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Temporal Variations in Ground Deformation Caused by Geothermal Processes in the Hengill Area, SW Iceland, During 2009-2019

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ABSTRACT

Fluid extractions and injections at shallow depth in geothermal areas cause deformation of the surrounding crust, which may be observable at the surface. The Hengill volcanic system, SW Iceland, is located at a tectonic triple junction and hosts several high-temperature geothermal systems. The high enthalpy geothermal fluids are harnessed in two geothermal plants, Nesjavellir and Hellisheiði, to provide hot water and electricity since 1990 and 2006, respectively. Both geothermal production fields are associated with local subsidence, up to ~25 mm/yr for Hellisheiði and up to ~20 mm/yr for Nesjavellir. In September 2011, injection of ~500 kg/s of wastewater started in the Húsmúli area, adjacent to the main production area of the Hellisheiði power plant, with the goal of improving the sustainability of the geothermal utilization and reducing surface waste water. During the first few months of injections, swarms of earthquakes were recorded near the injection area and up to 20 mm uplift was detected by InSAR and GPS during 2011 - 2012 measurements (Juncu et al., 2018). Seismicity has continued at lower levels up to present day. In late 2016, the Húsmúli area started to subside, with a total maximum displacement of -30 +/-10 mm within 1 km of the injection sites in the following 2 years despite the continuation of fluid injection. Changes in rates of extraction and injection of fluids, as well as changes in the location of production and injection wells affects the spatial and temporal deformation in the Hellisheiði and Nesjavellir geothermal fields since the respective start of their production. New wells have been drilled since 2016 in Hverahlíð, a few km south-east of the main Hellisheiði production field. This expansion of the production area, and plate spreading processes, further complicate the observed deformation pattern of the south-western area of Hengill. We present here the temporal and spatial variations in ground deformation near the extraction and production areas of the Nesjavellir and Hellisheiði geothermal power plants during 2009 to 2019. Geodetic data reveal alternating local ground uplift and subsidence motions between 2011 and 2019 in the Húsmúli injection field, as well as a gradual subsidence of the surface in the new Hverahlíð production field. InSAR and GNSS data combined with borehole measurements provide clues to the properties of geothermal systems (e.g. thermal contraction and pore-pressure changes) and the hydrothermal processes that may affect the geothermal systems in Hengill. This study shows the importance of surface deformation studies to observe and understand the long-term dynamic behavior of geothermal systems.

1. INTRODUCTION

Extraction and injection of geothermal fluids in high temperature geothermal fields can be associated with ground deformation (e.g. Krafla, Reykjanes, Hengill; Drouin et al. 2017, Juncu et al. 2017, Juncu et al. 2020, Parks et al. 2020). The Hengill area (Figure 1) is the locus of high temperature geothermal systems that are harnessed in two main localities, Nesjavellir and Hellisheiði. The area is at a triple junction, with two active volcanic systems (Hengill - peaking at 803 m a.s.l. - and Hrómundartindur), and presents a complex ground deformation pattern observable via geodetic methods. Natural tectonic deformation processes observed in the area range from plate motions (Árnadóttir et al. 2009) to M_w6 earthquake ruptures (Decriem et al. 2010). Additionally, deep-seated sources of uplift (1993-1999 (Feigl et al. 2000), 2017-2018 (Ducrocq et al. *in prep*)) and subsidence episodes (Juncu et al. 2017), induce broad scale motions across the whole area. However, recent geodetic studies (e.g. Juncu et al. 2017, 2020), reveal significant ground motions associated with the extraction and injection of fluids within the geothermal fields of the area. The production started in 1990 in Nesjavellir, North of the Hengill central volcano, to provide hot water for the neighboring city of Reykjavík and from 1998 also electricity. In 2006, the Hellisheiði geothermal power plant, SW of Hengill, started harnessing the geothermal power for electricity and hot water production. Since then, both power plants have expanded their capacities and main extraction fields of geothermal fluids. Juncu et al. (2017) related the observable subsidence (up to ~ 2.5 cm/yr in Hellisheiði and ~ 2 cm/yr in Nesjavellir) to pore-pressure changes in the geothermal reservoirs. To increase the sustainability of the geothermal exploitation in the Hellisheiði power plant, geothermal waste water is injected back into the reservoir. In the beginning, injection took place in the Gráuhnjúkar area, SW of the power plant, but from September 2011 injection has also taken place in the Húsmúli area, NW of the Hellisheiði geothermal plant. A short-lived uplift (reaching ~2 cm/yr) and thousands of earthquakes followed the start of injection of geothermal fluids into Húsmúli in September 2011 (Juncu et al. 2020). The capacity of the Hellisheiði power plant was further expanded in 2016, with the start of production in the Hverahlíð locality. Our study show, using long-term geodetic data sets, the average long term deformation and potential shorter term motions of the area, demonstrating dynamic sources of anthropogenic deformation during 2009-2019.

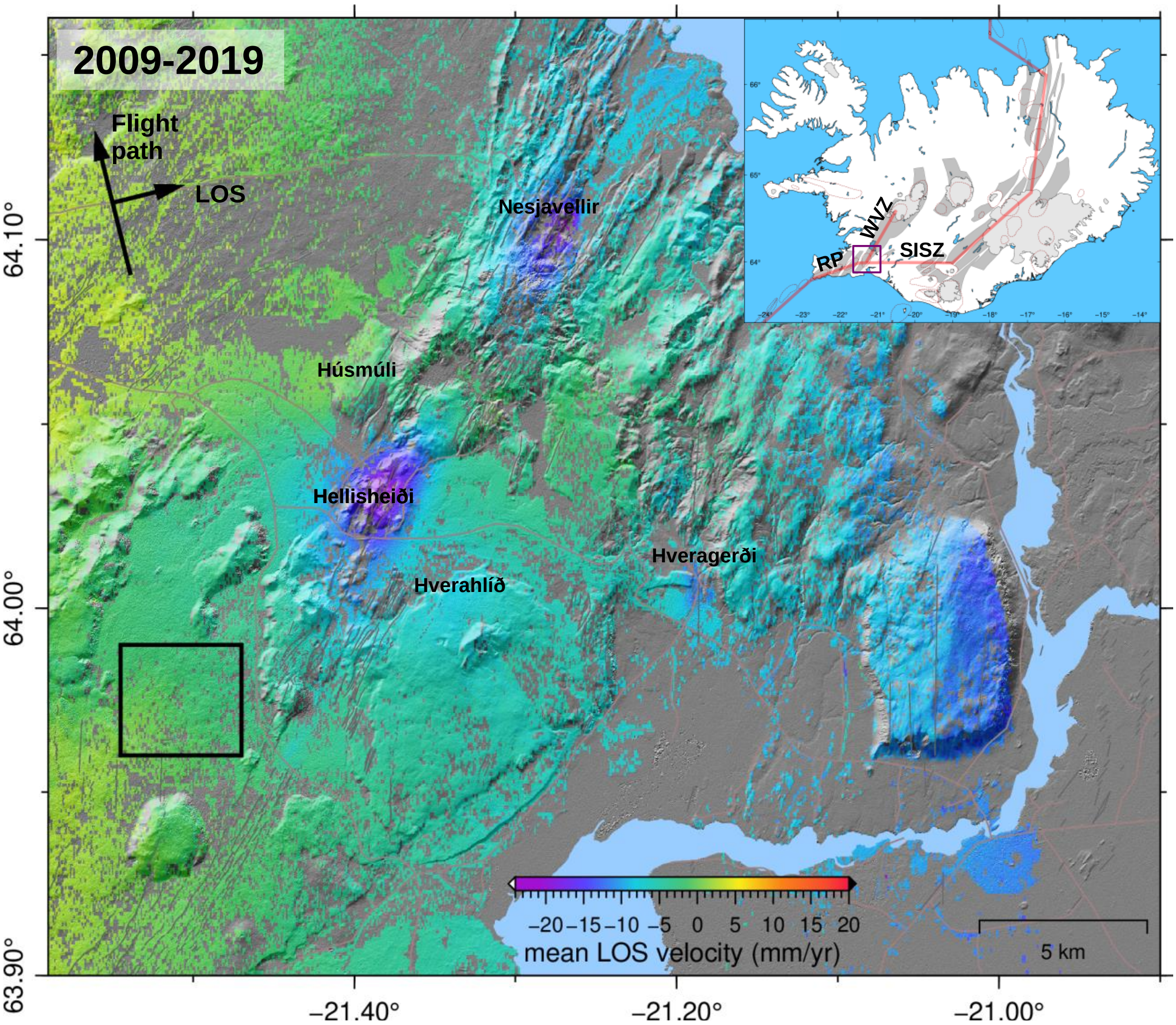

Figure 1: Mean line-of-sight (LOS) InSAR velocities over the Hengill area, SW Iceland, between 2009 and 2019 (shown with the color scale) from TerraSAR-X satellite track T41. The velocities have been corrected for plate motions and a deep-seated subsidence source (Árnadóttir et al. 2009; Juncu et al. 2017). The main extraction fields of the area, Nesjavellir and Hellisheiði, are associated with localized subsidence up to 25 mm/yr. The deformation is plotted relative to average of motions in the area outlined by the black box. The black arrows indicate the flight path and line-of-sight (LOS) of the TerraSAR-X satellite for track T41. Faults, fractures and fissure swarms are annotated using grey lines (Einarsson, 2008; Hjaltadóttir, 2009; Steigerwald, 2018). Inset: Simplified map of Iceland. The location of the Hengill area is shown with a purple box at the junction of the Reykjanes Peninsula (RP), Western Volcanic Zone (WVZ) and South Iceland Seismic Zone (SISZ). The red lines indicate a simplified plate boundary (Árnadóttir et al. 2009).

2. DATA AND METHODOLOGY

To study the temporal deformation of the Hengill area during 2009-2019, we use all available geodetic data. The spatial coverage from Interferometry Synthetic Aperture Radar (InSAR) analysis has the advantage to show clearly large and smaller deformation signals over the study area but is temporally limited by the number of SAR images acquired per year (4 or less), while a continuous GPS time series can reveal daily temporal variations of the ground motions at a benchmark.

2.1 Interferometric Synthetic Aperture Radar (InSAR)

To study the overall long term and yearly temporal variations of the deformation over the Hengill area, we use the 2009-2019 Synthetic Aperture Radar (SAR) data sets of the X-band right-looking TerraSAR-X satellite. Here, we use only SAR data from the ascending track T41, as it has the best spatial and temporal coverage (1 – 4 images per year) of the Hengill area, during the time we wish to study. See Juncu et al. (2017) for more details on the satellite and the track T41 used in our analysis. Most of the SAR images are acquired in the summer (May – September) when the ground is snow-free, however, some of the early images of our data sets (e.g. 2009, 2011, 2013) are taken in late autumn (October – November) and are more susceptible to be affected by poor atmospheric or ground conditions. To increase the signal to noise ratio of our yearly mean LOS velocity plots, we opt to use the Small-Baseline approach of the StaMPS software (Hooper, 2008). Initial interferograms are generated using DORIS (Kampes et al. 2003) and corrected for topographic effects according to the intermediate resolution digital elevation model from TanDEM-X. We applied options in the processing to select pixels with high signal to noise ratio in the aim to limit noise related to vegetated areas. We reduced the size of the unwrapping grid to avoid phase jumps in our resulting time series. This is relevant to study the narrow but high amplitude ground motion at the Nesjavellir geothermal field which is located between hyaloclastite ridges. Between the 80 interferometric pairs generated during the process, we then select pairs presenting the least atmospheric disturbances and orbital ramps to estimate the mean LOS velocities for each year. This selection is limited to the number of interferometric pairs available per year (which varies between 1 and 19 per year). All our time series are referred to the Geitafell area, which we consider to be relatively stable over time and not affected by the anthropogenic deformation that we plan to analyze here (black box in Figure 1).

As our interest lies in studying the deformation linked to geothermal extraction and injection in Nesjavellir and Hellisheiði, we correct the data for plate motions (Árnadóttir et al. 2009) by removing the model-predicted LOS from the mean velocity plots. We also correct each velocity plot for the deep-seated source of subsidence in eastern of Hengill, modeled according to the parameters of Juncu et al. (2017). The correction for the 2017-2018 mean LOS velocity plot is more complex as we correct for the part of the aforementioned deep-seated subsidence as well as a ~5-month deep seated uplift in the same locality, as per the methodology in Ducrocq et al. (*in prep*).

2.2 Global Positioning System (GPS)

The 2009 – 2019 ground deformation in the Hengill area is observable via 7 continuous GPS sites. In this paper, we focus on the analysis of a continuous time series from a single GPS site (HUSM) to observe temporal variations in ground motions in Húsmúli. Continuous GPS measurements (cGPS) here refer to instruments continuously recording the positions of benchmarks over a designated period time (years). These measurements give insights into the potentially short-term temporal ground motions, that may be difficult to observe with a more temporally sparse data set (e.g. the InSAR T41 track from TerraSAR-X analyzed in this paper). We use the GAMIT/GLOBK suites of programs (Herring et al. 2015) to process our GPS data sets of the Hengill area and generate time series between 2009 and 2019. The 24 hours solutions are determined in the ITRF14 reference frame (Altamimi et al. 2016) using global and Icelandic reference stations from which we then estimate the station positions and velocities.

We extend the time series at HUSM cGPS station, with campaign data from an adjacent benchmark (HH25). We estimate the seasonal and constant velocities for each component of the HUSM cGPS station between March 2012 – January 2017 and use these estimates to detrend the full 2009 – 2019 time series for our analysis. This allows us to observe the temporal ground deformation in Húsmúli with limited influence of plate motion, seasonal snow load and other constant linear and cyclic processes.

3. RESULTS AND DISCUSSION

In Figure 1 we present the 2009-2019 mean line-of-sight (LOS) velocities over the Hengill area, corrected for plate motions and a deep source of deformation (Juncu et al. 2017). This figure is not corrected for the short-lived uplift in 2017-2018 of the area (Ducrocq et al. *in prep*), as the amplitude of this uplift is relatively minor compared to long-term ground deformation of the area. This figure presents the overall long-term ground deformation of the Hengill area from anthropogenic sources in the two main geothermal fields of the area, Nesjavellir and Hellisheiði. A small deformation signal (subsidence rate of ~12 mm/yr) is also observable near the town of Hveragerði (Figure 1). The small extent of the deformation signal (~1 km) indicates a possible shallow contracting source, likely linked to localized harnessing of geothermal fluids. The difference of LOS motions (~5 mm/yr) observable between the eastern and western side of Ingölfsfjall (mount East of Hveragerði; Figure 1) may be indicative of small motions on faults, although it is likely caused by topographic or atmospheric errors resulting from our InSAR processing.

Errors from atmospheric disturbances and topographic errors in the individual (or yearly; Figure 2) mean LOS velocities series can reach ~20 – 25 mm/yr and our results should thus be accordingly taken with caution. Time series prior to 2015 are created with 5 or less interferometric pairs, and more prone to orbital errors and atmospheric delays in our resulting time series (e.g. 2012-2013). Our corrected time series in 2016-2017 and 2018-2019 both show little deformation at the Hellisheiði geothermal plant. This might, for example, be linked to an over-correction of the deep subsidence in the eastern part of the Hengill area. The parameters of the forward model used to correct the eastern subsidence in the area (described in Juncu et al. 2017) were estimated during 2012-2015. This may not accurately represent the motions during other time spans. Additionally, the plate motion model used to correct for the yearly horizontal displacements in each of the time series, results from the GNSS analysis of Árnadóttir et al. (2009) over the time span of 1993-2004. This model may thus not fully represent the plate motions during 2009-2019. The InSAR results presented here do not represent pure vertical motions, as they are in the LOS of the satellite. As the TerraSAR-X satellite follows near-polar trajectories, the mean LOS velocities presented here are mainly influenced by Vertical or East-West surface motions and little influenced by North-South surface motions.

We decide to not include in this paper the year-to-year mean LOS velocities for the years 2009-2010, 2010-2011 and 2013-2014, as we judge the results not reliable for this paper. This is mainly caused by the very few numbers of images available for these years due to large atmospheric disturbances and orbital ramps. However, we estimate that the mean LOS velocities for 2011-2012, 2012-2013, 2014-2015, 2015-2016, 2017-2018 and 2018-2019 are reliable. They are presented in Figure 2. Below, we detail further analysis and results on our main areas of interests, namely the extraction and injection zones within the geothermal fields of the Hengill area.

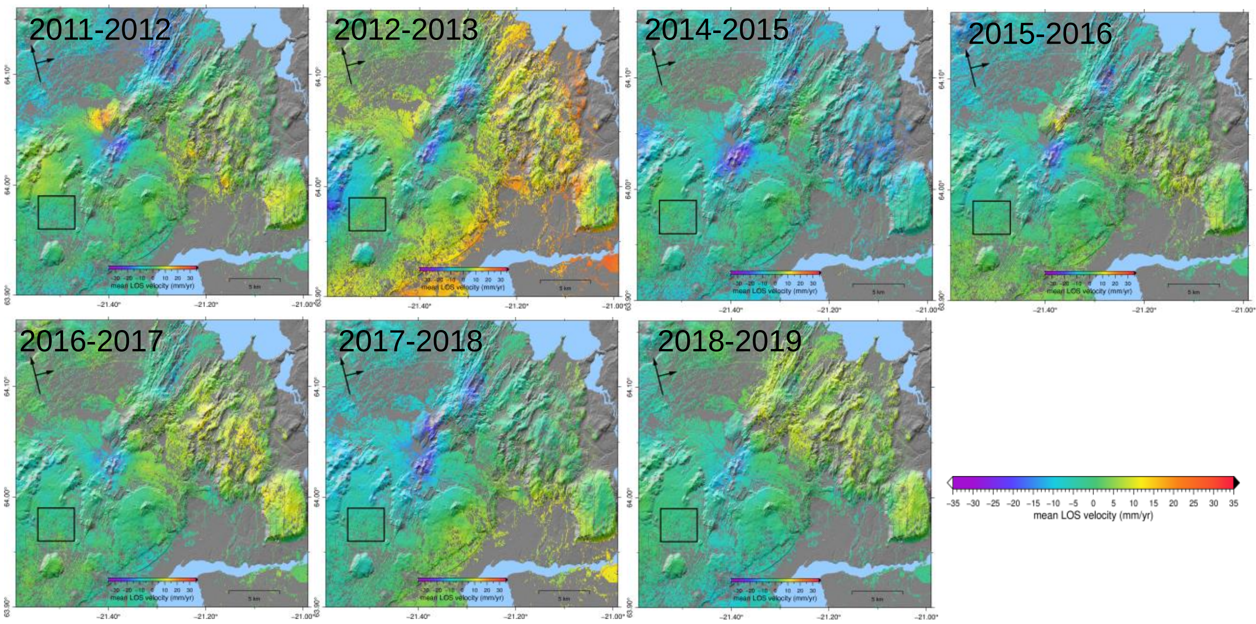

Figure 2: Yearly mean LOS velocities over the Hengill area from TerraSAR-X satellite (T41). The velocities were corrected for plate motions (Árnadóttir et al. 2009) and a deep source of deformation (Juncu et al. 2017, Ducrocq et al. *in prep)* to highlight the ground deformation resulting from anthropogenic sources. The scale ranges from -35 mm/yr (purple) to 35 mm/yr (red), negative values signify that the ground is moving away from the satellite (i.e. subsidence and/or east motion). The black arrows show the flight path and look direction of satellite. Black boxes outline the reference area (Geitafell) of our time series.

3.1 Nesjavellir

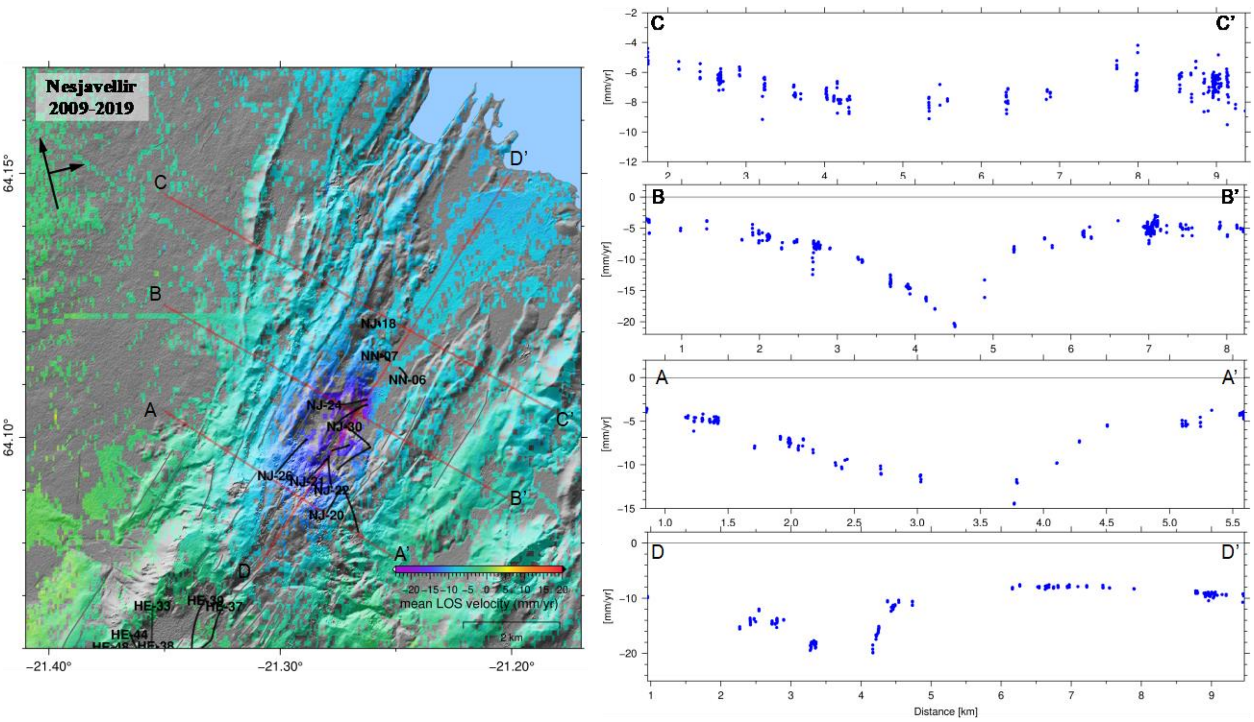

Figure 3: Left: Close-up of the Nesjavellir geothermal field. Mean LOS 2009-2019 velocity plot extracted from Figure 1. Black lines show well trajectories. Right: Profiles across the mean 2009-2019 LOS velocity plot.

The ground deformation between 2009-2019 at the Nesjavellir geothermal field is located in a graben-like structure between steep hyaloclastite ridges. The ground deformation pattern seems to be elongated in the NNE-SSW direction, similarly to the azimuth of the surrounding ridges. The maximum value of the subsidence rate is ~ 20 mm/yr, according to the mean LOS velocities of 2009-2019 (Figure 3). The ground deformation of the area seems to be closely linked to the western ridges rather than being within the center of the graben area, and is approximately 4 km wide (NW-SE) and extends for ~5 km (NE-SW). The area with significant ground deformation correlates closely with the main borehole extractions of the Nesjavellir geothermal plant.

The NNE-SSW profile (D-D’ in Figure 3) highlights the possible asymmetry of the ground deformation. A steeper gradient in the subsidence rates at the North of the geothermal field is clearly observable. This may be related to the choice in profile’s location or anthropogenic geothermal processes: changes in production and injection rates in the boreholes over our studied time span, as well as more inherent properties of the local geothermal field (e.g. changes in permeability, pressure-temperature).

3.2 Hellisheiði

The maximum subsidence rate of the Hellisheiði geothermal field according to the mean LOS velocity plot between 2009 and 2019 is around 25 mm/yr (see Figure 4). Our individual yearly times series shows slightly less subsidence rates with ~20 mm/yr. However, as the time span of these individual plots is limited to a year and result from 1-4 (prior to 2015) or 5-19 (after 2015) interferometric pairs, they have larger (reaching ~10 mm/yr) uncertainties on their individual mean LOS velocities. Overall, the subsidence rates in the longest utilized extraction area of the Hellisheiði geothermal field between 2011 and 2019 seems to be relatively constant (within the uncertainties and limitations of the method). Ground motions in the vicinity of the main extraction area (e.g. Húsmúli, Hverahlíð) as well as natural ground motions may influence the overall subsidence rates described here. The main area of subsidence is ~ 7 km wide and stretches in the NNE-SSW direction, in corresponding with the trend of the fissure swarms of the area. The ground deformation seems to stretch several kilometers south of the main extraction field, albeit with significantly smaller deformation rates (~-5 mm/yr; as can be observed by the A-A’ profile in Figure 4). Other profiles displayed in Figure 4 illustrate interesting asymmetry of the average ground deformation of the area, with a steeper gradient of deformation on the east of the area of subsidence relative to the western side.

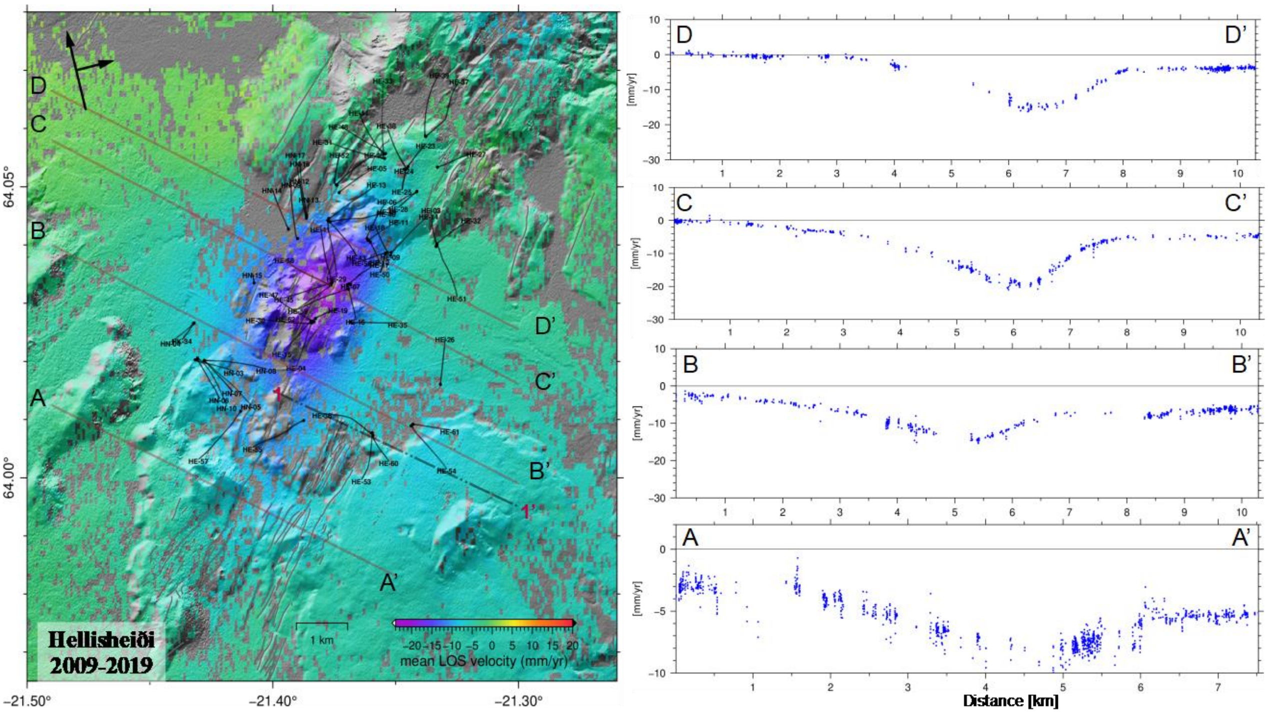

Figure 4: Left: Close up of the Hellisheiði geothermal field. Mean LOS 2009-2019 velocity plot extracted from Figure 1. Black lines show well trajectories. Right: Profiles across the mean 2009-2019 LOS velocity plot.

In 2016, extraction at the Hellisheiði geothermal plant was expanded to a new field, Hverahlíð, SE of the main production field of the area (Figure 1). Slight inflections in the mean 2009-2019 LOS velocities east of the main Hellisheiði subsidence area (Profile B-B’ in Figure 4), indicate possible slow deformation in the Hverahlíð geothermal field. This new local subsidence signal is more clearly visible in Figure 5, with an increase of ~5 mm/yr in subsidence rate in the area compared to rates prior to start of the exploitation of this area.

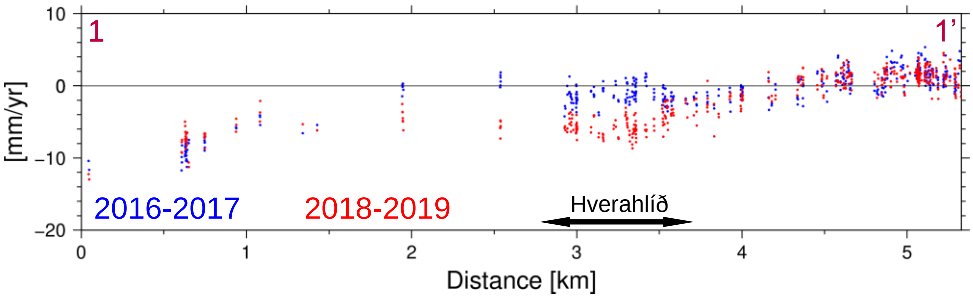

Figure 5: Profiles across the mean LOS velocity plot of 2016-2017 (blue) and 2018-2019 (red) crossing Hverahlíð. The profile location is shown in Figure 4 and the original velocity plots are shown in Figure 2. This figure highlights the increase of the subsidence rate in the Hverahlíð area since the start of the extraction in the area in 2016.

3.3 Húsmúli

The time series analysis of Húsmúli highlights the complex ground deformation of the area. Figure 2 presents successive episodes of deformation of the area, with possibly three uplift episodes between 2011-2012, 2013-2014 and 2015-2016. The 2011-2012 uplift episode in the western part of Húsmúli has been extensively studied in Juncu et al. (2020) and is linked to the start on the injection of geothermal fluids in the area. The InSAR data sets (Figure 2 and Figure 6b) presented here show the 2011-2012 uplift of the area. The Húsmúli continuous GPS station (HUSM) shows ~20 mm of westward motion during this uplift episode, i.e. away from the center of uplift. Notably, a similar shift towards west of HUSM can be observed between 2013-2014 and 2015-2016 (Figure 6c). This may indicates additional uplift episodes in the Húsmúli area. The short reversal of eastern motions could also be induced by more complex processes or limitations in the estimation of seasonal motions of HUSM. The profiles across the 2011-2012 and 2015-2016 mean LOS velocities (Figure 6a and 6b) highlight the disparity between the locus of maximum LOS amplitude of the uplifts (2011-2012: ~20 mm/yr; 2015-2016: ~17mm/yr). The wavelength of the 2015-2016 uplift signal seems to be about 4 km and the peak of the maximum motions of the ground towards the satellite seems to be located ~2 km east of the peak from the 2011-2012 uplift. This indicates that different sources are at the origin of the different uplift episodes. The changes in the deformation pattern (subsidence vs uplift) are most likely related to changes in production and injection in the Húsmúli area. As the line of sight of the satellite is a combination of horizontal and vertical motions, it is complex to deduce the amplitude of the 2015-2016 uplift episode using the InSAR data sets presented here. The subsidence episodes may be related to changes in production and injection in the Húsmúli geothermal field (e.g. increase in production and decrease in injection) or may be linked to changes within the vicinity of the Húsmúli geothermal field (e.g. possible increase of production in the main Hellisheiði geothermal field). The observed changes can also be linked to more complex inherent properties of the dynamic geothermal system of the area, such as changes in pore-pressure, permeability, flow rates or cooling of the geothermal system.

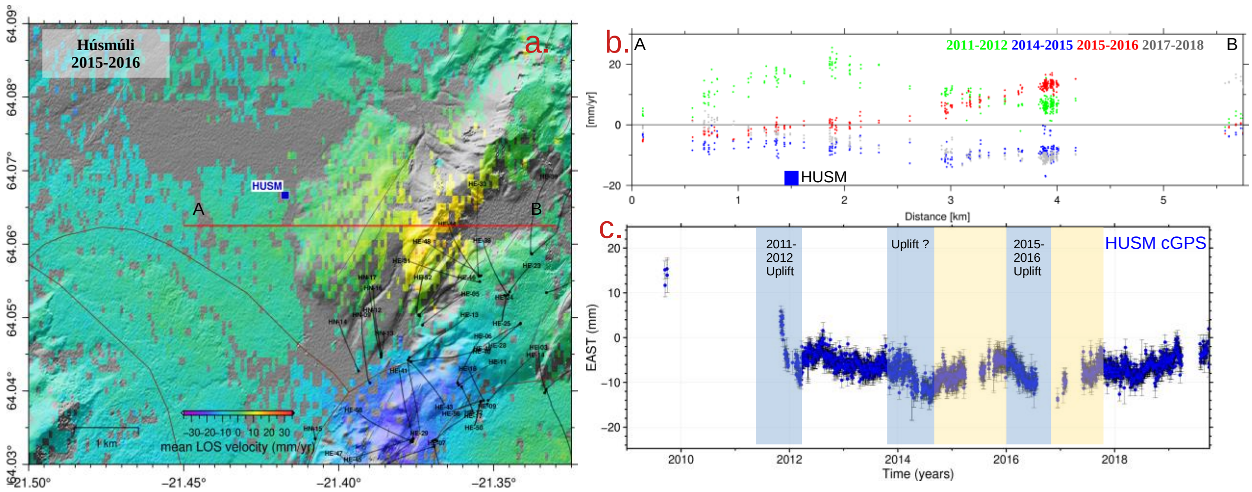

Figure 6: (a.) Close-up of the mean LOS velocities between 2015-2016 over the Húsmúli area, NW of the Hellisheiði extraction field extracted from the global mean LOS velocity plot of the same year (Figure 1). Main borehole traces and well heads are indicated using black lines. Main roads are indicated using brown lines. (b.) Color coded profiles across the mean LOS velocities plot of 2011-2012, 2014-2015, 2015-2016 and 2017-2018. The profile location is shown in (a.) via a red line. The blue square indicates the location of Húsmúli cGPS, also shown in (a.) (c.) 2009-2019 East component of the detrended time series of the HUSM continuous GPS station (cGPS). The location of the continuous GPS station is shown in (a.). Blue background highlights episodes of westward motion of HUSM, indicating possible uplift east of the station, in the vicinity of Húsmúli. The yellow background highlights episodes of eastward motion of HUSM, indicating possible subsidence of the Hśmúli area.

4. CONCLUSIONS

We analyze the ground deformation of the Hengill area between 2009-2019. The average mean velocities during this time span highlight localized subsidence associated with geothermal extraction of fluids at the Hellisheiði and Nesjavellir geothermal plants reaching amplitude up to ~25 mm/yr and ~20 mm/yr respectively. Yearly analysis of the mean LOS ground motions between 2011-2019 shows little variation in subsidence rates at both main extraction fields, within the uncertainties of the methods and associated corrections. However, clear temporal variations were observable at the Húsmúli injection field, NW of the Hellisheiði extraction field. The 2015-2016 uplift episode seems to reach an amplitude of ~15 mm/yr in the LOS of our satellite, a rate less than the prior known uplift of the area (2011-2012, ~2 cm/yr; Juncu et al. 2020). The location of this uplift seems to be a few kilometers East of the main deforming area of 2011-2012. Based on the continuous GPS time series, we suggest that additional uplifts (or horizontal motions) may also have happened in the Húsmúli area in 2013-2014 and 2015-2016. From GNSS and InSAR data, the Húsmúli area seems to have been the locus of subsidence episodes between 2014-2015 and 2016-2018. These uplifting and subsiding motions may be attributed to changes in injection in Húsmúli or its vicinity, or may reflect more complex inherent processes of the geothermal systems (e.g. changes in flow paths, cooling, permeability). More integrative analysis is needed to understand the episodic motions observed in the Húsmúli area. Since the start of production in the Hverahlíð geothermal field in 2016, SE of the Hellisheiði geothermal area, we observe a slight increase in subsidence rates (~5 mm/yr). Overall, our study highlights the spatial and temporal complexities that can be expected in changing geothermal production over large and geologically complex areas.

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REFERENCES

Altamimi, Z., Rebischung, P., Métivier, L., Collilieux, X.. Itrf2014: A new release of the international terrestrial reference frame modeling nonlinear station motions. *Journal of Geophysical Research: Solid Earth*, (2016) ;121(8):6109–6131.

Árnadóttir, T., Lund, B., Jiang, W., Geirsson, H., Björnsson, H., Einarsson, P., Sigurdsson, T.: Glacial rebound and plate spreading: Results from the first countrywide GPS observations in Iceland. *Geophysical Journal International* 177, (2009), 691–716.

Decriem, J., Árnadóttir, T., Hooper, A., Geirsson, H., Sigmundsson, F., Keiding, M., Ófeigsson, B.G., Hreinsdóttir, S., Einarsson, P., LaFemina, P., Bennett, R.A.: The 2008 May 29 earthquake doublet in SW Iceland. *Geophysical Journal International* 181, (2010), 1128–1146.

Drouin, V., Sigmundsson, F., Verhagen, S., Ófeigsson, B.G., Spaans, K., Hreinsdóttir, S.: Deformation at Krafla and Bjarnarflag geothermal areas, Northern Volcanic Zone of Iceland, 1993–2015. *Journal of Volcanology and Geothermal Research* 344, (2017) , 92–105.

Einarsson, P.: Plate boundaries, rifts and transforms in Iceland. *Jokull*, (2008); 58: 35–58.

Feigl, K.L., Gasperi, J., Sigmundsson, F., Rigo, A.: Crustal deformation near Hengill volcano, Iceland 1993-1998: Coupling between magmatic activity and faulting inferred from elastic modeling of satellite radar interferograms. *Journal Geophysical Research* 105, (2000), 25655–25670.

Herring, T., R. W. King, M. A. Floyd, and S. C. McClusky: Introduction to GAMIT/GLOBK, release 10.6, *Tech. Rep.*, Mass. Inst. Technol., Cambridge, Mass (2015).

Hjaltadóttir, S.: Use of relatively located micro- earthquakes to map fault patterns and estimate the thickness of the brittle crust in Southwest Iceland. *Master's thesis*, Faculty of Earth Sciences, University of Iceland, Reykjavík, Iceland (2009).

Hooper, A.J.: A multi-temporal InSAR method incorporating both persistent scatterer and small baseline approaches. *Geophysical Research Letters* 35 (2008).

Juncu, D., Árnadóttir, T., Hooper, A., Gunnarsson, G.: Anthropogenic and natural ground deformation in the Hengill geothermal area, Iceland. *Journal of Geophysical Research: Solid Earth* 122, (2017), 692–709.

Juncu, D., Árnadóttir, T., Geirsson, H., Guðmundsson, G.B., Lund, B., Gunnarsson, G., Hooper, A., Hreinsdóttir, S., Michalczewska, K.: Injection-induced surface deformation and seismicity at the Hellisheidi geothermal field, Iceland. *Journal of Volcanology and Geothermal Research* (2020).

Kampes, B. M., Hanssen, R. F. and Perski, Z.: Radar interferometry with public domain tools, paper presented at 3rd International, Workshop on ERS SAR Interferometry, 'FRINGE03', p. 6, Frascati, Italy (2003).

Parks, M., Sigmundsson, F., Sigurðsson, Ó., Hooper, A., Hreinsdóttir, S., Ófeigsson, B., Michalczewska, K.: Deformation due to geothermal exploitation at Reykjanes, Iceland, *Journal of Volcanology and Geothermal Research*, Volume 391, (2020), 106438, ISSN 0377-0273.

Steigerwald, L., Einarsson, P., Hjartardóttir, Á.R.: Fault kinematics at the Hengill Triple Junction, SW-Iceland, derived from surface fracture pattern. *Journal of Volcanology and Geothermal Research*, (2018).

Wessel, P., Luis, J.F., Uieda, L., Scharroo, R., Wobbe, F., Smith, W.H.F., Tian, D.. The generic mapping tools version 6. *Geochemistry, Geophysics, Geosystems*, (2019) ;20(11):5556–5564