Landsvirkjun

Lv-2023-005

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InSAR monitoring of Krafla, Bjarnarflag and Þeistareykir geothermal areas 2022 update

InSAR monitoring of Krafla, Bjarnarflag and Þeistareykir geothermal areas
2022 update

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Útdráttur

Synthetic Aperture Radar Interferometry (InSAR) of Sentinel-1 images was used to estimate the deformation at Krafla, Bjarnarflag and Þeistareykir geothermal fields between summer 2021 and summer 2022. Line-of-sight (LOS) velocity fields were calculated for three Sentinel-1 tracks covering the areas: two descending (T9 and T111) and one ascending (T147).
The Krafla caldera is relatively stable. Between 2021-2022 is detected a small uplift (< 5 mm) in western part of Krafla caldera and small subsidence near Hvíthólar. The deformation pattern at Hvíthólar correlates strongly with production from borehole KJ-21. When comparing deformation between 2015-2018 and 2018-2022 the main signal is a ~5 mm caldera uplift pattern centred around Leirhnjúkur.
At Bjarnarflag subsidence is ~6 mm/yr as has been observed since InSAR measurement started in the early 1990’s.
At Þeistareykir, the subsidence that started after the onset of production is continuing within the geothermal field. The subsidence between Bæjarfjall and the power station is <5 mm/yr with a local maximum of ~10-15 mm/yr in a 400 m x 800 m large area centred at the re-injection wells.

Lykilorð InSAR, ground deformation, Krafla, Þeistareykir, Bjarnarflag, Hvíthólar, geothermal fields

Samþykki verkefnisstjóra Landsvirkjunar

Anette K. Mortensen

InSAR monitoring of Krafla, Bjarnarflag and Þeistareykir geothermal areas.

2022 update

Prepared for Landsvirkjun

Vincent Drouin

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Contents

Glossary

ascending orbit When the satellite moves from south to north direction.

descending orbit When the satellite moves from north to south direction.

GNSS [Global Navigation Satellite System] Constellation of satellites providing positioning on a global basis. For instance, GPS.

InSAR [SAR interferometry] Technique consisting in looking at the phase difference between two SAR acquisitions to get information about the ground motion.

LOS [Line-of-sight] InSAR provides deformation measurements along the line-of-sight of the SAR satellite. This means these are one-dimensional deformation measurement, away or toward the satellite, unlike for instance GNSS measurements which are three-dimensional (East, North, Up).

near-East Estimation of the deformation along the East direction, derived from combining multiple LOS deformation.

near-Up Estimation of the deformation along the Up direction, derived from combining multiple LOS deformation.

SAR [Synthetic Aperture Radar] Technique consisting in using the motion of the radar instrument to improve resolution.

1 Introduction

Krafla and Þeistareykir are two active volcanic systems located in the northern part of the Northern Volcanic Zone in Iceland. There are active geothermal fields within both system. These geothermal fields are currently utilised by Landsvirkjun, the National Power Company of Iceland, to produce electricity and direct heating.

The Krafla power station began production in August 1977 with an initial capacity of 30 MW which was extended to 60 MW in 1999. The Bjarnarflag power station, located 8 km SW of the Krafla power station, has been in service since 1969 and has a capacity of 5 MW since 2019 (3 MW earlier). Both power stations are located along the same fissure swarm. A large rifting event with multiple dike intrusions took place within the Krafla volcanic system from 1975 to 1984 (Einarsson, 1991). A magma reservoir located beneath Leirhnjúkur, in the center of the caldera, inflated and deflated multiple time during this event. Following the end of the Krafla Fires in 1984, the magma chamber continued to inflate until 1989. It then started to deflate at a fast rate that quickly slowed down until no movements were visible in the late 1990's (Sturkell et al., 2008). From then on until 2018, the deformation in the area was dominated by subsidence within the Krafla and Bjarnarflag geothermal fields and by subsidence along the fissure swarm (Drouin et al., 2017). Between summer 2018 and summer 2020 a $\sim$11 mm/yr uplift was observed between Leirhnjúkur and the power station (Drouin, 2020).

The Þeistareykir power station began production in November 2017 and has a current capacity of 90 MW. InSAR measurements since the early 1990's show that two inflation events appear to have taken place within the Þeistareykir volcanic system, the first one around 1995 and second one around 2007 (Metzger and Jónsson, 2014). No significant deformation within the geothermal field north of Bæjarfjall was observed prior to the start of production. Between summer 2017 and summer 2020, a new subsidence of about 5 mm/yr is observed between the power station and Bæjarfjall (Drouin, 2020). The subsidence reaches about 15 mm/yr in the vicinity of the injection wells.

2 Data & methodology

Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technique that allows measurements of surface deformation over large areas. It has been successfully used to observe surface deformation caused by earthquakes, volcanoes, plate tectonics, landslides, glaciers, geothermal utilization, ground-water extraction, etc.

The InSAR principle is to use the phase information of two SAR acquisitions and calculate their difference to generate an interferogram. This interferogram contains various signals: topography, satellite orbits, ground deformation, atmospheric disturbances, and noise. It is possible to extract the deformation signal with time-series analysis. The deformation in the line-of-sight (LOS) of the satellite (i.e. away or toward the satellite) is obtained. An interferogram decorrelates (i.e. loses signal) in areas where the ground surface changes too much between acquisitions. The most common causes are vegetation changes, snow, new constructions, or extremely large deformations. In North Iceland, snow is a main issue, therefore only summer acquisitions (from early June to end of September) are used for InSAR.

There have been many public and commercial SAR satellite missions since the early 1990's. The Sentinel-1 SAR mission (late 2014 - present) is one of the most recent missions and it has been extremely valuable for the InSAR community by providing free-of-charge consistent acquisitions over most of the world. Over Iceland, it provided imaged every 12 days between 2015 and 2017 and every 6 days between 2017 and 2021. Since late December 2021, one of the two Sentinel-1 satellites failed and acquisitions are back to a 12 days repeat time. Each image covers about 240 km wide swath, divided in three sub-swaths of about 80 km. The resolution of a pixel is about 3 m x 14 m.

The images were pre-processed with the Interferometric synthetic aperture radar Scientific Computing Environment, ISCE, (Rosen et al., 2012) before doing the deformation time-series analysis with a in-house implementation of the small-baseline algorithm, SBAS (Berardino et al., 2002). Acquisitions with loss of signal because of snow or with strong atmospheric noise were removed from the analysis.

Three Sentinel-1 tracks covering the areas of interest were analyzed: two tracks on a descending orbits (T9 and T111) and one track on an ascending orbit (T147). The analysis was split into two areas: i) Krafla and Bjarnarflag and ii) Þeistareykir to keep the focus on the local deformation processes. The number of images used for each of the these areas can be found in Table 1 and 2, respectively.

Each track has a different point of view over the area of interest. That means it is possible to combine them to extract the East and Up components of the deformation, called near-East and near-Up, respectively, to show the approximation of the decomposition process (Drouin and Sigmundsson, 2019). The North component of the deformation cannot be retrieved because of the near-polar orbits of the satellite.

Table 1: Number of acquisitions selected over Krafla and Bjarnarflag per summer for each track.

Track	2015	2016	2017	2018	2019	2020	2021	2022	Total
T9	7	7	19	16	19	17	17	11	**113**
T111	9	8	18	17	17	17	14	9	**109**
T147	8	7	18	18	20	18	12	10	**111**

Table 2: Number of acquisitions selected over Þeistareykir per summer for each track.

Track	2015	2016	2017	2018	2019	2020	2021	2022	Total
T9	7	7	18	18	18	18	16	11	**113**
T111	9	8	19	17	17	17	14	9	**111**
T147	8	8	19	17	19	14	13	10	**108**

3 Results

3.1 Krafla

The deformation pattern at Krafla between summer 2021 and summer 2022 is fairly complex (Fig. 1). There is a general contraction along the fissure swarm of about 2-3 mm/yr, with a peak of about 10 mm/yr at the south rim of the caldera near Hvíthólar (Fig. 1a). The maximum of subsidence within the Krafla caldera, about 6-7 mm/yr, is also located at near Hvíthólar (Fig. 1b). There is also a 4 mm/yr uplift on the west side of the caldera. This uplift is easier to interpret when compared to the velocities prior to 2018 inflation (Fig. 2a). The deviation/difference between these background velocities and the following years velocities shows a clear uplift in the caldera during 2018-2019 and 2019-2020 (Fig. 2b,c). For 2020-2021 and 2021-2022, a general uplift of about 5-6 mm/yr is still visible, with a peak just west of Leirhnjúkur. These three phases can also be observed of the time-series plot (Fig. 4): subsidence during 2015-2018, uplift during 2018-2020, and slow subsidence during 2020-2022. When comparing the pre-inflation 2015-2018 period to the 2018-2022 period, a clear uplift is visible in the center of the caldera (Fig. 3a-c). As expected, it is associated with an horizontal outward motion (Fig. 3f).

At Hvíthólar the subsidence pattern observed during 2021-2022 is similar to the one observed during 2018-2019 (Fig. 2b,e). The time-series of vertical deformation at this location (Fig. 5) show significant variations with time. There is subsidence during 2015-2017, 2018-2019, and 2021-2022. There is little to no vertical deformation during 2017-2018 and 2020-2021. There is uplift during 2019-2020. These periods of subsidence and no vertical deformation show a strong correlation with the extraction rate at borehole KJ-21, the main production of this area (Fig. 6). When geothermal fluids are extracted, there is subsidence and when no extraction occurs, no vertical deformation is observed.

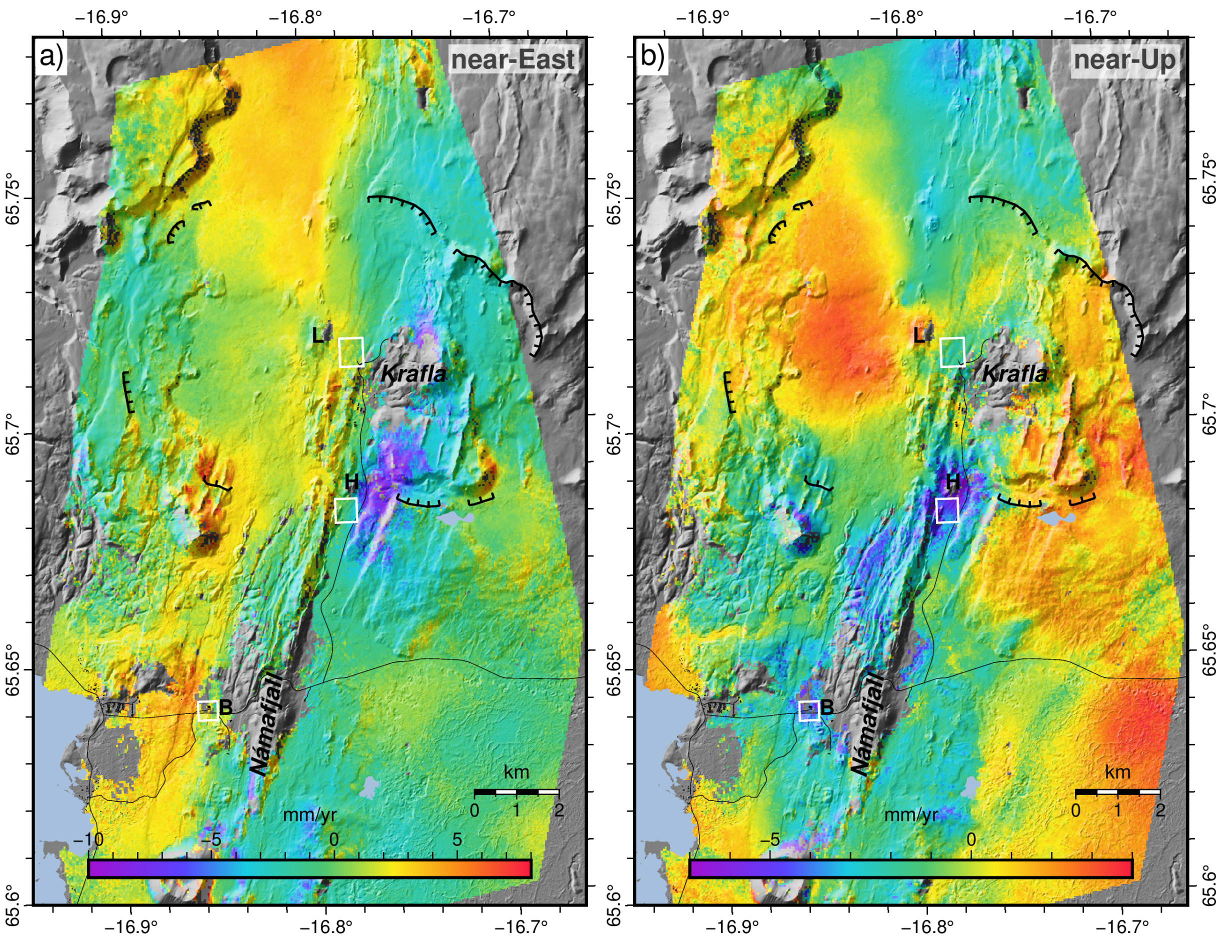

Figure 1: **(a)** Near-East and **(b)** near-Up velocities [mm/yr] between summer 2021 and summer 2022. Leirhnjúkur (L) and Hvíthólar (H) are indicated. White boxes show sampling areas for the time-series plots. Background shows shaded topography, the Krafla caldera boundary (comb line), roads (thin lines), and lakes (blue areas).

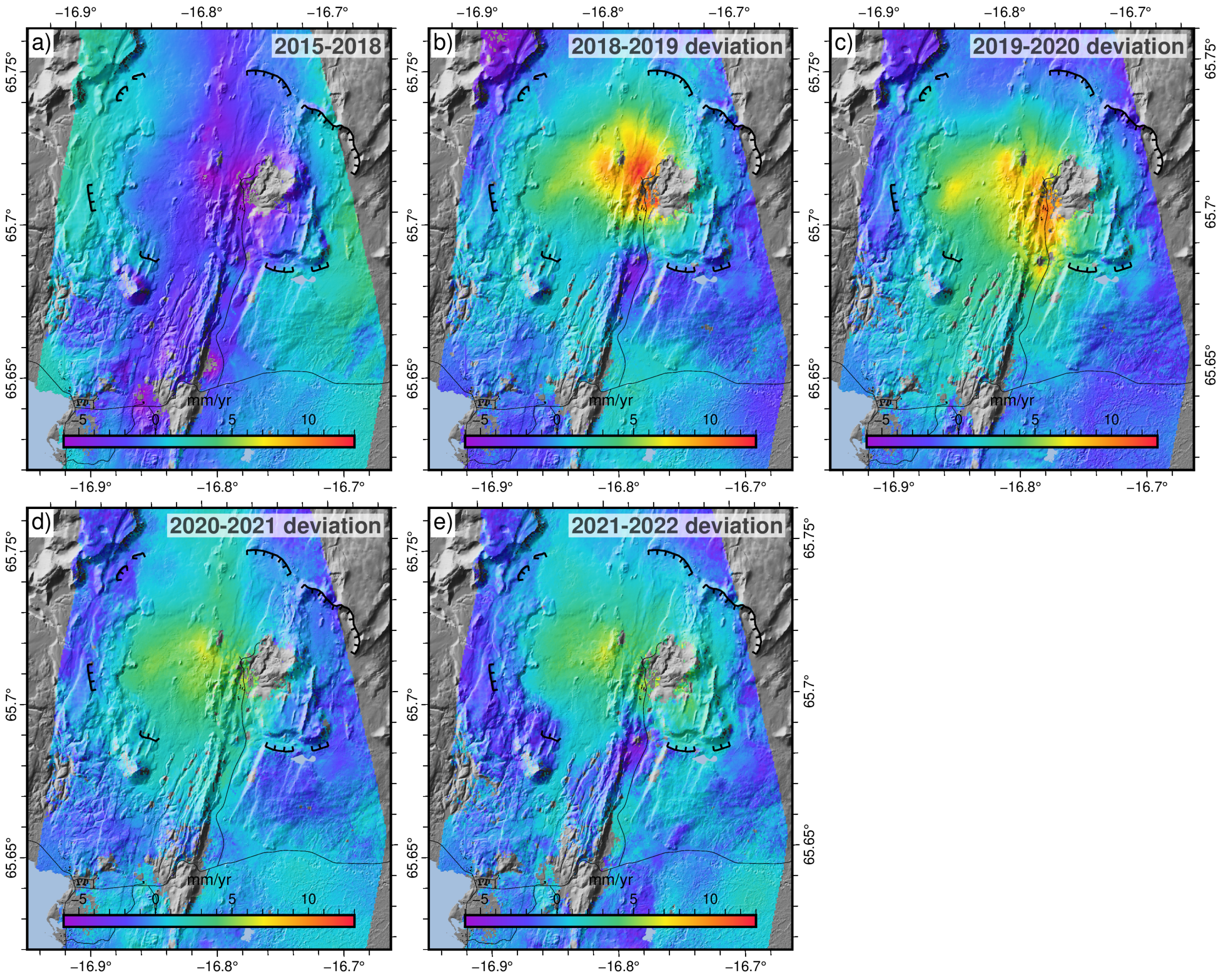

Figure 2: **(a)** Near-Up velocities [mm/yr] for 2015-2018 and **(b-e)** the deviation from it for the following summer-to-summer velocities. Background shows shaded topography, the Krafla caldera boundary (comb line), roads (thin lines), and lakes (blue areas).

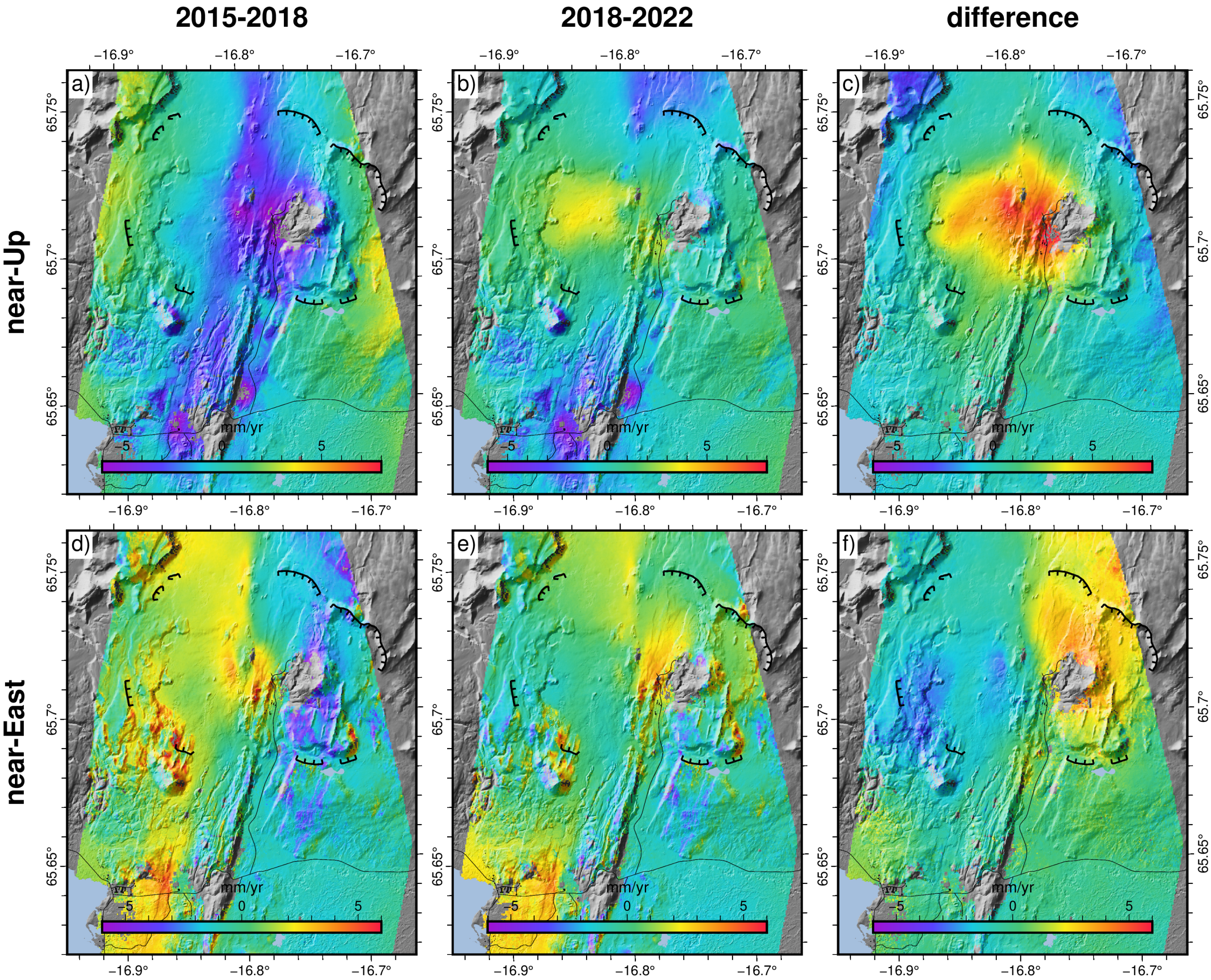

Figure 3: **(a)** Near-East and near-Up velocities [mm/yr] for 2015-2018, 2018-2022, and the difference between the two periods. Background shows shaded topography, the Krafla caldera boundary (comb line), roads (thin lines), and lakes (blue areas).

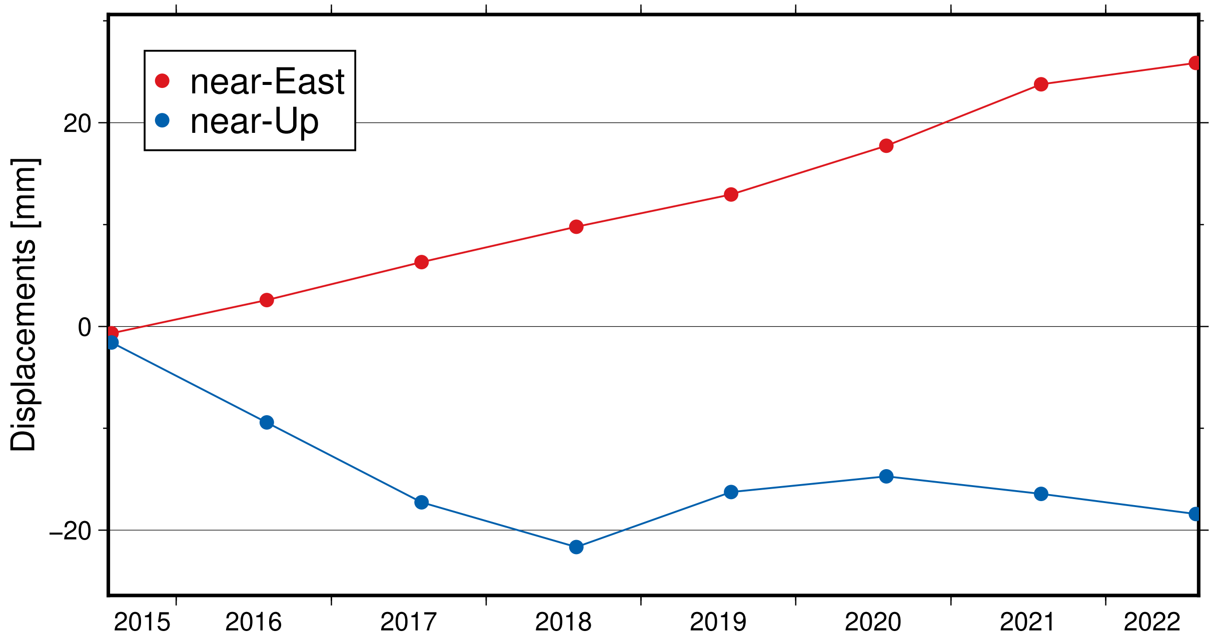

Figure 4: Near-East and Near-Up time-series of deformation near the maximum of uplift during 2018-2020. Location is indicated by the white box between Leirhnjúkur and Krafla on Figure 1.

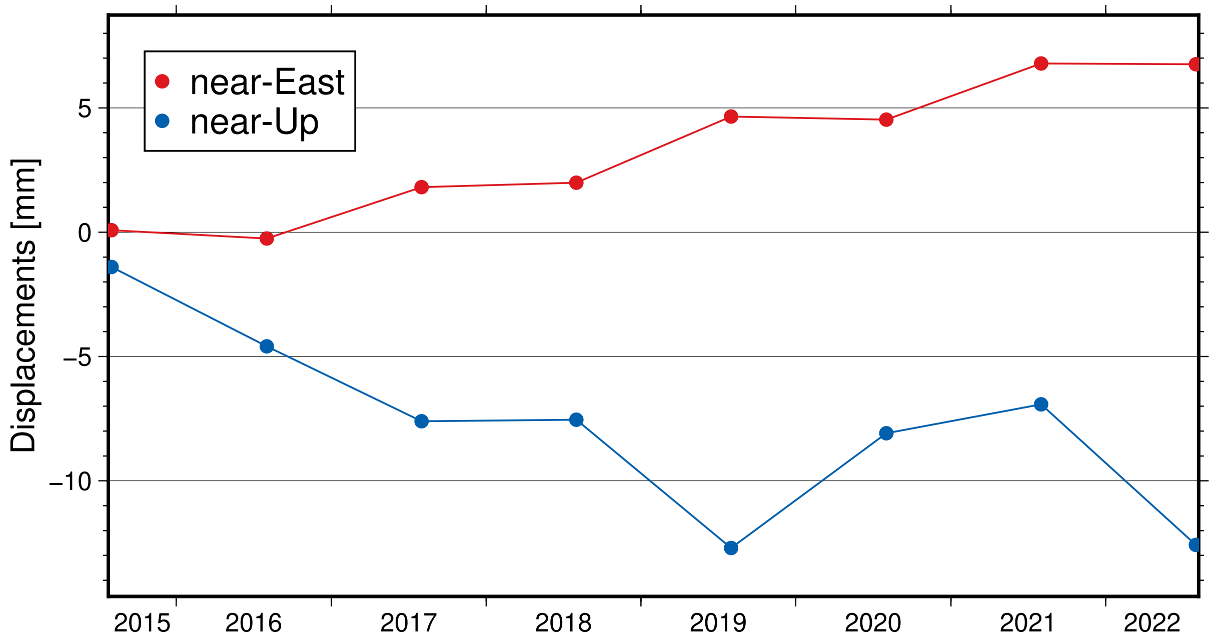

Figure 5: Near-East and Near-Up time-series of deformation near the maximum of uplift during 2018-2020. Location is indicated by the white box next to Hvíthólar on Figure 1.

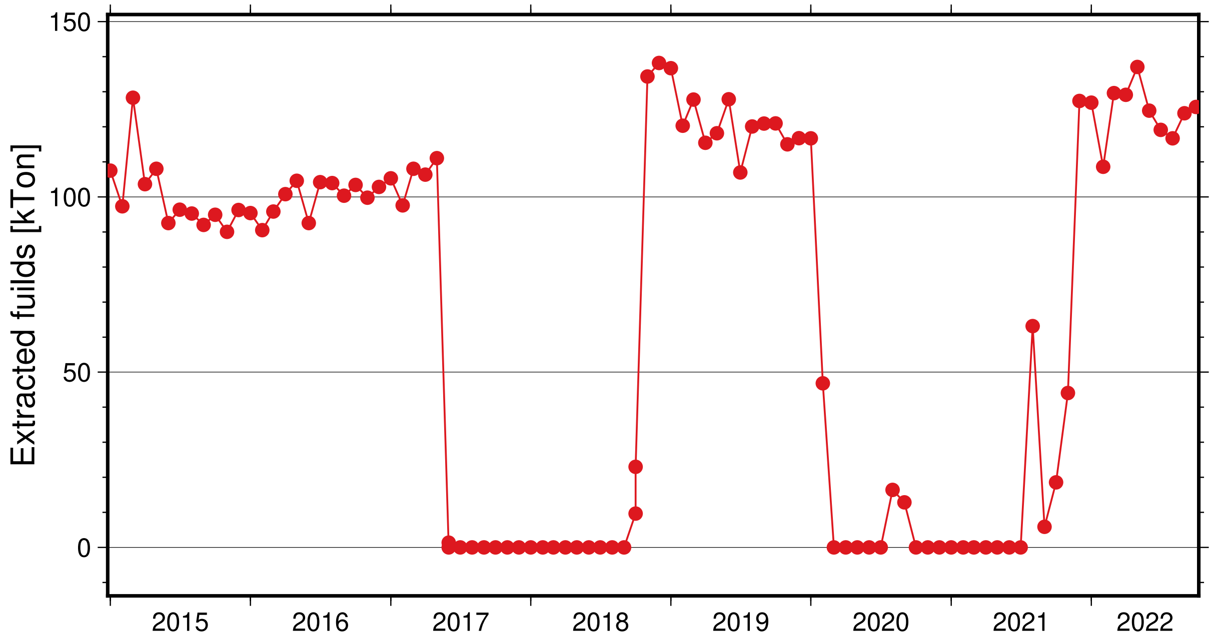

Figure 6: Mass of extracted geothermal fluids at borehole KJ-21 in Hvíthólar.

3.2 Bjarnarflag

Subsidence has been has been fairly constant at Bjarnarflag since 2015, at rate of about 5-6 mm/yr (Fig. 7). The maximum of subsidence is located west of Bjarnarflag (Fig 1). There is no change in deformation before and after the inflation at Krafla (Fig. 3).

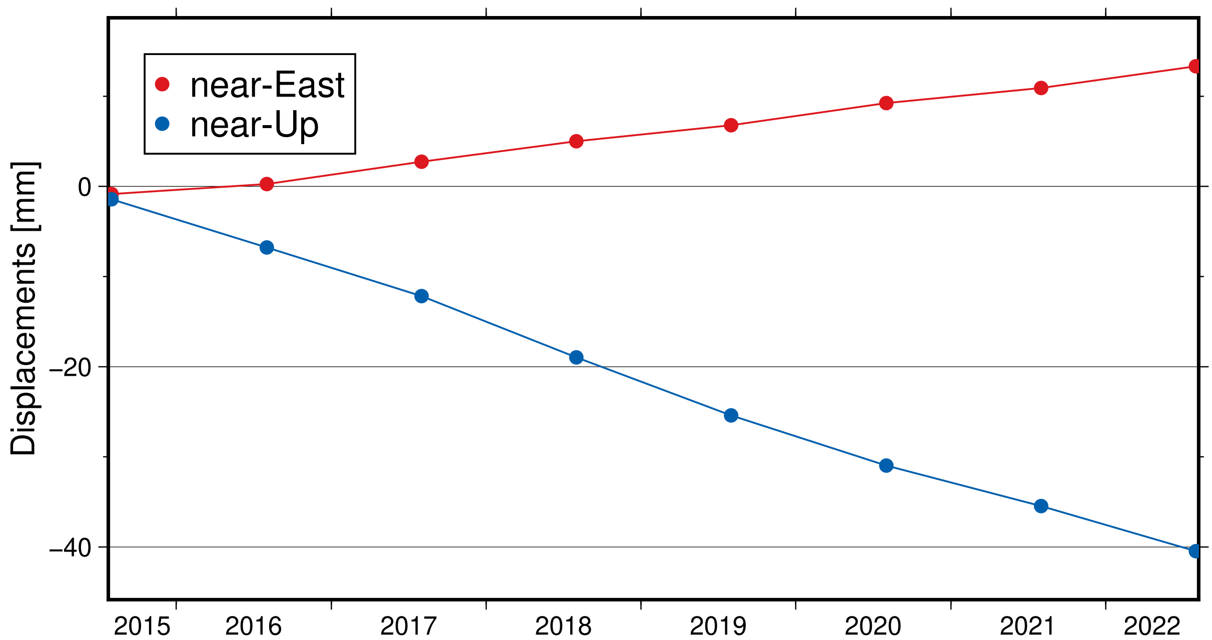

Figure 7: Near-East and Near-Up time-series of deformation at Bjarnarflag. Location is indicated by the white box west of Námarfjall on Figure 1.

3.3 Þeistareykir

Between summer 2021 and summer 2022, the deformation in Þeistareykir is similar to what was observed since 2017. A 3-4 mm/yr subsidence is visible in the geothermal field, with a local maximum of about 13 mm/yr (Fig. 8). The subsidence appears to be bound within two faults: on the west side by a fault a few hundred meters west of the road and on the east side by a fault along Ketilfjall. The west side fault is also clearly visible on the near-East velocities (Fig. 10f). The subsidence extends approximately from the power station in the north to the middle of Bæjarfjall in the south. The fastest subsidence is localized in the north-western part of the geothermal field at the location of three injection wells (ÞN-1, ÞN-2, ÞR-12). There the subsidence is slightly slower than between 2018-2020 and similar to 2020-2021 (Fig. 11).

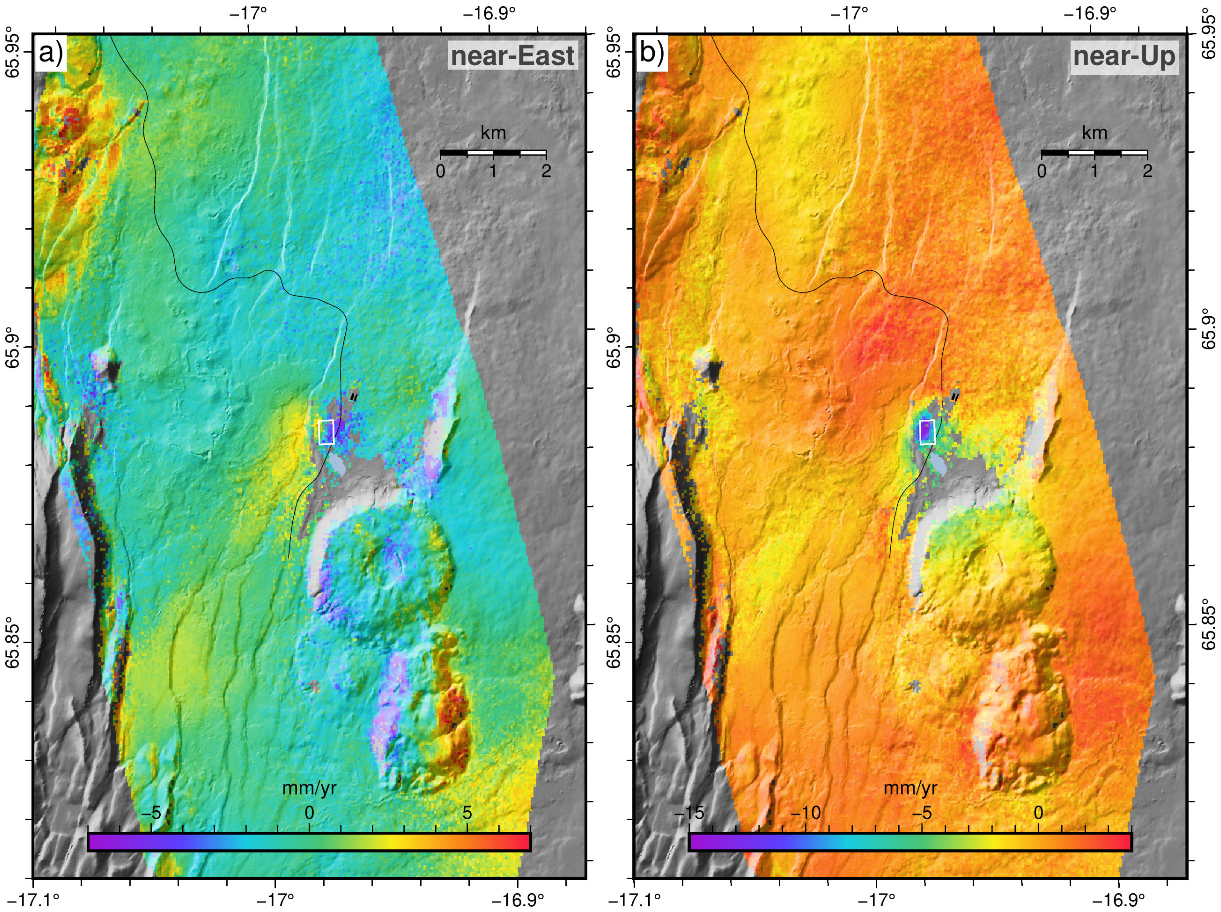

Figure 8: **(a)** Near-East and **(b)** near-Up velocities [mm/yr] between summer 2021 and summer 2022. Þeistareykir power station (Þ) is indicated. The white box shows the sampling area for the time-series plot. Background shows shaded topography and roads (thin lines).

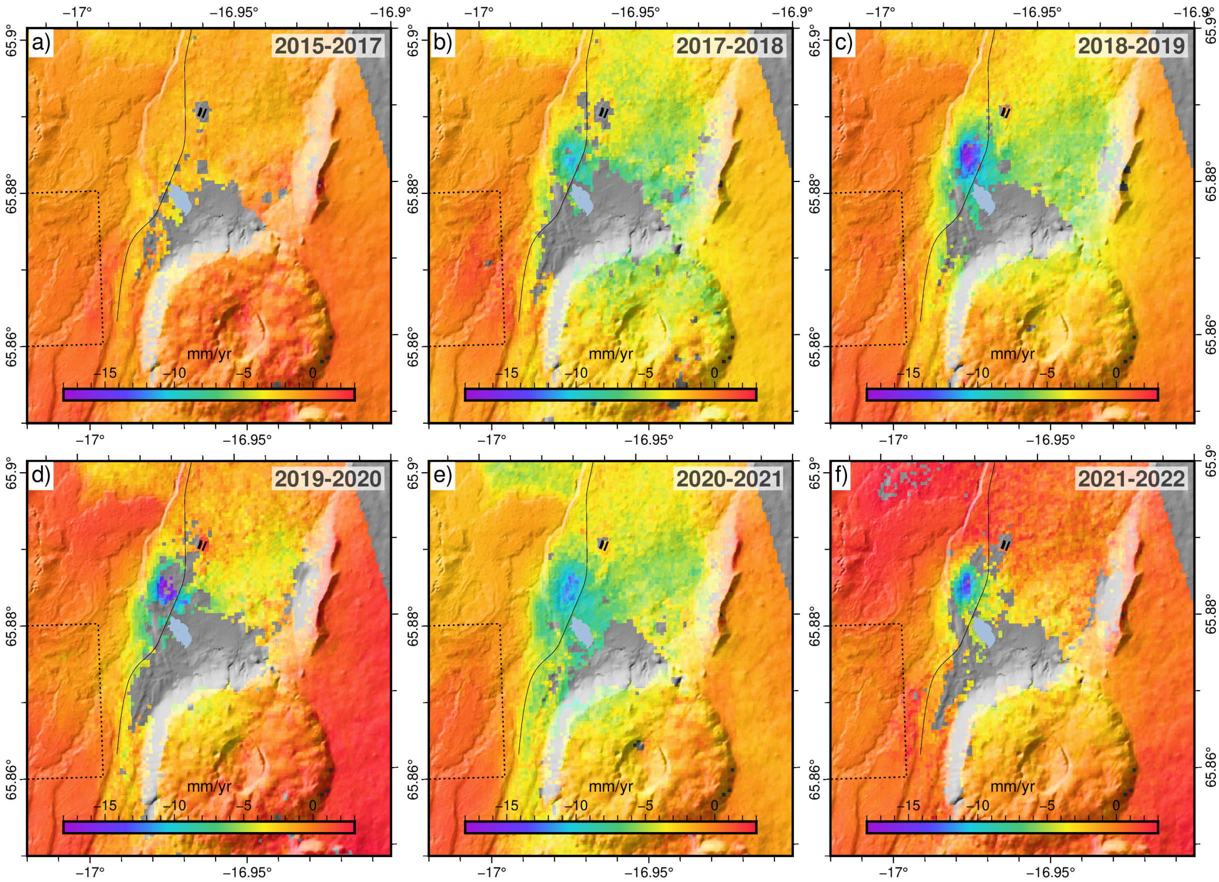

Figure 9: **(a)** Near-Up velocities [mm/yr] prior to production and **(b-f)** summer-to-summer velocities during production. Velocities are referenced to the area delimited by the dotted line. Background shows shaded topography and roads (thin lines).

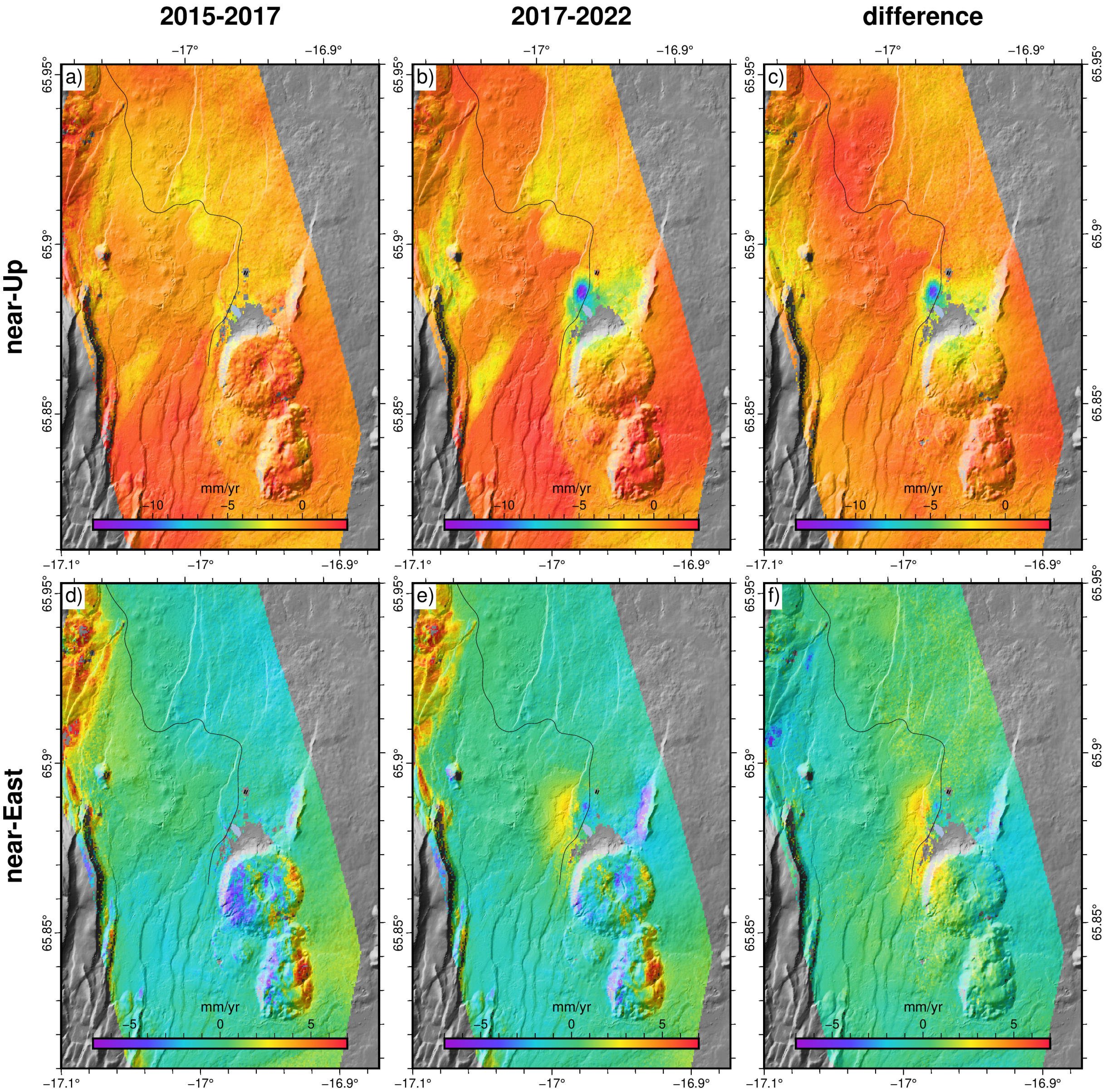

Figure 10: **(a)** Near-East and near-Up velocities [mm/yr] for 2015-2017, 2017-2022, and the difference between the two periods. Background shows shaded topography and roads (thin lines).

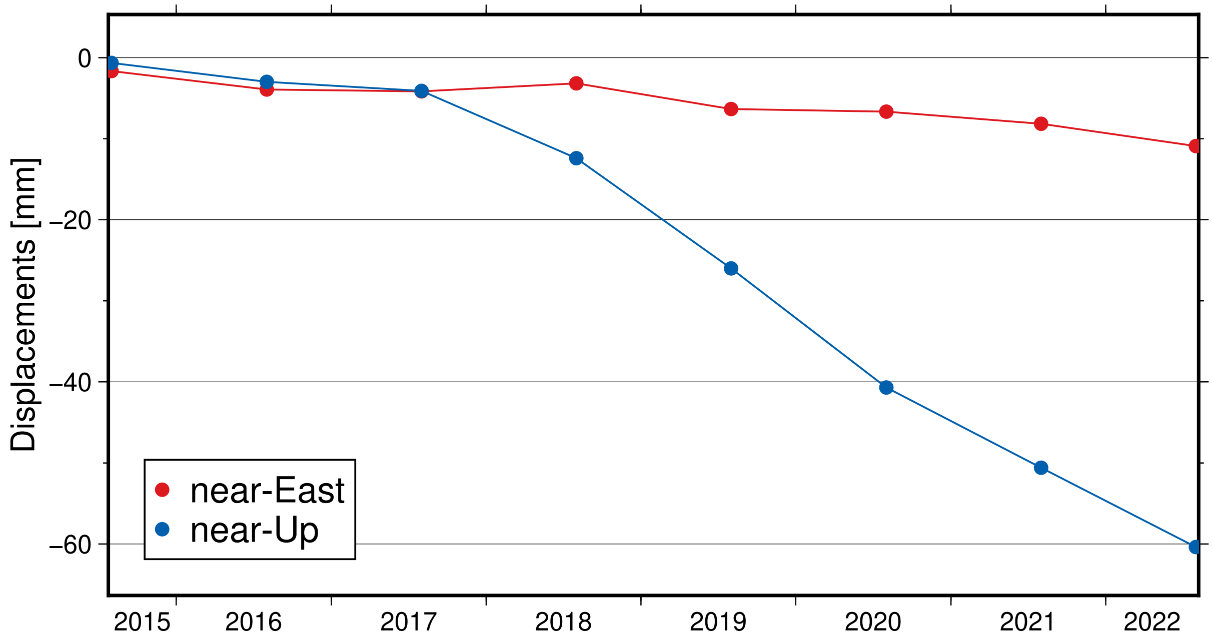

Figure 11: Near-East and Near-Up time-series of deformation at the maximum of subsidence since beginning of production in 2017. Location is indicated by the white box on Figure 8.

4 Discussion

At Krafla, the deformation pattern shows uplift on the west part of the caldera and subsidence near the power plant between summer 2021 and summer 2022. However both these signals are small (<5 mm). When compared to the 2015-2018 deformation, we can instead see a ∼5 mm caldera uplift pattern centered around Leirhnjúkur (Fig. 2). It is difficult to say if there is a new source behind this uplift or if it is simply an evolution of the source behind the 2015-2018 subsidence. Combining this deformation dataset with seismic measurements, gravimetry measurements, and extraction/injection data might help to narrow the list of potential explanations for these variations of the local deformation.

At Hvíthólar, the deformation pattern correlates strongly with the geothermal fluid extraction at the local borehole KJ-21. Subsidence is observed during extraction while no significant deformation is observed when the borehole is shut. One exception to this rule, is the 2019-2020 uplift. There was extraction during the first half of that period and the borehole was shut during the second half. Therefore, slow subsidence would be expected. However, the inflation that started in 2018 was still taking place during 2019-2020 and it extended to the south all the way to Hvíthólar (Fig. 2c). Therefore, this uplift at Hvíthólar was most likely caused by a non-local process.

At Bjarnarflag, the deformation pattern is the same since at least 1993 (Drouin et al., 2017). There is an about 6 mm/yr subsidence bowl centered a few hundred meters west of the power plant. Geothermal fluids extraction from local boreholes has been relatively stable since deformation measurements have been conducted in the area. Therefore, assuming the observed deformation is caused by the extraction, this would explain why the deformation is stable through time.

At Þeistareykir, the deformation pattern is the same since the start of production in 2017. There is a <5 mm/yr subsidence area between Bæjarfjall and the power plant. This subsidence is likely related to the geothermal fluid extraction from all the boreholes. However, the subsidence is the fastest (10-15 mm/yr) near the injection boreholes. This subsiding area is about 800 m long and 400 m wide, elongated along the fissure swarm direction. This suggest that the source of this deformation is shallow ($<$ 1 km deep). The injection boreholes are about 400 m deep. Therefore it is likely that this local subsidence is caused by the re-injection of geothermal fluids. However, the mechanisms behind this process are uncertain as uplift, not subsidence, is usually expected from re-injection (Juncu et al., 2020). Potential explanations include i) fast cooling and contraction of the host rock by the cold re-injected fluids ii) dissolution of a geological layer sensitive to water.

References

Berardino, P., Fornaro, G., Lanari, R., & Sansosti, E. (2002). A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Transactions on Geoscience and Remote Sensing*, *40*(11), 2375–2383. https://doi.org/10.1109/TGRS.2002.803792

Drouin, V. (2020). *InSAR Monitoring of Krafla, Bjarnarflag and Þeistareykir Geothermal Areas.* (tech. rep. ÍSOR-2020/43).

Drouin, V., & Sigmundsson, F. (2019). Countrywide Observations of Plate Spreading and Glacial Isostatic Adjustment in Iceland Inferred by Sentinel-1 Radar Interferometry, 2015–2018. *Geophysical Research Letters*, *46*(14), 8046–8055. https://doi.org/10.1029/2019GL082629

Drouin, V., Sigmundsson, b., Verhagen, S., Ófeigsson, B. G., Spaans, K., & Hreinsdóttir, S. (2017). Deformation at Krafla and Bjarnarflag geothermal areas, Northern Volcanic Zone of Iceland, 1993-2015 [Volcano Geodesy: Recent developments and future challenges]. *Journal of Volcanology and Geothermal Research*, *344*, 92–105. https://doi.org/10.1016/j.jvolgeores.2017.06.013

Einarsson, P. (1991). Umbrotin við Kröflu 1975-89. In A. Garðarsson & A. Einarsson (Eds.), *Náttúra Mývatns* (pp. 96–139). Hið íslenska náttúrufræðifélag.

Juncu, D., Árnadóttir, T., Geirsson, H., Guðmundsson, G., Lund, B., Gunnarsson, G., Hooper, A., Hreinsdóttir, S., & Michalczewska, K. (2020). Injection-induced surface deformation and seismicity at the Hellisheidi geothermal field, Iceland. *Journal of Volcanology and Geothermal Research*, *391*, 106337. https://doi.org/10.1016/j.jvolgeores.2018.03.019

Metzger, S., & Jónsson, S. (2014). Plate boundary deformation in North Iceland during 1992–2009 revealed by InSAR time-series analysis and GPS. *Tectonophysics*, *634*, 127–138.

Rosen, P. A., Gurrola, E., Sacco, G. F., & Zebker, H. (2012). The InSAR scientific computing environment. *Synthetic Aperture Radar, 2012. EUSAR. 9th European Conference on*, 730–733.

Sturkell, E., Sigmundsson, F., Geirsson, H., Ólafsson, H., & Theodórsson, T. (2008). Multiple volcano deformation sources in a post-rifting period: 1989–2005 behaviour of Krafla, Iceland constrained by levelling, tilt and GPS observations. *Journal of Volcanology and Geothermal Research*, *177*(2), 405–417. https://doi.org/10.1016/j.jvolgeores.2008.06.013

A Appendix

A.1 Krafla & Bjarnarflag

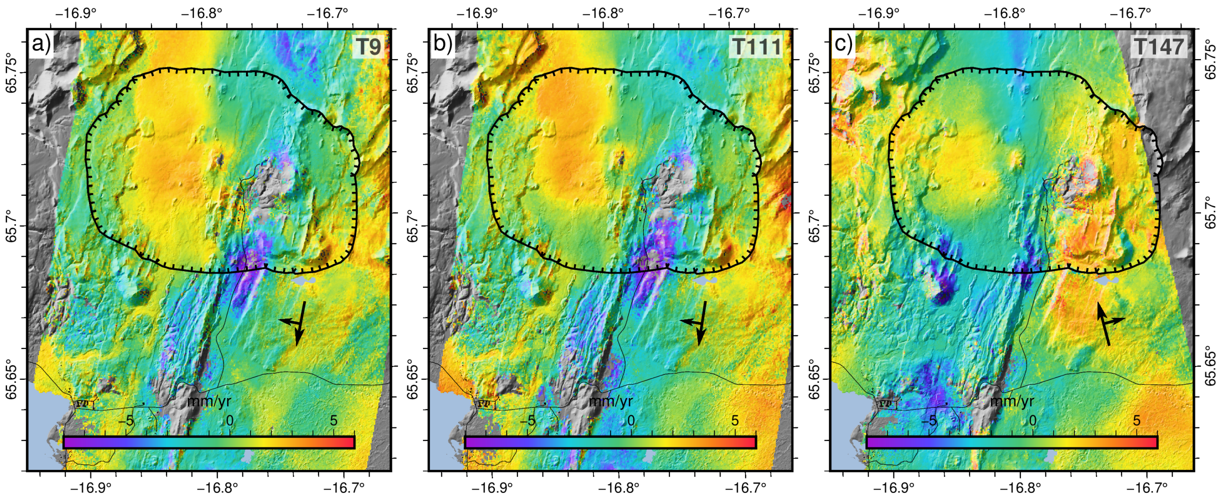

Figure 12: Average LOS velocities between summer 2021 and summer 2022 for all three Sentinel-1 track covering the area. Satellite heading and look direction is indicated by the large arrow and the small arrow, respectively. Background show shaded topography, the Krafla caldera boundary (comb line), roads (thin lines), and lakes (blue areas).

A.2 Þeistareykir

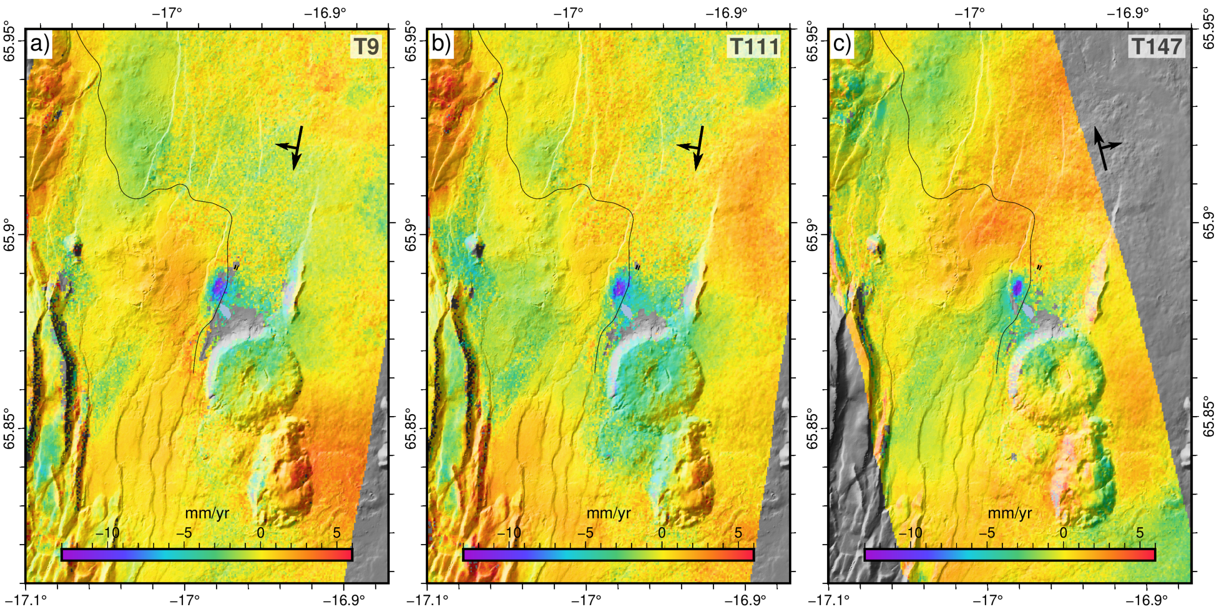

Figure 13: Average LOS velocities between summer 2021 and summer 2022 for all three Sentinel-1 track covering the area. Satellite heading and look direction is indicated by the large arrow and the small arrow, respectively. Background show shaded topography and roads (thin lines).