# The long-term evolution at Krafla Volcanic System, Iceland, by time-lapse microgravity.

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## 1 ) Krafla, the most important geothermal area in Iceland

**MOTIVATION**

Investigate changes in subsurface density in the magmatic and hydrothermal systems of the Krafla Volcanic System (KVS) by using a dynamic gravity survey.

Incorporating our survey with past campaigns, we will quantify subvolcanic reservoirs' long- and mid-term evolution and gain new insights into Krafla caldera unrest dynamics.

- **Study area**: The Northern Neovolcanic Zone (*Fig. 1*)[1, 2, 3].
- Last rifting event in Krafla: the **Krafla Fires** between **1975-1984**[4].
- It is an **important geothermal area** exploited since 1965, using the deepest reservoir at **2.2 km**[5].
- **Since 1965**, the Krafla Volcanic System has been **widely studied** using gravimetric techniques measuring and interpreting the effect of **pre, syn and post-rifting events**[6, 7, 8].

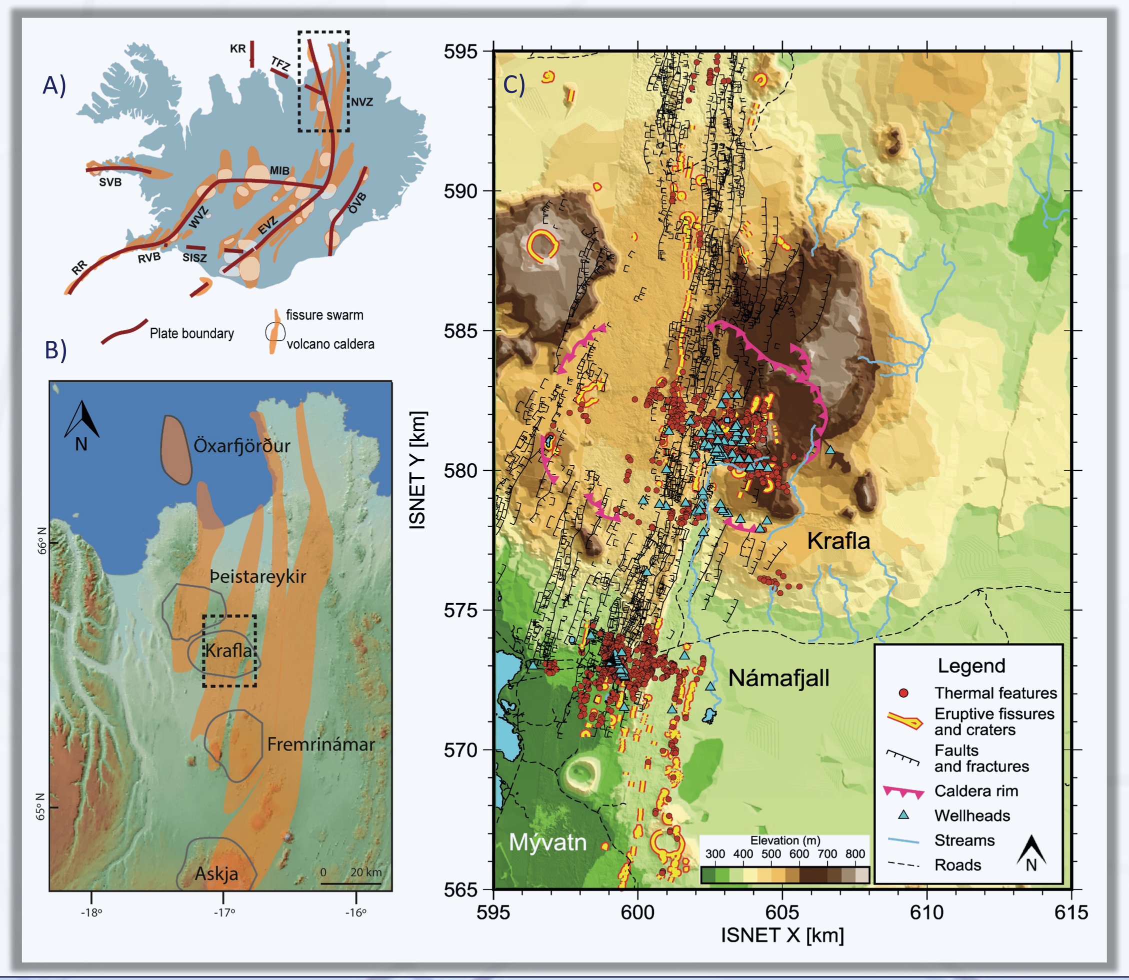
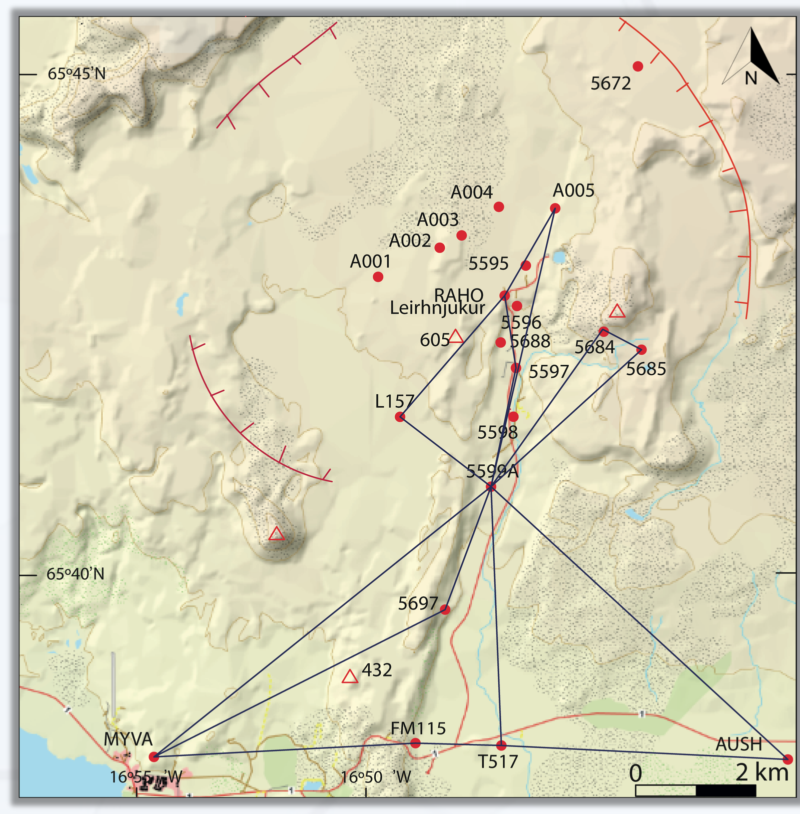



*Fig. 1 – A) Main spreading tectonic zones of Iceland with a closer view of the Northern Volcanic Zone[9]. B) The NVZ is configured by a series of five caldera volcanoes with its fissure swarm. C) In the centre of the NVZ the Krafla caldera is situated with a series of geothermal areas and volcanic features[10].*

## 2) Time-lapse microgravity




*June 2022 survey summary*

- ***Scintrex CG5** gravimeter*
- *Measured on concrete blocks or bed rocks*
- ***15 gravity stations** inside and outside the Krafla caldera (Fig. 2)*
- ***Reference Stations FM115** (to link with previous surveys) and **T517** (to link with future surveys, farther away from the system)*
- ***GPS measurements** at gravity benchmarks over the same period*
- *Tides, Drift and Free-Air Gradient **Corrections applied***

*Fig. 2 – Microgravity benchmarks (red dots) measured during the June 2022 survey with the different loops recorded by tie lines. Benchmarks without tie lines were measured during the 2000-2003 campaign and will be measured next in June 2023.*

- Micro-gravity is a **relative gravity method** which measures changes in gravity on benchmark relative to a reference point with **µGal precision over time** (1 µGal = $10^{-8}$ m/s²).
- This method is used to **investigate the sub-surface mass** or **density changes** over over time[11, 12, 13].
- Correcting observed **gravity changes** for the gravitational effect of ground deformation helps elucidate **material transport** within a volcanic system.
- Spatio-temporal variations in residual gravity changes imply **sub-surface mass changes**.

$$Residual\ gravity\ change = g_{corrected} - \text{Free-Air Effect}$$

$$g_{corrected} = g_{observed} - g_{Drift} - g_{Tide}$$

$$Free\text{–Air Effect} = -308.6\,\frac{\mu Gal}{m} * \Delta height(m)$$

## 3) 30 years of caldera unrest

**A) Residual Gravity Changes 1990-1995** | **B) Residual Gravity Changes 1996-2003** | **C) Residual Gravity Changes 2003-2022** | **GPS Elevation changes**

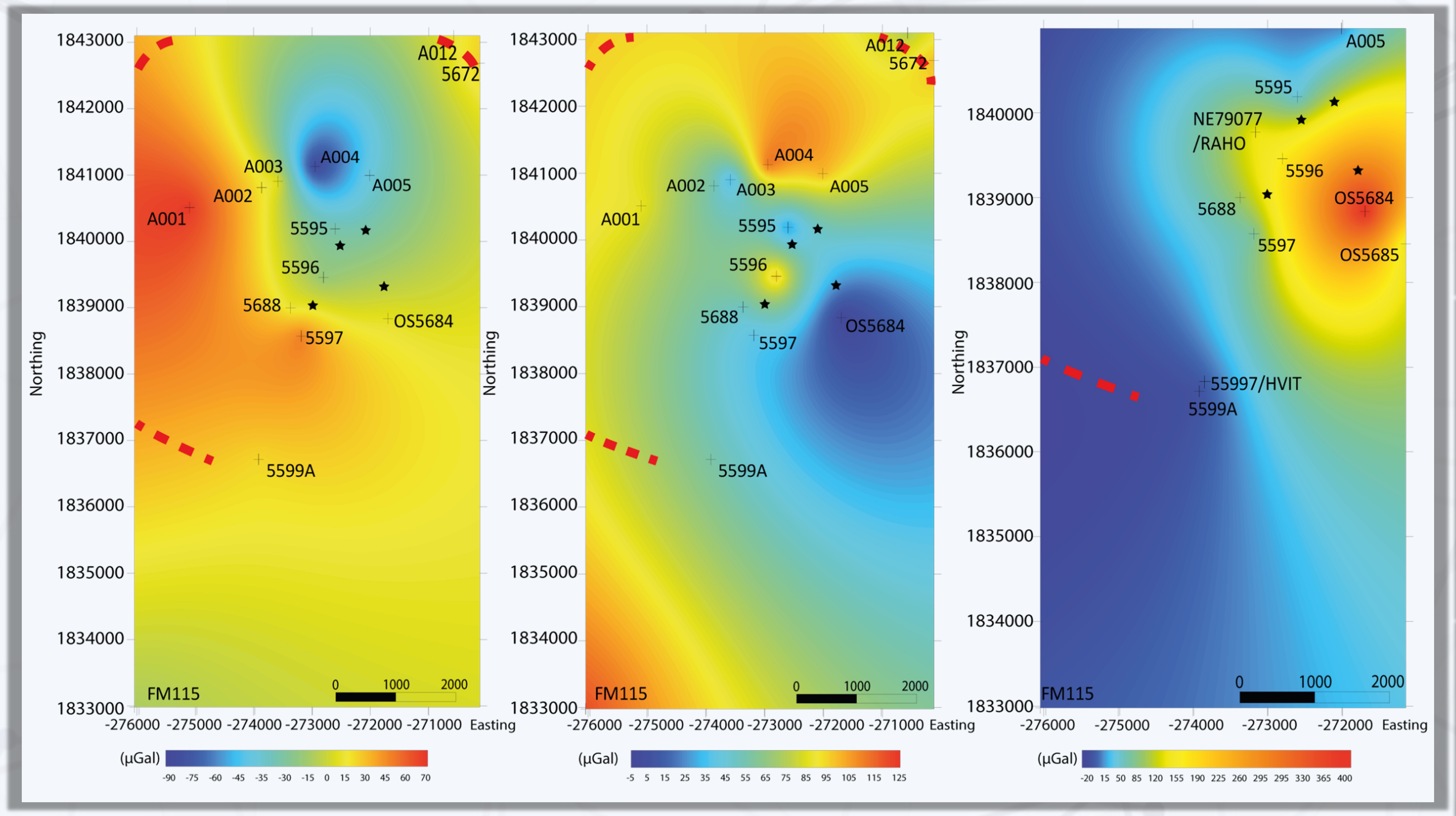



*Fig. 3 – Residual gravity maps for 1990-1995[8,11] (A), 1996-2003[8] (B) and 2003-2022 (C) in µGal. The dotted red line represents the caldera rim. Benchmarks are represented by black crosses, and production and reinjection wells are marked by black stars. The FM115 was used as a reference benchmark in the three surveys. The error average in the last 30 decades is less than ±15 µGal. The gravity anomaly since 1996 has been considered to be related to the production and reinjection activity.*

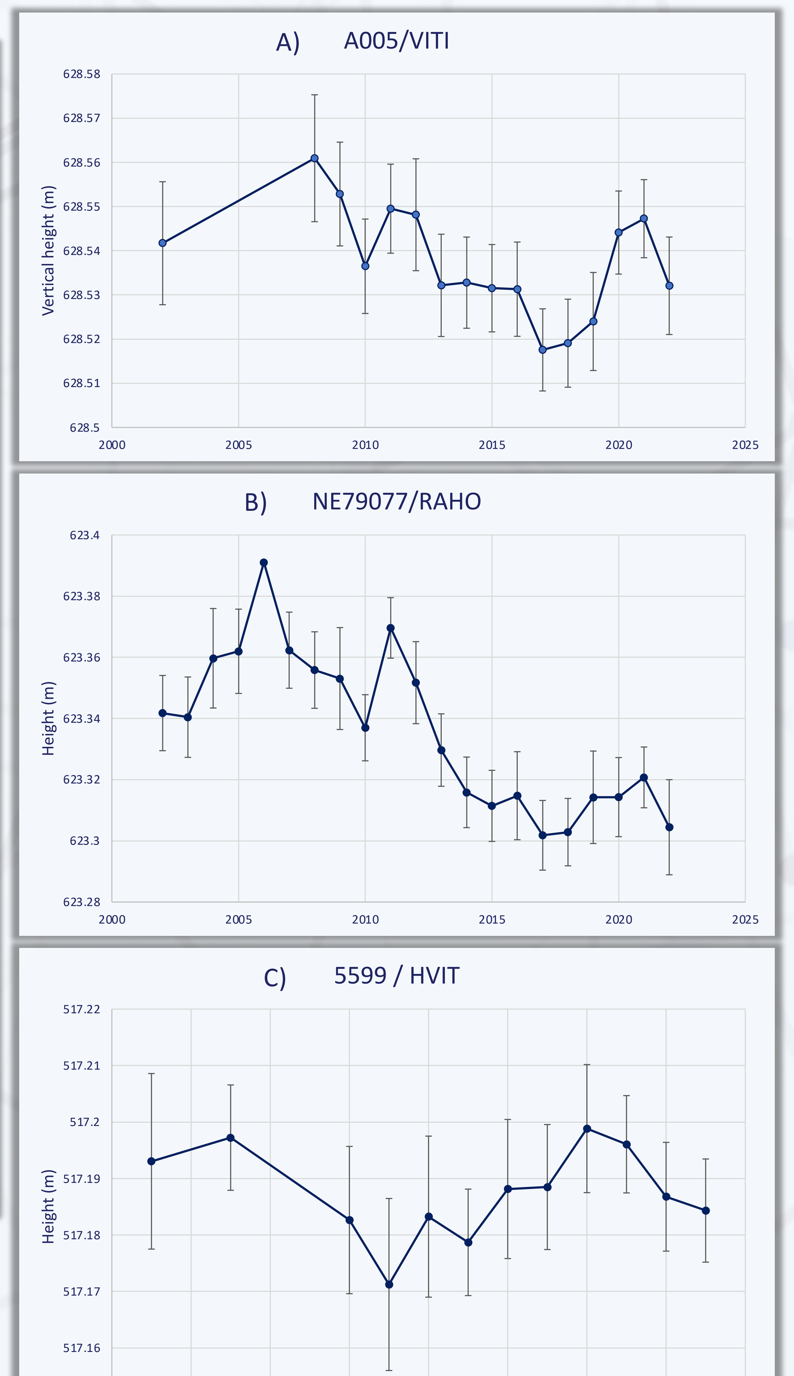



*Fig. 4 – A) Average GPS elevation data as function of time for A005/VITI between 2002-2022. B) GPS average measurement for NE79007/RAHO between 2003-2022. C) GPS average measurements for 5599/HVIT between 1997-2017. The annual vertical deformation rate from north to south in the Krafla area is on a millimetre scale, with an average error of less than 1 cm (provided by Yilin Yang – University of Iceland).*

- **1990 – 1996 (*Fig. 3A*):** a general decrease of **85 µGal** was interpreted to be related to **magmatic processes** following the the Krafla Fires (1975-84)[8,11].
- **1996 – 2003 (*Fig. 3B*):** there was a general decrease of **100 µGal** interpreted to be associated with **geothermal production[8], magma drainage from shallow reservoir and dyke injection intrusions[15]**.
- **2003-2022 (*Fig. 3C*):** a general increase in the gravity of up to **120 µGal** in the centermost part of the Krafla caldera.
- The Krafla caldera shows **spatio-temporal changes in the pattern** of residual gravity changes over the past 32 years.
- The GPS measurement in the last decades (*Fig. 4*) shows the slow **annual vertical deformation rate** in the last decades.

## 4) What is the cause for the gravity increase?

**1. Cooling of the volcanic System (*Fig. 5*)**

- **Exponential decay** in the **subsidence rate** since Krafla Fires.
- Closure of fractures
- Volatile loss

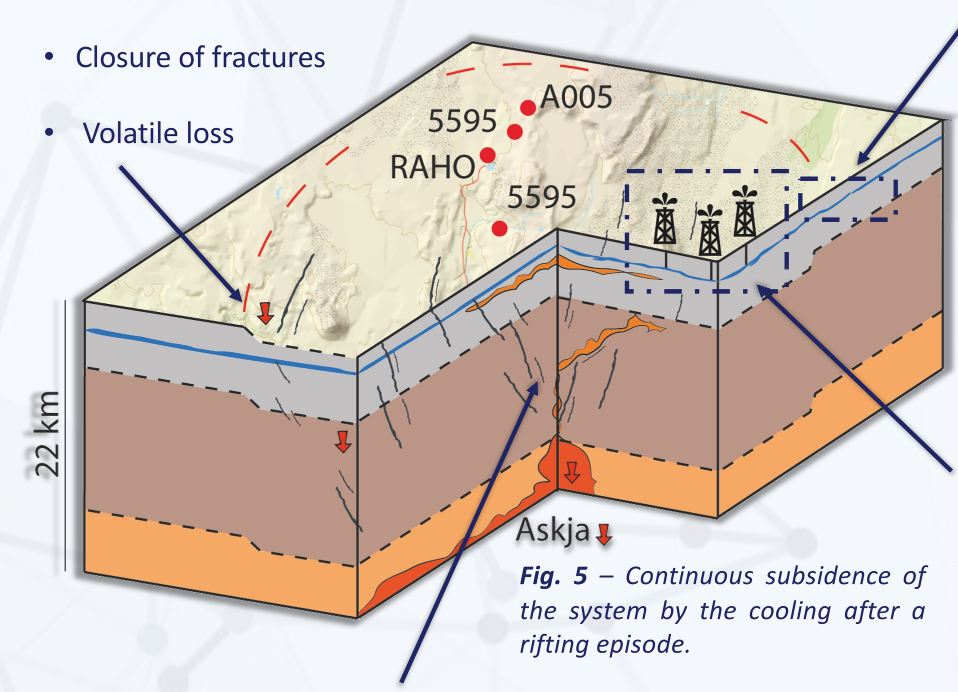



*Fig. 5 – Continuous subsidence of the system by the cooling after a rifting episode.*

**2. Magma drainage (*Fig. 5*)**

- **Connection between reservoirs** (2.8 km depth and 21 km depth)[14, 8].
- **Lateral magma migration** from Krafla to Askja[8].

**3. An uprising of the water table (*Fig. 6*)**

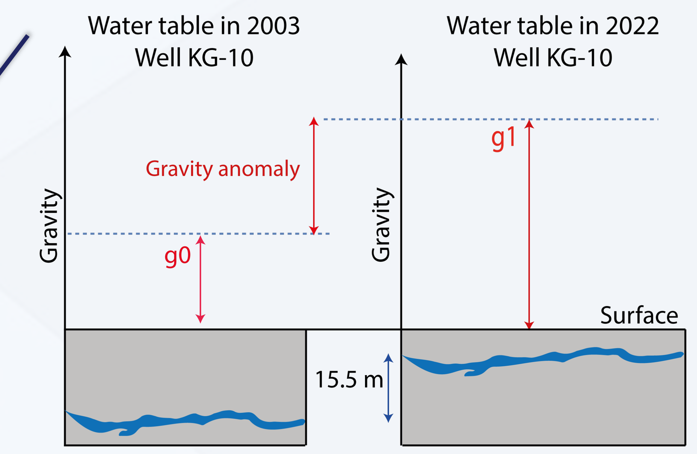



*Fig. 6 – Effect of the water table uprising[18].*

- **-47.5%** geothermal water production (2000-2022).
- **15.25 m** increase of water table with an average porosity of 17%[16], could explain **+108 µGal** gravity change.

$$\Delta g = 2\pi G\rho h\varphi^{17}$$

**4. Effect of water reinjection (*Fig. 7*)**

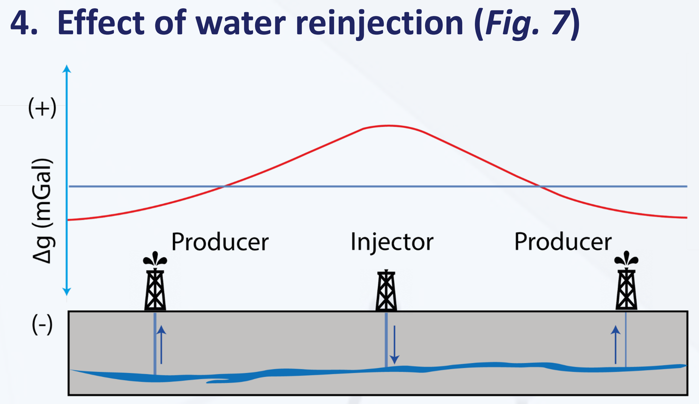



*Fig. 7 – Effect of the water injection[18].*

- **+ 263% water reinjection (2003-2016).**
- Reinjection well KG-10 (200 m from benchmark 5595), was active during the June 2022 survey.

## Outlook

- To develop a **numerical model** that describes the sub-volcanic system's **long-term evolution**.
- Comparison with **other geophysical methods** applied in Krafla during the same campaign (June 2022).
- **New survey in June 2023** in combination with GPS measurements.
- **Increase the stations measured** in the Krafla Volcanic Area to link with previous studied benchmarks.
- Possible **inclusion of data** from other gravity surveys between 2003 and 2022.

**Abstract** **References**

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