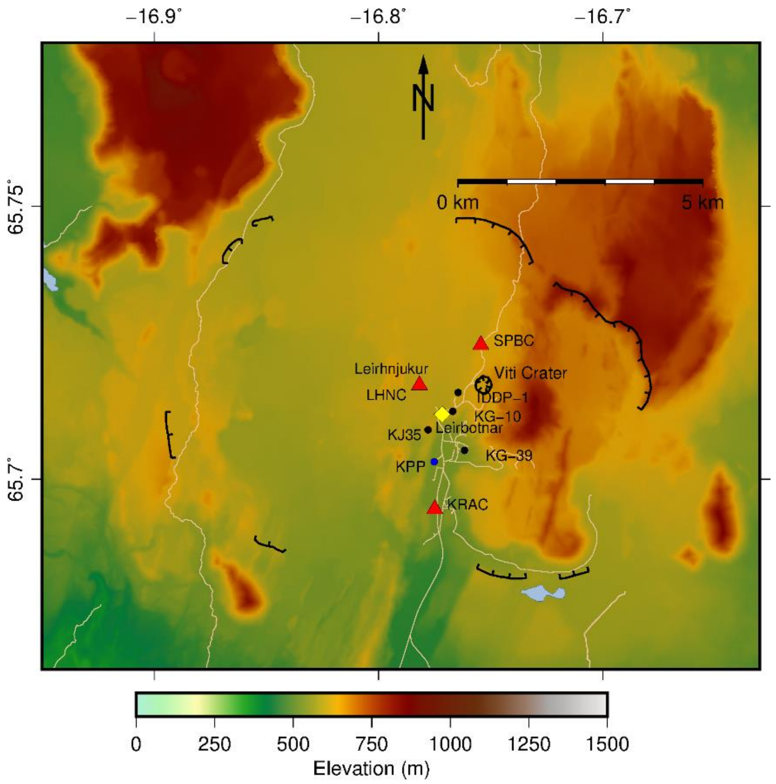

Figure 10. Outline of the Krafla caldera (hatched lines) and topography. Location of selected drilled wells are shown with black circles [IDDP-1, KJ35, KJ10, KG-39], and red triangles show location of continuous GNSS stations at Krafla. Yellow diamond is the best-fit location for a point source of deformation consistent with deformation data.

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Research products

Type of product	Product provider	How to access	Type of access
Reykjanes Sentinel-1 interferograms	*Vincent Drouin*	*http://brunnur.vedur.is/gps/insar/2021_fagradalsfjall_ifg/*	*public*
Catalogue of Icelandic Volcanoes	*Icelandic Met Office*	*http://icelandicvolcanos.is/*	*public*

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 Meteorological Office:

http://www.icelandicvolcanoes.is

This is the online catalogue of Icelandic Volcanoes. It has up-to-date information on the 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.

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 be approached with issues related to the catalogue.

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 Meteorological Office and University of Iceland) have presented on the radio and in TV interviews, as well as in TV documentaries, explaining the nature, behaviour 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 it has provided important input, facilitating improved understanding of volcanic activity.

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 Meteorological Office has continued the operation of the Icelandic Volcanoes data hub that is important for the supersite.

The EUROVOLC project (1 February 2018 – 30 November 2021), funded by the H2020 program of the European Commission, assisted with certain aspects of the supersite work, through for example, contribution of working hours and provision of GNSS data. The University of Leeds, Icelandic Meteorological Office, and University of Iceland played a leading role in the geodetic monitoring component of the project, thus facilitating advanced modelling of InSAR and GNSS observations and access to GNSS timeseries and interferograms in EPOS format.

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 populations in other parts of the world, in the event of major eruptive activity in Iceland that can influence air traffic and living conditions in other parts of the world.

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

This information is communicated most importantly to the Icelandic civil protection authorities and has been used in their analysis of volcanic 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 the 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 and geodetic modelling results have been presented at many of the meetings of the science committee of Icelandic civil protection authorities.

The most recent example is evaluation of the 2019-2021 unrest period at Reykjanes Peninsula that preceded the Fagradalsfjall eruption. Evaluation of ground deformation from Sentinel interferometry for the unrest period has been incorporated into deformation models, and provided important constraints on the pre-eruptive dike propagation and volume assessment. The co-eruptive and post-eruptive CSK interferograms were used to model the source of deflation throughout the eruption and also to confirm renewed inflation after the end of eruptive activity.

The interaction of the supersite scientists 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 utilising 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 on various occasions regarding volcano unrest 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

Throughout the reporting period (2020-2021) the Iceland supersite provided a wealth of information related to the monitoring and improved understanding of volcano-tectonic activity across Iceland. Results of the analysis of supersite data has been presented frequently at Civil Protection meetings and influenced decision making processes, thus benefiting the scientific community, decision makers and the local population. A key example of this, was the extensive use of InSAR and GNSS analysis throughout the 14-month long unrest on the Reykjanes Peninsula – especially throughout the ~3 week period of segmented dike propagation (starting on the 24th February) which culminated in the effusive eruption which commenced on the 19th March in the Fagradalsfjall region and continued for approximately 6 months. Throughout the dike emplacement, modeling of Sentinel and TSX interferograms was used to map the location of the dike, the top depth and the total volume change. Based on these models a map outlining a "danger zone" was constructed and following the onset of the eruption this was updated to produce an "exclusion zone" map, linked to areas where potential future eruptive fissures may open. Interferograms were also used to map active faults or fractures that displayed recent movements and to target specific areas for fieldwork e.g. to focus field teams to check specific areas on the ground for signs of recent movements that could be precursory to new fissure openings. In addition to this, analysis of CSK interferograms throughout the eruption, enabled scientists to confirm the location of the deep source feeding the eruption and identify a broad zone of possible recharge following the end of eruptive activity.

Pléiades data has been extremely beneficial in generating new DEMs in the vicinity of the Reykjanes eruption site in addition to those at multiple ice-covered volcanoes. In particular at Grímsvötn, where this data has been used to map surface elevation changes between June 2020 to November 2021. These DEMs are critical for identifying changes in the ice-cap, since this is Iceland's most active volcano and is the source of frequent jökulhlaups – in fact, at the time of writing a sub-glacial flood originating from Grímsvötn is currently underway!

Additional studies at Bárðarbunga have provided an improved understanding of distinguishing between renewed inflation related to the inflow of new magma or viscoelastic effects – this is essential for hazard forecasting purposes.

At Hengill the analysis of long-term InSAR timeseries is crucial for improved understanding of the relationship between geothermal, tectonic and magmatic processes and at Krafla, new geodetic models will help constrain whether recent uplift is related to geothermal utilisation or magmatic processes.

Successful collaboration between the satellite agencies and supersite members has been key to optimising the monitoring strategy in Iceland throughout the 2020-2021 period, disseminating crucial information to decision makers and producing new and exciting results for the scientific community, which are highlighted in this report. We look forward to continuing this fruitful collaboration in the future.

8. Dissemination material for CEOS (discretionary)

Any material within this report may be used by the GEO Secretariat for dissemination of GSNL results.