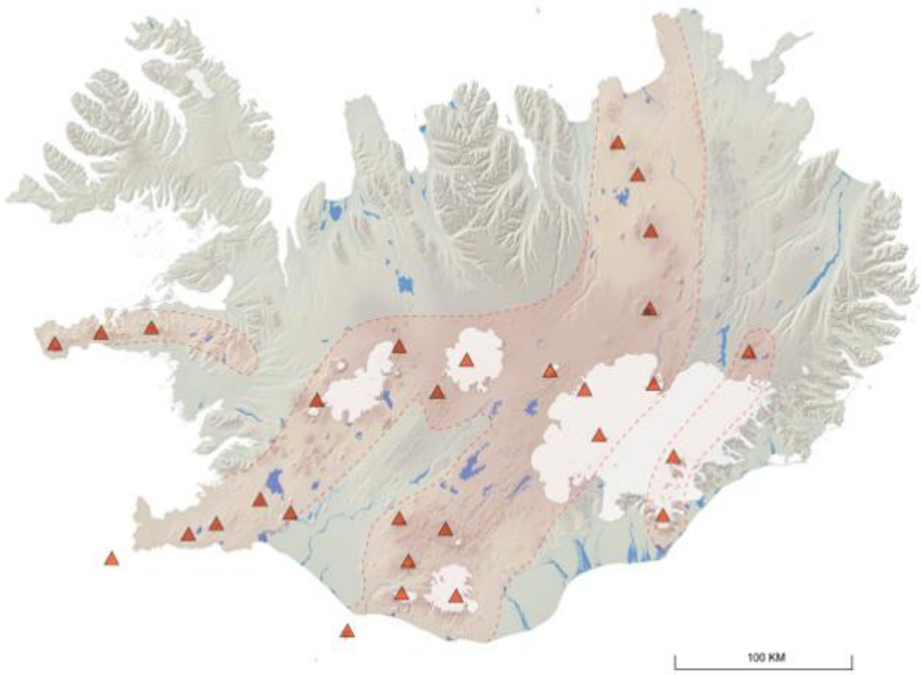
FUTUREVOLC

FUTUREVOLC FINAL REPORT

4.1 Final publishable summary report



Iceland's most active volcanoes marked with a triangle. Map from IMO

Why FUTUREVOLC

On the 15th of April 2010 Europe was thrown into social and economic chaos as its air space was shut down due to volcanic ash in the air, with the closure lasting for several days. Many European businesses and citizens were deeply unhappy, but the cautious approach taken towards the hazard posed by the Eyjafjallajökull eruption demanded no less of a response. Decades of prior work had led scientists and engineers to a certain level of understanding of volcanic ash dispersal and its effects on aircraft engines, but in the white heat of an eruption there was very significant uncertainty about how, in practice, to respond. Since the turn of the century the term 'Earth System Science' had been used to highlight the interconnectivity between the various sub-disciplines in the study of processes involving the solid earth, the oceans and the atmosphere. The eruption in 2010 demonstrated just how important this interconnectivity is in today's technology-dependent society. A process of magma formation and movement that originated deep in the Earth's crust in a small region on an island in the northern mid-Atlantic lead to the onset of a moderate-sized volcanic eruption. This eruption was nevertheless capable of causing massive disruption right across Europe. The disruption was amplified by the need for a response that minimised the risk – that is, closing most of the air space based on computer models of estimated future ash dispersal. In turn the need for a cautious response was driven by gaps in our understanding of how to integrate the solid earth and atmospheric components on the 'Earth System', in an evolving real time situation.

Serious as these economic losses of the 2010 eruption are, the impact of much larger events, similar to the Laki eruption in 1783-4 that lasted for eight months, could be much more severe. The eruption resulted in 15% of the population of Iceland perishing in a famine. A persistent sulphuric haze affected the whole northern hemisphere, resulting in crop failures and causing famine and increased mortality rates in Europe and America with tens of thousands of deaths attributed to the eruption outside Iceland. Eruptions of comparable magnitude to Laki 1783-84 occur in Iceland once every 200-500 years.

FUTUREVOLC grew from a need for a more holistic approach to volcanic hazard estimation and eruption response following the lessons from Eyjafjallajökull eruption in 2010 and other eruptions.

Overview and Objectives

The FUTUREVOLC project was funded by the FP7 Environment Programme of the European Commission and aimed at addressing the topic "Long-term monitoring experiment in geologically active regions of Europe prone to natural hazards: the Supersite concept". The project started 1 October 2012 and had a duration of 3.5 years, with 26 partners from countries representing academic, civil protection and industry groups. The supersite concept implies integration of space and ground based observations for improved monitoring and evaluation of volcanic hazards, and an open data policy. The project was led by University of Iceland together with the Icelandic Meteorological Office.

The main objectives of FUTUREVOLC were to:

i) Establish an innovative volcano monitoring system and strategy by integrating transdisciplinary knowledge and subject areas, and developing new methods for near real-time integration of multi-parametric data, thus building the bridge to achieving best practice in future volcano monitoring, early warnings, data sharing and eruption response at a European level, in the context of the volcanic risk management cycle.

ii) Develop new methods for near real-time integration of multi-parametric datasets and the development of innovative instrumentation for monitoring magma movements and volcano behaviour before, during and after volcanic crises.

iii) Apply a seamless transdisciplinary approach to further scientific understanding of physical processes ranging from deep magma transport, through eruption dynamics to plume dispersion and deposition of eruptive products.

iv) Improve delivery, quality and timeliness of transdisciplinary information from monitoring scientists to civil protection and governing authorities, locally and internationally, based on the fact that volcanic eruptions can generate cross-border hazards.

To reach these objectives the project combined broad European expertise in seismology, volcano deformation, volcanic gas emissions and geochemistry, infrasound, eruption monitoring, physical volcanology, satellite studies of plumes, meteorology, ash dispersal forecasting, and civil protection. The aim for this European consortium was to lead the way for multi-national, multi-stakeholder volcanological collaboration, mitigating the effects of major eruptions at a European level that pose cross-border hazards.

During the project the largest effusive lava eruption in Iceland since 1783 occurred in the Holuhraun area within the Bárðarbunga volcanic system from 31 August 2014 – 27 February 2015. It was preceded by major unrest, including seismic activity and ground deformation related to lateral injection of magma into the crust in a rifting event. A slow subsidence of the Bárðarbunga caldera occurred throughout the eruption, resulting in a caldera collapse of about 2 cubic kilometres. These events have influenced the project, and provided opportunities to test equipment and methods for analysis, derive new scientific understanding and improve communication systems.

Fissure eruption within the Bárðarbunga volcanic system (2014-2015). Photo Þórdís Högnadóttir.

Data Policy

At the onset of the project all FUTUREVOLC partners agreed that successful integration of space-based and *in situ* data was a timely and important step towards their common goal of improving geohazard monitoring and research. FUTUREVOLC needed to allow access to large and diverse data volumes, hitherto unprecedented at volcano observatories or at World Organization of Volcano Observatories (WOVO) (http://www.wovo.org/). Under coordination of the Committee on Earth Observation Satellites (CEOS), nearly all satellite data providers have already established procedures and means for electronic data provision, some of which are included in the FUTUREVOLC e-infrastructure. Under the coordination of the European Plate Observatory System (EPOS) and the U.S. institutions (U.S. Geological Survey and UNAVCO/Earthscope), the data providers of the FUTUREVOLC partnership adopted the concept of a volcanic data supersite, providing real-time data viewers as well as sophisticated data and tool sharing mechanisms. Users gain access to the supersite data sharing facilities through a one-time registration (similar to GEBCO, the General Bathymetric chart of the Oceans). Data was to be stored at the supersite with the sole purpose of sharing it among registered users. Under special circumstances, private data storage space was to be available to users, but a reasonable publication date was to be provided for the data. Necessary measures were taken to ensure safety of all data at the site, and the reliability of the site's services, and to protect it from abuse. Collaboration with the consortium is not mandatory, but recommended for scientists outside of the FUTUREVOLC consortium.

FUTUREVOLC followed the GEO (Group on Earth Observations) recommendations on architecture and data management thereby following the vision set forth by GEOSS (the Global Earth Observation System of Systems). The aim of the FUTUREVOLC project was to develop and implement a data access policy based on the GEO 2012-2015 work plan agreed during the GEO-VIII plenary meeting in Istanbul 2011. The European Plate Boundary Observatory (EPOS), which also served as the co-lead of the GEO Supersites (http://supersites.earthobservations.org), gave advice and guided the implementation of data sharing. CEOS was to provide the space-based data, and FUTUREVOLC would provide the in situ data.

The objectives of the FUTUREVOLC data policy were to (http://futurevolc.hi.is/data-policy):

- To converge and harmonize observation methods and tools, to promote the use of standards and references, inter-calibration and data assimilation.
- To enhance interoperability between participating organizations, including production of technical specifications for collecting, processing, storing, and disseminating shared data, metadata and data products.
- To facilitate data management, information management, and common services, to promote the data sharing principles of the GEO Plenary, recognizing relevant international organizations, national policies and legislation.

Project structure

The FUTUREVOLC project consisted of ten work packages (WP) in total:

WP1: Project management and coordination

WP2: Database development and programming

WP3: Communications and supporting risk management

WP4: Evaluation of known eruption source parameters

WP5: Long term magma tracking

WP6: Imminent eruptive activity, eruption onset and early warning

WP7: Determination and evolution of eruption source parameters

WP8: Distribution and description of eruptive products

WP9: Demonstration of FUTUREVOLC

WP10: Dissemination, outreach and exploitation of results

The management of the whole project was provided through WP1, which oversaw all aspects, received feedback from all project components and facilitated appropriate progress of individual components and effective interaction between all work packages.

Five work packages (WPs 2, 3, 4, 9 and 10) interacted strongly with all other packages:

- WP2 was central to the project, dealing with database development. In order to facilitate near-real time response and joint interpretation, data sharing was essential and needed from all WPs. A strong interaction was required between all of them.

- WP3 had an important role of providing communication and support for risk management across Europe. It ensured that all WPs combined to give effective warnings, and facilitated preparedness and response. It therefore tied in with and influenced what was done in all subsequent WPs, drawing on the resources of WP2.

- WP4 summarized and improved the known eruptive behavior of Icelandic volcanic systems and thus provides the vital background data for WP5 and subsequent WPs.

- WP9 required input from all WPs to enable demonstration of results and the systems developed. It formed the basis for dissemination.

- WP10 coordinated dissemination and communication activities ensuring greater impact of the project results to all stakeholders.

The bulk of the earth and atmospheric science work occurred in WP5-WP8. Information from WP4 influenced how volcanoes were monitored and the search for evidence for long-term magma movements, leading to WP5. The output of long-term research and monitoring provided in WP5 influenced the monitoring of immediate pre-eruptive activity addressed in WP6. The output from WP6, on imminent eruptions provided the vital data that alerts and activates the multiple sensors applied in WP7 to evaluate the mass eruption rate in volcanic eruptions. For explosive eruptions, WP7 also provided as fast as possible further data of major importance for WP8, including magma composition and grain sizes, where it is used to assess the distribution of eruptive products.

The study area of the project covered all the volcanic zones of Iceland, with special focus on the most active volcanic systems in the Eastern Volcanic Zone of Iceland, including those of Katla, Grímsvötn, Hekla and Bárðarbunga, that are responsible for 80% of all eruptions in Iceland. The great variety of styles of volcanic activity demonstrated in Iceland through historic time is unique in Europe and provided the project with a natural laboratory setting and a potential to advance understanding and modelling of a variety of magmatic and volcanic processes. The project plan was to develop new and much-needed in-situ sensors, and early warning instrumentation. Sensors proven useful during research trials were to be integrated into existing operational monitoring networks in Iceland and procedures to be developed to ensure that the great depth of knowledge and experience within the consortium could be tapped in real-time during unrest or eruption. FUTUREVOLC explicitly encouraged interaction and knowledge exchange between different scientific disciplines, in particular between solid earth and atmospheric science, and between social and physical sciences.

S&T results / foregrounds

The main results, information and knowledge generated within FUTUREVOLC (the project foreground) were reported in a series of publications in international scientific journals, extensive open access deliverable reports on various topics and numerous presentations at international conferences and meetings. Algorithms and approaches to analyze data are also reported. The following overview of the results generated is reported relative to each work package. The specific objectives of each WP are initially detailed, followed by overall description of the work and the main results and products generated.

WP1: Project management and coordination

The objectives of WP1 were to:

- Provide efficient and effective management of the project to ensure all milestones and deliverables were met within the proposed timescale
- Ensure that the necessary resources were made available to carry out the aims and objectives of the project
- To coordinate communications internally within the consortium, between the consortium and European Commission and externally to stakeholders

The management of the project was carried out by a team from University of Iceland (UI), Icelandic Meteorological Office (IMO) and University College Dublin. The coordinator was at UI, and the lead project manager was based at IMO resulting in a successful close collaboration between the two institutes. The project was governed by a Steering Group, and a committee of Work Package leaders. Several IT resources have been utilized for the project management, most importantly the Basecamp project management software.

Results/Products:

The FUTUREVOLCc consortium. Photo Þórdís Högnadóttir

The management team organized meetings, kept the FUTUREVOLC community updated, followed and recorded the project progress and ensured the delivery of the milestone and deliverable reports. FUTUREVOLC partners have used the FUTUREVOLC website, and also social media, to communicate their main actions and results, in particular during the Bárðarbunga unrest and Holuhraun eruption which lasted over 6 months.

WP2: Database development and programming

The main objective of WP2 was to create a database system that fulfilled the FUTUREVOLC data policy, where users and stakeholders could have access to and are able to download: historical data, near real time data, and processed data related to Icelandic volcanoes in a standardised formats. Designated users would be able to share their data and scientific studies through the database system.

The database system followed the recommendations of the International Volcanic Ash Task Force (IVATF), which was established by the ICAO (International Civil Aviation Organisation) in close coordination with the WMO (World Meteorological Organisation). The IVATF had encouraged organisations to improve the availability of, and access to, airborne volcanic ash detection data. This included historical eruption data from Icelandic volcanoes, data from operational institutes, scientific institutes and universities. WP2 addressed this request by establishing a bespoke web-portal for Icelandic volcanoes, which includes catalogue information and a data hub. Disseminating observation data, processed data and analyses made by experts related to Icelandic volcanoes to operational centres, research institutes, universities, civil protections etc. in an understandable form was a challenging task, both during periods of volcanic unrest as periods of quiescence. In response to this challenge partners involved in WP2 developed the Icelandic Volcanoes data-hub and catalogue web-portal which is now open.

The work in WP2 was carried out in three main tasks. It started with a requirement analysis where FUTUREVOLC partners were requested to define their data and comment on defined “use case” scenarios. Based on this, the FUTUREVOLC data sharing system was designed and developed in parallel to enable more interaction with users and obtain their input in the process. This made it easier for users to understand the expected output, and to comment and advise on the development of the FUTUREVOLC system during its initial stages.

Results/Products:

The FUTUREVOLC system comprises four main components:

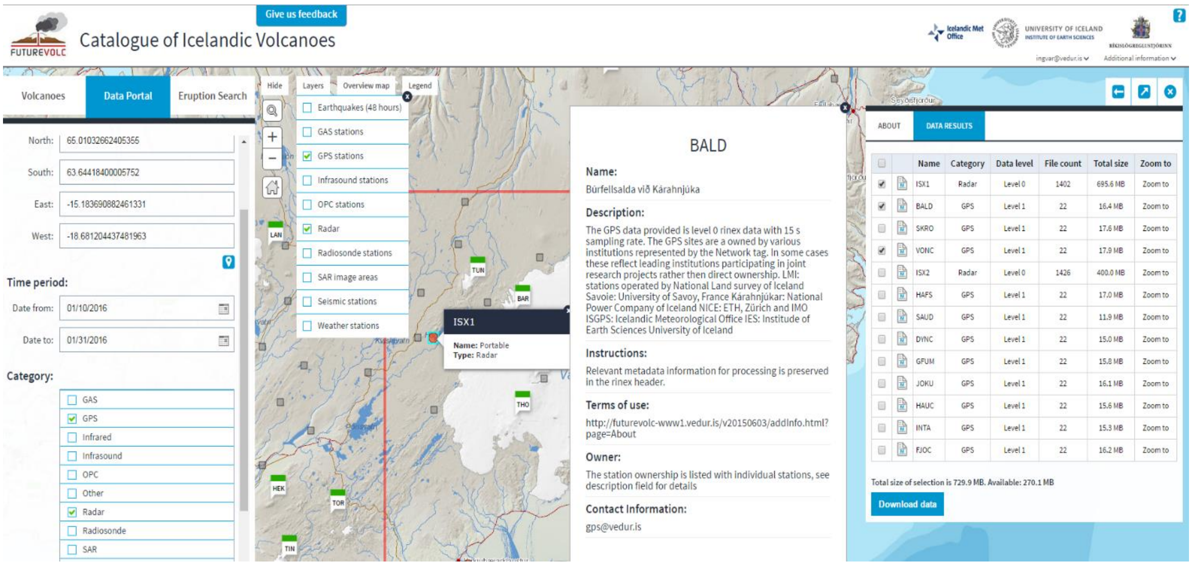
(i) user interface (website GIS based),

(ii) databases storing mostly metadata and system configurations,

(iii) shared domain data mostly stored within IMO file systems or databases,

(iv) a service layer integrating the other components.

The final deliverable and main output of WP2 was a web-portal for Icelandic Volcanoes. Scientific users can download data and approved users can upload their data, information regarding studies and analyses. Operational users, such as airlines and civil protection, can find information about the Icelandic Volcanoes (WP4) and download data and reports they require for their decision-making processes. At Icelandic Volcanoes the users have single point access for near real-time data, processed data and historical data related to Icelandic Volcanoes. The data are easy to find and registered users can download the data and use them according to the terms free of charge. The current address for the web-portal is: **futurevolc.vedur.is**



The search interface from data portal of the FUTUREVOLC system. futurevolc.vedur.is

WP3: Communications and supporting risk management

This work package focused on optimising the interaction and transfer of information between responding scientists, Civil Protection, government departments, regulators, met services, private sector and other stakeholders, with the aim of establishing best practice at a national and international level.

The main objectives of WP3 were to:

- Establish a framework for effective coordination and communication across Europe before, during and after volcanic unrest/eruption,
- Develop state-of-the-art protocol in crisis communication between scientists and civil protection agencies during volcanic crises including cross-border affected countries,
- Establish lessons learned from past eruptions and analyse the risk management process on an on-going basis.

The eruptions of Eyjafjallajökull in 2010 and Grímsvötn in 2011 and their widespread impacts demonstrated the urgent need for awareness raising and good communication networks across Europe. In 2010, the reporting from Iceland was already excellent and enabled the rapid though *adhoc* response that followed across Europe. This work package was aimed at enhancing communications further so that the needs of a variety of different stakeholders in Iceland and across Europe were met.

The main research approach was to use questionnaires and interviews to assess lessons learned from the eruptions in 2010 and 2011, establish the needs of stakeholders, and then to apply new methods/techniques of communication. Subsequently further questionnaires investigated the value and efficacy of particular approaches and identified what communication methods are most valuable to stakeholders. The final stage is to consult end-users as to the impact of FUTUREVOLC and any outstanding requirements.

Icelandic Coastguard helicopter and staff with scientists and technicians on November 11th, 2014 (photo Magnús Tumi Guðmundsson)

The research was divided into a series of four tasks:

i) Forensic analysis of the lessons learned in the collection, collation, analysis and transfer of data, and national and international communication from recent Icelandic eruptions. This demonstrated some surprising results such as the lack of awareness about the value of monitoring and early warning for volcanic eruptions. The results enabled a targeted approach in subsequent tasks.

ii) Identification of appropriate response indicators of Icelandic volcanoes, with the aim to improve early warning systems and preparedness. This included establishing a new alert level system for aviation and the development of indicators to help ensure consistent scientific decision-making despite uncertainties.

iii) Improve communication of volcanic risk, which for operational partners has included enhanced reporting, visualisation and communication methodologies. For example, following the Holuhraun eruption, a questionnaire was distributed to the recipients of the Scientific Advisory Board Factsheet. The Factsheet was sent to 774 email addresses (397 in Icelandic and 377 in English). The survey reveals that the total circulation of the Factsheet was about 8000 recipients. Over 90% of responders believe communication and flow of information was either better or much improved during Bárðarbunga in 2015 than in Eyjafjallajökull in 2010 and Grímsvötn in 2011.

iv) Consult end-users as to the impact of FUTUREVOLC and any outstanding requirements. This will ensure that any outstanding matters can be taken forward beyond the project.

Results/Products:

A series of reports was produced containing 1) an analysis of lessons learned from the Eyjafjallajökull and Grimsvötn eruptions, 2) development of early warning systems, standards of information for EU and scenarios for major events, 3) a best practice report on communication and 4) a report on the impact of FUTUREVOLC and the feedback of stakeholders. Questionnaire results showed that communications from Icelandic agencies about the status of Icelandic volcanoes were enhanced over the course of the project, as have communications within and between stakeholders across Europe.

It was originally anticipated that exercises might be needed to test new methods but in fact a series of episodes of unrest and the Holuhraun eruption in 2014-2015 enabled new methods to be applied and tested in real-time, with real data and with existing communication systems.

Specific communication tools produced in Iceland and supported by FUTUREVOLC now include:

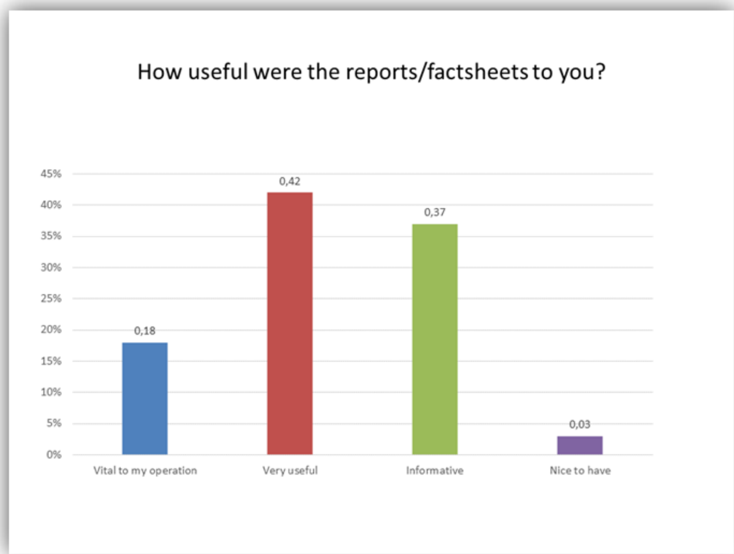
- - An aviation color code system and map supported by rigorous scientific decision-making (Icelandic Meteorological Office)

The aviation colour code scheme available on the website of the Icelandic Met Office (http://en.vedur.is/weather/aviation/volcanic-hazards/) and on the FUTUREVOLC 'Catalogue of Icelandic Volcanoes' page (http://futurevolc.vedur.is/).

- http://en.vedur.is/earthquakes-and-volcanism/volcanic-eruptions/

- The postlist receiving immediate communication regarding any aviation color code has been extended to additional contacts. More countries, institutions and sectors are now included.

- A daily Factsheet during eruptions compiled by a Scientific Advisory Board containing a range of information on status, monitoring, forecasts, recommendations, future scenarios and advice to the public, e.g. (see WP9)

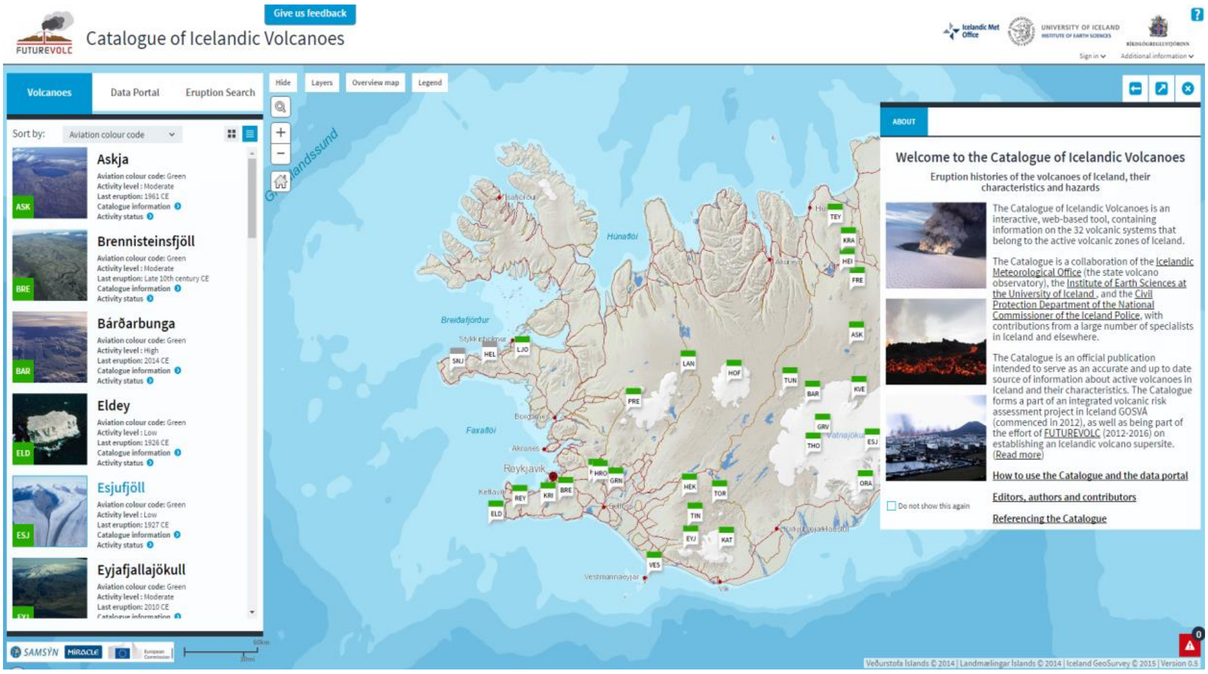


- Weekly status reports to key stakeholders (including ERCC) (Icelandic Meteorological Office)
- Regular, complementary and consistent communications from three Icelandic institutions through a variety of media (e.g. web sites, social media, press)

WP4: Evaluation of known eruption source parameters (Catalogue of Icelandic volcanoes)

The main objective of WP4 was to compile a catalogue of active volcanic systems in Iceland, outlining the known history of activity, eruption frequency, magnitude and the characteristics of the volcanic products. The catalogue is an official publication (available as an open-access website) intended to serve as an accurate and up to date source of information about volcanism in Iceland.

Iceland has 32 active volcanic systems that have very varied activity in terms of eruption styles, eruptive environments, eruptive products and their distribution. Extensive research has taken place on Icelandic volcanism, and the results reported in scientific papers and other publications. Within WP4 we collated the current state of knowledge to create a comprehensive catalogue readily available to decision makers, stakeholders and the general public. Work on the Catalogue of Icelandic Volcanoes was supported by the International Civil Aviation Organisation and forms a part of an integrated volcanic risk assessment project in Iceland (2012-ongoing), in addition to FUTUREVOLC.

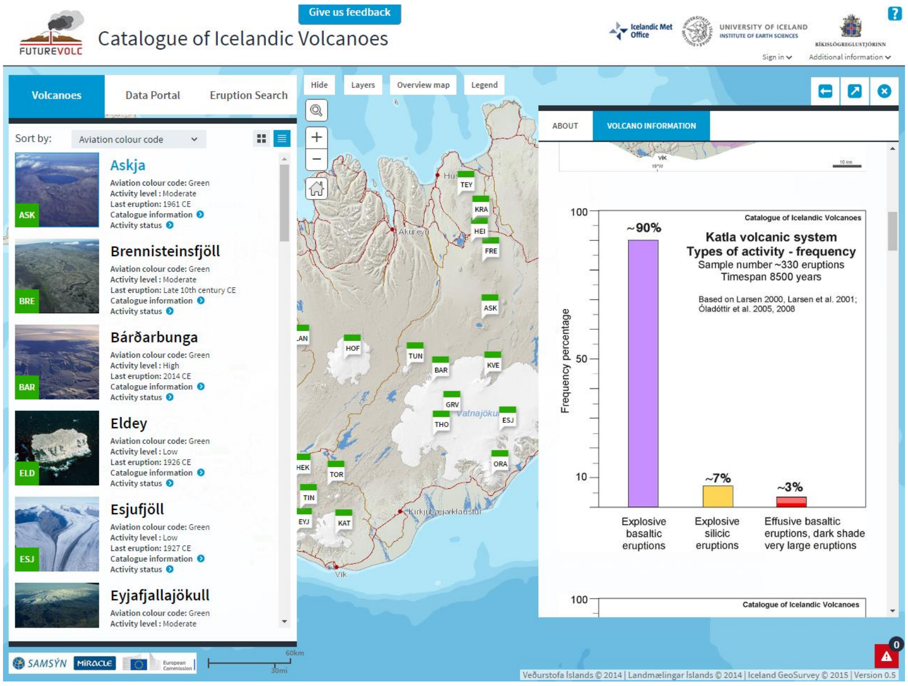


The main home page of the Catalogue of Icelandic volcanoes (http://futurevolc.vedur.is). Each of the volcanic systems is represented by an icon both on the left hand side list, and on the map view. Volcanic systems can be searched using Sort by according to various parameters, such as last eruption year and activity level

This work package was a collaborative effort between the Icelandic Meteorological Office (the national volcano observatory), the Institute of Earth Sciences at the University of Iceland, and the Icelandic Civil Protection, with contributions from a large number of specialists in Iceland and elsewhere.

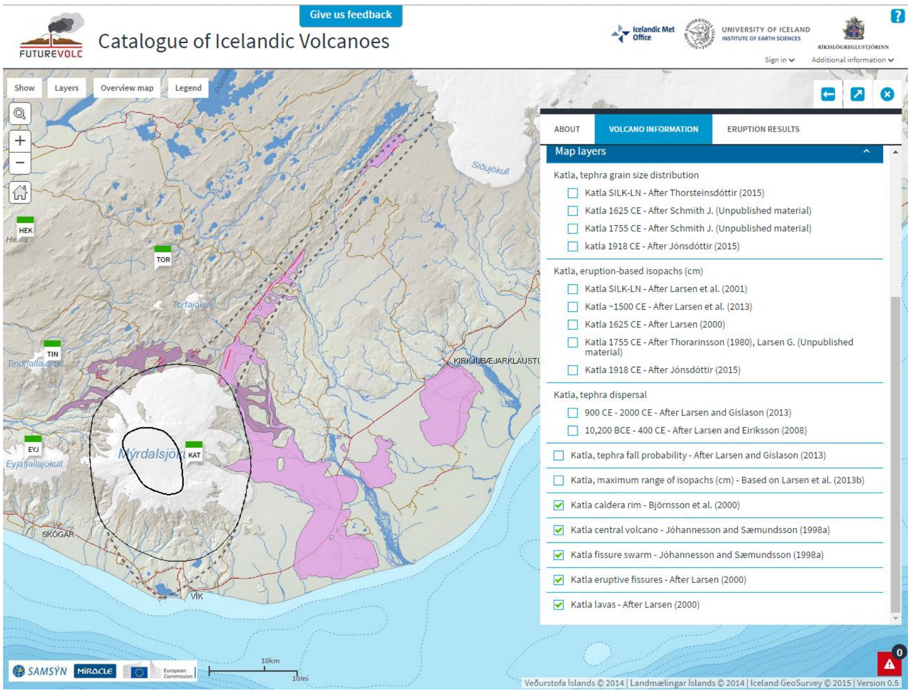
Results/Products:

- The Catalogue of Icelandic Volcanoes is accessible at futurevolc.vedur.is
- The 32 volcanic systems can be interactively searched and viewed according to their activity level, aviation colour code, most recent eruption year, or simply alphabetically. A volcanic system can be selected either from a list or by being selected from the map.
- - An overview of each volcanic system is given in a summary chapter (“Short Description”), followed by summary tables under “Central Volcano” and “Fissure Swarm”. More in depth information is available from the relevant subchapters.
- - Eruption source parameters for individual eruptions from the 4 most active volcanic systems (Bárðarbunga, Grímsvötn, Hekla and Katla which account for >80% of eruptions) can be accessed using the “Eruption Search” option. The search results are downloadable.



Statistical analysis for types of activity is shown graphically for the volcanic systems which are sufficiently well known.

- Detailed and interactive maps, including Holocene lava flows and tephra layers can be accessed under "Map layers". Information about tephra grain size for selected eruptions can also be viewed on the maps and downloaded.



Examples of maps available in CIV. Map items can be queried for metadata by clicking on them. Top image: Katla lava flows, eruptive fissures, outlines of caldera, central volcano and fissure swarm.

- A new live webtool has been developed to help assess and understand the current level of activity ("Activity status"). The recent number of seismic events ('recent' being defined as either one day, one week, one month or one year) is compared with the background value. The seismic data used by this webtool is accessed directly from the IMO database.

WP5: Long term magma tracking

The objectives of this WP were to:

- Track subsurface magma movements with high spatial and temporal resolution, with a focus on the most active volcanoes in Iceland,
- Quantify volatile emissions from volcanic systems, in order to verify models of magma source depth, migration, differentiation and interaction with hydrothermal systems,
- Develop an integrated system that could be rolled out to volcanoes worldwide, for monitoring and tracking subsurface magma movements.

To achieve the overall objective of an integrated volcanological monitoring system, the movement of magma needed to be tracked while still in the ground. Before the project began, this was achieved in Iceland primarily through networks monitoring surface deformation and seismicity. There were also hydrological monitoring systems on rivers around Mýrdalsjökull and Vatnajökull, which measure basic properties of river water, such as temperature and electrical conductivity, but there were no permanent measurements of gas emissions. Automatic processing systems were in place for most, but not all, of the data being collected.

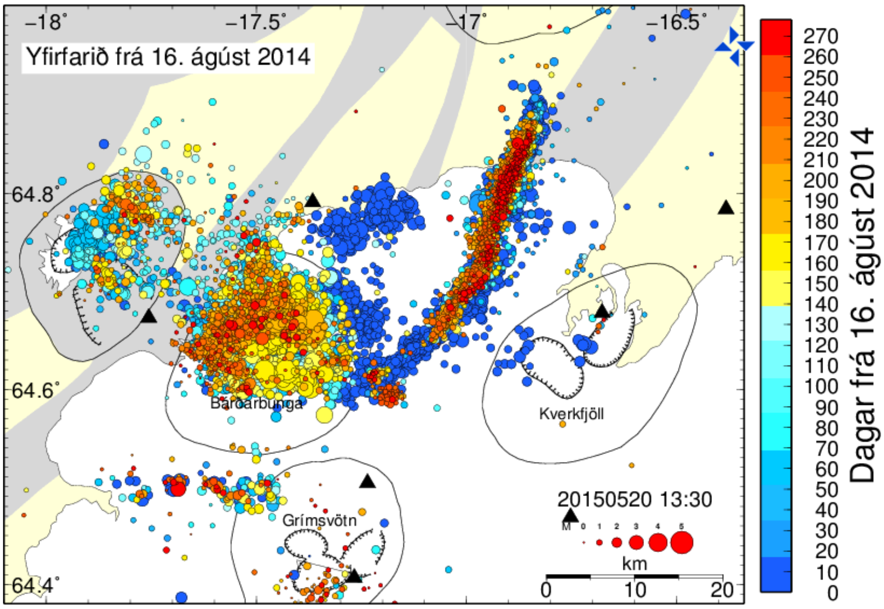
Specific aims of this WP were therefore to:

- Fill in data gaps by installing new monitoring instrumentation and systems,
- Develop near real-time processing software for data that are currently processed offline,
- Develop algorithms to automatically constrain models of magma movement using various combinations of data,
- Carry out short-term studies to better constrain the accuracy of these models.

Results/Products:

Eight new, temporary broadband seismic stations and three new, permanent GPS (Global Positioning System geodesy) stations were installed around Vatnajökull. In addition two permanent, broadband seismic stations were installed on rock outcrops inside the glacier and two sites with new glacial seismometers were developed and deployed on the Vatnajökull ice cap itself. The constraints provided by the additional data recorded by the glacier sites, as well as other rapid installations in and around the glacier during the 2014-2015 unrest and eruption in the Bárðarbunga volcanic system were crucial in the mapping of seismicity and therefore constraining the associated dyke intrusion in space and time. During and after the

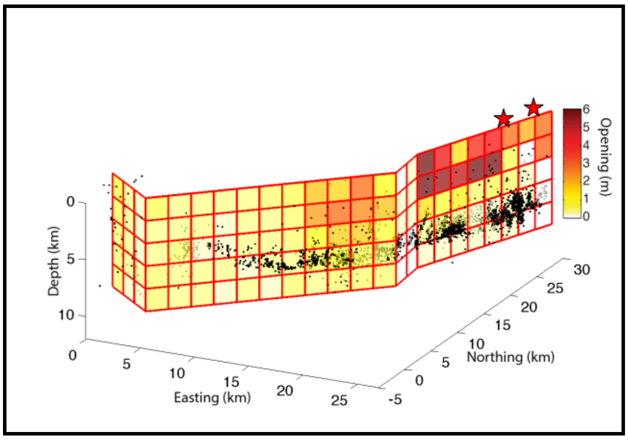
Bárðarbunga unrest, 16 new GPS sites where installed. These sites played a major role in constraining the deformation field of the dyke intrusion and the subsidence of the Bárðarbunga caldera, thus enabling the modelling of the magma migration and volume change. This monitoring continued during the post eruptive period with the main focus to monitor possible re-inflation of Bárðarbunga.



For gas monitoring, two scanning UV-instruments and one MultiGas instrument have been installed. MultiGAS measurements of the concentrations of potentially toxic gases released from the subglacial flood at Sólheimajökull outlet glacier during the first week of July 2014 were provided to the Icelandic Civil Protection, and were used to help decide how long access to the affected area close to the river should be restricted.

In terms of new software, an automatic earthquake relative relocation system has been implemented, which proved its worth in mapping progress of magma migration during the Bárðarbunga rifting event. An automatic processing algorithm for InSAR data was also developed, and for the first time it was possible to map deformation associated with a rifting event in near real time using InSAR data in addition to the GPS data. A joint inversion tool was developed to jointly invert the relocated seismicity and deformation data and used to infer the progression of the Bárðarbunga dyke in terms of position, depth distribution and volume change. Once the eruption started at Holuhraun, rapid installation of equipment to measure gas was key for monitoring the local hazard in near real-time, using newly developed software for flexible downloading and evaluation of the Differential Optical Absorption Spectrometry (DOAS) data.

Other data that were collected during the Bárðarbunga unrest include repeated elevation measurements using a combination of satellite SAR data, satellite stereo optical data and airborne radar altimetry data. These data were crucial to monitoring the remarkable slow collapse of the Bárðarbunga caldera. In addition, thermal signals observed outside the caldera provided evidence of short-lived, minor subglacial eruptions along the pathway of magma migration between Bárðarbunga and Holuhraun, where the eventual flood basalt eruption occurred in August-February.



Model of dyke opening for the Bárðarbunga rifting episode, constrained by relocated seismicity (black dots) and deformation data from InSAR and GPS. From Sigmundsson et al. Nature, 2015.

Additional tasks linked to the third objective included constraining three-dimensional (3-D) crustal velocity structure and source characterisation of earthquakes. Analysis of ambient noise revealed the 3-D velocity structure across central Iceland; low group velocities are consistently associated with the volcanic rift zones whereas the non-volcanically-active regions exhibit much faster wave speeds. A mid-crustal low-velocity zone is apparent over the whole region. More than 20 years worth of earthquakes from the SIL catalogue were relocated, revealing more clustering of seismicity in volcanic zones and producing error estimates for position that are robust. Analysis of earthquakes associated with the Bárðarbunga - Holuhraun dyke intrusion led to interpretation of failure at the dyke tip in the presence of magmatic fluids, moderated by the regional stress direction caused by plate spreading.

WP6: Imminent eruptive activity, eruption onset and early warning

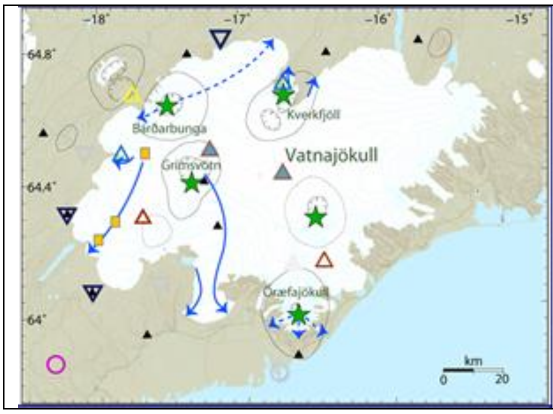
The objectives of this WP were to:

- To identify precursory geophysical and geochemical signals of an imminent eruption and characteristic signals associated with eruption onset.
- To distinguish the characteristics of the different seismic-tremor-generating processes at glacier-covered volcanoes, in order to minimize the number of false eruption alarms.
- To implement real-time, automatic processes for detecting the diagnostic changes in geophysical and acoustic signals indicative of magma moving towards the surface.

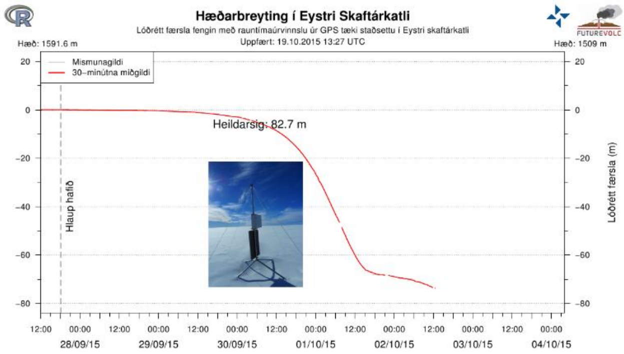
This work package considered the signals and processes associated with shallow magma migration, once it enters the final pre-eruptive stage with an emphasis on real-time analysis. The primary focus was to strengthen existing real-time monitoring and analysis systems at the Icelandic volcano supersite, incorporating new observations and processing of additional geophysical, geochemical and acoustic signals, to facilitate early warnings of an imminent eruption and detection of the onset of an eruption.

To implement this real-time monitoring for volcanoes in Vatnajökull ice cap, the sensitivity to their seismic signals required improvement. This was achieved through the four new, permanent seismic stations installed inside the glacier under WP5. This WP added two broadband seismic arrays west of the glacier margin and a third array north of the ice cap to also enable location and tracking of seismic tremor emanating from inside the glacier, and eventually allowed discrimination between the different tremor sources; volcanic eruption, lava flow, hydrothermal explosion and subglacial floods (jökulhlaups). The tremor study included temporary installations of three GPS receivers on the ice, two above the flood track from the eastern Skaftá cauldron and one in the cauldron itself. The cauldron installation included real-time data transmission and processing to enable early detection and warning of floods. The same developments were applied to monitor in real time the slow collapse of the Bárðarbunga caldera in 2014-2015. To understand the composition and source of the seismic tremor, numerical modelling of the seismic wavefield was performed for sources at different depths under the Vatnajökull ice sheet, taking into account bedrock and ice surface topography. To study the detection of open vent eruption, cross-correlations of data from closely located seismic and infrasound stations near the Holuhraun eruption site were performed.

To study and quantify the volatile emissions from glacier covered volcanoes (where the gases are dissolved in meltwater draining from the volcanoes) technologies were developed to enable continuous monitoring of element fluxes in glacial rivers issuing from the volcanoes, especially during jökulhlaups from subglacial, geothermal and volcanic areas.



(Left) a map of Vatnajökull glacier, showing volcanoes (stars), tracks of subglacial flood routes (arrows), seismic stations (triangles) and arrays (inverted triangles), as well as GPS stations (squares) monitoring the eastern Skaftá cauldron and its flood route, transmitting the cauldron elevation in real time for processing in near-real time at the supersite data center. (Right) Photo of Skaftárhlaup October 2015. Photo Benedikt Ófeigsson.



(Left) the ~80 m subsidence measured at the Eastern Skaftá cauldron from 27/09 – 02/10 2015. The flood came out of the glacier shortly after midnight on 1 October. The inset shows the installation in the cauldron. (Right) photo of the cauldron from the surface… Photo Magnús Tumi Guðmundsson.

Products/Results:

(i) An electricity-free, cost-efficient, continuously recording geochemical (osmotic) sampler for monitoring element fluxes in floods from subglacial volcanic areas, was developed to quantify emissions of volatile gases from volcanoes. The instrument was used to monitor subglacial floods from the two Skaftá cauldrons and the Bárðarbunga 2014 eruption. The methodology and results were published in an international peer reviewed article presenting the instrument construction and analysis of a jökulhlaup from the western Skaftá cauldron in 2014.

(ii) Analysis of shallow microseismicity at Hekla volcano. The persistent seismicity along the steepest slope on Hekla's northern flank, and near the summit is likely structurally controlled. It aligns parallel to the eruptive fissure along the summit and the seismicity rate may act as a sensitive pre-eruptive 'stress gauge', possibly enabling earlier warnings (than the current 1-2 hours) for future Hekla eruptions.

(iii) Analysis and identification of helicopter tremor recordings at Hekla volcano and Vatnajökull. The distinguishing features of helicopter tremor are identified and described in order to assist the volcano seismologist when interpreting tremor signals in areas with significant helicopter traffic.

(iv) Seismic analysis of a small hydrothermal explosion at Kverkfjöll volcano in 2013, incorporated in a multidisciplinary analysis of the event and publication in a peer reviewed scientific journal. The explosion craters and ejected material were observed on the surface, making the tremor signal a possible calibration for other subglacial hydrothermal explosions, like the ones probably generated by the draining of meltwater from the Eastern Skaftá cauldron in 2015.

(v) Two 7-element seismic arrays installed outside the western margin of Vatnajökull glacier in 2013 with fully functioning, real-time data processing implemented during the project and a third temporary array installed during the Bárðarbunga 2014-2015 event, near the eruption site. Application of the three arrays to locate the sources of tremor recorded during the eruption, both at the eruption site and under the ice cauldrons, which formed on the ice surface during the first weeks of the unrest. Application of the two initial arrays to monitor and track the sources of tremor during the subglacial flood from the eastern Skaftá cauldron in September/October 2015. Slowness analyses of array signals provide a good indication of processes at the Earch surface beneath the glacier (as opposed to activity at depth in the geology).

(vi) Numerical simulations of seismic tremor in the ice covered area of Vatnajökull, taking into account the surface topography and ice thickness, in order to model tremor generation by sources related to shallow magma movements and propagation along a glacier-covered path.

(vii) Installation of two GPS receivers on the ice surface above the track of the subglacial floods from the Skaftá cauldrons and one receiver in the eastern Skaftá cauldron itself, transmitting data in real time. Automatic fast-track processing of the data and publishing of the cauldron elevation on IMO's web site. This installation enabled real-time monitoring and issuing of an early warning, two days before the subglacial eastern Skaftá flood emerged from Vatnajökull glacier on 1 October 2015. This early warning enabled farmers, the road authority and tourist managers to implement contingency plans and mitigate potential damage caused by the flood, which was the largest ever recorded Skaftá flood. The slow collapse of the Bárðarbunga caldera in late 2014 was monitored and published in real time on IMO's web site using the same developments.

(viii) A strong correlation was demonstrated between acoustic and the seismic wavefields during the Holuhraun eruption, and no correlation after the eruption ended, indicating a strong contribution of an infrasonic source to the seismic tremor. There was also good correlation between seismic amplitude and acoustic pressure signals, suggesting that the seismic signals were related to eruptive product output rates. Co-location of seismic and infrasound sensors near an eruption site is therefore a potential real-time tool for monitoring eruption onset and its temporal evolution.

WP7: Determination and evolution of eruption source parameters

The objective of WP7 was to provide systems that use the best available methods to determine the rate of magma flow from volcanic craters during eruptions. Specifically several instruments were set up around key volcanoes in Iceland and models defining the eruption rate from measureable parameters were implemented. A multi-parameter system that can provide the eruption rate in near real-time for eruptions where continuously streaming sensor data are available (explosive eruptions) was developed.

The single most important parameter in determining the impact and possible hazards associated with a volcanic eruption is the rate of magma flow out of the crater. For an explosive eruption the eruption rate determines the height and size of the eruption plume, fallout of volcanic tephra, and the amount of ash that can be transported long distances and potentially disrupt air traffic. In a subglacial eruption the meltwater generation is determined by the eruption rate. In an eruption producing lava the eruption rate determines the length of the lava flow, the amount of gas produced and therefore the atmospheric pollution and potential health hazards. It is therefore of major importance to be able to estimate the eruption rate as fast and as accurately as possible. This was the primary goal of WP7.

Gro M. B. Pedersen and Stephanie Dumont (postdoctoral researchers from the University of Iceland) collecting infrared images and time lapse video at the lava flow (photo Magnús Tumi Guðmundsson)

Five main tasks were designed to achieve the objectives of WP7:

i) Development and implementation of new near-real time source monitoring systems. This task was a major effort involving the setting up of new sensors around some of the most active volcanoes in Iceland, including Hekla, Katla and Grímsvötn. These sensors included infrasound, automated cameras, electric field sensors, radiosondes, tephra samplers and analysers, gas monitoring systems, radars, lightning detection networks and thermal cameras. This included the development of an automated device (AshSizer) measuring ash fallout in real time, as well as estimating the grain size distribution of the tephra fall.

ii) Field and air observations during volcanic eruptions. This involved the establishment of a mobile field laboratory and development of protocols for aircraft observations during eruptions.

iii) Plume model calibration and refinement. This involved comparing information from recent eruptions in Iceland with simple models that people have used to relate plume height and eruption rate, and building a model that takes into account the effects of wind on volcanic plumes.

iv) Interpretation and software development. In this task information from microwaves transmitted and received by weather radars was used to estimate the mass of ash particles in a volcanic plume. In order to devise new ways of estimating the eruption source parameters, software was developed to use infrasound data as fully as possible to detect and analyse signals travelling through the atmosphere from erupting craters. Similar development has taken place to analyse digital images from cameras, electric fields generated by eruptions, and study and validate models on tephra fallout from plumes. Moreover, a procedure was developed and proposed to evaluate in real time the total grain size distribution of the tephra fall-out during volcanic eruptions. This procedure is based on real time measurements at selected sites by using the AshSizer developed within FUTUREVOLC

v) Multi-parameter system. In this task the information from all available sensors was combined to create a unique automated system that estimates the eruption rate of an explosive eruption in near real-time.

Results/Products:

The main products of WP7 are:

- The arrays of instruments that now monitor the most active Icelandic volcanoes, listed under task i;
- New software and models of volcanic plumes, tephra settling, grain size, interpretation of radar signals and images from cameras,
- A new instrument to sample and analyze tephra in the field in real time,
- The multi-parameter system for very fast estimates of eruption rates during explosive eruptions.

The monitoring systems set up in WP7 are to a large extent aimed at explosive eruptions. However, both subglacial and effusive eruptions are also being analyzed while none of the continuously streaming instruments available at present allow direct conversion to mass eruption rate. As a consequence, such eruptions require discrete on ground, aircraft or satellite-based measurements for mass eruption rate estimates. From August 2014 to February 2015 the largest eruption in Iceland in 230 years took place in Holuhraun in central Iceland, accompanied by the slow collapse of the Bárðarbunga caldera. The monitoring of these major events dominated the work relating to eruption monitoring in WP7. The main scientific efforts that have resulted from the work apart from the establishment of the sensor network include:

- Extensive measurements of gas emissions, including sulfur dioxide (SO_2), took place during the eruption in Holuhraun using FUTUREVOLC sensors. The dispersal of SO_2 was also modelled. This required several field campaigns and provided vital information on total gas flux and pollution hazard.
- A major field campaign took place both on ground and from aircraft throughout the six months of the eruption to estimate the magma eruption rate. The extent of lava field was mapped using both airborne and satellite techniques. Thickness measurements for volume estimates were made from the air using aircraft altimetry and on the ground where lava margins were observed. A detailed time series of geochemical data was obtained from samples collected throughout the eruption, using a mobile field laboratory established in FUTUREVOLC.
- An experiment for calibration of various ash quantification sensors took place in Würzburg, Germany with participation of many FUTUREVOLC partners. The results

are useful for determining the best method to convert observed signals from a sensor to eruption rate.

- Extensive collaborations across WPs within FUTUREVOLC took place during this major eruption in Iceland as it called for the efforts and expertise of many partners. This event involved lateral dyke formation, caldera collapse, formation of a large lava field and minor subglacial volcanic activity. It clearly illustrated the importance of a truly interdisciplinary approach in understanding complicated events.

The gas-rich plume of the eruption north of Vatnajökull in September 2014. Photo: Magnús Tumi Guðmundsson.

WP8: Distribution and description of eruptive products

The objectives of WP8 were to provide quantitative information about volcanic eruptive products in the near and far-field during and after eruptions, to expand and refine existing methods for detection of eruptive products, and develop new measurement and retrieval methods for these quantities. To reach the objectives WP8 used ground-based in situ measurements, ground- and satellite-based remote sensing, and radiative transfer and dispersion models.

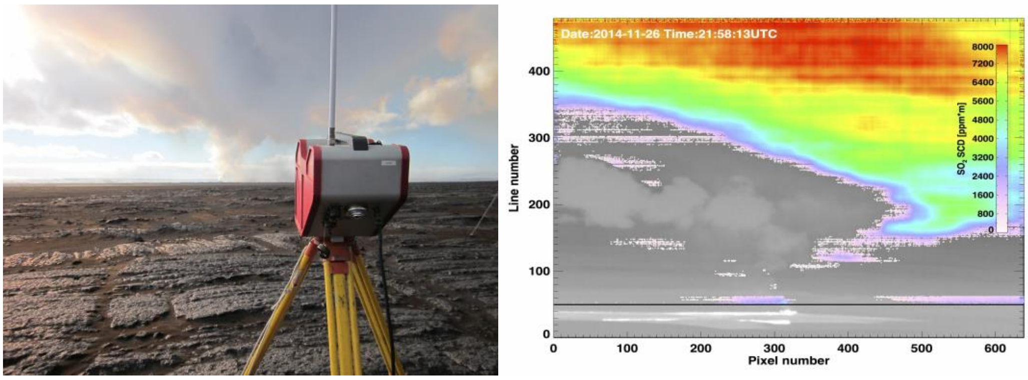
WP8 was divided into four tasks:

i) Satellite and air-borne techniques, which included the investigation of the potential of space-borne microwave radiometry for ash detection and retrieval, and the improvement of infrared satellite retrievals. For selected cases the synergy of satellite-borne microwave data with lightning, radar, infrared and dispersion model data was explored. Furthermore, sensitivity studies of ash concentration retrieval algorithms for satellite infrared (IR) measurements were made, the height and paths of eruptive plume features tracked and the time dependent changes in an eruptive cloud quantified through ground-based photogrammetric monitoring.

ii) Ground-based techniques, which included building three multispectral IR cameras for operation in the Icelandic climate, and putting them into operational work. These cameras can provide cloud height and mass eruption rate. Furthermore, two weatherproof aerosol particle counters have been deployed and methods developed for automatic processing of data from ash suspension and re-suspension events, and of volcanic aerosols in the atmospheric boundary layer in the near-field during and after eruptions.

iii) Dispersion model analysis which aimed to increase our understanding of the behaviour of dispersion models and their uncertainties, specifically (i) the influence of meteorological data resolution and topographical resolution on model prediction of ash distribution; (ii) the influence of improved observations, as delivered by WP7 and WP8, on model prediction of ash distribution; (iii) the influence of near-vent model outputs from WP7, on model prediction of ash distribution.

iv) Synthesizing near and far-field observations of eruptive products. This task utilizes the unique set of measurements and models simulations to construct a comprehensive dataset of the eruptive products in the near and far-fields from the satellite-based data, the ground-based data and the dispersion modelling for specific case studies.



*(Left) Infrared imaging camera (nicAIR-II) measuring close to the active lava from at Holuhraun. The camera was able to measure SO2 gas at relatively high frequency (~1 Hz) and estimate mass loadings and emission rates. (Right) Example of an SO2 retrieval from the Holuhraun gas plume. Mass loadings were extremely high (>5000 ppm*m) and in some places saturation occurred.*

Results/Products:

The main products and results from WP8 are the instrumentation developed and delivered (optical particle counters (OPC) and infrared (IR) cameras), software developed, peer-reviewed articles and presentations at conferences, and milestone and deliverable reports. Main findings include:

i) Space-borne microwave radiometer observations have, due to the sensitivity to the volcanic tephra, the potential to monitor the erupted plume in the proximity of the eruption vent where satellite-based infrared measurements are often saturated.

ii) An algorithm has been developed that can track identifiable features, and also map the velocity structure throughout the elevation of an eruption cloud. The algorithm was applied to a series of images from the 2010 eruption of Eyjafjallajökull and the results show a highly variable plume driven by intermittent explosions. The results indicate a high degree of spatial and temporal variability within the plume. Both the pulsating nature and fallout from the plume lead to characteristics different from those expected from standard integral plume models.

iii) Two Optical Particle Counters (OPC) have been made operational, including an automated data processing tool, remote communication and data streaming to the FUTUREVOLC database. The OPC measures the aerosol size distribution and number concentrations. The OPCs have been in operation at different locations in Iceland, including near the Holuhraun-Bárðarbunga eruption site north of Vatnajökull in 2014-2015.

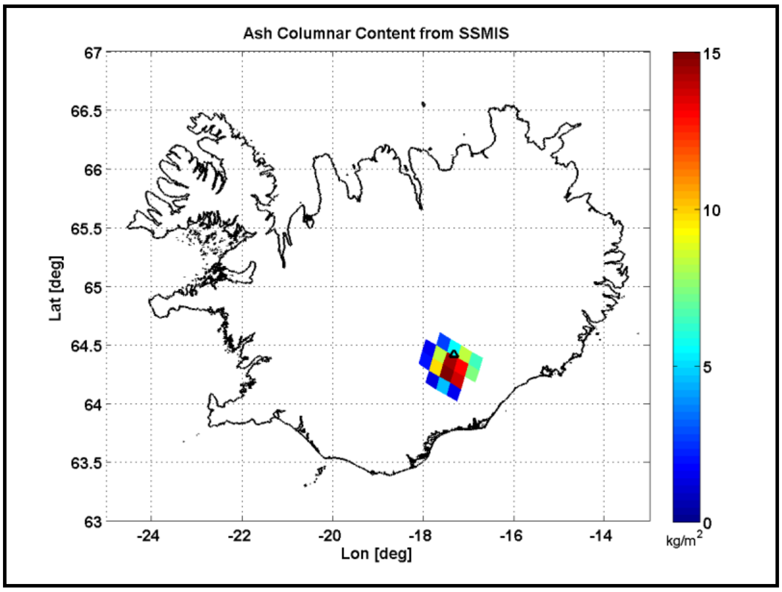
iv) Three automated NicAIR II camera systems for the visualization and detection of volcanic ash and SO_2 were designed and built. Each system has a multispectral IR camera, a webcam, GPS and an internal clinometer to enable more accurate retrievals of plume geometry. The systems are housed in a custom-made weatherproof casing and were deployed during the Holuhraun-Bárðarbunga eruption 2014-2015.

v) Software was developed to reconstruct volcanic plume structure from images of mass column densities obtained from IR and ultraviolet (UV) cameras.

vi) The sensitivity of dispersion model forecasts to the numerical weather prediction model configuration was investigated. The analyses of the sensitivities of model forecasts have improved our understanding of the behaviour of dispersion models and the uncertainties associated with the forecasts they produce. The best choice of weather prediction model depends on the altitude of the released material (ash or SO_2), which is different for explosive and effusive eruptions. Dispersion model forecasts are also highly sensitive to the particle size distribution. Use of radar data from the 2011 eruption of Grímsvötn show that it cannot be relied upon for accurate height information on ash emission for this eruption. However, the development of new retrieval algorithms as part of the FUTUREVOLC project may help to resolve these uncertainties in future eruptions.

vii) Microwave model simulations have been performed to investigate the behavior of the observed space-based brightness temperatures and their variance with terrain emissivity, water vapor and ice concentration within the volcanic plume.

viii) The effect of ash particle shape on IR satellite measurements have been investigated and it was found that the assumption of mass-equivalent spheres for ash mass loading estimates will underestimate ash mass loading compared to morphologically complex inhomogeneous ash particles.



Estimated ash columnar content from the Special Sensor Microwave Imager Sounder (SSMIS). Data recorded 08:34 UTC, 21 May 2011, during the Grimsvötn eruption.

WP9: Demonstration of FUTUREVOLC

The overall objective of WP9 was to demonstrate that the FUTUREVOLC supersite was fulfilling the project's objectives and improving on current procedures. This involved testing the end-to-end FUTUREVOLC "system" to ensure that it can be used in operational real-time capacity and showcasing the "system" as a model for future volcano supersites.

Fundamental to demonstrating that the FUTUREVOLC project was working and having an influence on response activities in Iceland over all timescales was being able to show the "pull through" of new science into operations. What this meant in practice for WP9 was:

- Facilitating work to determine how FUTUREVOLC partners will support the Icelandic Met Office (IMO), University of Iceland and Iceland Civil Protection during a volcanic unrest or eruption situation.

- Ensuring that IMO, and the situation response in general, can make the best use of all data from FUTUREVOLC partners and equipment.

- Ensuring FUTUREVOLC partners can discuss multi-disciplinary data in near real time.

- Showcasing the Supersite concept to stakeholders and demonstrating a fully functioning system.

"The early detection of this outburst flood (jökulhlaup) is a resounding success for FUTUREVOLC! We were delighted to be able to issue a three-day advanced warning of the oncoming flood, based on measurement and data-processing techniques developed in WP6. This is a leading example of how FUTUREVOLC has made direct contributions to volcanic monitoring in Iceland".

Icelandic Meteorological Office, Hazard Monitoring Section

To achieve this, the main components of the work were to run two exercises during the course of the project and feedback lessons learnt and areas where improvements could be made. The unrest and eruption in the Bárðarbunga volcanic system from August 2014 – February 2015 provided a real-world test for the project from which further developments were identified. Other geothermal and volcanic activity in 2014 and 2015 provided additional demonstration of the impact of FUTUREVOLC.

Results/Products:

In June 2014 an exercise, that considered an eruption at Hekla, was held to test the alerting and communications procedures between FUTUREVOLC partners. Pre and post-exercise questionnaires were used to evaluate the exercise and new SMS and email alerts were introduced as a result of identified requirements. In August 2014, these were put to good use at the start of the unrest in the Bárðarbunga volcanic system and allowed partners to react quickly and mobilise data and field equipment. The subsequent eruption at Holuhraun led to a major amount of work for the FUTUREVOLC partners and proved a real test of the consortium. FUTUREVOLC equipment and expertise were vital to the response effort.

Three other events in 2014-2015 also allowed the capabilities introduced by FUTUREVOLC to be tested, for both communications and the use of new monitoring equipment. These were flooding and gas emissions at Mýrdalsjökull in July 2014; a major rockslide within the Askja caldera in July 2014, causing a tsunami in Lake Öskjuvatn; and the Skaftá ice-cauldron jökulhlaup in September-October 2015. Each of these events has been reviewed and the findings show that FUTUREVOLC has had a direct impact on all of the responses through the rapid utilisation of equipment installed both before and during the events.

A stakeholder day was held in November 2015 titled "Exploiting the outcome of FUTUREVOLC" which showcased the project, its impacts and the online tools developed by it. About 100 people from across industry, academia, civil protection and the Volcanic Ash Advisory Centres attended and were shown the advances made under the project.

A second exercise within the project was held over three days at the end of January 2016. All 26 FUTUREVOLC partners, together with additional external Stakeholders (including the London VAAC), were involved in responding to an evolving unrest and eruption scenario at

Katla volcano. Large volumes of simulated data based on a complex, but realistic eruption scenario were compiled in advance by a few members of the project and external experts. These were transmitted to project partners in near real-time over the course of the three days allowing participating partners to practice and test their response procedures and test the new ways of sharing and discussing data implemented by the project. The exercise was the first of this magnitude and scope in Iceland and a great test of the new instrumentation and procedures introduced by FUTUREVOLC. Following the exercise 90% of partners said that they felt better prepared for the next eruption.

Lessons learned from the exercises and real events have led to:

- The introduction of a FUTUREVOLC blog site for sharing information and multidisciplinary scientific discussion,
- Implementation of a single email address for dissemination of daily updates from Iceland during events,
- Development of field safety procedures, including purchase of additional equipment and new training/briefing materials, and a refined processes for centralised fieldwork coordination in Iceland,
- The ability to easily add new monitoring sites to the FUTUREVOLC data hub. Much of the new monitoring data has been streamed directly to IMO during the course of the project, but in June 2015 the FUTUREVOLC data hub was publicly launched, allowing access to the project’s data and the Catalogue of Icelandic Volcanoes.

Þorgils Ingvarsson technician working on IMO instruments near the lava flow in Holuhraun Photo: Baldur Bergson

WP10: Dissemination, outreach and exploitation of results

See report section on the potential impact and the main dissemination activities and the exploitation of results.

Potential impact

New user-friendly "Icelandic Volcanoes" data hub (futurevolc.vedur.is) is expected to have a large impact. It was developed during the project, providing access to both basic information on volcanic systems as well as monitoring data with multiple data sets. Users can search for data through a web-based geographical information system and following registration can download and use data according to terms, free of charge. A Catalogue of Icelandic Volcanoes, supported by ICAO, has been populated with information on the 32 volcanic systems in Iceland and is accessible as an open-access website at the data hub.

Communication of hazards was improved by integrating research-based learning on responses to Eyjafjallajökull 2010, and other eruptions, into operational activities during the project. This includes the Aviation Colour Code system and new reporting protocols, which were tested and demonstrated during two FUTUREVOLC exercises and the response to the Bárðarbunga unrest and eruption.

Other outcomes of FUTUREVOLC that will improve the response to future volcanic events are many, including:

Magma tracking has been improved the installation of new monitoring equipment around target volcanoes and establishing Icelandic volcanoes as a permanent geohazard supersite under the framework of GEO Geohazards Supersites and Natural Laboratories. The project has furthermore resulted in newly-developed algorithms, which have been applied to Iceland's volcanic systems. All of this will improve the response to future volcanic activity.

A multi-parameter system for near real time estimates of mass eruption rate in explosive eruptions was developed and tested. An automated sampler and real-time analyser of ash fallout was also developed and tested. These will be available in the next eruptions in Iceland.

Improved algorithms for analyzing satellite and ground-based microwave and thermal infrared radiometric imagery of volcanic clouds have been developed in FUTUREVOLC, available for next eruptions.

Dissemination, outreach and exploitation of results

FUTUREVOLC included a separate work package on dissemination, outreach and exploitation of results, with the following aims:

- Disseminate scientific findings through high impact, peer reviewed publications, conference presentations and conference session organization and promote data sharing policies developed within the network.
- Disseminate scientific results to all stakeholders and improve communications between these groups.
- Promote science within the community, and to encourage future generations of scientists and researchers.

- Ensure researchers are trained to both undertake and develop scientific research and disseminate their work and results with the highest possible impact at all levels.
- Ensure smooth pathways for internal communication within the consortium, which will promote collaboration and lead to an open working environment for all partners beyond the FUTUREVOLC project.

The focus was to disseminate the results and outputs of FUTUREVOLC and to ensure the activities and findings reached the widest possible audience and had the highest impact possible. The objectives were developed with a range of target audiences in mind; scientific communities, policy and decision makers and general public; each of these groups was successfully engaged.

Results/Products:

Members of the FUTUREVOLC team have published peer-reviewed scientific articles in high-impact international journals. In addition, team members have presented results at both international conferences and workshop sessions. The workshops have included representatives of relevant stakeholder groups (e.g. policy, volcano observatories, database managers, civil protection etc.). The involvement of these external partners ensured focus and relevance of FUTUREVOLC research. Beyond the scientific community and direct stakeholders, FUTUREVOLC has made significant efforts to reach a wide, international, public audience. This has included public groups of all ages (from young school children to older generations) and backgrounds (farming communities to air travel operators). FUTUREVOLC has also contributed to the professional training of academic researchers, observatory staff and technical support staff. In particular, the experience gained through deployment of equipment before and during the eruption in 2014-2015 has significantly increased the technical ability and problem solving skills of all participants.

Highlights of dissemination activities include:

About 260 public outreach articles or events including:

i) Two articles about the project and volcanoes were published in the Scholastic children's science magazines in USA; Science World and Superscience, with a circulation of several million units each and available online

ii) An interview and footage shown on the BBC of the team in Iceland carrying out fieldwork

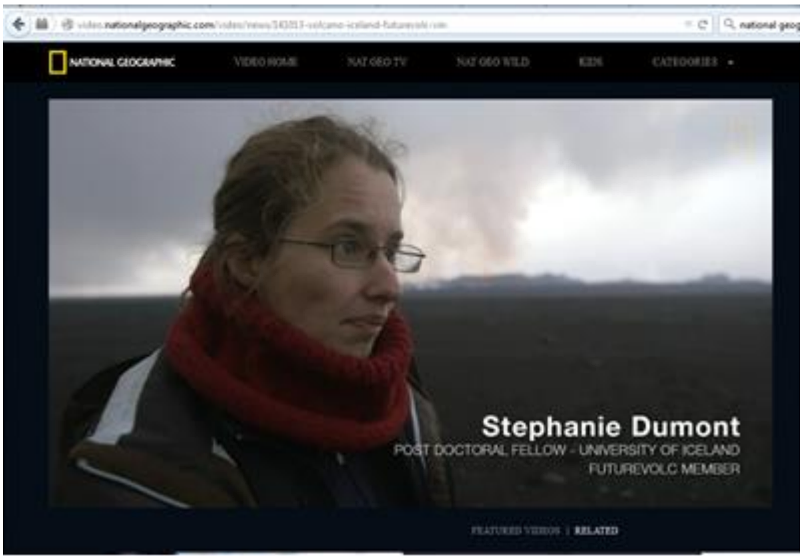
http://futurevolc.hi.is/bbc-news-futurevolc

iii) A short segment about the FUTUREVOLC project on Euronews including interviews with Freysteinn Sigmundsson and Kristin Vogfjord and footage of the installation of infrasound equipment in Iceland by Maurizio Ripepe and the team from University of Florence

http://futurevolc.hi.is/futurevolc-euronews

iv) A short film available on the National Geographic website about the FUTUREVOLC project (published October 13th, 2014)

http://video.nationalgeographic.com/video/news/141013-volcano-iceland-futurevolc-vin



Researcher, Dr Stephanie Dumont of Univeristy of Iceland being interviewed near the eruption site as part of the National Geographic online short film.

http://news.nationalgeographic.com/news/2014/10/141013-iceland-volcano-bardarbunga-lava-science/

v) A separate news article featuring FUTUREVOLC was also published on the National Geographic website on October 14th 2014

http://news.nationalgeographic.com/news/2014/10/141013-iceland-volcano-bardarbunga-lavascience/

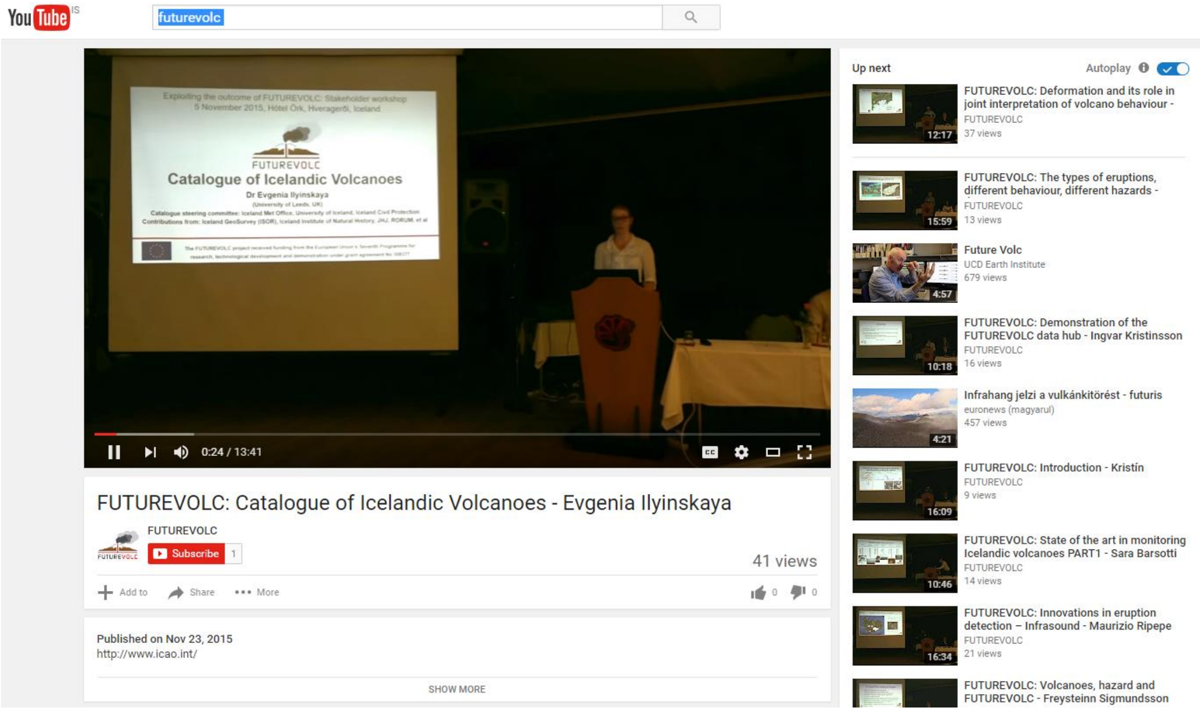
vi) YouTube videos by consortium partners about the project including footage of deployment of monitoring equipment

vii) Numerous local and national interviews during the Bárðarbunga system eruption in 2014

viii) Regular presentations by members of the consortium to local groups and schools about the project and the scientific work being undertaken

ix) Several contributions to high level training workshops for university students and technical staff

x) YouTube videos of presentations at the FUTUREVOLC Stakeholders meeting including demonstrations of the volcano catalogue and the data hub



Tutorials are available through You Tube. This example is for the Catalogue of Icelandic volcanoes https://www.youtube.com/watch?v=hVly2B32cbk

The IMO and Icelandic Civil Protection websites were used very effectively during the Bárðarbunga system eruption and were updated every day to inform the public, academic groups and decision makers in Iceland and further afield. This information was also used by members of the consortium, for example by the UCD group to:

- Plan and safely deploy additional instruments in the area to monitor the eruption
- Complement the seismic data streaming live to the Seismology Laboratory in Dublin
- Provide regular summaries to the Geological Survey of Ireland (the Government representative on the Office for Emergency Planning in Ireland) and
- Provide information to media outlets through informed interviews about the eruption and potential risks to the public and/or commercial interest groups.

Overall outputs in terms of dissemination, outreach and exploitation of results include:

Approximately 230 conference presentations including large international meetings such as: American Geophysical Union (San Francisco), European Geoscientists Union (Vienna), International Association of Volcanology and Chemistry of the Earth's Interior (Japan), Cities on Volcanoes conference (Indonesia), Volcanic and Magmatic Studies Group (UK), ESA Fringe (Frascati, Italy), Global Risk Forum (Davos, Switzerland), Buenos Aires Volcanic Ash Advisory Centre and Aerolinas Argentina (Argentina), International Geoscience and Remote Sensing Symposium (Canada), Chemistry of Volcanic Gases (CCVG)/International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) (Chile)

Approximately 140 stakeholder events including meetings with: Volcanic Ash Advisory Centres, members of the airline industry, World Meteorological Organisation, Salvation Army, Cascades Volcano Observatory USGS, Banff international Research Station, Colombian Geological Survey, Iceland interest groups, Icelandic Rescue Centre and Emergency Response Coordination Centre

Over 40 peer reviewed publications (+ 6 further publications in press or in review) including articles published in: Nature, EOS, Annals of Geophysics, Journal of Volcanology and Geothermal Research, Geophysical Research Letters, Journal of Geophysical Research, Procedia Technology, Journal of Geophysics – Solid Earth, Bulletin of Volcanology, Geophysical Journal International, Journal of fluid Mechanics, Geochimica et Cosmochimica Acta, Earth and Planetary Science Letters.

Approximately 280 public events and media presentations including interviews, You Tube videos, exhibitions, blogs, websites, popular science articles, children's materials/articles, newsletters, press releases and presentations to public groups.

FUTUREVOLC has also contributed to the professional training of academic researchers, observatory staff and technical support staff. In particular, the experience gained through deployment of equipment before and during the eruption in 2014, and the subsequent data handling, has significantly increased the technical ability and problem solving skills of all participants.

Publications in international scientific journals

See updates at: http://futurevolc.hi.is/publications

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Further dissemination (outside reporting period)

Peer review publications

Publication type	Title	Author(s)	Journal	Volume/ Issue	Date	Status

Peer review journal	Long-period events with strikingly regular temporal patterns on Katla volcano's south flank (Iceland)	Sgattoni, G., Z. Jeddi, O. Gudmundsson, P. Einarsson, A. Tryggvason, B. Lund and F Lucchi	J. Volc. Geoth. Res.		08/2015	submitted
Peer review journal	Relative reslocation of earthquakes without a predefined velocity model: an example from a peculiar seismic cluster on Katla's south flank (Iceland)	Sgattoni, G., O. Gudmundsson, P. Einarsson and F. Lucchi	Geophys. J. Int.		02/2016	submitted
Peer review journal	The Katla volcanic system imaged using local earthquakes recorded with a temporary seismic network	Jeddi, Z., A. Tryggvason and O. Gudmundsson	J. Geophys. Res. Solid Earth		03/2016	submitted
Peer review journal	Silent Magma Flow Follows Tremor-rich shallow dyke formation: Bárdarbunga eruption, Iceland	Eibl, E.P.S., Bean, C.J., Vogfjörd, K.S., Ying, Y., Lokmer, I., Möllhoff, M., Palsson, F.	Nature Geosciences			In revision
Peer review journal	Mapping surface displacement using a single InSAR pair: a Singular Value Decomposition approach	S. Dumont, F. Lopes, K. Michalczewska, F. Sigmundsson	Geophy. Journal. International		16/03/2016	submitted
Peer review journal	Near Real-Time Detection of Tephra Eruption Onset and Mass Flow Rate using Microwave Weather Radar and Infrasound Array	F. Marzano, E. Picciotti, S. DI Fabio, M. MOntopoli, L. Mereu, W. Degruyter, C. Bonadonna, M. Ripepe	IEE Transactions on geoscience and remote		/2016	accepted

Conferences

Type of activitiy	Main leader (First author's institute)	Title	Date	Place	Type of audience *Scienticic – Insdustry – Civil – Policy makers - Medias*	Size of audience (approx.)	Countries addressed
Poster	Chalmers	Measurements of the gas emission from Holuhraun volcanic fissure eruption on Iceland, using Scanning DOAS instruments	19/04/2016	EGU Vienna, Austria	Scientific Community	500	International
Oral	UI	Futurvolc and the Bardarbunga eruption 2014-15 Iceland, success in the field and	18/04/2016	EGU Vienna, Austria	Scientific Community	500	International

		laboratory					
Poster	UCD	What Generated the Eruptive Tremor During the Bardarbunga Eruption, Iceland?	18/04/2016	EGU Vienna, Austria	Scientific Community	500	International
Poster	UCD	The Acoustic Signal of a Helicopter can be Used to Track it With Seismic Arrays	22/04/2016	EGU Vienna, Austria	Scientific Community	500	International
Poster	UCD	Array observations of seasonal seismic noise variations induced by glacier-fed rapids near Vatnajökull, Iceland	22/04/2016	EGU Vienna, Austria	Scientific Community	500	International
Poster	UCD	Subglacial Tremor Burst during the Bardarbunga Eruption, Iceland: Flood or Magma?	22/04/2016	EGU Vienna, Austria	Scientific Community	500	International
Oral	IMO/UCD	Seismic tremor signals from Bárðarbunga, Grímsvötn and other glacier covered volcanoes in Iceland's Vatnajökull ice cap	18/04/2016	EGU Vienna, Austria	Scientific Community	500	International
Oral	UI	The eruption in Holuhraun, NE Iceland 2014-2015: Real-time monitoring and influence of landscape on lava flow	19/04/2016	EGU Vienna, Austria	Scientific Community	500	International
Poster	UI	Emplacement dynamics and lava field evolution of the flood basalt eruption at Holuhraun, Iceland: Observations from field and remote sensing data	18/04/2016	EGU Vienna, Austria	Scientific Community	500	International
Oral	UI	The 2014 Lake Askja rockslide tsunami – optimization of landslide parameters comparing numerical simulations with observed run-up	20/04/2016	EGU Vienna, Austria	Scientific Community	500	International
Poster	UI	Exploiting the outcome of FUTUREVOLC: The 2014-2015 rifting event, effusive eruption and gradual caldera collapse at Bardarbunga volcanic system, Iceland	18/04/2016	EGU Vienna, Austria	Scientific Community	500	International
Oral	UCD	Tracking Tremor Sources during the Bardarbunga eruption with an Array	26/04/2016	LMU Munich, Germany	Scientific Community	50	International

Oral	UI	Futurvolc and the Bardarbunga eruption 2014-15 Iceland, success in the field and laboratory	18/04/2016	EGU Vienna, Austria	Scientific Community	500	International

Public outreach

Type of activitiy	Main leader (First author's institute)	Title	Date	Place	Type of audience *Scienticic – Insdustry – Civil – Policy makers - Medias*	Size of audience (approx.)	Countries addressed
Interview	IMO	Where fire freezes: All eyes, ears and instruments on Iceland's volatile volcanoes	April/2016	International	Earth Magazine, EARTH The American Geosciences Institute Alexandria, VA 22302	>1000	International