EUROVOLC

European Network of Observatories and Research Infrastructure for Volcanology

Deliverable Report

D6.3 : Eruption Data and Products (Eruption DP)

Work Package:	*Networking volcano observations of sub-surface processes and initiating access to observations from the Krafla Volcano Laboratory*	
Work Package number:	*WP6*	
Work Package leader:	*Freysteinn Sigmundsson*	
Task (Activity) name:	*Case studies of recent eruptions in Italy and Iceland*	
Task number:	*Subtask 6.1.3*	
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Type of Deliverable:	*Report [X]* *Prototype [ ]*	*Demonstrator [ ]* *Other [ ]*
Dissemination level:	*Public [X]* *Prog. Participants [ ]*	*Restricted Designated Group [ ]* *Confidential (consortium) [ ]*

Programme: H2020

Project number: 731070

Contents

Summary

This deliverable reports work in relation to subtask 6.1.3 in EUROVOLC on making accessible selected multidisciplinary data concerning specific eruptions in Italy and Iceland. Etna was selected as the volcano in Italy. In Iceland, data from the Bárðarbunga-Holuhraun 2014-2015 and Fagradalsfjall 2021 eruptions have been made available. They were selected rather than originally planned Grímsvötn 2011 and Eyjafjallajökull 2010 eruptions, as they are more recent and there is more scientific work focusing on these eruptions at present. The data includes seismic and geodetic data as described below.

Data from the Bárðarbunga-Holuhraun eruption 2014-2015

GNSS data from IMO and UI made available in FAIR access

Data from Icelandic GNSS stations near the Bárðarbunga caldera and the Holuhraun eruption site of 2014 have been made available by Icelandic Meteorological Office (IMO) and University of Iceland (UI) for the period January 2014 to November 2021. This period encompasses the unrest, deformation, and eruption at Bárðarbunga volcano from August 2014 to February 2015 (Sigmundsson et al., 2015; Gudmundsson et al., 2016). The episode includes (i) propagation of a magma dyke 16 – 27 August, from Bárðarbunga caldera 45 km NNE to the location of the eruption fissure, (ii) the first, short-lived eruption at Holuhraun on 29 August, which lasted 4 hours, (iii) the second eruption, which started on 31 August and lasted nearly six months until 27 February 2015,(iv) 60 m subsidence of the caldera floor from 20 August until the end of the eruption and (v) a post rifting phase after the end of the eruption (Li et al., 2021).

The data are from 14 GNSS stations, including DYNC, VONC, HAFS, KIDC, FJOC, HAUC, SKRO, GSIG, HRIC, THOC, KISA, RJUC, JOKU and GFUM (see Figure 1). These data make it possible to see a clear story of pre-eruptive inflation of Bárðarbunga caldera on nearby stations as well as the whole unrest/eruption process. This time history is best seen on station VONC from June 2014.

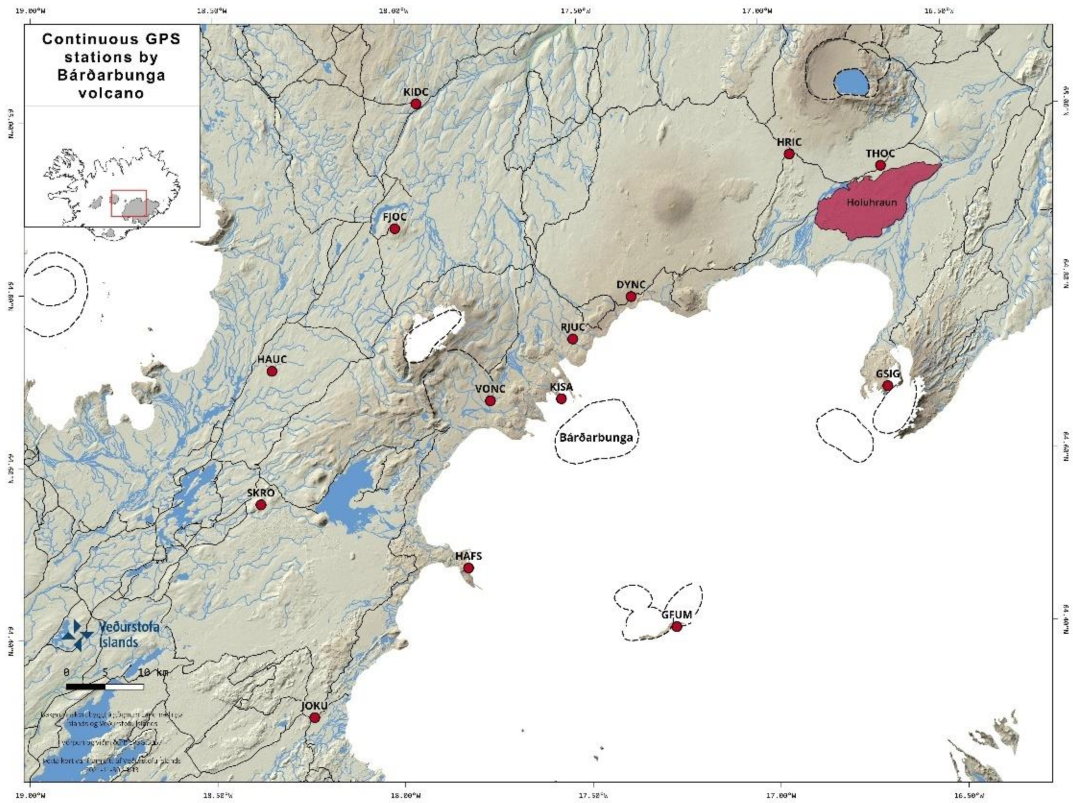

***Figure 1**. Map showing location of Bárðarbunga volcano in the Vatnajökull ice cap in the mountainous areas of east-central Iceland. Locations of the GNSS stations opened for FAIR access are shown (red circles). The outline of Bárðarbunga caldera is shown, as well as the erupted lava at Holuhraun (red).*

The GNSS stations are located in the central mountainous areas of Iceland, where harsh weather conditions and difficult access prevail during most of the year. These conditions sometimes affect power generation and transmission. As a result, there can be gaps in the data, sometimes for weeks or months until power and communication have been restored. Five of the stations were newly installed or changed to continuous recording from a previous campaign GNSS station during the volcanic event. These stations and their continuous starting dates respectively are: GSIG 2014-08-20, THOC 2014-08-30, HRIC 2014-08-23, KISA 2015-07-09 and RJUC 2015-09-15. Two stations, VONC and DYNC were installed under the FP7 FUTUREVOLC project.

The quality checked GNSS data and associated metadata for the period January 2014 to November 2021 are accessible in an API service at IMO, with information on access provided at: https://docs.vedur.is/api/epos/#/GNSS.

The service is connected to the *EPOS VO-TCS* (Volcano Observations Thematic Core Service). The metadata consist of station and site-log information, including the location of each GNSS station, their starting date, GNSS receiver and antenna types and their serial numbers, antenna height, dates when equipment was changed and when firmware and software updates were made. The GNSS data themselves are in RINEX format and sampled at 15s.

The GNSS data for the 2014-2015 Bárðarbunga-Holuhraun eruption and following post-eruptive period has also been made accessible via the UNAVCO platform for GNSS data by UI and IMO. Search Iceland at the following site: https://www.unavco.org/data/doi/search/search.html
The data is presented and interpreted in a recent publication (Li et al., 2021), as well as in a publication by Sigmundsson et al. (2020).

Seismic data from IMO and UI made available in FAIR access

Data from the Icelandic SIL/VI seismic network is being made accessible in *FAIR* open access for the period of the Bárðarbunga unrest and eruption. The unrest started on 16 August 2014 with intense seismicity at the Bárðarbunga volcano, but quickly propagated out of the caldera and toward NE, along a 45-km-long dyke intrusion, which ended in the effusive eruption at Holuhraun lava field, north of the Vatnajökull ice cap. First a short-lived eruption on 29 August and then a second one on 31 August, which lasted 6 months, until the end of February 2015. The seismicity was mainly concentrated at the dyke intrusion and around the caldera rim, and the largest events were mainly at the caldera, where 80 Mw>5 events occurred on the caldera rim over the next 5 months (Sigmundsson et al., 2015; Gudmundsson et al., 2016).

Raw waveform data: Waveform data from 17 seismic stations near the Bárðarbunga volcano during the period 1 August 2014 to 28 February 2015 are made available in *FAIR* open access. Locations of the stations; *bjk*, *djk*, *dyn*, *fag*, *grf*, *hus*, *iey*, *jok*, *kal*, *kre*, *ksk*, *skr*, *tho*, *urh*, *von*, *vot*, *vsh* are shown in Figure 2. Their proximity to the volcano, the dyke intrusion NE of the volcano, and the eruption site north of the glacier (see Figure 1) ensures detection of thousands of earthquakes related to the magma migration along the dyke, as well as the thousands of earthquakes generated on the caldera rim as the caldera floor subsided by 60 m during the period of the unrest (Sigmundsson et al., 2015; Gudmundsson et al., 2016).

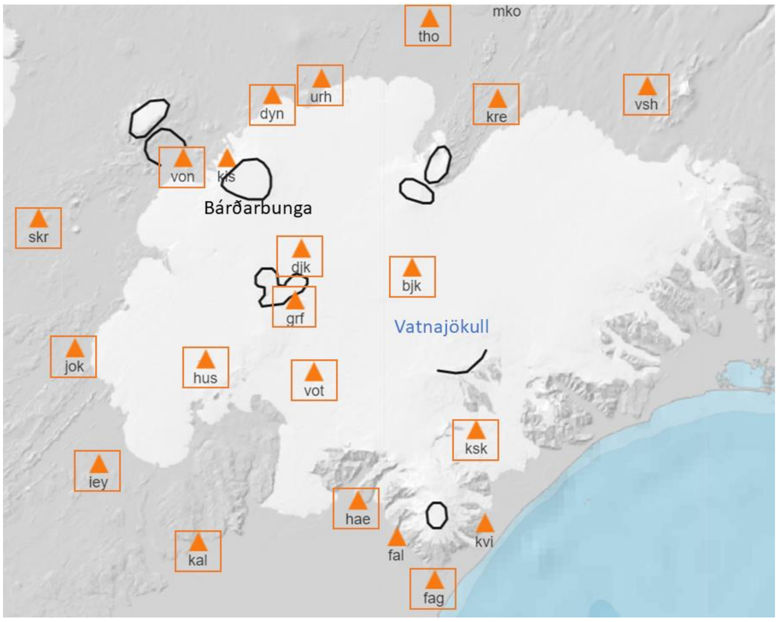

Figure 2*. Seismic stations (triangles) of the SIL/VI network in the Vatnajökull (Bárðarbunga) area. Waveform data are made available for the 17 stations operating during the period 1 August 2014 -28 February 2015. Metadata for the same stations have been checked and corrected for the period January 2014 – December 2015.*

Of the seven stations within the Vatnajökull ice cap, five (*hus*, *ksk*, *dkj*, *bjk* and *kis*) were installed under the FP7 FUTUREVOLC project as well as two stations (*iey* and *tho*) outside the ice cap. The construction of two of the stations within the ice cap (*dkj* and *bjk*) consisted of specially designed vaults within the glacier ice itself to enable year-round continuous operation. During the first few weeks these two glacier stations were operated with temporary sensors and over the first year, they also experienced significant outages due to initial operational difficulties and sensor instability. Three of the stations (*grf*, *kal*, *vsh*) have short period (Lennartz 5s) sensors and two (*kre*, *skr*) have the same kind of short period sensors for part of the period and broadband for the remainder of the period. The remaining twelve stations (*bjk*, *djk*, *dyn*, *fag*, *hus*, *iey*, *jok*, *ksk*, *tho*, *urh*, *von*, *vot*) have broader band sensors (10s, 30s, and 60s), mostly Guralp 3T (2), 3ESPC (3), 6TD (5), and 40T (1), and Nanometrics Trillium Compact (2) for whole period, or some part of it.

Overall, because most of the stations are located either in the Icelandic highlands or within the ice cap, their operation can be problematic due to prevailing harsh conditions a large part of the year. Intense icing and snow accumulation can interfere with data transmission and together with darkness during several months in mid-winter – because of the northerly latitude – these conditions can prohibit power generation, necessary to maintain uninterrupted operation and data transmission from the instruments. The harsh environment also makes station maintenance difficult. As a result, long or short interruptions frequently occur in the transmission of data to the center. Present software and procedures at the data center do not fully manage backfilling the data streams, resulting in frequent data gaps in the archived waveform data.

IMO's seismic waveform data archive from the SIL/VI network stores all waveforms since the beginning of the network in 1991 in an in-house binary format called *bc* (auth. E. Kjartansson). Over the last nearly two decades, most stations in the network have contained digitizers manufactured by Güralp systems (https://www.guralp.com/).

Most of the raw data streams, therefore, arrive at the data center in binary Güralp Compressed Format (*GCF*), and are subsequently converted to the in-house binary format before processing. Since 2013, waveforms from many stations are also stored in the original *GCF* data format. Furthermore, since 2013 a small but growing number of stations contain digitizers transmitting data in the present standard seismic format, *mSEED* (Standard for the Exchange of Earthquake Data format) maintained by FDSN (the International Federation of Digital Seismograph Networks). These data streams are also converted to *bc* format for processing and archiving, but the original *mSEED* files are also stored separately. The *bc*-format archive is the most complete but contains a significant amount of short data gaps. The *mSEED* archive also contains some data gaps, while the *GCF* archive is the least affected by gaps.

All the different archives were used to build an as complete as possible standard *mSEED SDS archive.* See *SeisComP* Data Structure:

https://www.seiscomp3.org/doc/applications/slarchive/SDS.html

The archive has minimum amounts of data gaps for all 17 stations during the period 1 August 2014 to 28 February 2015. The existing original *mSEED* files transmitted from the stations (*hus* and *ksk*) were used, and because the *GCF* archive was less affected by data gaps than the *bc* archive, *mSEED* files for the other stations were created from the *GCF* files. If *GCF* files were missing, then the *bc*-format files were used to create *mSEED* files. The program *gcf2msd_v17* provided by Güralp was used to convert data from *GCF* format to *mSEED* format, while an in-house program *bc2mseed.py* (auth. T. Sonnemann) was used to convert *bc*-format data to *mSEED* format. The program *qmerge:*

https://git.passcal.nmt.edu/passoft/passoft_c_programs/tree/875e0e7ed9cdb507b8237a06a385e1ea7f8810bd, provided by PASSCAL (https://www.passcal.nmt.edu/) was then used to merge the *mSEED* files into one-day-long files. *qmerge* (with option -v) was also used to check and, where necessary, enable fixing the integrity of the *mSEED* files.

State of health information from the status stream in the *GCF* files, so called *00.txt* files https://www.guralp.com/documents/html/MAN-D24-0004/s7.html, were collected and placed in a directory structure named: SOH.L. The *bc2mseed.py* program also outputs information from the *bc*-header on clock status received from the GPS of the digitizer and they are collected into a separate BCH.L directory structure.

Finally, the program *obspy-scan*

https://docs.obspy.org/tutorial/code_snippets/visualize_data_availability_of_local_waveform_archive.html, was used to visualize the data availability. The display for the vertical channels (Z) of all stations is shown in Figure 3. The filenames, according to the *mSEED* standard, contain the network name (VI), the station name, as well as the appropriate convention for 100 Hz sample rate (H), high gain (H), and sensor component (Z, N or E), the year, and the day-of-year (DOY), most of which is shown on the left side of the figure. On the right side of the figure the % completeness of the waveform data during the period 1 August 2014 to 28 February 2015 is shown. Of the 17 stations, 7 have over 90% data availability and 4 have less than 70% data availability. Some of the stations with the least data availability were installed in a hurry in late August and September 2014, at the beginning of the Bárðarbunga eruption crisis so the temporary quality of the installations may be affecting the data yield.

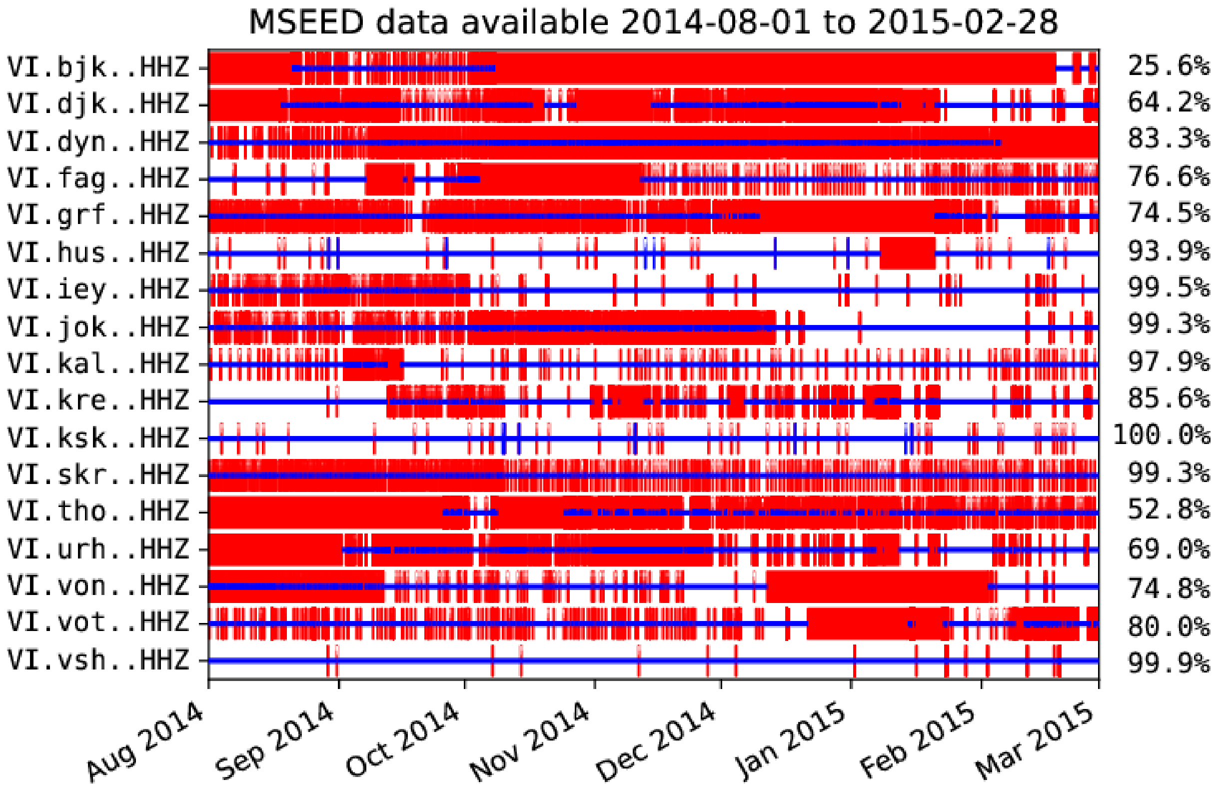

Figure 3. *Data availability for the seismic stations around Vatnajökull ice cap during 1 August 2014 to 28 February 2015 (blue lines). Availability for vertical channels are shown. Data gaps (red vertical lines) are frequent for the highland stations, mainly due to weather conditions and maintenance difficulties. A few data overlaps (blue vertical lines) occur in the raw mSEED files from stations ksk and hus. The percentage of data availability for each station is shown on the right (0.1 % corresponds to around 5.1 hours). The stations in the ice (bjk, djk) were operated with temporary sensors for the first 1-2 months and after that experienced significant outages due to initial operational difficulties and sensor instability.*

Metadata: Station metadata were checked and, if necessary, corrected for the 17 SIL/VI network stations in the Vatnajökull – Bárðarbunga area (Figure 2) during the period 1 January 2014 – 31 December 2015. The stations checked were: bjk, djk, dyn, fag, grf, hus, iey, jok, kal, kre, ksk, skr, tho, urh, von, vot, vsh. The parameters checked and corrected were station start time, latitude, longitude, and elevation. Also checked/corrected were sensor and digitizer types and available serial numbers, and the period of each instrument at the site. Parameters of the instrument response files, poles, zeros and sensitivity for the sensors and gains for the digitizers were also reviewed. The metadata information was available in system files of the SIL/VI network (station locations, response files of instruments) and in the headers of the *bc* waveform files (sensor and digitizer types). These files were reviewed and, where necessary, the information was corrected, but serial numbers of instruments, particularly digitizers, were not always available. Furthermore, the coefficients corresponding to the digital down-sampling of the data to the final 100 Hz sampling rate are not reviewed, since IMO has not kept records of the corresponding digitizer settings through time. The default settings are therefore used in the metadata files.

In the review of station locations, some discrepancies/errors were observed in the station elevations, especially at stations in mountainous areas. The differences were mostly due to differences in the reference elevation, being either the geoid (sea level) or the ellipsoid (as determined by GNSS); in the mountains of the Icelandic highlands the difference between the two can be up to 60 – 70 m. The seismic stations in the SIL/VI network have in general not been consistently referenced to the geoid. At 13 of the stations made available, the elevation was within 15 m from that referenced to the geoid and was not changed at this time. At the remaining 4 stations (*dyn*, *hus*, *ksk*, *urh*), the deviation/error was 50 – 200 m. Their elevations were therefore corrected and referenced to the geoid. Correction for all SIL/VI stations to the geoid level will be done in one step at a later time.

During the period provided, both sensors and digitizers were changed at many of the stations, mostly due to instrument failure. When such changes occur a new data stream is defined in the metadata file, recording the time of change and the new type of instrument, its serial number and corresponding response. Failure to keep track of these changes, or the exact time they occur is the most frequent error in the SIL/VI metadata, particularly for the digitizers.

For some of the stations the metadata information during the period had already been entered into the *smp* database of Gempa: https://smp.gempa.de/.

With IMO's station database still under construction and presently incapable of exporting the seismic station metadata into a standard station metadata format, the collection of reviewed and corrected metadata was entered into the *smp* database and from there exported to *SeisComp XML* format.

The *mSEED* seismic waveform data in the *SDS* standard file structure for the 17 stations provided during the Bárðarbunga volcano unrest, were written to a thumbdrive and have been sent to the Orfeus data center (https://www.orfeus-eu.org/), where *FAIR* open access to the waveforms will be serviced. The review of the metadata is being finalized and the final *SeisComp XML* file will be e-mailed to Orfeus.

Data from the Fagradalsfjall eruption 2021

An eruption began on 19 March 2021 in Geldingadalir at Mt. Fagradalsfjall at the Reykjanes Peninsula oblique rift in Iceland, terminating about 800 year long period of no eruptions in this oblique rift. High rates of deformation and seismicity occurred from 24 February to mid-March in relation to gradual emplacement of about 9 km long magma-filled dyke and triggered strike-slip earthquakes up to Mw5.64, as tectonic stress accumulated over decades or centuries prior to the eruption was released. Seismicity and ground deformation observations show that this period of tectonic stress release ended with a decline in deformation and seismicity over several days preceding the eruption onset.

A unique data set was prepared to be networked in relation to precursors to the eruption. The data is analyzed and reported in a manuscript entitled "Deformation and seismicity decline preceding a rift zone eruption at Fagradalsfjall, Iceland" (Sigmundsson et al., in review). All data is available in repository: https://osf.io/n73cm/?view_only=97c944a29fe1471b8f663eec3d78fe54

This includes data for 25 GNSS stations on Reykjanes Peninsula in RINEX format. The stations are: ASFT, ARSE, ELDC, FAFC, FEFC, FEFJ, GRIC, HAFC, HELF, HERV, HVAS, KLVC, KRIV, LISK, MOHA, NAMC, ODDF, SELA, SENG, SKSH, SVAR, THOB, UNDH, VOGA, VOGC

The repository also includes series of Sentinel-1 interferograms over the period 23 February to 21 March 2021. The interferograms cover the Fagradalsfjall region of the Reykjanes Peninsula in Iceland, and span the period of a dyke intrusion, which began propagating on 24 February 2021 and ended at the start of an effusive fissure eruption on 19 March 2021 (Sigmundsson et al., in review).

Wrapped interferograms, Unwrapped interferograms and Coherence files are provided. The Wrapped and Unwrapped interferogram directories include interferograms covering the initial dyke intrusion and start of the eruption at Fagradalsfjall in 2021.

IMO is also making the InSAR data and metadata are accessible on IMO's ftp site at:
http://brunnur.vedur.is/gps/insar/2021_fagradalsfjall_ifg/.

The data, which represent 10 interferograms are provided in *GeoTIFF* format, and include three files for each image containing respectively the unwrapped and wrapped interferogram, plus coherence file. Metadata for each *tif* file are provided as *xml* files. Both data and metadata are provided in the EPOS compliant standard, but a service to manage and maintain access to the data has yet to be built.

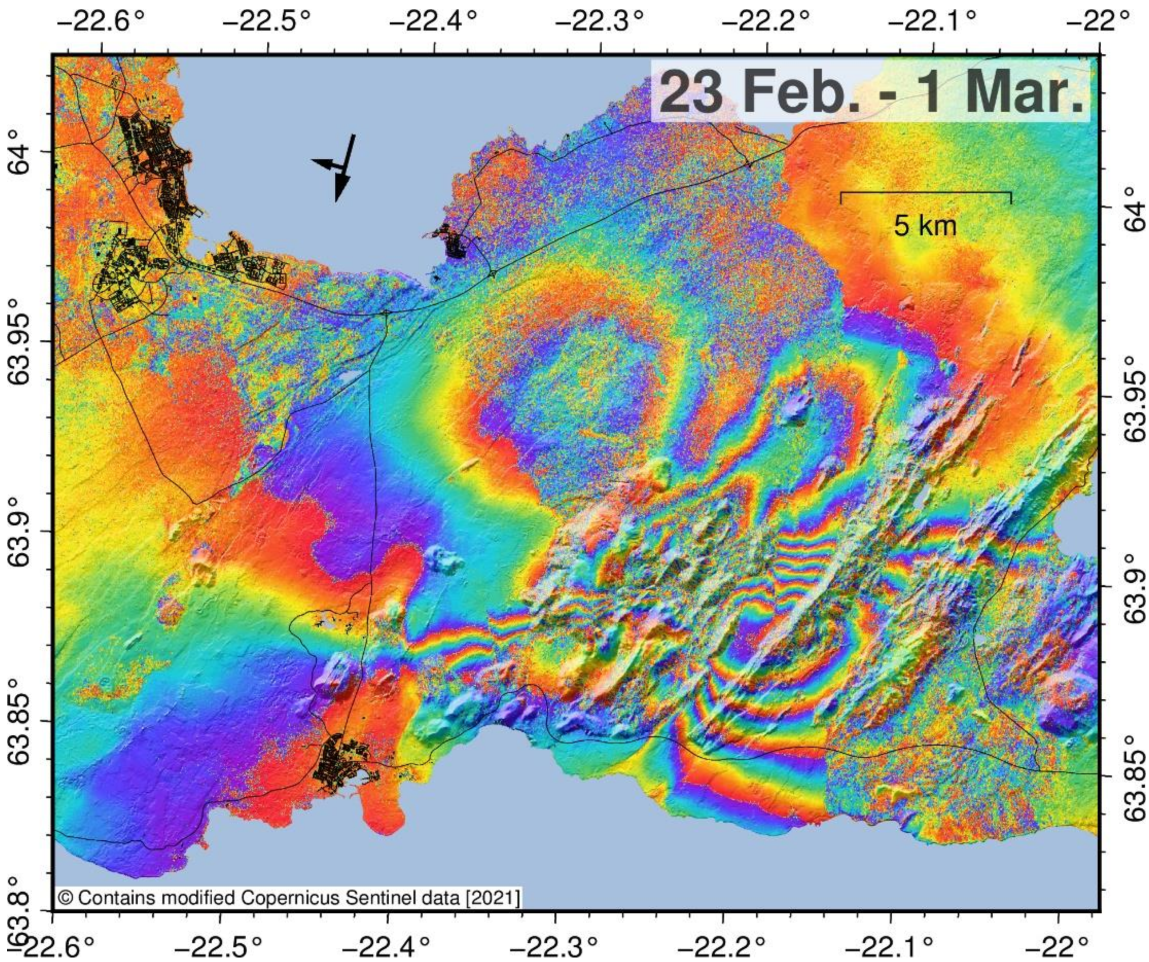

***Figure 4**. Wrapped Sentinel-1 interferogram from track 155, covering Reykjanes Peninsula, Iceland spanning the period 23 February to 1 March 2021. The interferogram displays deformation in the satellite's line-of-sight (here displayed as phase change) related to a Mw5.64 earthquake that occurred on the 24 February 2021, and the initial phase of the dyke intrusion that preceded the Fagradalsfjall 2021 eruption.*

Eruptions of Mt. Etna, Italy

For the Etna eruption of 2008-2009 (start 13 May 2008 - end 6 July 2009), part of the data is available in INGV data repositories. To evidence potential precursors of the 2008-2009 eruption, as well as possible signals following its end, the available data covers a longer than the eruption itself i.e. from to January 2007 to December 2009. An effort is necessary to export the data repository and create a public database that can be used to access the data for all.

The aim is to make available a multidisciplinary dataset, which contains data of magma composition, gas composition and flux from the plume and soil, water temperature in drainage gallery, seismic velocimeters, tiltmeters, optical earth observations, remote sensing, periodic GNSS ground deformation.

The data have been archived in a database, named TSD System, which works at Osservatorio Etneo in Catania, exclusively for the management of INGV activities. All the necessary information were provided to the IT staff of Work Package 20 in EUROVOLC (WP20 Virtual Access to EPOS VO-TCS), in order to create the necessary tools to make the current dataset discoverable within Eurovolc Gateway Portal and compliant with EPOS standards, through the Volcano Observation - Thematic Core Service (VO-TCS).

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