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# Ground Deformation at the Theistareykir Volcanic System, Iceland following Onset of Geothermal Utilization

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## ABSTRACT

A 90 MW power-plant operated by Landsvirkjun, the National Power Company of Iceland, began production in November 2017 at the active geothermal area in the Theistareykir central volcano, in the Northern Volcanic Zone of Iceland. Eruptive activity of the central volcano is low: the last eruption took place about 2500 years ago and other lava flows are more than 10,000 years old. Rifting events without eruptions may have occurred in the area in 1618 and 1885 but it is uncertain if these originated from the Theistareykir central volcano or from a nearby off-shore volcano. However, geodetic measurements show two possible inflation episodes during the last 25 years: in 1995-1996 and in 2006-2008. In order to obtain a good overview of the deformation prior to the onset of production at the power-plant, the Theistareykir area has been well monitored since 2009-2011. Network of GPS geodetic stations was densified in 2010 and 2011 for annual summer campaign measurements. TerraSAR-X SAR images have also been acquired yearly since 2009. Starting in 2015, the Sentinel-1 SAR mission has provided very good observations of the local deformation, with images acquired every 6-12 days. We observe that the area has been deforming at fairly stable rate between 2009 and 2017. In addition to plate spreading, the main noticeable feature is a slow subsidence in the north-west part of the central volcano in a similar location as an inflation episode took place in 2006-2008. This deformation field is then compared to the summer 2017 - summer 2018 deformation field to detect changes possibly related to geothermal fluid extraction. Results indicate additional subsidence at the Theistareykir geothermal area: the subsiding area is elongated north-south along the fissure swarm but appears not to be centered next to the most productive wells. The area subsided at a rate of about 6-8 mm/yr; a low rate when compared to what has been observed at the onset of production at other geothermal power-plants operating in Iceland. Knowing the deformation induced by geothermal fluid extraction is important to estimate the effect of the current production rate on the geothermal reservoir and assess its sustainability and the potential of increasing the production in the future. Monitoring the activity of the volcano also gives us insight on how much potential heat is added in the system during intrusive episodes.

## 1. INTRODUCTION

Iceland is a hotspot, located at the intersection of the mid-Atlantic ridge and a mantle plume of excessive mantle upwelling. The heat carried by the hot mantle plume generates additional magma within the crust which results in high volcanic activity at the surface (Sigmundsson et al., in press). The volcanic activity provides ideal conditions for the formation of several geothermal system around the country. There are currently seven main powerplants that use these geothermal reservoirs to generate energy: Reykjanes, Svartshengi, Hellisheidi, Nesjavellir, Krafla, Bjarnarflag, and Theistareykir (see Figure 1).

Theistareykir is the northernmost on-land active volcanic system in Iceland within the Northern Volcanic Zone of Iceland. Its eruptive activity is fairly low: the latest eruptive activity took place 2,500 years ago and more than 10,000 years ago before that. The origin of rifting events happening in 1618 and 1885 in the area is uncertain (Sæmundsson and Sigmundsson, 2013). These rifting events may have been associated to the Theistareykir central volcano or to an off-shore central volcano to the north. In recent decades two inflation events without eruptive activity have occurred within the Theistareykir central volcano, in 1995-1996 and 2006-2008 (Metzger et al., 2013; Drouin et al., 2017b).

In November 2017, Landsvirkjun (the National Power Company of Iceland), started production at the Theistareykir geothermal area. The power-plant started with two 45 MW turbines for a total of 90 MW. The powerplant is designed such that two others 45 MW turbines could added in the future. The powerplant is designed so that most of the extracted geothermal fluid is reinjected back in the reservoir. This is the most recent time a powerplant starts production in Iceland, in an area that have been well monitored by geodetic techniques. We focus on observing the response of the geothermal reservoir to the extraction/injection.

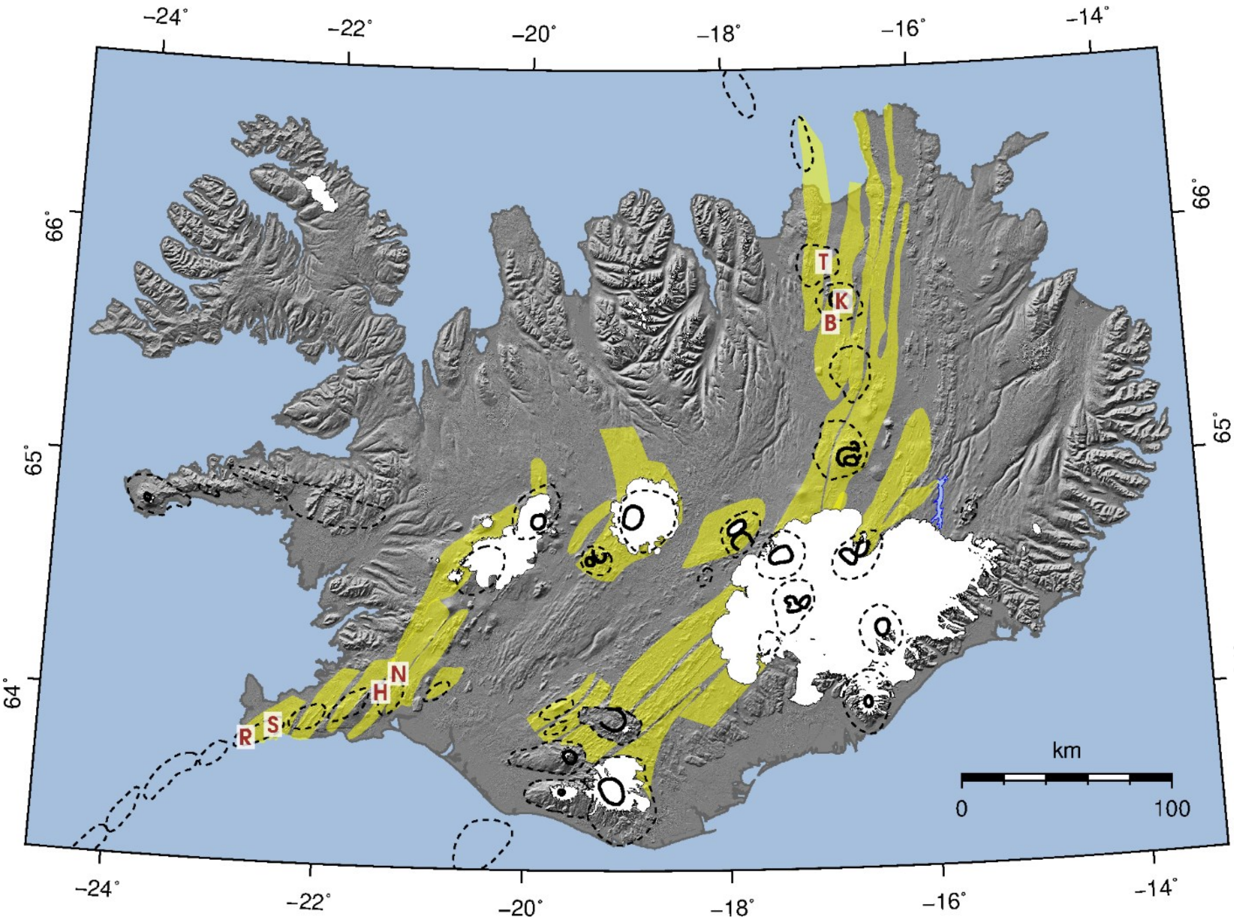


**Figure 1: Locations of the main geothermal power plants in Iceland: Reykjanes (R), Svartsengi (S), Hellisheidi (H), Nesjavellir (N), Bjarnarflag (B), Krafla (K), and Theistareykir (T). Backgrounds show topography (shaded relief), ice caps (white areas), outlines of central volcanoes (dashed lines), calderas (thick lines) and fissure swarms (yellow areas).**

## 2. DATA

### 2.1 InSAR

The Copernicus Sentinel-1 SAR mission has provided the main dataset for this study. The mission consists of two C-band SAR satellite: Sentinel-1A, launched in 2014, and Sentinel-1B, launched in 2016. They continuously acquire images without the need to place orders and the data is available for free. In the case of Iceland, images suitable for interferometry are acquired every 6 days since early 2017 (every 12 days since 2015). The main image acquisition mode used is Interferometric-Wide (IW). Each of these images covers a ~250-km wide swath of the country at the cost of the lower resolution (~2.3 m in range and ~14.1 m in azimuth) than the traditional Stripmap mode from commercia l missions (e.g., TerraSAR-X and COSMO-SkyMED: ~2 m or less in both range and azimuth).

We analyzed the data in a similar manner as Drouin and Sigmundsson (2019). However, we used the SBAS approach (Berardino et al., 2002) for time-series instead of single master approach. We calculated time-series over three tracks: one from ascending satellite pass (T147) and two from descending satellite passes (T9 and T111). These observations are then combined to extract information about the near-East and near-Up component of the deformation.

We split the data in four time periods (from summer to summer): 2015-2017, 2017-2018, 2018-2019, and 2019-2020. The 2015-2017 period covers a period before the start of production at the powerplant in November 2017. The 2017-2018 period covers the first year during which production started. The 2018-2019 and 2019-2020 periods cover the first and second year respectively during which production was continuous.

### 2.2 Boreholes

Extraction and reinjection data were provided by Landsvirkjun, the operator of the Theistareykir powerplant until summer 2019 for the 19 boreholes in the area (see Figure 2). It was used to derive the average extraction and injection rate at each borehole for the same periods as our InSAR time-series (see Figure 3). We observe a clear increase in both extraction and injection rate following the onset of production in fall 2017. Most of the extracted water is reinjected. About 1.7 Mton/yr, 6.4 Mton/yr, and 8.0 Mton/yr of geothermal fluids were extracted for 2015-2017, 2017-2018, and 2018-2019 respectively. Over the same time periods, 0.6 Mton/yr, 4.2 Mton/yr, and 7.4 Mton/yr were reinjected. Most of the extraction took place at the south end of the geothermal field while the reinjection took place in the north and north-west of the geothermal field.

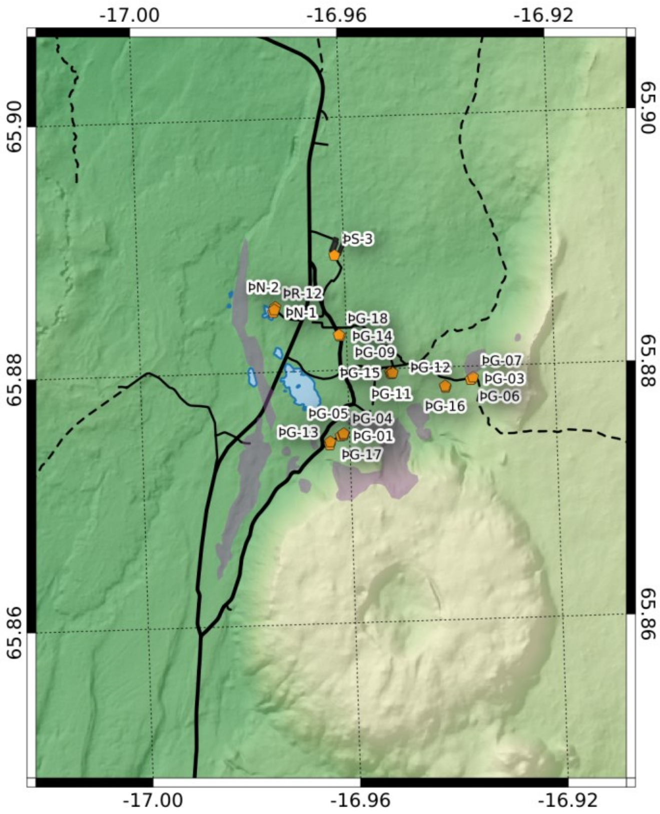

**Figure 2: Map of the Theistareykir geothermal field: boreholes (orange pentagons) and their name, surface alterations (purple), roads (black lines), tracks (dashed lines), water (blue), and topography (color and shaded relief).**

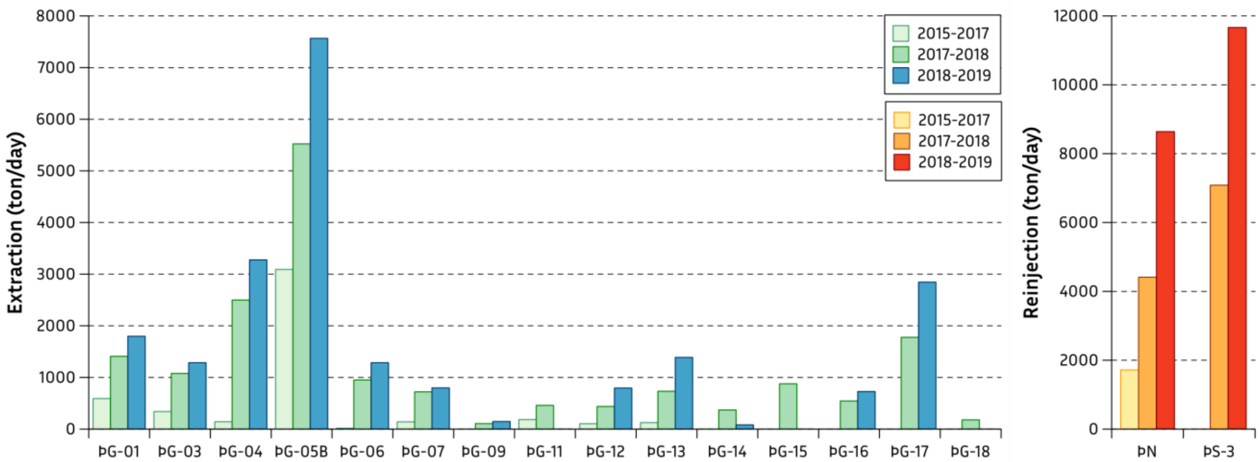

**Figure 3: Extraction (left) and reinjection (right) rates in ton per day at each borehole for 2015-2017, 2017-2018, and 2018-2019. Boreholes locations can be seen on the upper left panel of Figure 2. For the reinjection, ÞN refers to three boreholes next to each other: ÞN-1, ÞN-2, and ÞR-12.**

## 3. RESULTS AND DISCUSSION

Average vertical (near-Up) velocities for the four time periods are shown in Figure 4. For 2015-2017, there is no specific signal that can be related to the geothermal field. However, an average subsidence of about 6-8 mm/yr is visible within the geothermal field for later time periods (2017-2018, 2018-2019, and 2019-2020). This is about the same deformation rate as in Krafla and Bjarnarflag geothermal fields (Drouin et al., 2017a).

Subsidence is expected to happen when extracting geothermal fluids. This can be caused by various processes within the geothermal reservoir: pressure drawdown (Juncu et al., 2016), temperature decrease (Drouin et al., 2017a), formation of a steam cap (Receveur et al., 2019). At Theistareykir, the absence of deformation within the geothermal field for 2015-2017 indicates that the geothermal system was at equilibrium and that the low extraction rate didn't influence it. With the start of production in 2017, the extraction rate increased fourfold. The reservoir appears to have responded to this increase, as subsidence is observed at the surface. The subsidence rate is faster for 2018-2019 than for 2017-2018, which correlates with the extraction rate during these time periods.

We observe a local maximum of subsidence near three re-injection boreholes (ÞN-1, ÞN-2, ÞR-12) in the north-western part of the field for 2018-2019 and 2019-2020 (see Figure 4, lower panels). The 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 re-injection boreholes are reaching a depth of 400 m. Therefore, it seems there is a link between the re-injection of geothermal fluids and the local subsidence. However, re-injection is usually used to compensate subsidence caused by geothermal fluid extraction (Axelsson, 2012). Potential explanations for subsidence caused by re-injection are i) thermal contraction of the host rock by the colder re-injected fluids (Im et al., 2017) ii) chemical dissolution of a geological layer by the water (Michelena et al., 2020). Figure 5 shows time-series sampled at this area. A clear drop in the near-Up component is observed after summer 2017, when the power station started its operation.

The geothermal field is located within the Theistareykir volcanic system, which has a clearly defined fissure swarm like other volcanic systems in the Northern Volcanic Zone of Iceland (Hjartardóttir et al., 2015). The faults and fissures are orientated NS and appear to constrain the deformation within two large faults about 2.5 km apart. This could indicate the extent of the geothermal reservoir, which would then be about 2.5 km wide and elongated along the NS direction. The deforming area is not centered on the main extraction area at the south end of the field (boreholes ÞG-05B, ÞG-04, ÞG-17, ÞG-13, and ÞG-01) but 1 km NE of it.

Although the presently shown deformation field for 2015-2017 does not show any specific signal that can be related to the geothermal field, other deformation signals are visible within the Theistareykir volcanic system on 2015-2018 country-wide observations (Drouin and Sigmundsson, 2019). Vertical velocities show a 5-6 km wide area of relative subsidence (2-3 mm/yr) to the northwest of Theistareykir. This area is about the same area that experienced uplift in 2006-2008, in relation to an inferred magma intrusion during an inflation period. It is noteworthy that the 2006-2008 uplift and its subsequent subsidence are not centered on the geothermal field. The observed pattern of deformation prior to onset of geothermal utilization is valuable for future studies of the influence of the new power plant in the area and serves as basis to evaluate the impact of geothermal utilization. Also, magmatic intrusions at depth could potentially influence the deep root of the geothermal system and increase the productivity of the field by injecting heat into it.

InSAR usually works well in Iceland because of the high amount of lava which are good reflectors for the technique and slow-growth and sparse vegetation. However, the Theistareykir geothermal field has been challenging. Time-series analysis using the permanent-scatterers technique or full resolution images provided no-data or noisy results for the area of interest. The images needed to be multi-looked to increase the signal-to-noise ratio which gave lower resolution results. Campaign GPS measurements have been conducted in the area for a long time and will help to better constrain the deformation within the geothermal field.

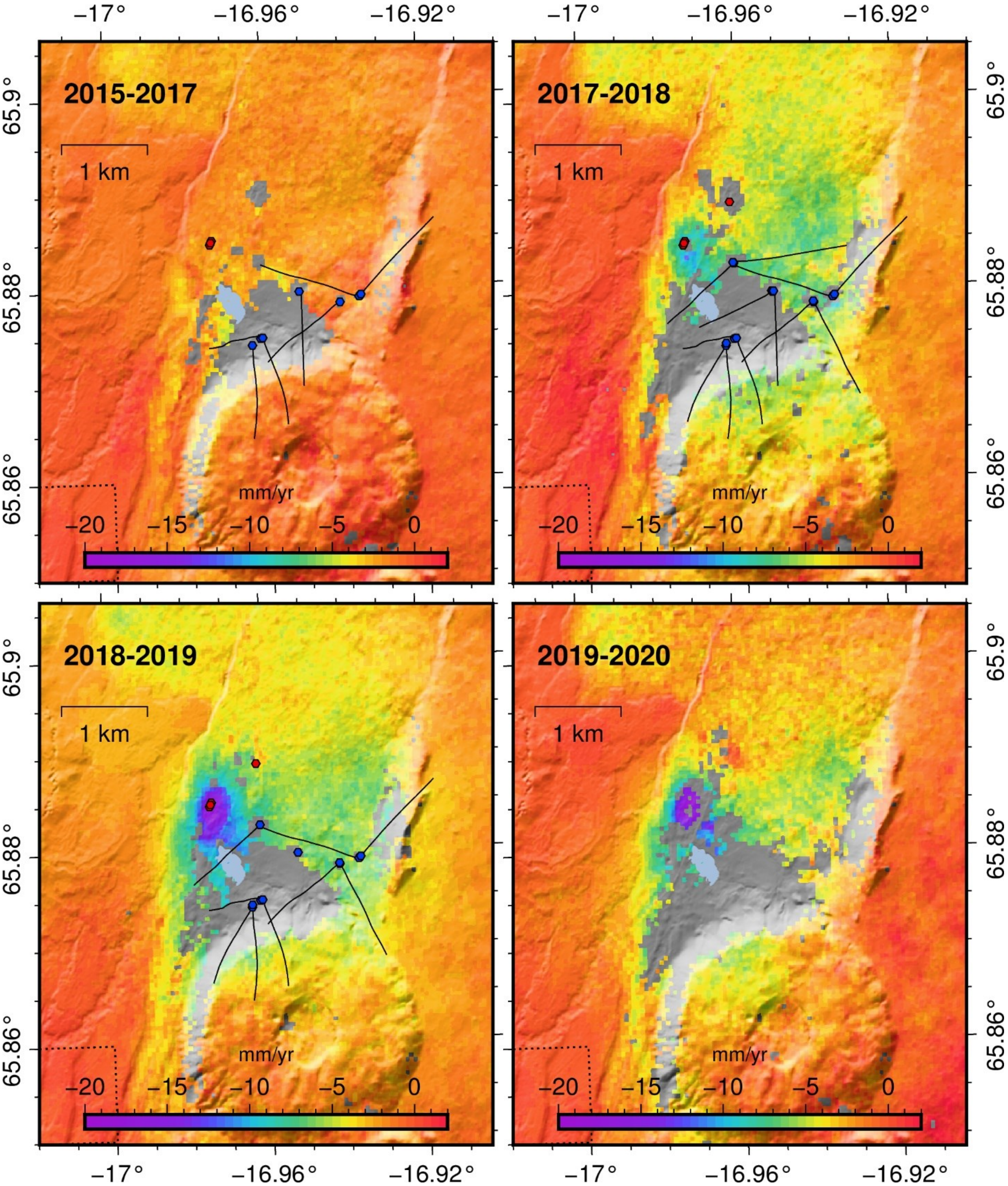


**Figure 4: Average vertical (near-Up) velocities over the time period indicated in the upper left corner. Color scale is the same for all four panels, no data show as grey/transparent. Hexagons show boreholes used for extraction (blue) or reinjection (red) during each time period. If not vertical, the borehole path is shown by the black line. The reference area is indicated by the dashed lined. Background show topography (shaded relief) and the local pond (blue/grey area).**

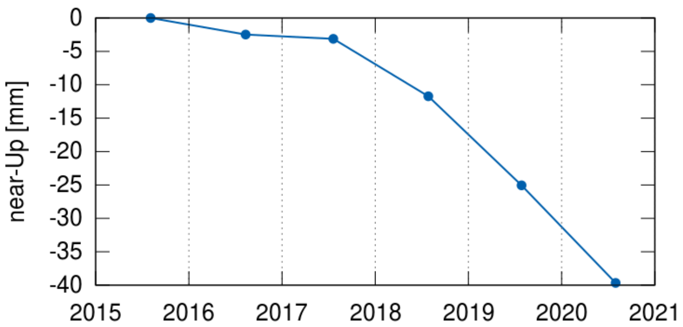


**Figure 5: Time-series of vertical deformation at the location of the three re-injections wells (ÞN-1, ÞN-2, ÞR-12).**

## 4. CONCLUSION

InSAR time-series of Sentinel-1 images show the deformation within the Theistareykir geothermal field before and after the onset of production at power-plant in fall 2017. The area is stable from summer 2015 to summer 2017 and starts to subside during between summer 2017 and summer 2018, at a rate of 6-8 mm/year. It continues to subside at a similar rate between 2018-2019 and 2019-2020. This subsidence is relatively small when compared to other geothermal fields (Reykjanes, Hellisheiði) and appears to be constrained by the local fissure swarms. There is also a very localized subsidence of over 15 mm/year near the some of the reinjection boreholes.

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