**European volcanological supersite in Iceland:**
**a monitoring system and network for the future**

# Report

## D5.8 – Joint analyses of long-term magma movements

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|---|---|
| Work Package: | *Long term magma tracking* |
| Work Package number: | *5* |
| Deliverable: | *Joint analyses of long-term magma movements* |
| Deliverable number: | *5.8* |
| Type of Activity: | *RTD* |
| Responsible activity leader: | *Andy Hooper* |
| Responsible participant: | *University of Iceland* |
| Authors: | *Freysteinn Sigmundsson, Magnús Tumi Gudmundsson, Andy Hooper, Kristín Vogfjörð, Kristín Jónsdóttir, Stéphanie Dumont, Melissa Anne Pfeffer, Sigurður Reynir Gíslason* |

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|---|---|---|
| Type of Deliverable: | *Report* [X]<br>*Prototype* [ ] | *Demonstrator* [ ]<br>*Other* [ ] |
| Dissemination level: | *Public* [X]<br>*Prog. Participants (FP7)* [ ] | *Restricted Designated Group* []<br>*Confidential (consortium)* [ ] |

**Seventh Framework Programme**
**EC project number: 308377**

**Summary**

Deliverable 5.8 of FUTUREVOLC relates to Task 5.12 of the project on joint analyses of long-term magma movements. Modelling of deformation and seismic data (Task 5.7) provides constraints on the position and volume of magma sources. Thermal modelling (Task 5.8) can provide similar constraints when magma sources are below an ice cap. Data on volatiles (Tasks 5.10 and 5.11) provide extra constraints on magma source depth, as well as differentiation and movement. The aim of this task was to bring together data from all the aforementioned tasks, in order to track magma movements in a unified way. The planned work stated that models of magma sources from geophysical data would be combined with models of fluid flow to derive a single model that is able to explain all observables. An algorithm was to be developed considering the heat transfer from identified magma sources and gas emissions associated with magma movements.

Significant steps have been taken in this respect, in particular with the opportunities provided by the unrest and eruption within the Bárðarbunga volcanic system 2014-2015. Full understanding of magma movements in these events requires a joint model to explain seismicity, deformation, thermal signals above the path of magma movements and the released gas during the events that provided the maximum source of gas pollution in Iceland since the Laki 1783-1784 eruption in Iceland.

Series of publications form the basis for a joint model of magma movements as explained below. At present, the joint model of magma movements relies on a series of separate algorithms to interpret parts of the available data sets, but the massive data collected during the recent Bárðarbunga eruption and unrest have all been interpreted in the context of one common model for magma movements, namely of subsurface lateral flow of magma from the beneath the Bárðarbunga caldera along about 50 km long subterranean path towards an eruption site in the Holuhraun area.

**Joint analyses of long-term magma movements in the Bárðarbunga volcanic system 2014-2015**

The largest effusive lava eruption in Iceland since 1783 occurred in 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 collapse of the Bardarbunga caldera occurred throughout the eruption, resulting in a caldera collapse of about 2 cubic kilometers.

Steps in developing a joint model of magma movements during these events include the following:

Joint modeling of geodetic and seismic data related to a lateral dyke formed during the events have been reported in the following FUTUREVOLC publications:

Freysteinn Sigmundsson, Andrew Hooper, Sigrún Hreinsdóttir, Kristín S. Vogfjörd, Benedikt Ófeigsson, Elías Rafn Heimisson, Stéphanie Dumont, Michelle Parks, Karsten Spaans, Gunnar B. Guðmundsson, Vincent Drouin, Thóra Árnadóttir, Kristín Jónsdóttir, Magnús T. Gudmundsson, Thórdís Högnadóttir, Hildur María Friðriksdóttir, Martin Hensch, Páll Einarsson, Eyjólfur Magnússon, Sergey Samsonov, Bryndís Brandsdóttir, Robert S. White, Thorbjörg Ágústsdóttir, Timothy Greenfield, Robert G. Green, Ásta Rut Hjartardóttir, Rikke Pedersen, Rick Bennett, Halldór Geirsson, Pete LaFemina, Helgi Björnsson, Finnur Pálsson, Erik Sturkell, Christopher J. Bean, Martin Möllhoff, Aoife Braiden, and Eva P.S. Eibl, **Segmented lateral dyke growth in a rifting event at Bárðarbunga volcanic system, Iceland**, *Nature*, 517, 191–195, doi:10.1038/nature14111, 2015 (Online 15 December 2014).

http://www.nature.com/nature/journal/v517/n7533/abs/nature14111.html

Green, R. G., T. Greenfield, and R. S. White (2015), **Triggered earthquake suppressed by an evolving stress shadow from a propagating dyke**, *Nat. Geosci*., 8, 629–632, doi:10.1038/ngeo2491.
http://www.nature.com/ngeo/journal/v8/n8/full/ngeo2491.html

Ágústsdóttir, T., J. Woods, T. Greenfield, R. G. Green, R. S. White, T. Winder, B. Brandsdóttir, S. Steinthórsson, and H. Soosalu (2016), **Strike-slip faulting during the 2014 Bárðarbunga-Holuhraun dike intrusion, central Iceland**, *Geophys. Res. Lett*., 43, doi:10.1002/2015GL067423
http://onlinelibrary.wiley.com/wol1/doi/10.1002/2015GL067423/references

The geodetic and seismic data on the lateral dyke inspired the development of a new model to explain the path of a laterally propagating dyke. This model integrates geodetic and seismic observations with preexisting plate boundary strain field and topography to explain the evolution and propagating of magma filled cracks. The model is reported in FUTUREVOLC publication:

Heimisson, E. R., A. Hooper, and F. Sigmundsson (2015), **Forecasting the path of a laterally propagating dike**, *J. Geophys. Res. Solid Earth*, *120*, doi:10.1002/2015JB012402.
http://onlinelibrary.wiley.com/doi/10.1002/2015JB012402/abstract

The thermal signals associated with the dyke formed have been reported in a conference presentation:

Hannah I. Reynolds, Magnús T. Gudmundsson, and Thórdís Högnadóttir, Subglacial melting associated with activity at Bárdarbunga volcano, Iceland, explored using numerical reservoir simulations, Geophysical Research Abstracts, Vol. 17, EGU2015-10753-2, 2015, EGU General Assembly 2015.
http://meetingorganizer.copernicus.org/EGU2015/EGU2015-10753-2.pdf

The gas release during the eruption and its environmental impact is reported in the following FUTUREVOLC publication:

Gíslason S. R., G. Stefánsdóttir, M.A. Pfeffer, S. Barsotti, Th. Jóhannsson, I. Galeczka, E. Bali, O. Sigmarsson, A. Stefánsson, N.S. Keller, Á. Sigurdsson, B. Bergsson, B. Galle, V.C. Jacobo, S. Arellano, A. Aiuppa, E.B. Jónasdóttir, E.S. Eiríksdóttir, S. Jakobsson, G.H. Guðfinnsson, S.A. Halldórsson, H. Gunnarsson, B. Haddadi4, I. Jónsdóttir1, Th. Thordarson1, M. Riishuus, Th. Högnadóttir, T. Dürig, G.B.M. Pedersen, Á. Höskuldsson, M.T. Gudmundsson (2015). **Environmental pressure from the 2014–15 eruption of Bárðarbunga volcano, Iceland**, Geochem. Persp. Let. 1, 84-93, doi: 10.7185/geochemlet.1509.

Table 1 below, reproduced from supplementary information of the article by Gíslason et al., gives an overview of magma effusion and gas emissions during the eruption.

| | Total | | | Average | | | First weeks (2.5 times average) | | | December-January | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Magma Mt | Petrologic Mt | DOAS MultiGAS Mt | Magma $kg\ s^{-1}$ | Petrologic $kg\ s^{-1}$ | DOAS MultiGAS $kg\ s^{-1}$ | Magma $kg\ s^{-1}$ | Petrologic $kg\ s^{-1}$ | DOAS MultiGAS $kg\ s^{-1}$ | Magma $kg\ s^{-1}$ | Petrologic $kg\ s^{-1}$ | DOAS MultiGAS $kg\ s^{-1}$ |
| Magma | 4200 | | | 2.69E+5 | | | 6.71E+5 | | | 1.75E+5 | | |
| $H_2O$ | | 16.8 | 284 | | 1070 | 1.81E+4 | | 2690 | 5.21E+4 | | 698 | 1.15E+4 |
| $SO_2$ | | 10.7 | 11.8 | | 684 | 754 | | 1710 | 1380 | | 445 | 546 |
| $CO_2$ | | 6.33 | 5.60 | | 405 | 358 | | 1010 | 1500 | | 263 | 187 |
| HCl | | 0.10 | | | 6.4 | | | 16.0 | | | 4.2 | |
| HF | | BD | | | BD | | | | | | | |

**Table 1.** Total magma effusion and gas emissions during the 2014-2015 eruption in the Bárðarbunga volcanic system. The columns show total, average rates, first weeks' rates, and December-January rates. Total magma volume, 1.6 ± 0.3 $km^3$, density; 2600 kg $m^{-3}$, the total mass erupted during the eruption, after 181 effusion days was (4.2 ± 0.8) × $10^{12}$ kg. The average magma flow rate for the 181 days was 100 $m^3\ s^{-1}$ with the corresponding mass flow rate being 2.7 × $10^5$ kg $s^{-1}$. During the first weeks, the flow rate was two to three times the average (2.5), while 50-80 $m^3\ s^{-1}$ occurred in December and January (0.65 times the average), followed by gradual decline in February leading to the termination on 27 February. The error on the effusion rate is 20%, for the petrologic gas fluxes it is; $H_2O$ 22%, $SO_2$ 28%, $CO_2$ 26%, HCl ~100% and HF was below detection (BD). The error of $SO_2$ measured by DOAS is 38% and the one for $CO_2$ and $H_2O$ measured by the combination of DOAS and MultiGas is 65% and 69% respectively.

A study of the correlation of the gas release and formation of the dyke path at the northernmost end of the dyke was reported in the following presentation:

Dumont S., Parks M., Sigmundsson F., Hooper A., Hreinsdóttir S., Ófeigsson B., Vogfjörd K., Spaans K., Drouin V., Hensch M., Jónsdóttir K., Gudmundsson G., Hjartardóttir A.R., Barsotti S., Pfeffer M., Stefansdottir G., Magnússon E., Heimisson E.R., Árnadóttir T., Pedersen G. and the field team, **Contribution of geodetic observations towards a multi-disciplinary approach for studying the plumbing system feeding the 2014 fissure eruption at Holuhraun**. 26th IUGG General Assembly, IAVCEI, Prague (Czech Republic), 22 June-2 July 2015,
https://www.czech-in.org/cm/IUGG/CM.NET.WebUI/CM.NET.WEBUI.scpr/SCPRfunctiondetail.aspx?confID=05000000-0000-0000-0000-000000000053&sesID=05000000-0000-0000-0000-000000003251&absID=07000000-0000-0000-0000-000000026242

The study reported a multi-disciplinary approach to better understand the northernmost part of the 2014-2015 Bárðarbunga dyke/feeding system and the eruption. The aim was to better understand the plumbing system feeding the eruption and its space-time evolution. This approach integrates geodetic, seismic and gas observations for the first two months of the eruption, in order to investigate the link between ground deformation, magma transfer at depth and the eruptive activity (Figure 1). A large data set of synthetic aperture radar (SAR) images, acquired by the TerraSAR-X and CosmoSky-Med satellites, was used to form individual interferograms. This data is complemented with three dimensional displacements observed by GPS in the area. Using the series of interferograms, we perform a joint inversion of interferometric SAR (InSAR) images and GPS for different time periods using a Bayesian approach to characterize the time evolution of the dyke opening at depth. The $SO_2$ flux and plume height are considered in this study as a proxy of the eruptive activity.

The first-order comparison between the curves showing the time evolution of the opening, the $SO_2$ flux and the plume height (Figure 2) show a drop for these three components up to mid-September. From mid-September, the cumulative dyke opening does not increase while the $SO_2$ flux and plume height show small-scale variations associated with the eruption, which was still ongoing and relatively strong at that time. Theses changes suggest two different phases that we interpret as reflecting first the dyke emplacement and the setting up of a new regime associated with the regular flow of magma feeding the eruption. This interpretation is supported by the deformation data which shows large displacements associated with the dyke emplacement until the middle of September, and no further increase in dyke opening thereafter. Further work on this joint interpretation is in progress and will include a comparison with seismicity.

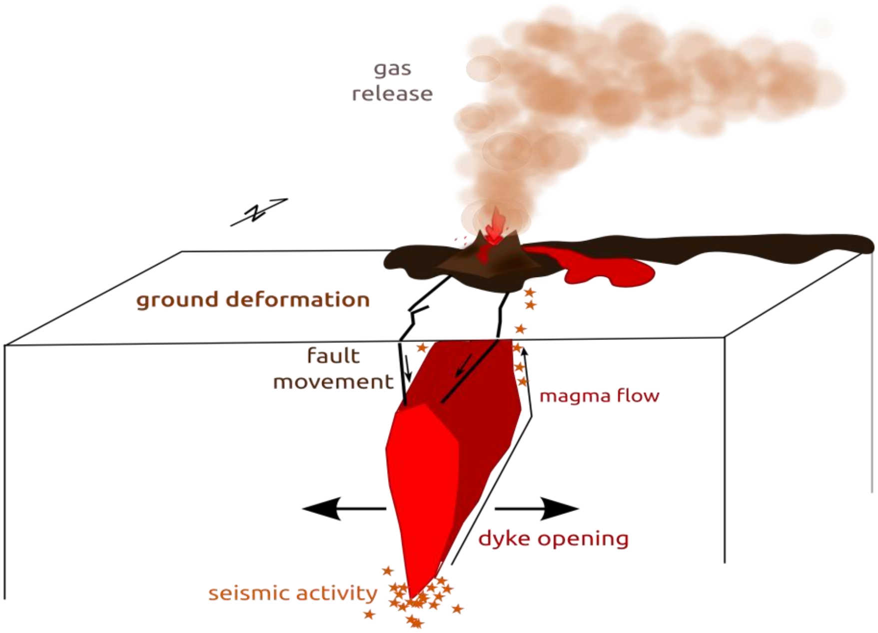



**Figure 1.** A multi-disciplinary approach aimed at improving understanding of the relationship between surface processes (ground deformation, fault movement), processes occurring at depth and associated to the magma transfer (seismicity, dyke opening) and the eruptive activity (plume height, $SO_2$ flux).

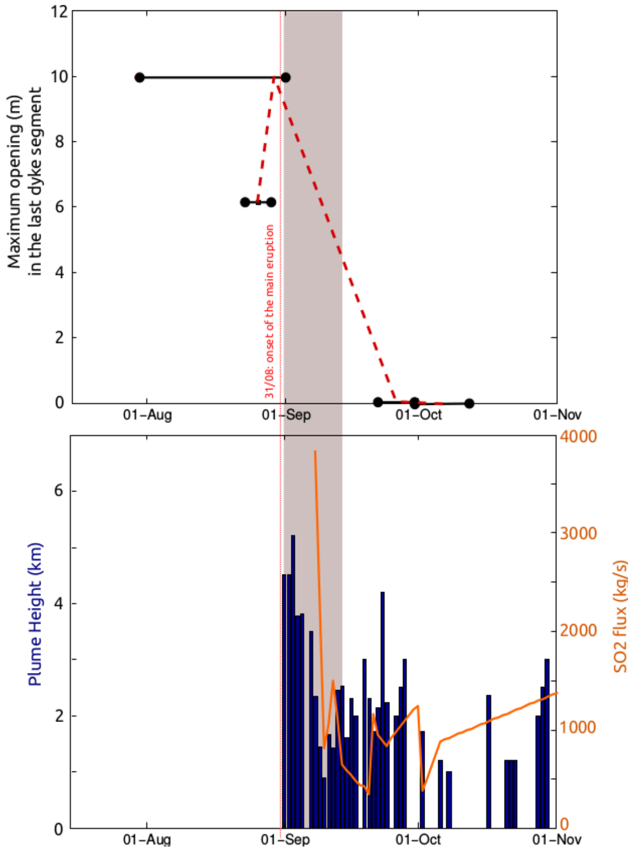



**Figure 2.** (Upper) Maximum opening on individual dyke patch in the northernmost dyke segment as a function of the time, obtained for time periods spanned by the different interferograms. The model used was a dyke with 2×2 km patches (see Nature paper by Sigmundsson et al 2015 for the detailed description of the modelling approach). (Lower) Plume height and $SO_2$ flux. The first measurements of the plume height and the $SO_2$ flux were carried out after the onset of the first eruption (31st August 2014). The time series show clearly significant drops from the beginning until about mid-September for both types of observations.

Finally, a joint model of magma movements has been developed considering all available data. It is reported in the following manuscript that has been submitted for publication:

Magnús T. Gudmundsson, Kristín Jónsdóttir, Andrew Hooper, Eoghan P. Holohan, Saemundur A. Halldórsson, Benedikt G. Ófeigsson, Simone Cesca, Kristín S. Vogfjörd, Freysteinn Sigmundsson, Thórdís Högnadóttir, Páll Einarsson, Olgeir Sigmarsson, Alexander H. Jarosch, Kristján Jónasson, Eyjólfur Magnússon, Sigrún Hreinsdóttir, Marco Bagnardi, Vala Hjörleifsdóttir, Michelle M. Parks, Finnur Pálsson, Thomas R. Walter, Martin P.J. Schöpfer, Sebastian Heimann, Hannah I. Reynolds, Stéphanie Dumont, Eniko Bali, Gudmundur H. Gudfinnsson, Torsten Dahm, Matthew Roberts, Martin Hensch, Joaquín, M.C. Belart, Karsten Spaans, Sigurdur Jakobsson, Gunnar B. Gudmundsson, Hildur M. Fridriksdóttir, Vincent Drouin, Tobias Dürig, Gudfinna Adalgeirsdóttir, Morten S. Riishuus, Gro B.M. Pedersen, Tayo van Boeckel, **Gradual caldera collapse at Bárdarbunga volcano, Iceland, regulated by lateral magma outflow**.

The manuscript describes how a joint model of magma movements in the Bárðarbunga volcanic system 2014-2015 can be used to address the primary question of formation of caldera collapse and its link to an eruption out in a fissure swarm of a volcano. The data sets provide constraints on a fluid flow model coupling drainage of a magma reservoir with associated caldera collapse above, to fluid flow in about 50-km-long subterranean channel established in relation to lateral dyke formation that fed a major eruption far away from the caldera.

The manuscript addresses all the issues of a joint model referred to in the FUTUREVOLC description of work, including the dynamics of fluid flow of magma. Additionally, it includes constraints from petrology and geochemistry not mentioned in the Description of work for the project, that provides additional important observations that have been combined into the model. Further steps can be taken towards a joint model for magma movements, but based on the efforts described above we conclude the deliverable is finished in an acceptable manner.

Progress towards the development of the joint model presented in the manuscript have been reported in a series of conference presentations including:

Magnus Tumi Gudmundsson, Kristín Jónsdóttir, Matthew Roberts, Benedikt G. Ófeigsson, Thórdís Högnadóttir, Eyjólfur Magnússon, Alexander H. Jarosch, Finnur Pálsson, Páll Einarsson, Freysteinn Sigmundsson, Vincent Drouin, Vala Hjörleifsdóttir, Hannah I. Reynolds, Tobias Dürig, Kristín Vogfjörd, Martin Hensch, Joaquin Munoz-Cobo Belart, and Björn Oddsson, **The 2014-2015 slow collapse of the Bárðarbunga caldera, Iceland**, Geophysical Research Abstracts, Vol. 17, EGU2015- 12521, 2015, EGU General Assembly 2015.
http://meetingorganizer.copernicus.org/EGU2015/EGU2015-12521.pdf

Andrew Hooper, Freysteinn Sigmundsson, Sigrún Hreinsdóttir, Elías Heimisson, Benedikt Ófeigsson, Stéphanie Dumont, Michelle Parks, Karsten Spaans, Vincent Drouin, Thóra Árnadóttir, Kristín Vogfjörd, Kristín Jónsdóttir, Hildur Fridriksdóttir, and Martin Hensch, **Deformation modelling of the 2014 Bárðarbunga rifting event in Iceland**, Geophysical Research Abstracts, Vol. 17, EGU2015-11899-5, 2015, EGU General Assembly 2015
http://meetingorganizer.copernicus.org/EGU2015/EGU2015-11899-5.pdf

Andrew J Hooper, Magnus Tumi Gudmundsson, Marco Bagnardi, Alexander H. Jarosch, Karsten Spaans, Eyjólfur Magnússon, Michelle Parks, Stephanie Dumont, Benedikt Ofeigsson, Freysteinn Sigmundsson, Sigrun Hreinsdottir, Torsten Dahm and Kristin Jonsdottir**, Forecasting of flood basalt eruptions: lessons from Bárðarbunga**, Abstract V24B-03, Am. Geophys. Un. Fall meeting, San Francisco, December 2015.
https://agu.confex.com/agu/fm15/meetingapp.cgi/Paper/84358

Kristín Jónsdóttir, Benedikt Ófeigsson, Kristín Vogfjörd, Matthew Roberts, Sara Barsotti, Gunnar Gudmundsson, Martin Hensch, Bergur Bergsson, vilhjálmur Kjartansson, Pálmi Erlendsson, Hildur Friðriksdóttir, Sigrún Hreinsdóttir, Magnús Guðmundsson, Freysteinn Sigmundsson, Thóra Árnadóttir, Elías Heimisson, Vala Hjorleifsdóttir, Jón Soring, Bogi Björnsson, Björn Oddsson and the FutureVolc Partners Team, **Real-time monitoring of seismicity and deformation during the Bárdarbunga rifting event and associated caldera subsidence**, Geophysical Research Abstracts, Vol. 17, EGU2015-13796, 2015, EGU General Assembly 2015.
http://meetingorganizer.copernicus.org/EGU2015/EGU2015-13796.pdf

Kristin Jonsdottir, Kristjan Jonasson, Magnus Tumi Gudmundsson, Martin Hensch, Andrew J Hooper, Eoghan P Holohan**,** Freysteinn Sigmundsson, Saemundur A Halldorsson, Thordis Hognadottir, Eyjólfur Magnússon, Finnur Pálsson, Thomas R Walter, Benedikt Ofeigsson, Michelle Parks, Matthew J Roberts, Vala Hjorleifsdottir, Simone Cesca, Gunnar Guðmundsson, Sigrun Hreinsdottir, Alexander H. Jarosch, Stephanie Dumont, Hildur María Fridriksdóttir, Sara Barsotti and Pall Einarsson, **Communication between earthquake clusters separated by over 30 km supports simple volcano**

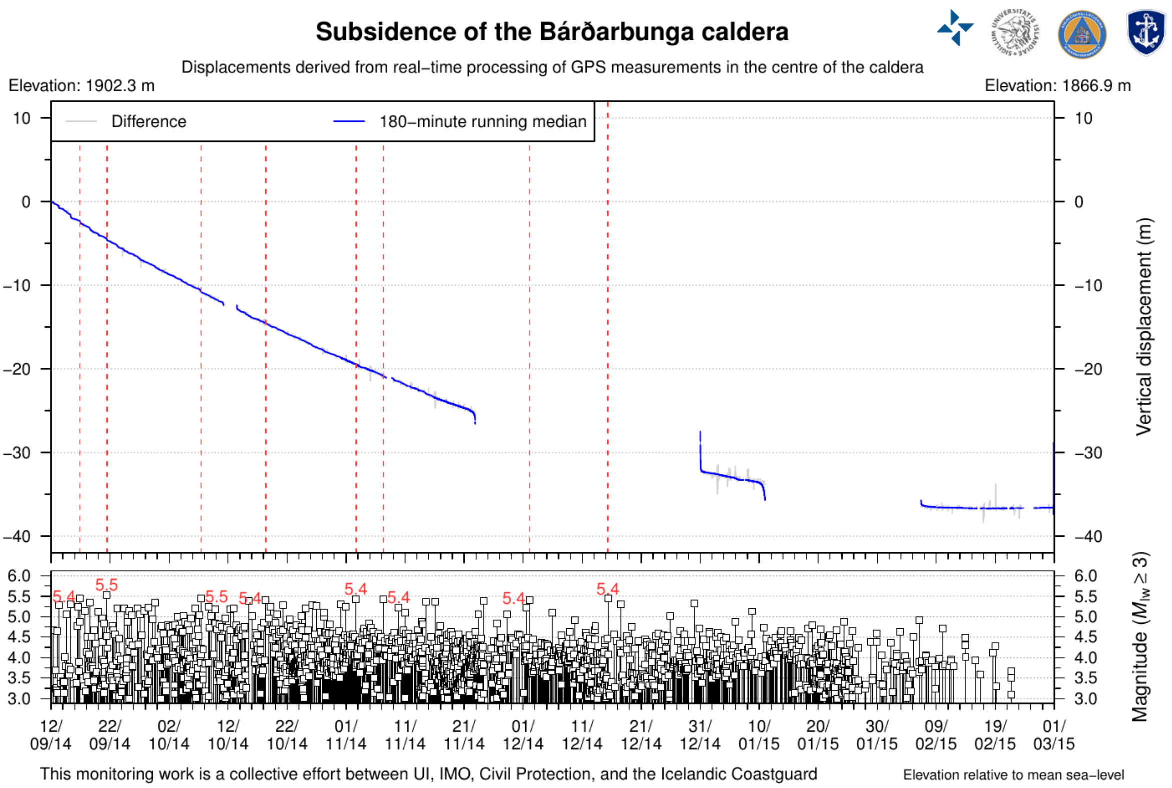
**plumbing**, Abstract S51D-2717, Am. Geophys. Un. Fall meeting, San Francisco, December 2015.
https://agu.confex.com/agu/fm15/meetingapp.cgi/Paper/81185

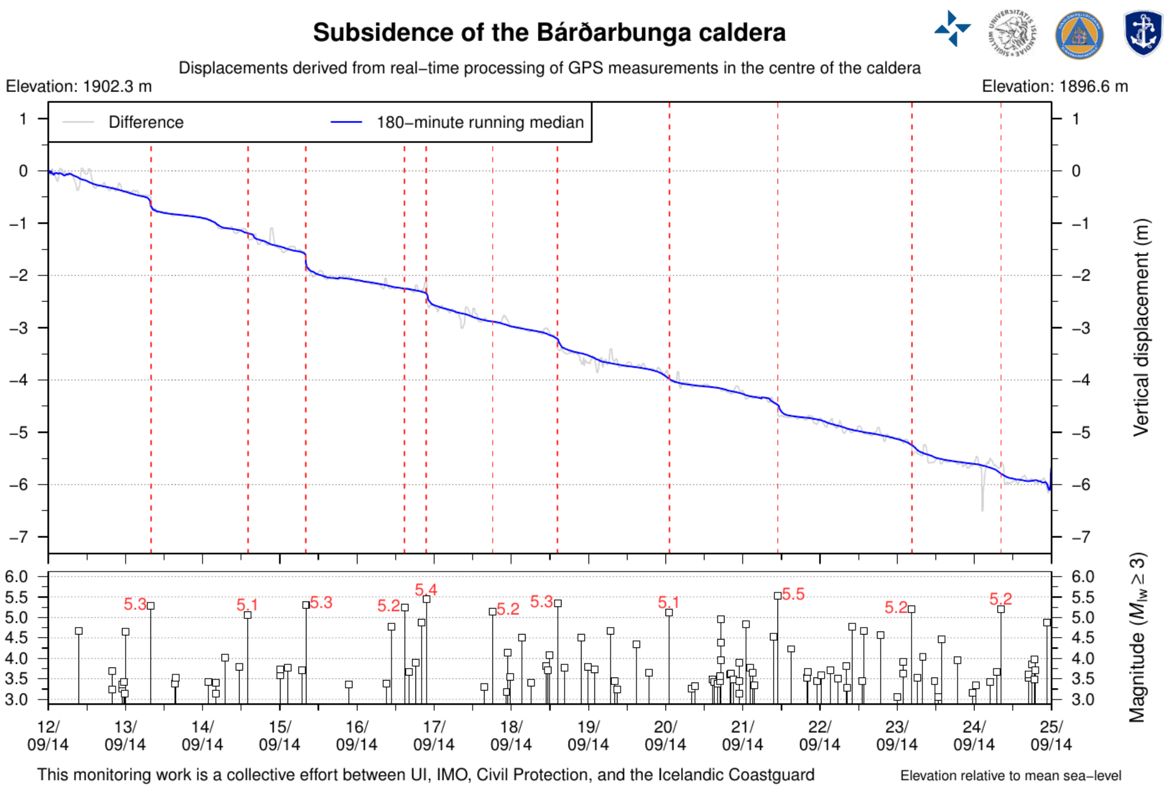
Freysteinn Sigmundsson, Michelle Parks, Stephanie Dumont, Benedikt Ofeigsson, Elias Rafn Heimisson, Vincent Drouin, Andrew J Hooper, Magnus Tumi Gudmundsson, Pall Einarsson, Kristin S Vogfjord, Bryndis Brandsdottir, Kristin Jonsdottir, Hildur María Friðriksdóttir, Sigrun Hreinsdottir, Carolina Pagli, Tim J Wright, Erik C Sturkell and Rikke Pedersen, **Comparison of the Bardarbunga 2014- 2015 rifting event, slow caldera collapse and major effusive eruption with the 1975- 1984 Krafla and 2005-2010 Dabbahu, Afar, rifting episodes** (Invited), Abstract T43H- 05, Am. Geophys. Un. Fall meeting, San Francisco, December 2015.
https://agu.confex.com/agu/fm15/meetingapp.cgi/Paper/60381

Benedikt Ofeigsson, Sigrun Hreinsdottir, Michelle Parks, Hildur María Friðriksdóttir, Freysteinn Sigmundsson, Stephanie Dumont, Thora Arnadottir, Andrew J Hooper, Matthew J Roberts, Ronni Grapenthin, Sui Tung, Gunnar Guðmundsson, Halldor Geirsson, Sigurjon Jonsson, Erik Sturkell, Peter Lafemina, Richard A Bennett, Sara Barsotti, Kristin Jonsdottir and Tim Masterlark, **Deformation derived from GPS geodesy associated with Bárðabunga 2014 rifting event in Iceland**, Abstract T51G- 2998, Am. Geophys. Un. Fall meeting, San Francisco, December 2015.
https://agu.confex.com/agu/fm15/meetingapp.cgi/Paper/80023

Figure 3 (next page) displays part of the unique data set used as input to the joint model of magma movements associated with the Bárðarbunga caldera collapse.

**Figure 3 (next page)**: Vertical displacement derived from GPS station installed on ice in the center of the Bárðarbunga caldera. Upper figure shows the time interval September 12 until the end of the eruption, and the lower spans 12-25 September. From 12 September until the end of the eruption the station subsided 35 m with the rate of subsidence decreasing gradually as the eruption intensity diminishes. At least 25 m of subsidence already occurred prior to the installation of the station. Below the vertical change in each panel is an impulse plot of earthquakes larger then M3 within the caldera. Red dotted lines mark earthquakes larger then M5.  Subsidence jumps of up to 40 cm where observed coinciding with M5 events.


Subsidence of the Bárðarbunga caldera
Displacements derived from real–time processing of GPS measurements in the centre of the caldera
Elevation: 1902.3 m
Elevation: 1866.9 m
Difference
180–minute running median
10
0
−10
−20
−30
−40
Vertical displacement (m)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
Magnitude ($M_{lw} \geq 3$)
5.4
5.5
5.5
5.4
5.4
5.4
5.4
5.4
12/ 09/14
22/ 09/14
02/ 10/14
12/ 10/14
22/ 10/14
01/ 11/14
11/ 11/14
21/ 11/14
01/ 12/14
11/ 12/14
21/ 12/14
31/ 12/14
10/ 01/15
20/ 01/15
30/ 01/15
09/ 02/15
19/ 02/15
01/ 03/15
This monitoring work is a collective effort between UI, IMO, Civil Protection, and the Icelandic Coastguard
Elevation relative to mean sea–level


Subsidence of the Bárðarbunga caldera
Displacements derived from real–time processing of GPS measurements in the centre of the caldera
Elevation: 1902.3 m
Elevation: 1896.6 m
Difference
180–minute running median
1
0
−1
−2
−3
−4
−5
−6
−7
Vertical displacement (m)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
Magnitude ($M_{lw} \geq 3$)
5.3
5.1
5.3
5.2
5.4
5.2
5.3
5.1
5.5
5.2
5.2
12/ 09/14
13/ 09/14
14/ 09/14
15/ 09/14
16/ 09/14
17/ 09/14
18/ 09/14
19/ 09/14
20/ 09/14
21/ 09/14
22/ 09/14
23/ 09/14
24/ 09/14
25/ 09/14
This monitoring work is a collective effort between UI, IMO, Civil Protection, and the Icelandic Coastguard
Elevation relative to mean sea–level