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Biennial report for Permanent Supersite/Natural Laboratory

Icelandic Volcanoes Supersite 2022-2023

History	*http://geo-gsnl.org/supersites/permanent-supersites/iceland-volcanoes-supersite/*
Supersite Coordinator	*Michelle Parks (michelle@vedur.is)* *Icelandic Meteorological Office* *Bústaðavegur 9, 105, Reykjavík, Iceland*

1. Abstract

The 2022-2023 reporting period was characterised by a significant increase in volcanic activity in Iceland, including continued inflation at Askja volcano, multiple jökulhlaups generated from Grímsvötn volcano, two additional dike intrusions and two resulting eruptions in the Fagradalsfjall volcanic system and two dike intrusions and one eruption within the Svartsengi volcanic system. As in prior years, satellite data provided through the Iceland volcanoes supersite continues to play a major role in assisting with the interpretation of volcanic activity and also in assessing potential hazards and informing the Icelandic Civil Protection and other decision makers.

Numerous presentations at scientific meetings have utilised 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 and viscoelastic responses.

On the Reykjanes Peninsula, the analysis of InSAR, GNSS and geodetic modelling has improved our understanding of differences between volcanic activity and the source of dike intrusions and eruptions at Fagradalsfjall vs the Svartsengi volcanic systems. Additional studies at Askja have identified different magmatic sources responsible for the 2021-2023 volcanic unrest.

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, however we are now also receiving additional data from both Radarsat-2 and SAOCOM satellites. Furthemore, Pléiades optical stereo images were used to obtain digital elevation models (DEMs) at four ice covered volcanic areas. The www.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 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

Researcher/team	***Name, affiliation, address, e-mail, website/personal page of team leader***
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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. Michelle Parks, Vincent Drouin and Kristín Vogfjörð are the key contacts at the Icelandic Meteorological Office providing access to in-situ data.

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/Katla/ http://hraun.vedur.is/ja/hekla http://hraun.vedur.is/ja/vatnajokulsvoktun	public
Seismicity	IMO	https://en.vedur.is/earthquakes-and-volcanism/earthquakes	public
Seismicity	IMO	https://skjalftalisa.vedur.is/#/page/map	public
Near-real time DD automatic relocation of seismicity at Grímsvötn and Oræfajökull volcanoes	IMO	http://hraun.vedur.is/ja/EUROVOLC/grimsvotn/ http://hraun.vedur.is/ja/EUROVOLC/oraefaj/	Public
N-r-t DD automatic relocation of seismicity on main faults in Iceland's South Iceland Seismic Zone	IMO	http://hraun.vedur.is/ja/REAKT/SISZ/	Public
Earthquake Mw & Shakemaps	IMO	http://hraun.vedur.is/ja/Mpgv	Public

GNSS	IMO	http://brunnur.vedur.is/gps/time.html https://docs.epos-iceland.is/#/GNSS and Volcano Observations at: https://www.ics-c.epos-eu.org/	GSNL scientists
GNSS	UI	https://strokkur.raunvis.hi.is/gipsy/icel_100p.html	public
Gas	IMO	http://brunnur.vedur.is/gas/time.html https://docs.epos-iceland.is/#/ (DOAS data) and Volcano Observations at: https://www.ics-c.epos-eu.org/	GSNL scientists
Geological Maps	NÍ	Geological Information and Modeling at: https://www.ics-c.epos-eu.org/	
Borehole core data	NÍ	Metadata on borehole cores from Iceland in: Geological Information and Modeling at https://www.ics-c.epos-eu.org/	

IMO leads Icelandic participation in the *European Plate Observing System*, *EPOS* and leads the National infrastructure project *EPOS Ísland*, whose aim is to quality check and standardise Earth science data from Iceland, create virtual FAIR (Findable, Accessible, Interoperable and Re-usable) access services for the data and operate them in collaboration with *EPOS* for the long term. Other participating Icelandic institutions are University of Iceland (UI), Icelandic Land Survey (LMI), Institute of Natural History (NÍ) and Iceland Geosurvey (ÍSOR). IMO, as part of the *EPOS VOLC-TCS* (*Volcano Thematic Core Service*) functions as service provider for most of the Icelandic data provided through *EPOS*, but some data are serviced through the *EPOS TCS Geology* and some are or will be available through the *Orfeus* seismic *Data C*enter (https://www.orfeus-eu.org/data/odc/) which is part of the *EPOS TCS Seismology*. Some of the data listed in the table above are already available on the *EPOS Data Portal* https://www.ics-c.epos-eu.org/ and some will be made available in the coming months or years. The API service at IMO which the *EPOS Data Portal* links to is accessible directly at: https://docs.epos-iceland.is/#/Volcanoes, and also through the EPOS Iceland web page: https://epos-iceland.is/#. Since IMO actively participates in the *EPOS VOLC-TCS*, the initial emphasis is on creating access to volcanologcial data and products from volcanically active periods and areas. GNSS data is already available through the IMO API service, which is not yet a standardized EPOS service, but will be later in 2024, when a GLASS GPS service will be installed at IMO.

Currently there are 19 volcanological services, including 3 GNSS services and 1 seismic service, available on IMO's API platform and more will be added in the near future. Access to seismic waveforms will be through the *Orfeus ODC*, but Icelandic shakemaps and the earthquake bulletin will at least initially be serviced on the API platform. There is a GNSS service with metadata (station and site information) and 15s rinex data are accessible from 16 GNSS stations (FJOC, KISA, SKRO, VMEY, HAFS, GSIG, ISAK, KIDC, DYNC, RJUC, HUSM, HVEL, RHOF, THOC, HAUC and VONC).

There are 15 volcanological services available on the API platform and the EPOS Data Portal; including volcanic hazard maps, volcano colour codes, weekly status volcanic reports and

VONA reports and volcanic ash dispersion models. The services are under continuous development and improvement regarding capability and data volume.

Since 2017, IMO has transmitted seismic data to *Orfeus EIDA* from 6 seismic stations in the national VI/SIL network (these stations are GIL, ADA, SKR, FAG, ASB, GOD). Additional data from 17 stations located in near Bárðarbunga volcano during 2014 and 2015 have already been transcribed and are ready for shipping to *Orfeus*, but there has been a delay due to IMO's problem in getting a proper DOI for the national network before sending. This will be cleared up in the first quarter of 2024. During 2024, seismic waveforms from an additional 10 VI/SIL stations around Katla and Eyjafjallajökull volcanoes during 2009 – 2011 will be quality checked, standardised, and transcribed and shipped to *Orfeus* as well. The seismic bulletin from the VI/SIL network is being checked and corrected as necessary before publishing on the API platform. The first batch to be completed and opened for access, will cover the years 2016 through 2019. It will be followed by the catalogue for the two previous years containing the Bárðarbunga eruption, 2014-2015. The Shakemap service, still under construction at IMO, already provides access to shakemaps (in jpg format) for M_W>3.5 earthquakes in Iceland since 2020 and information files with measured Peak-Ground Velocities (PGV) as well as calculated PGA and Mercalli Intensities at VI seismic stations. The development will add access to standardized files with gridded calculations of PGV, PGA and Intensity.

Automated interferometric processing of Sentinel-1, CSK and TSX images over Iceland is available at: https://brunnur.vedur.is/pub/vincent/insar/leaflet/

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://dataspace.copernicus.eu/browser/*	*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 individual users register on DLR website: https://download.geoservice.dlr.de/supersites/files/Iceland/*	*Registered public*
COSMO-SkyMed (CSK)	*ASI*	*Individual users are required to sign the ASI User Agreement form and send to POC, data is then made accessible through the ESA GEP platform: https://geohazards-tep.eu/geobrowser/?id=globalapp#!&context=Community%2FTerrainMotionDemo*	*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*
SAOCOM	*CONAE*	*POC requests access from CONAE for individual users, data then made accessible by POC*	*GSNL scientists*
Pleiades	*CNES*	*Available after Data Request submission to, and acceptance by, Airbus and CNES*	*GSNL scientists*

Table 1. *SAR images available through the Iceland Volcanoes Supersite.*

Year	Envisat	Cosmo-SkyMED	TerraSAR-X	Radarsat-2	Sentinel-1	SAOCOM
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		464	179	69	16	
2015		361	174	22	416	
2016		355	153	42	469	
2017		239	112		1080	
2018		344	104		1197	
2019		752	101		1216	
2020		678	181		1203	
2021		791	202		1226	
2022		680	195		631	12
2023		694	200		636	23
Total:	**742**	**5490**	**1964**	**165**	**8090**	**35**

Additional images:
Pléiades optical stereo images were provided by CNES, including ~5000 km^2 of images in 2022 (~2500 km^2 of stereo images) and ~3500 km^2 of images in 2023 (~1750 km^2 of stereo images).

Satellite data issues

Cosmo-SkyMED

Some supersite members using the GEP for CSK downloads have commented that images are typically not available for several days or longer following their acquisition. If it is possible for images to be made available on the GEP sooner this would be much appreciated.

Downloading of images by the coordinator is straightforward and images are downloaded directly via the ASI ftp site. Download times may vary between ~30 minutes to 6 hours. In the latter case it is unclear what is causing the long download period. ASI were extremely helpful in November 2023, during the volcanic crisis at Grindavík, and solved this issue by making images available on an emergency site so that IMO could access these in near-real time to assist with emergency management.

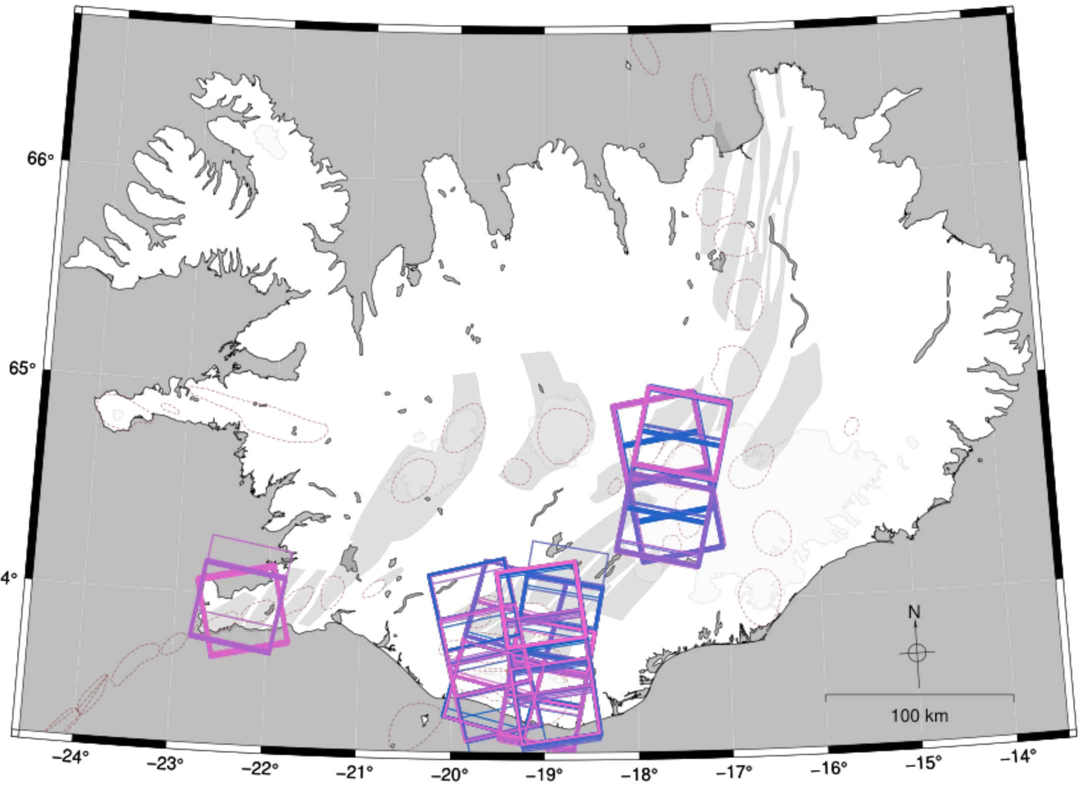


Figure 1. *Outlines of current COSMO-SkyMed (CSK) acquisitions across Iceland.*

TerraSAR-X

The ordering of TerraSAR-X images is done via the online portal and downloading with file transfer (lftp). Generally, the images are ready for download about 5 days after the acquisition time; however, longer delays occurred several times, especially in 2023. Sometimes, orders are not delivered due to conflict with other satellites or when the final orbits are not available. In the latter case, the option to order, from the archive, with rapid orbits is provided.

In 2022, around 230 orders were placed; with 195 successfully delivered. In 2023, 235 orders were placed and 200 images delivered. The TerraSAR-X images have been ordered over different places in Iceland (Figure 2, ascending tracks, Figure 3, descending tracks, and Table 2), mostly located along the plate boundary and at active volcanic and seismic areas.

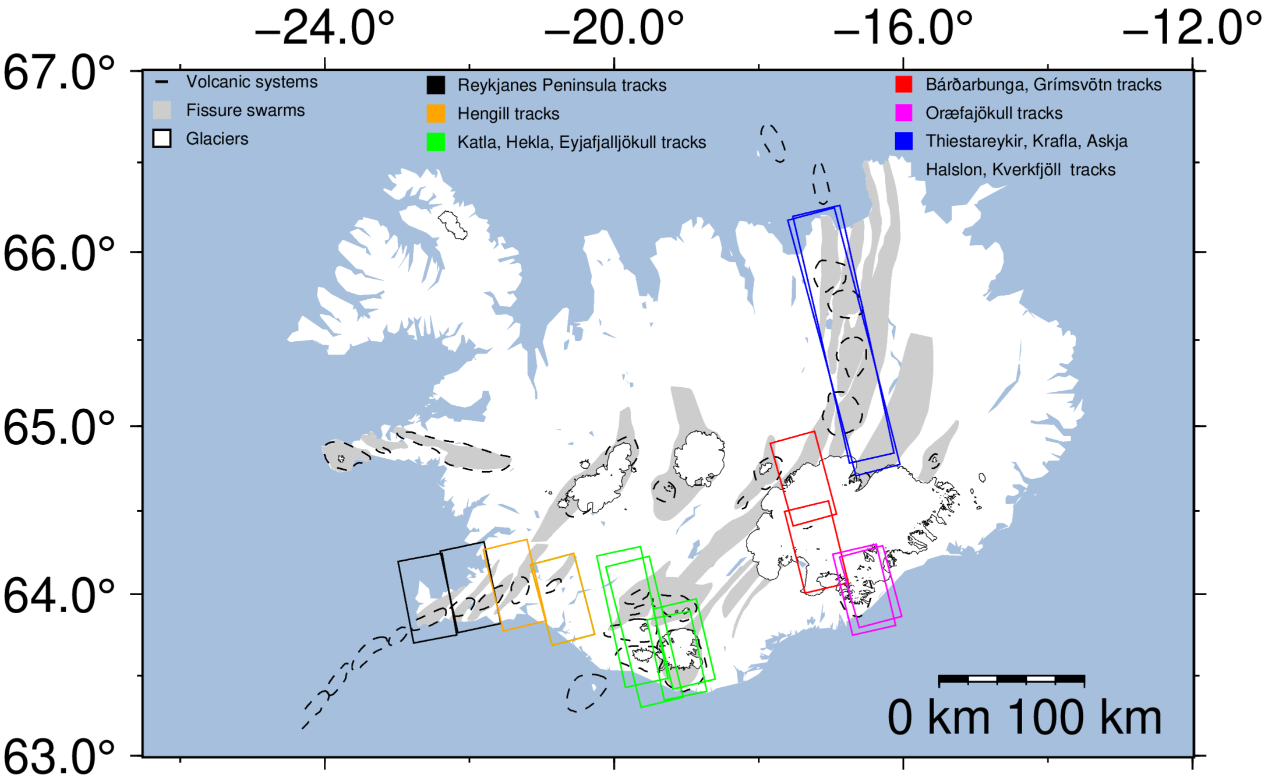


Figure 2. *TerraSAR-X ascending tracks ordered in different areas in Iceland.*

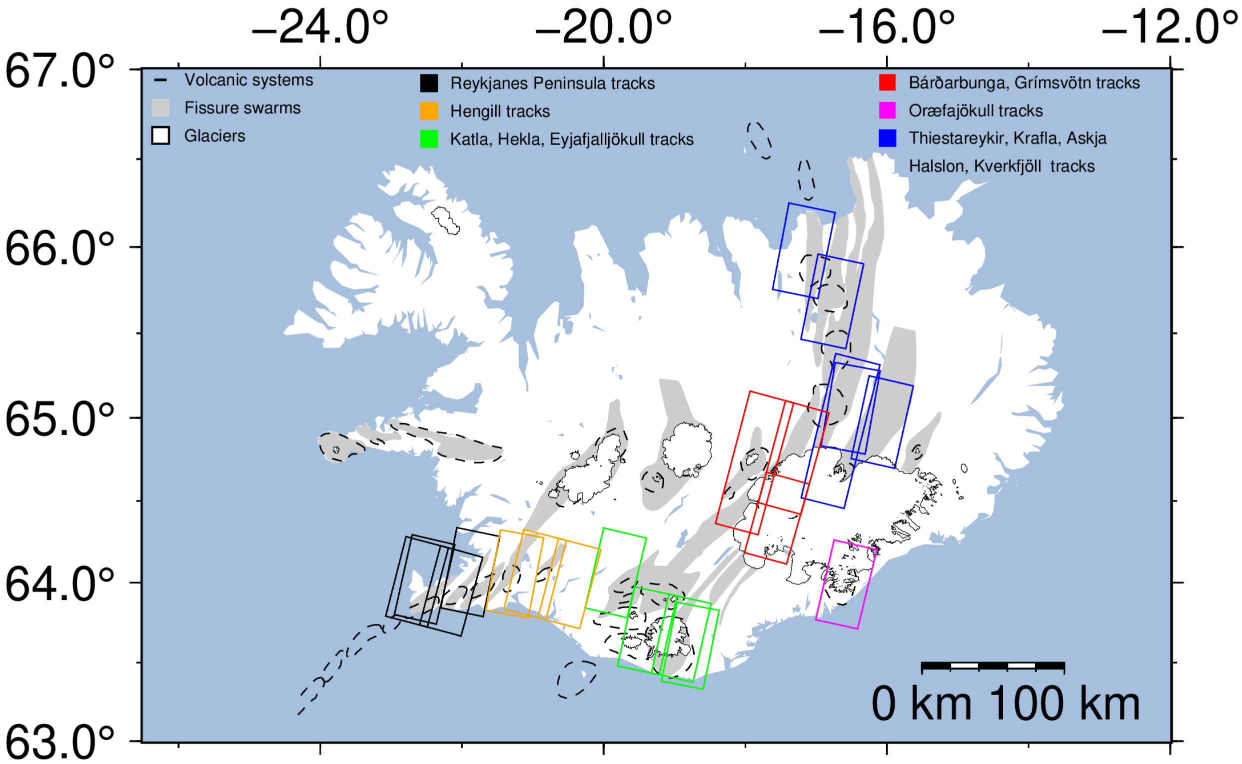


Figure 3. *TerraSAR-X descending tracks ordered in different areas in Iceland.*

Table 2. *TSX acquisitions. Name of the track and area, Looking Direction, Pass Direction.*

Name images	Pass Direction	Looking Direction
T49 - Krafla	Descending Path	Right looking
T49 - Theistareykir	Descending Path	Right looking
T49 - Katla	Descending Path	Right looking
T49 - Öræfajökull	Descending Path	Right looking
T49 - Halslon	Descending Path	Right looking
T125 - Hengill	Descending Path	Right looking
T125 - Eyjafjallajökull	Descending Path	Right looking
T125 - Katla	Descending Path	Right looking
T125 - Askja	Descending Path	Right looking
T34 - Krisuvík	Descending Path	Right looking
T34 - Hekla	Descending Path	Right looking
T34 - Grímsvötn	Descending Path	Right looking
T34 - *Bárðarbunga* 3	Descending Path	Right looking
T34 - *Bárðarbunga* 4	Descending Path	Right looking

T19 - Reykjanes 3	Descending Path	Right looking
T19 - Reykjanes 4	Descending Path	Right looking
T110 - *Keflavík*	Descending Path	Right looking
T110 - Þingvellir	Descending Path	Right looking
T110 - South volcanic seismic zone	Descending Path	Right looking
T132 - South volcanic seismic zone	Ascending Path	Right looking
T132 - Eyjafjallajökull	Ascending Path	Right looking
T132 - Katla	Ascending Path	Right looking
T132 - Hekla	Ascending Path	Right looking
T147 - Öræfajökull	Ascending Path	Right looking
T147 - Northern Volcanic Zone	Ascending Path	Right looking
T147 - *Bárðarbunga*	Ascending Path	Right looking
T26 - *Keflavík*	Ascending Path	Right looking
T117 - Krisu*vík*	Ascending Path	Right looking
T41 - Hengill	Ascending Path	Right looking
T41 - Katla	Ascending Path	Right looking
T41 - Hekla	Ascending Path	Right looking
T41 - Eyjafjallajökull	Ascending Path	Right looking
T56 - Northern Volcanic Zone	Ascending Path	Right looking
T56 - Öræfajökull	Ascending Path	Right looking
T56 - Grímsvötn	Ascending Path	Right looking

At the end of 2023, we began receiving SAOCOM satellite images from Comisión Nacional de Actividades Espaciales (CONAE). SAR images are currently being acquired on tracks displayed in Figure 4.

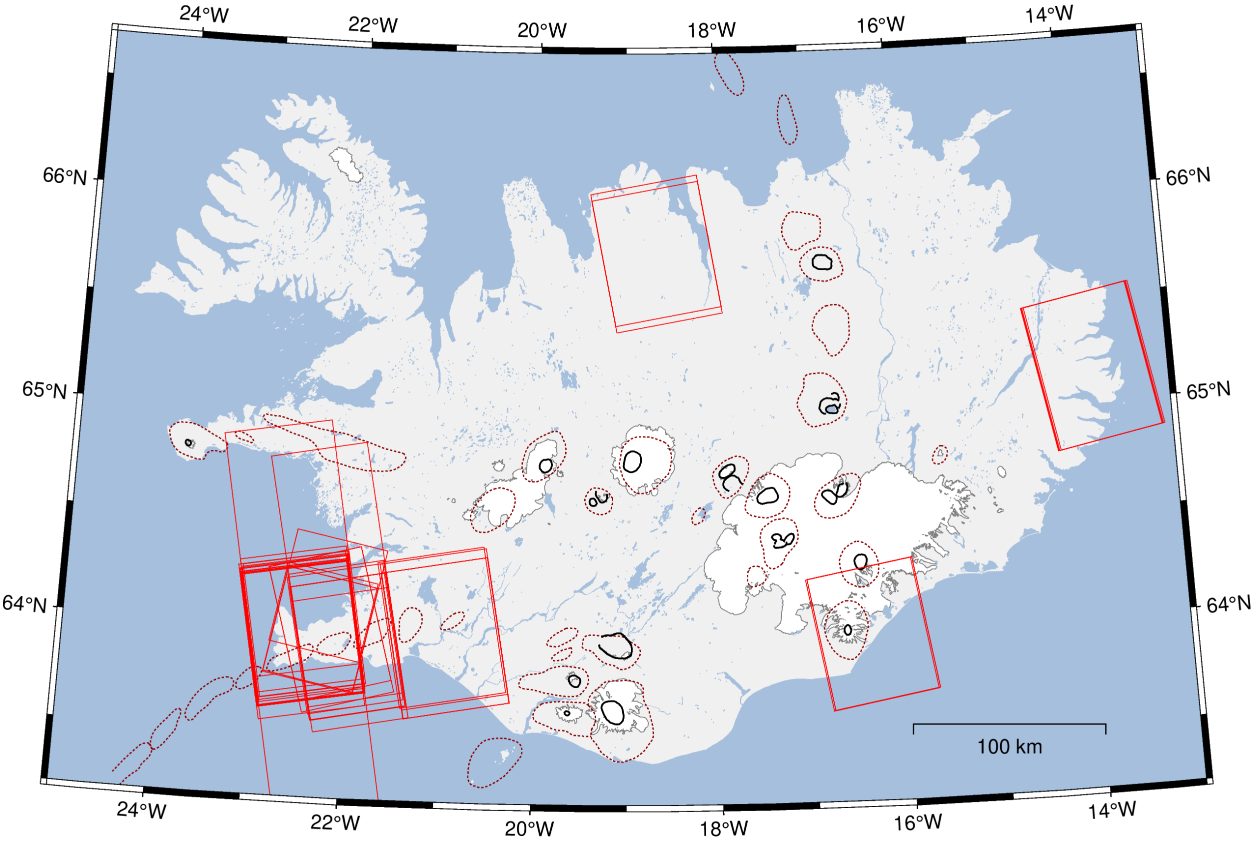


Figure 4. *SAOCOM ascending tracks ordered in different areas in Iceland.*

There are no issues to report concerning other satellite acquisitions.

3. Research results

Reykjanes Peninsula (SW Iceland) (Michelle Parks, Freysteinn Sigmundsson, Vincent Drouin)
Volcano-tectonic reactivation of the Reykjanes Peninsula commenced in December 2019, when a series of earthquakes were detected in the Fagradalsfjall region at depths between 3-7 km. The timing of this was not unusual, considering the historic record, with the average interval between eruptive activity being between 800-1000 years. The last period of eruptive activity ended in 1240 CE. The first clear sign of new magma migration beneath the peninsula was detected on 21 January 2020 – with a strong increase in seismicity and deformation marking the first sill-type intrusion/magma injection, beneath the Svartsengi area. The first diking and eruptive activity in the ongoing activity period on the Reykjanes Peninsula was, however, in the Fagradalsfjall area. From February 2021 until August 2023 four dike intrusions and three eruptions occured there (Figure 5). Geodetic data has been crucial for evaluating the nature of the hazards in the areas influenced.

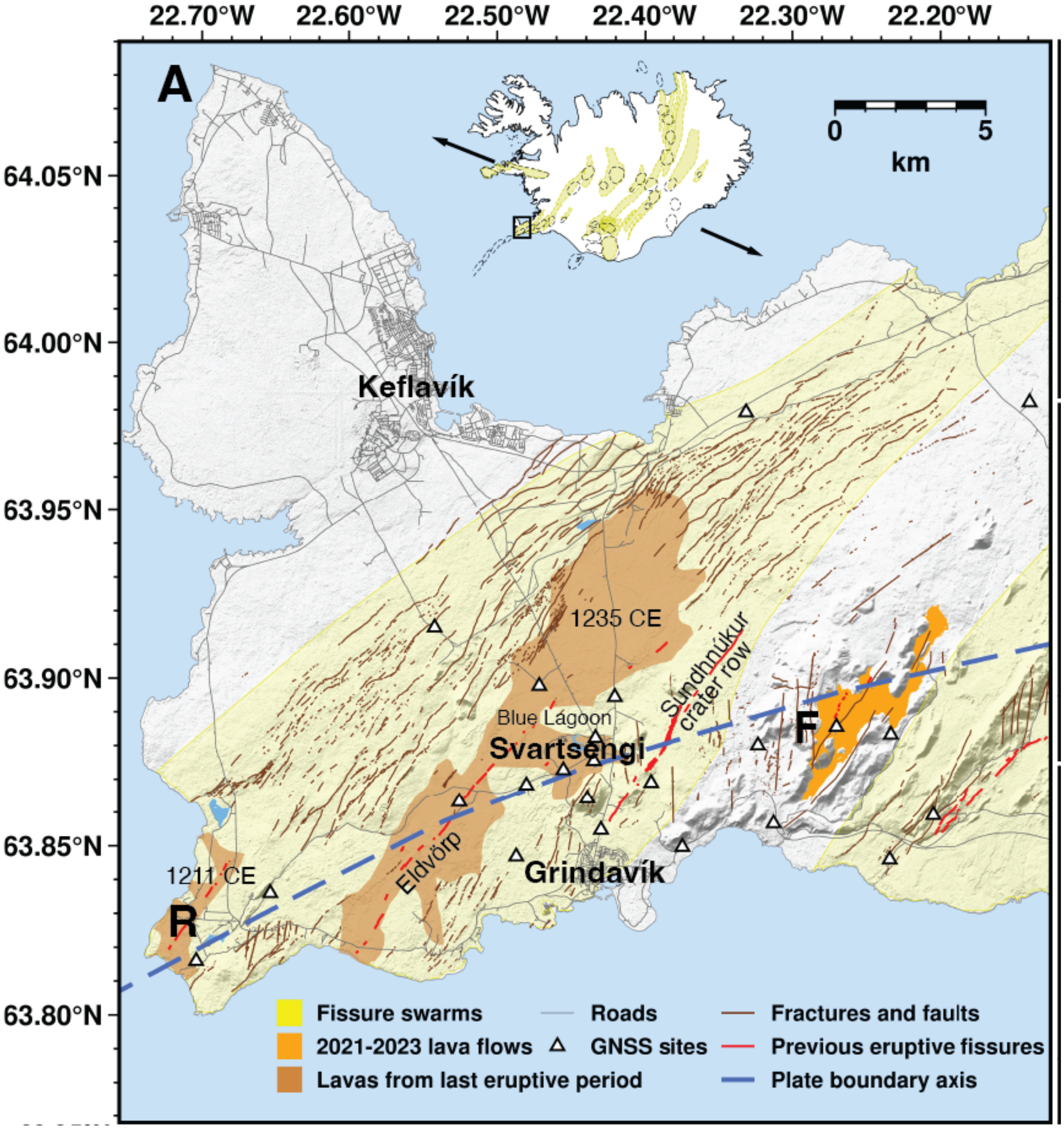


Figure 5. *Western part of the Reykjanes Peninsula in SW-Iceland showing the Svartsengi, Reykjanes (R) and Fagradalsfjall (F) volcanic systems, fractures, fissure swarms, plate boundary central axis, the 2021-2023 Fagradalsfjall lavas, and lava fields from previous eruptive period ending in the 13th century CE. Inlet show Iceland with fissure swarms (yellow areas) central volcanoes (dashed ovals) and far-field spreading direction and the area of the main map. Reproduced from Sigmundsson et al. (2024).*

At Fagradalsfjall, the first dike intrusion (the largest to date in this area) took place mostly from 24 February 2021 until 19 March 2021, when an eruption began. Ground deformation was studied and reported by Sigmundsson et al. (2022). The dike propagation lasted for approximately 3 weeks with an initial magma inflow rate of 30-35 m^3/s which reduced to <10

m^3/s prior to the eruption onset. Our analyses have shown a strong correlation between modelled inflow rate to the dike immediately before eruption onset and the initial lava extrusion rate, which is very important for determining the risk related to lava flows.

At Fagradalsfjall, the magma is being transferred from around 10-15 km depth, which is feeding lateral dike intrusions in the upper crust between depths of ~1 to 6 km. When the main dike has finished propagating laterally, and if the pressure is still building due to continued magma inflow into the dike, then it will begin to form what we call a dikelet and start its final ascent towards the surface. When this occurs, we have observed a decline in both the deformation and seismicity – we believe this occurrs when the dike can no longer propagate laterally as it has released the previously built up stress in the crust, but if magma is still flowing into the dike from below, the pressure continues to build and then it begins to migrate upward. The upper 1 km of the crust is weak thus magma migration within the higher level does not produce any significant seismicity. This is why it has been possible to forecast the onset of eruptions at Fagradalsfjall during 2022 and 2023 using extensive geodetic data sets and seismicity patterns (Figures 6 and 7), based on modelled top depth of initial dike intrusion and identifying the decline in seismicity (Parks et al., 2023).

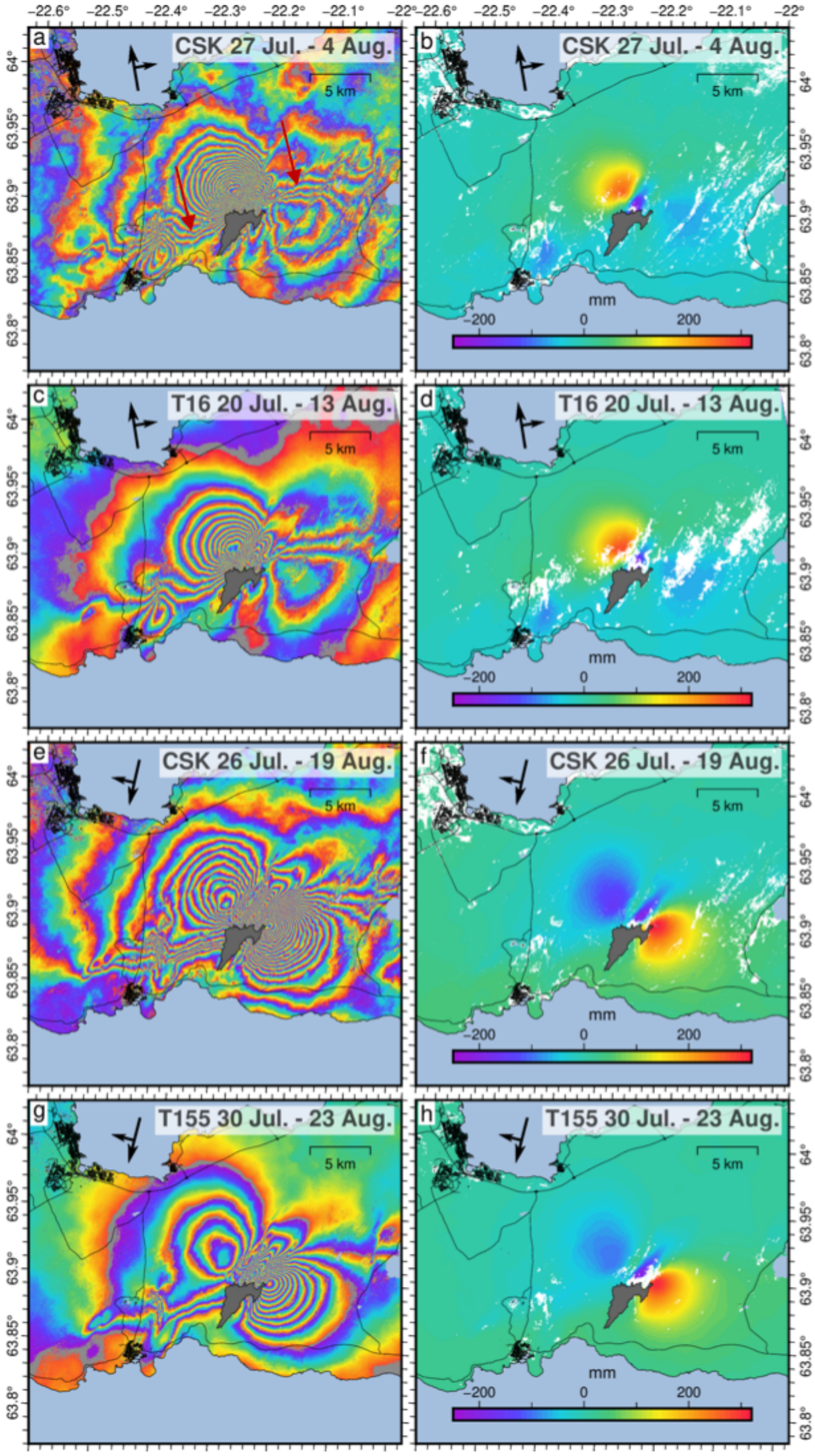


Figure 6. *Interferograms spanning July-August 2022 dike intrusion in the Fagradalsfjall area (dike 3 in that area, shown in Figure 7). Red arrows (a) show deformation associated with movement along the plate boundary. Reproduced from Parks et al. (2023).*

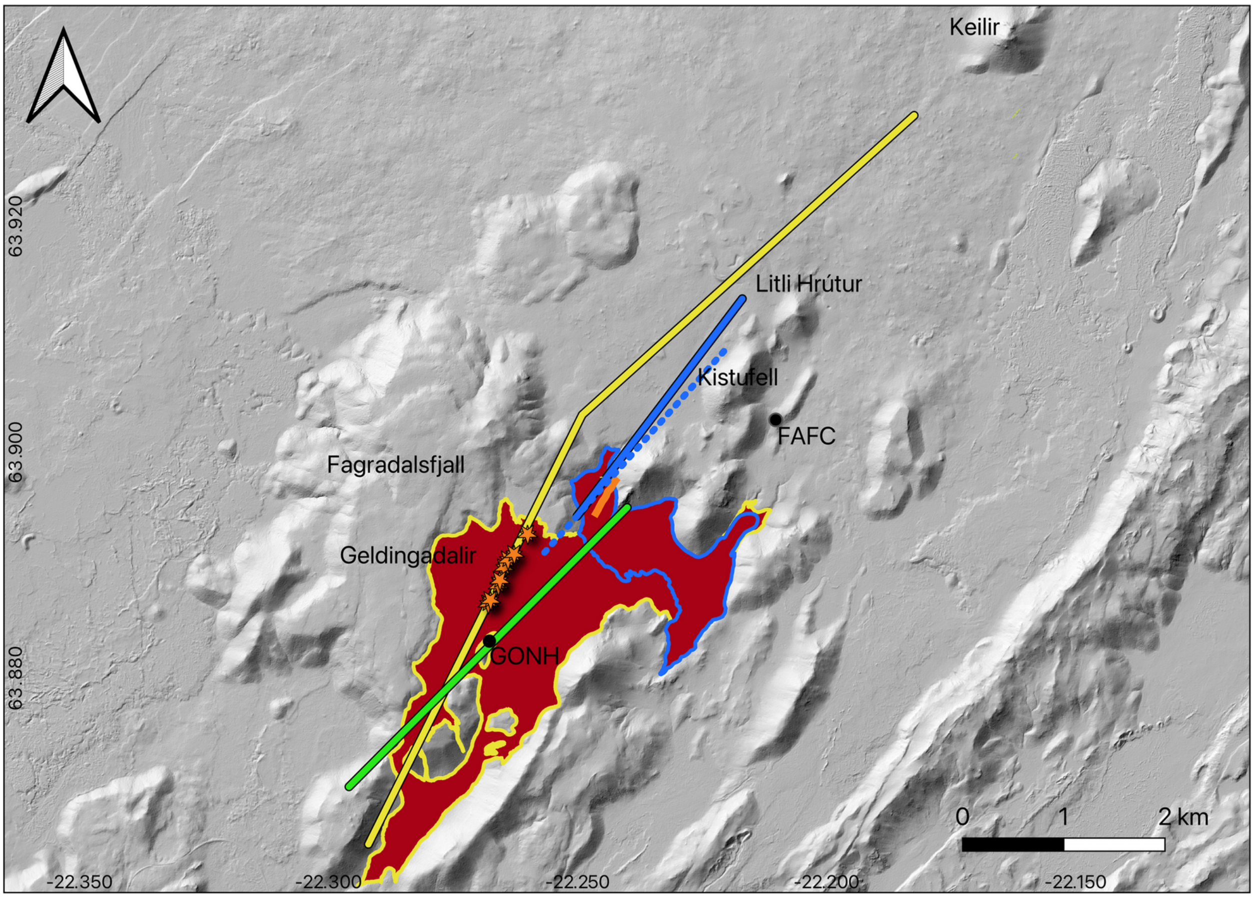


Figure 7. *Projected surface location of the modeled dikes 1-3 in the Fagradalsfjall area, based on geodetic observations. The yellow line is dike 1 (intruded February to March 2021) from Sigmundsson et al. (2022), green line is modeled dike 2 (December 2021), initial dike 3 model (July–August 2022, using data up until 1 August 2022) prior to eruption onset is the dashed blue line, and final dike 3 model (July–August 2022) is the solid blue line. 2021 eruptive fissures are displayed as orange stars. The location of the eruptive fissure that opened on 3 August 2022 (~13:30 UTC) is shown by the orange line. The 2021 lava outline is displayed as the red-filled region with yellow outline. GNSS stations are marked as filled black circles. Reproduced from Parks et al. (2023). In 2023, a diking event and eruption occurred in the area between Mt. Litli Hrútur and Keilir (not marked on the figure).*

In Svartsengi, the initial perod of uplift was followed by 4 additional intrusions/magma injections here with depths located between 3-5 km (two of which occurred between March – April and May – July 2020, one in April 2022 and an additional injection from 27 October to 10 November 2023), the last of which triggered a major dike intrusion on 10 November 2023 under the Sundhnúkur crater row and the town of Grindavík (Figures 8 and 9). The main difference between the dike intrusions and eruptions thus far at Fagradalsfjall and the Sundhúkur/Grindavík is how the magma is being sourced and how it is migrating.

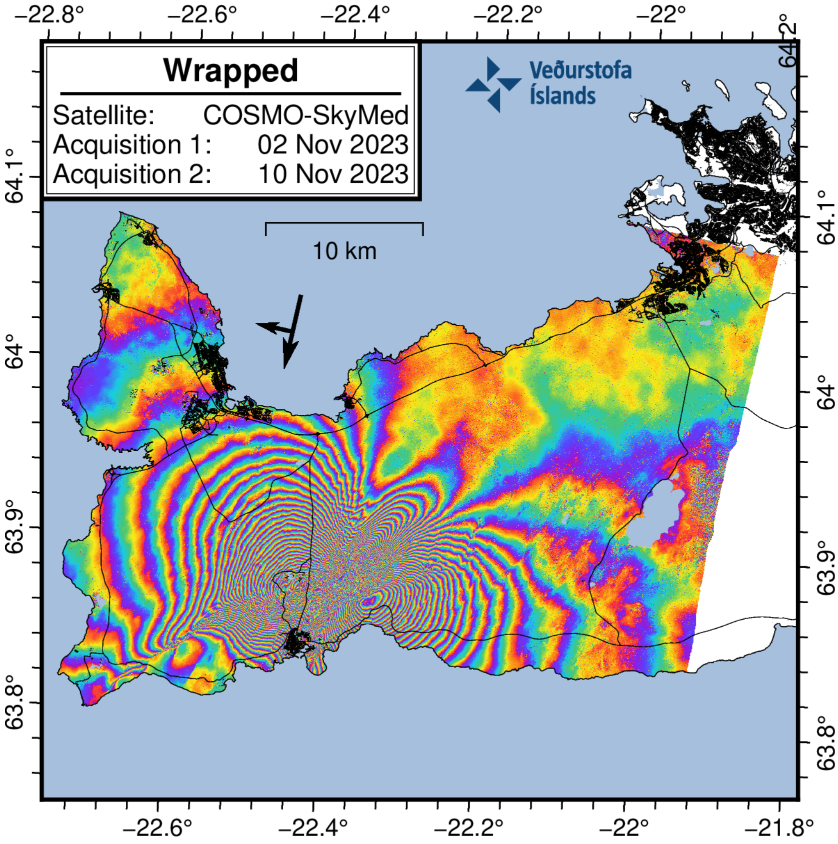
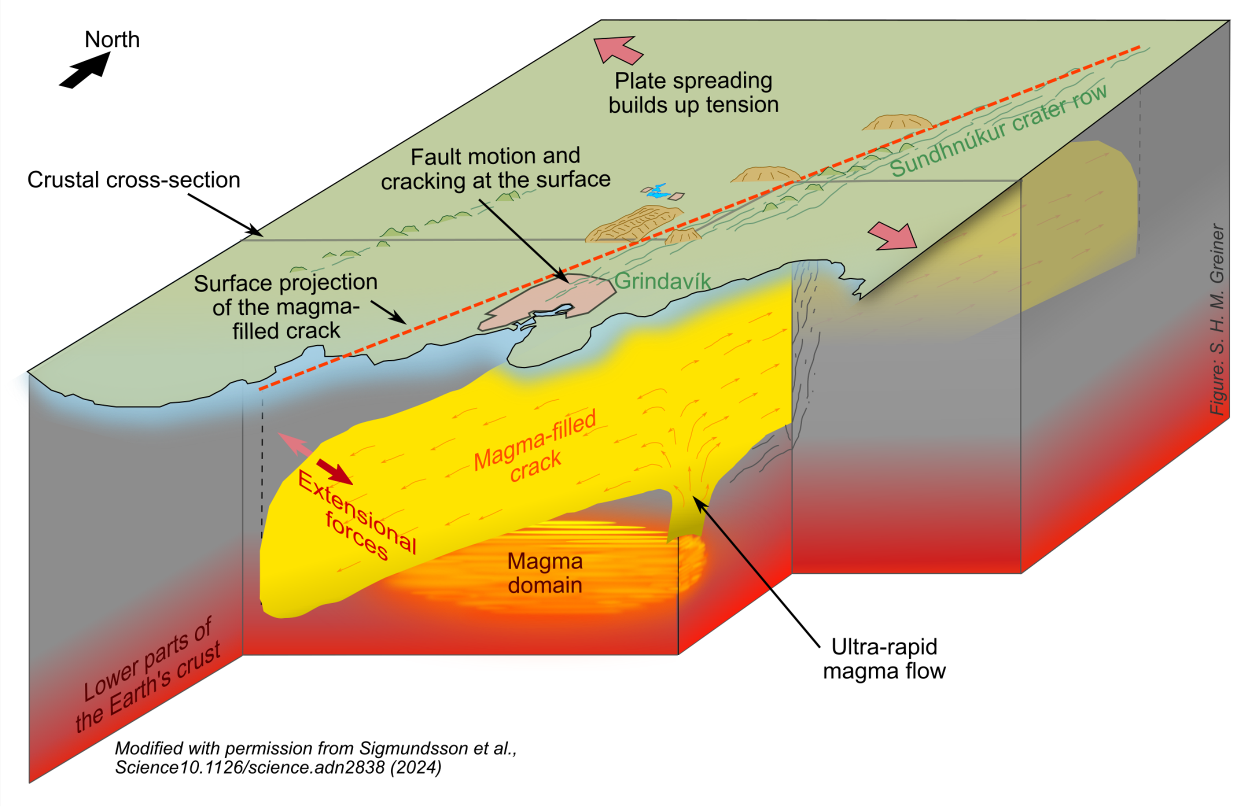


Figure 8. *COSMO-SkyMed (CSK) wrapped interferogram covering the Grindavík dike intrusion in November 2023.*

At Sundhúkur/Grindavík the magma feeding the dike intrusions resides at a much shallower level, at about 4 to 5 km, and is being injected rapidily into dike intrusions when the crictical pressure is reached and the boundary of the magma domain fails, allowing magma to flow from it. Data and modelling indicates that the five inflation episodes in this area that occurred between 2020-2023 were in fact injections of magma into an extensive pre-existing magma domain. It is referred to as Svartsengi magma domain, as it is in the center of the Svartsengi volcanic system. However, it extends over a very broad region (spanning close to Eldvörp in the west to the Sundhúkur crater row in the east). The reason why the current activity is potentially more harzardous results from both a combination of close proximity to the town of Grindavík, the Blue Lagoon, Svartsengi Power Plant and critical infrastructive, in addition to the much higher magma inflow and lava extrusion rates when compared to Fagradalsfjall. This is because crictial failure of the Svartsengi magma body is occuring over a wide fractured zone, facilitating formation of a conduit that enables rapid injection of magma into dikes at a shallow level. A schematic of outlining the sources feeding the most recent activity and the processes involved is displayed in Figure 9.



Modified with permission from Sigmundsson et al.,
Science10.1126/science.adn2838 (2024)

Figure 9. *Illustration of the Grindavík dike and a proposed magma domain, where magma accumulated prior to the magma intrusion. On 10 November 2023, a dike propagated suddenly under the Sundhnúkur crater row and the town of Grindavík, where fault motion and cracking occurred at the surface. Surface projections of the Grindavík dike and the crustal cross section are outlined by red dashed and grey solid lines on the surface, respectively. Modified from Sigmundsson et al. (2024).*

During the 10 November dike injection, the intial estimates of the magma inflow rate to the dike were around 5000 m^3/s and revised estimates suggest peak-values over 7000 m^3/s (Sigmundsson et al., 2024). Two orders of magnitude greater than the fastest dike injection observed at Fagradalsfjall. This information, combined with confirmation from both GNSS and seismic data that the dike had indeed been intruded beneath Grindavík, necessitated the urgent evacuation of the town on 10 November, 2023. On 18 December, the Svartsengi magma domain once again reached critical pressure and this time triggered the rapid formation of a dikelet extending from the top of the dike emplaced on 10 November. The eruption onset was rapid – commencing only 1.5 hours following the start of the seismic swarm, with an inferred peak magma inflow rate to the dike of ~800 m^3/s. Similar events occurred in January and February 2023.

Activity during the past 3 years has switched between Svartsengi and Fagradalsfjall volcanic systems, with four dike intrusions and three eruptions in the Fagradalsfjall area and two dike intrusions and one eruption in the Sundnhúkur/Grindavík area (Svartsengi volcanic system) until end of 2023. During the previous phase of volcanic activity on the Peninsula, some 800 years ago, activity also switched between neighbouring volcanic sytems. Although the volcanic eruptions in recent years have been relatively small to date, historic activity suggests that future eruptions may involve larger volumes of erupted lava.

Digital elevation models from Pléiades data (Eyjólfur Magnússon)

Pléiades optical stereo images were provided by CNES, including ~5000 km^2 of images in 2022 (~2500 km^2 of stereo images) and ~3500 km^2 of images in 2023 (~1750 km^2 of stereo images), which were used to obtain digital elevation models (DEMs) of four ice covered volcanic areas (Figure 10). This included one DEM each year for Öræfajökull ice cap (2×260 km^2) for Bárðarbunga and the Skaftár cauldrons (2×250 km^2), 3 times for Grímsvötn in 2022 and twice in 2023 (5×~230 km^2). Additional DEMs of the area south of Grímsvötn, effected by a glacier outburst flood (jökulhlaups) in 2021 (~600 km^2) and the center part of Mýrdalsjökull ice cap were covered 4 times for each in 2022 and 2023 (8×183 km^2).

The data from Grímsvötn was particularly useful (Figure 10). It has enabled monitoring of water collection in the subglacial lake Grímsvötn and estimation of drainage during jökulhaups in 2021 (comparison between DEMs in November 2021 and January 2022) and 2022.

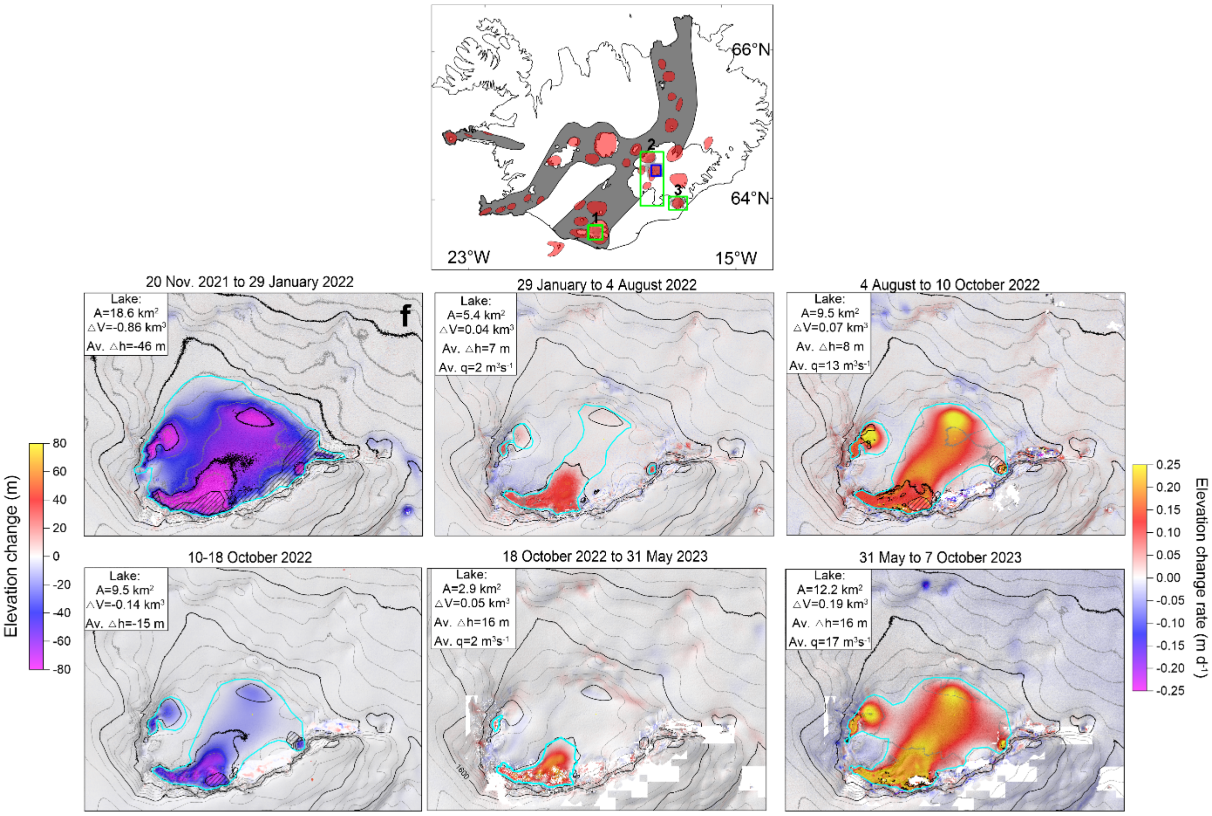


Figure 10. *Top: Map of Iceland showing its ice caps, volcanic belts (grey), central volcanoes (red) and areas of Pléiades stereo acquisitions in 2022-2023 on Mýrdalsjökull (green box signed 1), Grímsvötn and vicinity, Bárðarbunga and Skaftá Cauldrons (green box signed 2) and Öræfajökull*

(green box signed 3). Below: Elevation changes of Grímsvötn (blue box on top panel) derived from Pléiades DEMs during jökulhlaups (on left shown as net elevation change) and in between jökulhlaups (in centre and on right shown as elevation change rate). Within the corner boxes the of each panel the max area of the lake during the period, lake volume change, and average elevation change within the lake (shown with cyan outlines) is given. Additionally, the average filling rate of the lake (Av. q) is given for the periods without jökulhlaups.

Continued unrest at Askja volcano (Michelle Parks and Vincent Drouin)

Askja volcano is situated in the Northern Volcanic Zone in Iceland, and comprises both a central volcano and a fissure swarm covering an area of approximately 190 × 20 km. The central volcano includes a series of nested calderas formed during previous plinian eruptions. Historic eruptions have comprised both basaltic effusive eruptions and silicic explosive eruptions although the former are more common. Eruptions occur on average three times per century. The last eruption at Askja occurred in 1961. This was predominantly effusive and produced a lava field of approximately 0.1 km^3. The last plinian eruption to occur here was in 1875. This major event formed the most recent caldera, which is now filled with lake Öskjuvatn (~200 m deep).

At the beginning of August 2021, inflation was detected at Askja volcano, on a continuous GNSS station located to the west of Öskjuvatn (OLAC) and on interferograms generated using data from four separate Sentinel-1 tracks. As of December 2023, deformation is continuing, with ~70 cm of uplift measured at GNSS station OLAC (Figures 11 and 12). Ground deformation measurements at Askja commenced in 1966 with levelling observations, and since this time additional ground monitoring techniques have been employed, including GNSS and Satellite interferometry (InSAR) to detect long-term changes. Ground levelling measurements undertaken between 1966-1972 revealed alternating periods of deflation and inflation. Measurements from 1983-2021 detailed persistent subsidence of the Askja caldera, decaying in an exponential manner. Shortly after the onset of unrest, three additional GNSS stations were installed at Askja and campaign measurements undertaken in summer 2021 and 2022. GNSS time series and InSAR decomposition results indicate that the observed deformation results from upward and lateral migration of magma, potentially feeding multiple shallow sources (Parks et al., 2024).

This work has been beneficial by identifying future eruptive scenarios and potential hazards, based on interpretation of the modelling results and historic activity.

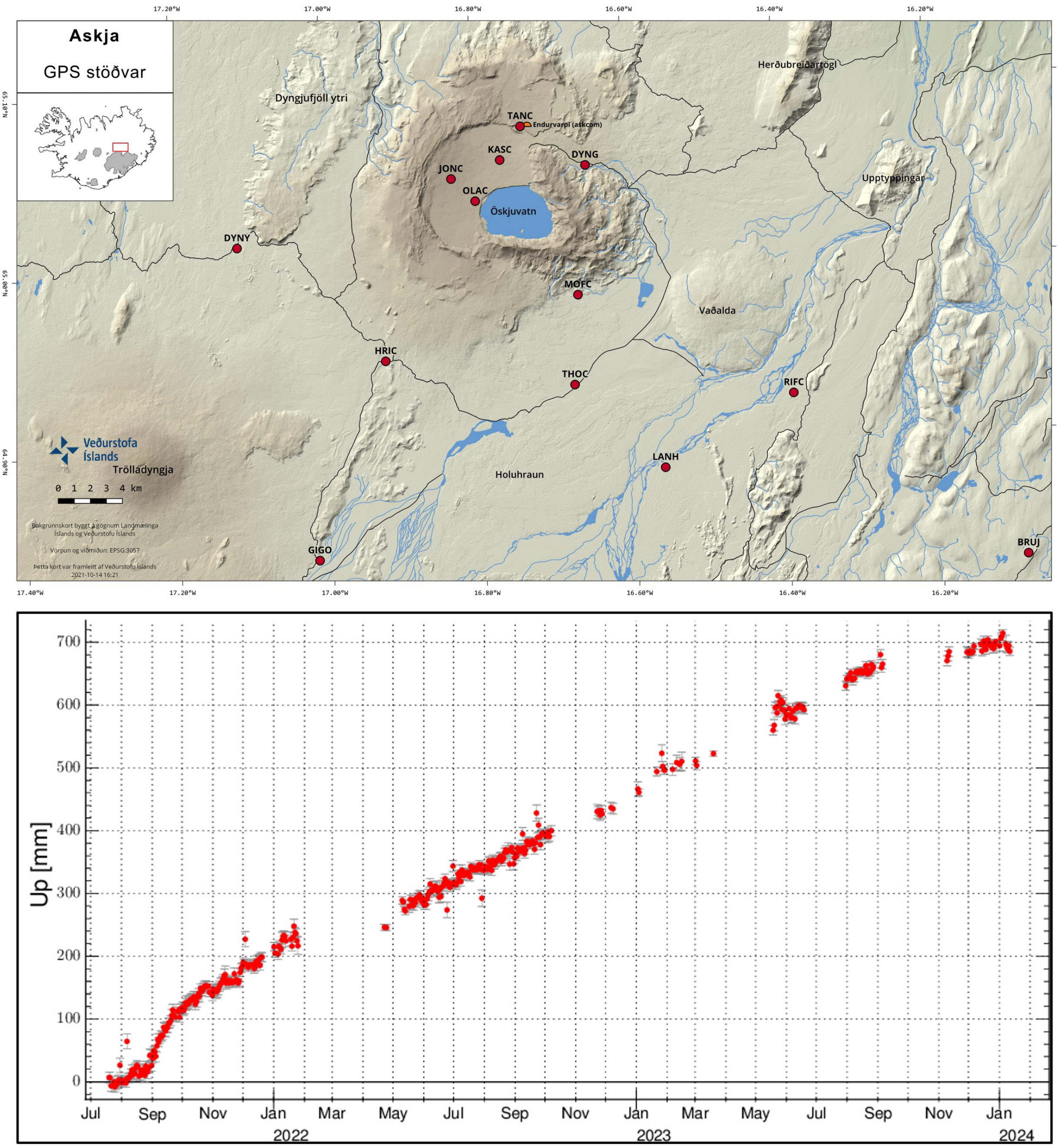


Figure 11. *Vertical displacements at GNSS station OLAC.*

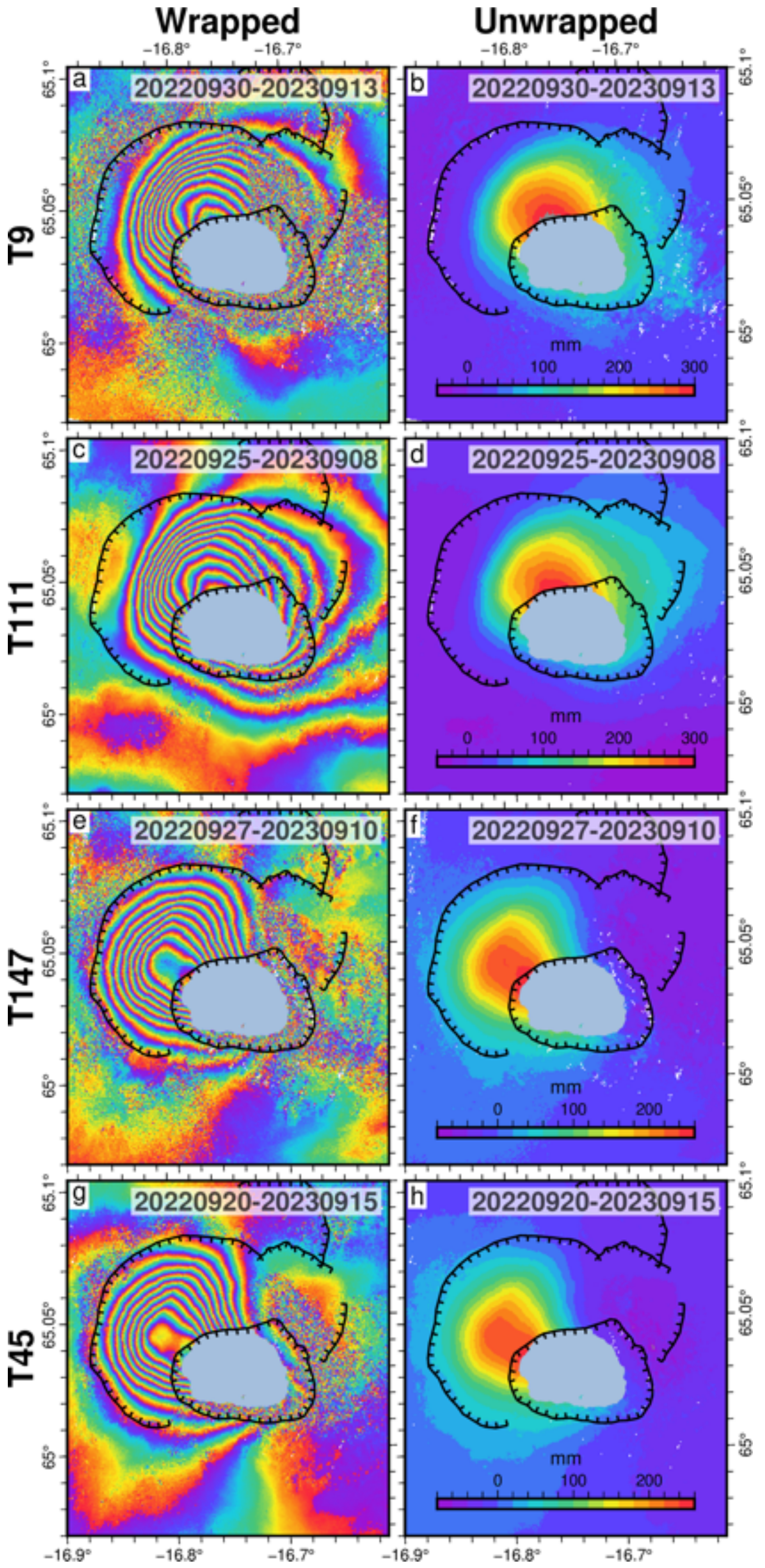


Figure 12. *Wrapped and unwrapped Sentinel-1 interferograms spanning September 2022 to September 2023.*

Long-term subsidence at volcanoes undergoing extension in the Northern Volcanic Zone of Iceland: Application on the Krafla and Askja volcanic systems (Chiara Lanzi and Freysteinn Sigmundsson)

The Askja and Krafla volcanic systems, in the Northern Volcanic Zone (NVZ) of Iceland, are located along a divergent plate boundary. They consist of a fissure swarm and caldera complex, which have been showing subsidence inside since 1983 and 1989, respectively. The subsidence has been reported to show an exponential decay at both volcanoes, but faster rates are recorded at Askja caldera (Figure 13). Levelling (since 1983), and GNSS and InSAR (early 1990s) show an initial maximum deflation rate, ~5 cm/yr, in the middle of the Askja caldera, decaying to 2.5-3 cm/yr in the 2000-2009 period. Subsidence was observed until 2021, when inflation began (Parks et al., 2024; also see *Continued unrest at Askja volcano* section). At Krafla caldera, subsidence rate was of ~5 cm/yr in 1989-1992 then, declining to ∼3-5 mm/yr in 1995-2015. In summer 2018, the GNSS and InSAR monitoring show the deformation pattern inside the caldera occurred (Lanzi et al., 2023). Changes in the geothermal production and increase in the pressure measurements in one of the monitoring well occurred at similar times as the onset of the deformation, suggesting a possible link between the geothermal exploitation, ground deformation and pressure changes. A joint inversion of GNSS and InSAR (Sentinel1 images) inferred a pressure source depth at or near the magma-hydrothermal boundary at Krafla (2.1–2.5 km deep). Finite Element Method (FEM) modelling with low-rigidity crust in the Krafla subsurface demonstrates that the observed ground deformation may be caused by pressure increase at similar level as observed in the monitoring well, assuming the increase as representative for the whole geothermal reservoir.

To study the long-term subsidence at the Askja and Krafla volcanic systems, we use a two-layer FEM model where an upper elastic layer overlies a viscoelastic layer (with viscosity = 5×10^{18} Pa s), which locally reaches shallower levels (2 km deep) in the magmatic system, simulating a rheological anomaly there. Above the rheological anomaly a low-rigidity volume, like the one used to study the deformation change in Krafla in 2018, is present. Additionally, a fissure swarm geometry is introduced into the model north and south of the caldera in the case of the Krafla volcanic system, while for the Askja volcanic system only one fissure swarm is present to the north of the caldera. The FEM models relate strain localization at volcanoes undergoing extension to the presence of a rheological anomaly, where different viscosity values in the rheological anomaly are investigated. The fit of the model predictions to observed long-term deformation at the Krafla and Askja volcanic systems inferred from Sentinel-1 images covering the 2015-2018 period suggests that plate divergence may account for most and ~30% of the observed subsidence at Krafla and Askja volcanic systems, respectively.

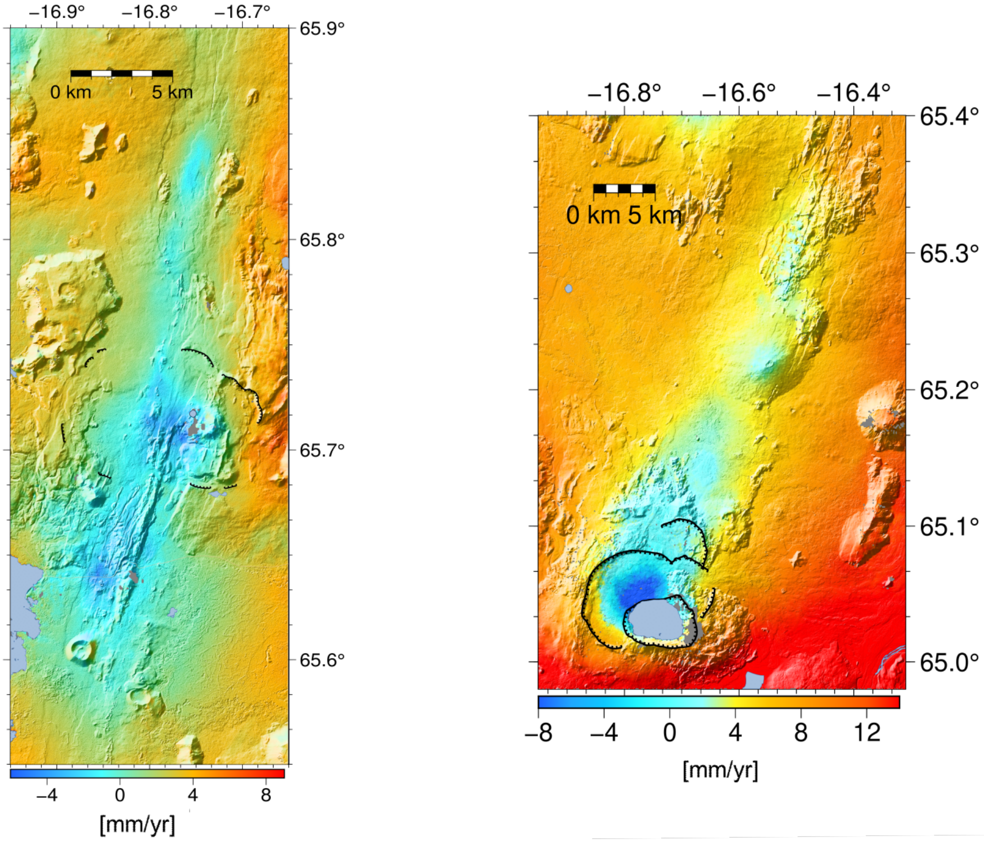


Figure 13. *Vertical displacement based on InSAR data (near-up) in the 2015-2018 period at Krafla (left panel) and Askja (right panel) volcanic systems.*

Publications

Peer reviewed journal articles
Sigmundsson, F., Parks, M., Geirsson, H., Hooper, A., Drouin, V., Vogfjörd, K. S., Ófeigsson, B. G., Greiner, S. H. M., Yang, Y., Lanzi, C., De Pascale, G . P., Jónsdóttir, K., Hreinsdóttir, S., Tolpekin, V., Friðriksdóttir, H. M., Einarsson, P., Barsotti, S. (2024). Fracturing and tectonic stress drives ultrarapid magma flow into dikes. *Science.* DOI: 10.1126/science.adn2838
Parks, M. M., Sigmundsson, F., Drouin, V., Hreinsdóttir, S., Hooper, A., Yang, Y., et al. (2024). 2021–2023 unrest and geodetic observations at Askja volcano, Iceland. *Geophysical Research Letters*, *51*, e2023GL106730. https://doi.org/10.1029/2023GL106730
Parks, M., Sigmundsson, F., Drouin, V., Hjartardóttir, Á. R., Geirsson, H., Hooper, A., ... & Fridriksdóttir, H. M. (2023). Deformation, seismicity, and monitoring response preceding and during the 2022 Fagradalsfjall eruption, Iceland. Bulletin of Volcanology, 85(10), 60.
Hjartardóttir, Á. R., Dürig, T., Parks, M., Drouin, V., Eyjólfsson, V., Reynolds, H., ... & Pedersen, G. B. (2023). Pre-existing fractures and eruptive vent openings during the 2021 Fagradalsfjall eruption, Iceland. Bulletin of Volcanology, 85(10), 56.
Lanzi, C., Drouin, V., Sigmundsson, F., Geirsson, H., Hersir, G. P., Ágústsson, K., ... & Guðmundsson, Á. (2023). Pressure increase at the magma-hydrothermal interface at Krafla caldera, North-Iceland, 2018–2020: Magmatic processes or hydrothermal changes?. Journal of Volcanology and Geothermal Research, 107849.

Barsotti, S., Parks, M. M., Pfeffer, M. A., Óladóttir, B. A., Barnie, T., Titos, M. M., ... & Sigurðsson, E. M. (2023). The eruption in Fagradalsfjall (2021, Iceland): how the operational monitoring and the volcanic hazard assessment contributed to its safe access. Natural Hazards, 116(3), 3063-3092.

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Conference presentations/proceedings

Geirsson, H., Parks, M., Lanzi, C., Birgisdottir, A. G., Drouin, V., Ducrocq, C., ... & Greiner, S. H. M. (2023). Reykjanes Peninsula Unrest and Fagradalsfjall Fires 2020-2023, Iceland: Deformation History of a Multi-Event Rifting Episode in a Trans-Tensional Environment. AGU23.

Sigmundsson, F., Parks, M., Geirsson, H., Vogfjord, K. S., Drouin, V., Tolpekin, V., ... & Einarsson, P. (2023). The 4th Diking Event of the Fagradalsfjall Rifting Episode (2021-?) in July 2023: Geodetic and Seismic Imaging of the Dike Propagation and Effects of Imposed Stresses on the Dike and the Associated Eruption. AGU23.

Sepulveda, J., Hooper, A. J., Ebmeier, S. K., Lazecky, M., Lanzi, C., Yang, Y., ... & Parks, M. (2023). Ground deformation at Askja Volcano: a poroelastic finite element model to explain the observed uplift that commenced in the summer of 2021. AGU23.

Sturkell, E., Sigmundsson, F., Parks, M., Geirsson, H., Rut, Á. (2023). Decades of deflation of the Askja volcano, Iceland, prior to ongoing inflation. AGU23.

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Vogfjord, K. S., Parks, M., Geirsson, H., Ofeigsson, B., & Sigmundsson, F. (2022, December). Tracking and Modeling Magma Migration, Dyke Intrusions and Fault Activation on the Reykjanes Peninsula, Iceland During the 2020–2022 Rifting and Eruption Event at Fagradalsfjall. In AGU Fall Meeting Abstracts (Vol. 2022, pp. T16A-07).

Sigmundsson, F., Parks, M., Hooper, A. J., Geirsson, H., Vogfjord, K. S., Drouin, V., ... & Ágústsdóttir, T. (2022, December). Seismicity and Deformation Increase or Decrease prior to Eruption? Lessons Learned from Eruptions and Dike Intrusions at Mt. Fagradalsfjall, Iceland. In AGU Fall Meeting Abstracts (Vol. 2022, pp. V25A-07).

Magnússon, E., Drouin, V., Pálsson, F., Hannesdóttir, K., Belart, J., Sigurðsson, G., ... & Berthier, E. (2022, May). The jökulhlaup from the subglacial lake Grímsvötn, beneath Vatnajökull ice cap, in November-December 2021, revealing new insight in to slowly rising jökulhlaups. In EGU General Assembly Conference Abstracts (pp. EGU22-8240).

Rut Hjartardóttir, Á., Dürig, T., Parks, M., Drouin, V., Eyjólfsson, V., Reynolds, H., ... & Einarsson, P. (2022, May). Eruptive vent openings during the 2021 Fagradalsfjall eruption, Iceland, and their relationship with pre-existing fractures. In EGU General Assembly Conference Abstracts(pp. EGU22-10330).

Parks, M., Vogfjörd, K. S., Sigmundsson, F., Hooper, A., Geirsson, H., Drouin, V., ... & Ágústsdóttir, T. (2022, May). Evolution of deformation and seismicity on the Reykjanes Peninsula, preceding the 2021 Fagradalsfjall eruption, Iceland. In EGU General Assembly Conference Abstracts (pp. EGU22-13461).

Geirsson, H., Parks, M., Sigmundsson, F., Ófeigsson, B. G., Drouin, V., Ducrocq, C., ... & Hooper, A. (2022, May). Co-eruptive subsidence during the 2021 Fagradalsfjall eruption: geodetic constraints on magma source depths and stress changes. In EGU General Assembly Conference Abstracts(pp. EGU22-12435).

Parks, M., Ófeigsson, B., Drouin, V., Sigmundsson, F., Hooper, A., Geirsson, H., ... & Óladóttir, B. (2022, May). Deformation observations and geodetic modelling during the recent unrest at Askja volcano. In EGU General Assembly Conference Abstracts (pp. EGU22-9381).

Drouin, V., Tolpekin, V., Parks, M., Sigmundsson, F., Leeb, D., Strong, S., ... & Ófeigsson, B. G. (2022, May). Conduits feeding new eruptive vents at Fagradajsfjall, Iceland, mapped by high-resolution ICEYE SAR satellite in a daily repeat orbit. In EGU General Assembly Conference Abstracts (pp. EGU22-8679).

Research products

Type of product	Product provider	How to access	Type of access
Reykjanes Sentinel-1 interferograms	*IMO*	*https://data.epos-iceland.is/files/insar/fagradalsfjall/*	*public*
Catalogue of Icelandic Volcanoes	*IMO*	*http://icelandicvolcanos.is/*	*public*
GNSS, SAR data, earthquakes and geodetic modelling results for inflation events and dike intrusions on Reukjanes Peninsula	*POC*	*https://osf.io/n73cm/* *https://osf.io/9rcq7/*	*public*

The primary research products of the Icelandic Volcanoes supersite are the scientific publications in the international literature (see list above) and the associated data repositories. We are currently in the process of transferring data in these repositories to the EPOS data portal.

In addition, the results of these studies are routinely presented to civil protection authorities. An additional important research product that relates to the supersite is the Catalogue of Icelandic Volcanoes, available at the website:

http://www.icelandicvolcanoes.is

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

Research product issues

The POC may be contacted regarding datasets residing in the OSF Home repositories and 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 ISVOLC project (started 1 April 2023), funded by the Icelandic Research Fund, assisted with certain aspects of the supersite work, through for example, contribution of working hours, field work and provision of GNSS data. ISVOLC studies the effects of climate change on ice-retreat, associated glacial isostatic adjustment, and influence of these processes on seismic and volcanic activity. The Icelandic Meteorological Office and University of Iceland play a leading role in the project especially concerning 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. Although snow cover during winter often causes loss of coherence in interferograms and limits to use of InSAR during this season, recent L-band SAOCOM interferograms have maintained coherence despite snow coverage, thus are promising for future use in monitoring during wintertime periods of volcanic unrest/eruption.

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 2023 unrest and dike intrusion within the Svartsengi volcanic system. Evaluation of ground deformation from CSK and Sentinel-1 interferometry for the diking espisode and December 2023 eruption has been incorporated into deformation models and provided important constraints on the nature of the dike propagation, volume assessment and magma inflow rates.

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 (2022-2023) 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 unrest and eruptions on Reykjanes Peninsula – especially on 10 November when a massive dike propagated beneath the town of Grindavík. During the dike emplacement, geodetic inversions using initially GNSS observations, then both GNSS and various interferograms as the input, were used to map the location of the dike, the top depth and the total volume change and magma inflow rates. Based on these models a map outlining “danger zones” was constructed which was regularly updated to highlight areas where future eruptive fissures were most likely to open and what areas were most likely to be affected by lava flows, or additional hazards.

Pléiades data has been extremely beneficial in generating new DEMs in the vicinity of multiple ice-covered volcanoes in 2022-2023. In particular at Grímsvötn, where this data has been used to derive DEMs during and in between jökulhlaups. These DEMs are critical for identifying changes in the ice-cap, since this is one of Iceland's most active volcanoes and is the source of frequent jökulhlaups.

Additional studies at Askja have provided an improved understanding of the magma plumbing system beneath this volcano and the processes behind the ongoing unrest - this is essential for defining future eruption scenarios and for hazard forecasting purposes.

Successful collaboration between the satellite agencies and supersite members has been key to optimising the monitoring strategy in Iceland throughout the 2022-2023 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.