Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Subsurface Dynamics and Geohazard Monitoring in NE Iceland: Insights from Krafla and Theistareykir Geothermal Fields

Anette K. Mortensen[1]*, Vincent Drouin[2], Freysteinn Sigmundsson[3], Yilin Yang[3], Egill Árni Gudnason[4], Thorbjörg Ágústsdóttir[4], Rögnvaldur Líndal Magnússon[4], Karl Gunnarsson[4].

[1]Landsvirkjun, The National Power Company of Iceland, Katrínartún 2, IS-105 Reykjavík

[2]Bylgjuvíxl, IS-105 Reykjavík. Iceland

[3]University of Iceland, IS-102 Reykjavík, Iceland

[4]Iceland Geosurvey (ÍSOR), IS-203 Kópavogur, Iceland

anette.mortensen@landsvirkjun.is

Keywords: Geodetic monitoring, InSAR, Seismicity, Krafla, Theistareykir

1 INTRODUCTION

Geohazards in geothermal fields can arise from natural or human-induced sources. Naturally occurring seismic and geological hazards arise from volcanic activity, tectonic stress, and fault movement. In contrast, ground deformation and induced seismicity are commonly linked to changes in reservoir pressure, often due to fluid extraction and reinjection.

Advances in geodetic and seismic monitoring have improved the ability to observe subsurface processes with high spatial and temporal resolution. At three geothermal fields in NE-Iceland, Landsvirkjun operates a dedicated monitoring system for early detection of potential geohazards related to geothermal production and volcanic activity. This integrated monitoring system enables real-time tracking of the interactions between geothermal production, reinjection, ground deformation and seismicity. In doing so, it provides critical insights into subsurface permeability structures and fault behaviour, enhancing both operational safety and long-term resource management.

This paper presents geodetic and seismic observations from Krafla and Theistareykir geothermal fields in NE Iceland. The data reveal that both steady and variable ground deformation as well as changes in seismic activity, are frequently observed in these active geothermal systems. The findings suggest that magmatic intrusions occur much more frequently than volcanic history alone indicates, and that even small-scale changes in fluid extraction can produce detectable deformation and seismic signals. This information significantly enhances the ability to assess and anticipate geohazards, contributing to safer and more informed geothermal field management.

2 MONITORING METHODS AND EXAMPLES

Landsvirkjun operates a dedicated monitoring system at the Theistareykir, Krafla, and Námafjall high-temperature geothermal fields, all of which lie within the Theistareykir and Krafla volcanic systems, but both systems have been volcanically active within the past 3,000 years. The monitoring program includes a seismic network operated by Iceland Geosurvey (ÍSOR) and Icelandic Met Office (IMO), GNSS stations operated by University of Iceland, and annual analysis by Bylgjuvíxl of satellite radar imagery using InSAR techniques.

2.1 Seasonal variations in seismicity

The seismic network provides real-time earthquake detection and characterization. Seismic activity varies across the three fields: Theistareykir and Námafjall exhibit relatively low activity, with approximately 6–700 and 125 earthquakes per year, respectively, while Krafla experiences high seismicity with more than 3,000 events annually (Guðnason et al., 2025). Krafla volcano experienced a rifting episode from 1975–1984 including repeated dyke intrusions and eruptions, and magma is known to reside at a depth of 2–3 km (Mortensen et al., 2010, Zierenberg et al., 2013). Geothermal power production has been sustained in Krafla since 1978.

Calculated b-values using the Gutenberg-Richter relation and Vp/Vs ratios estimated using the Wadati method indicate a weak crust and suggesting a reduced likelihood of large earthquakes, with high b-values and relatively low Vp/Vs ratios. This is consistent with the observation that seismicity has changed very little in response to

variations in production or abrupt reinjection changes. Earthquake locations align with lineaments mapped during drilling of new production wells and during temporary in-field reinjection tests, highlighting permeable structures. Focal mechanisms indicate distinct tectonic settings across the fields: Krafla within an intracaldera environment, Námafjall along the rift zone, and Theistareykir at a central volcano influenced by both rift and nearby transform structures.

In Krafla, seismicity exhibits seasonal variations in both frequency and magnitude, peaking in winter and spring (Fig. 1). This coincides with periods when precipitation accumulates as snow and groundwater levels are low. These seasonal patterns are interpreted as pore-elastic pressure changes driven by variations in recharge. As snow melts in spring pore pressure increases as the water table in the reservoir is raised from infiltration of meltwater, leading to a decrease in seismic activity.

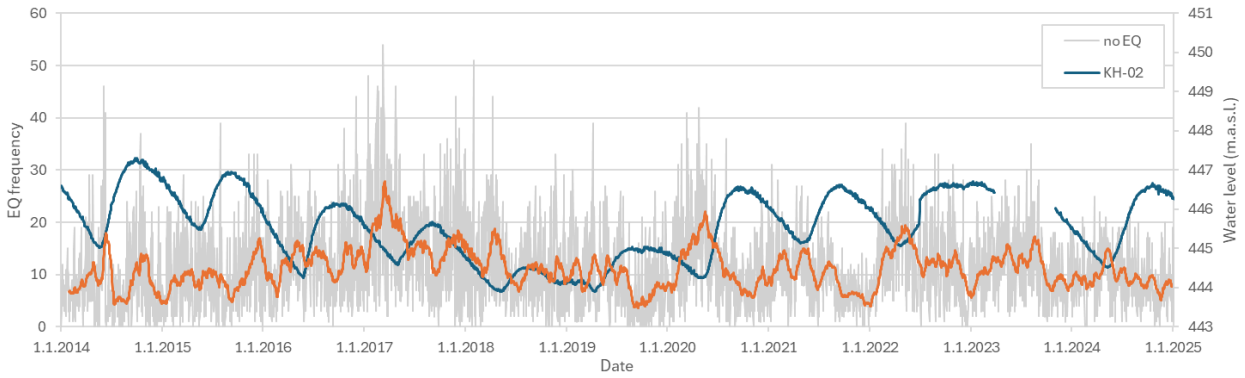


Figure 1. Frequency of earthquakes in Krafla geothermal area compared to seasonal changes in groundwater level (borehole KH-02). Orange line shows temporal smoothing of earthquake frequency using a moving average.

2.2 Monitoring crustal deformation with InSAR and GNSS

GNSS and InSAR techniques are both employed to monitor crustal deformation across the geothermal fields. Each method provides complementary strengths. InSAR offers broad spatial coverage and millimetre scale resolution, making it possible to detect subtle deformation patterns over large areas. The generally sparse vegetation cover in Iceland is also highly favourable for InSAR, as it provides stable ground scatterers and improves the quality of the radar signal. However, InSAR is limited by seasonal conditions: during the winter months, snow cover prevents reliable radar returns, and therefore no usable deformation signal can be obtained.

In contrast, GNSS stations operate continuously throughout the year, allowing precise tracking of deformation in real time. This continuous operation makes GNSS particularly valuable for determining the onset of deformation events and for maintaining deformation records during winter, when InSAR data are unavailable. GNSS stations also serve as essential reference points for processing and validating satellite radar images, thereby improving the accuracy of the InSAR deformation maps.

Together, the two systems provide a robust monitoring framework, where GNSS ensures temporal continuity and absolute positioning, while InSAR contributes detailed spatial information during the snow-free season.

2.3 Examples of magmatic and production induced deformation

Several deformation sources have been identified using GNSS and InSAR. These observations reveal both magma-tectonic and geothermal-production–related processes operating across the fields.

At Theistareykir, an uplift signal was detected during 2023 with the uplift centre approximately 2 km northwest of the geothermal field (Fig. 2)(Drouin (2024). A continuous GNSS station is located at the centre of uplift, thus the timing of the uplift is well constrained from February 2023 until the end of 2023 (Gudnason et al., 2024). Modelling indicates that this deformation is consistent with a shallow magmatic intrusion at a depth of 4,5–5 km. Similar small intrusions have been observed in the region in 1995-1996 and 2006-2009 (Metzger and Jónsson, 2014), suggesting that small episodic magmatic recharge may be characteristic of the system.

In addition to the episodic uplift, a localized deformation signal is present at the reinjection zone within the geothermal field, where subsidence has occurred at a rate of 15 mm/yr since the onset of power production in

2017. This subsidence is attributed to reservoir cooling and pressure changes associated with shallow fluid reinjection at 200-500 m depth.

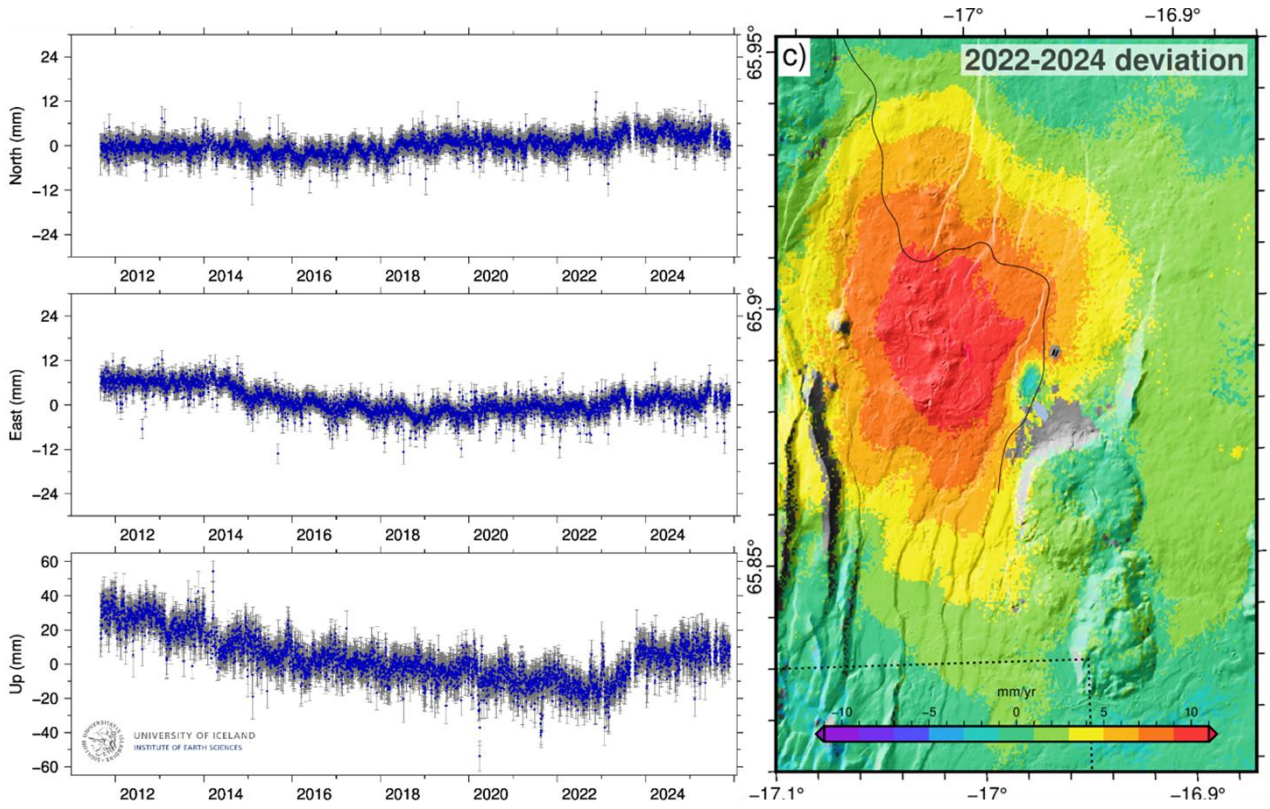


Figure 2. GNSS timeseries and INSAR image associated with the 2023 magmatic intrusion at Theistareykir geothermal area.

In Krafla, deformation has long been dominated by subsidence driven by more than 45 years of sustained geothermal production, while also affected by crustal relaxation following the Krafla Fires in 1975-1984. However, after 2018 the deformation pattern changed markedly. A broad uplift developed, centred within the caldera and extending toward its margins (Lanzi *et al.*, 2023). This uplift gradually decreased between 2019 and 2023. Between 2023 and 2024, the area again exhibited subsidence, followed by a renewed transition to uplift in 2024–2025. These alternating deformation phases correlate with operational changes of up to 2500-3000 ktonn at the Krafla geothermal field (Fig. 3).

Crustal deformation has also been repeatedly detected in the Hvíthólar subfield of Krafla, where the signal is closely linked to changes in geothermal production. When extraction from well KJ-21 resumes after a resting period, localized subsidence of approximately 5–7 mm/yr is observed (Drouin 2023). This deformation is consistent with a shallow source related to fluid withdrawal from the reservoir.

3 DISCUSSION AND CONCLUSIONS

The geodetic and seismic observations from Krafla and Theistareykir provide important insights into the dynamic interplay between geothermal operations, crustal structure, and magmatic processes in NE Iceland. The results clearly demonstrate that the deformation behaviour in these high-temperature geothermal systems is governed by both natural and anthropogenic drivers, often operating simultaneously.

A recurring theme across all sites is the role of Iceland's weak upper crust. High b-values and low Vp/Vs ratios indicate a fractured, fluid-rich and mechanically compliant crust, which responds readily to pressure changes. This inherent weakness allows small fluctuations in reservoir pressure, whether from fluid extraction, reinjection, or natural magmatic recharge, to produce measurable deformation signals. At the same time, the weak crust limits the accumulation of large elastic stresses, helping explain why seismicity remains moderate and shows limited sensitivity to operational changes. This behaviour underscores that geodetic and seismic data are powerful tools to identify subtle subsurface processes and changes in such environments.

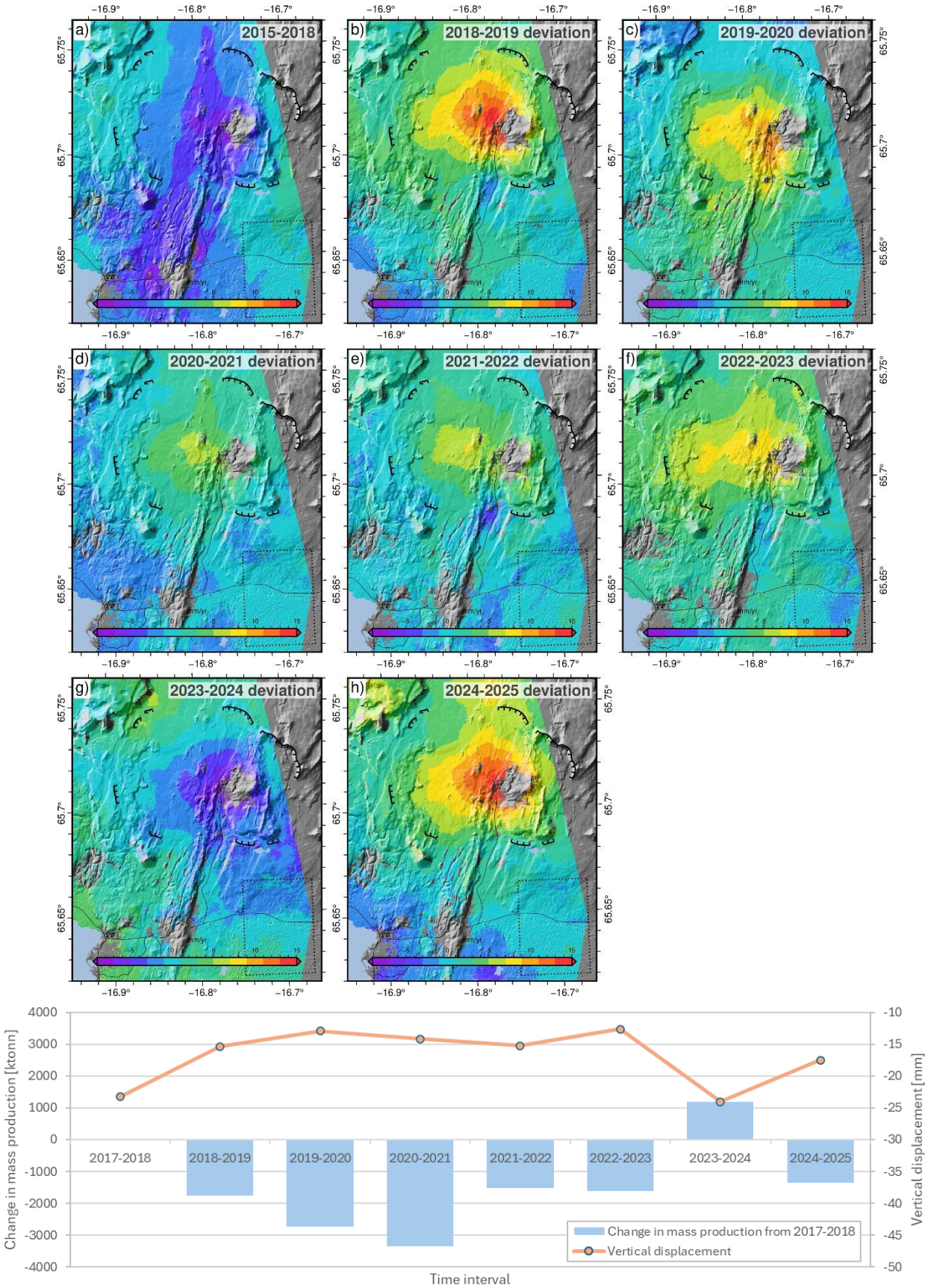


Figure 3. InSAR images 2017-2025 (top) highlight crustal deformation associated with changes in mass production at Krafla geothermal field (bottom).

The deformation examples illustrate this sensitivity clearly. At Theistareykir, the 2023 uplift episode aligns with a shallow magmatic intrusion at 4.5–5 km depth. Similar intrusions in 1995–1996 and 2006–2009 highlight that magma replenishment occurs more frequently than the eruptive history would suggest. These findings

underscore the importance of continuous monitoring, as small intrusions may represent early stages of larger magmatic processes, even if they do not necessarily progress toward eruption.

Localised deformation related to geothermal operation is equally evident. The persistent 15 mm/yr subsidence at the Theistareykir reinjection site demonstrates how reinjection-induced cooling and pressure changes can alter the near-surface stress field. The Hvíthólar subfield in Krafla provides a particularly clear example of the direct coupling between production activities and ground deformation. Here, vertical motion correlates almost instantaneously with the extraction rate at well KJ-21, underscoring the shallow, pressure-sensitive nature of the reservoir.

Krafla shows the most complex deformation pattern, influenced by the legacy of the 1975–1984 rifting episode, long-term power generation, and ongoing magmatic processes. The transition from decades of subsidence to broad uplift after 2018, followed by alternating subsidence and renewed uplift or rebound in 2023–2025, suggests that production-related mass extraction interacts with deeper crustal processes. The observed uplift and subsidence between 2018-2025 correspond to reduced or increased extraction. The magnitude and spatial extent of the deformation, which is centred within the caldera, points toward a deep-seated source, likely at the deeper part of the geothermal reservoir and at the transition to the shallow magma chamber system known to reside at 2–3 km depth.

Taken together, these examples show that deformation in Icelandic geothermal fields cannot be interpreted through a single mechanism. Instead, the observed signals arise from the interaction of a weak, permeable crust, active magmatic plumbing systems, and variable geothermal operations. The synergy between InSAR and GNSS has proven essential for resolving these processes across a range of timescales, from seasonal cycles to multi-decadal trends.

Overall, the monitoring results significantly enhance the ability to assess geothermal-related geohazards, improve operational decision-making, and support sustainable reservoir management. The findings demonstrate that continuous, multi-sensor monitoring is essential for understanding the evolving interaction between geothermal production and the active volcanic environment characteristic of NE Iceland.

Acknowledgements

This paper was edited with assistance from Chat-GTP.

REFERENCES

Drouin, V.: InSAR Monitoring of Krafla, Bjarnarflag and Þeistareykir Geothermal Areas, 2022 update. *Landsvirkjun* **LV-2023-005** (2023), 18 pp.

Drouin, V.: InSAR Monitoring of Krafla, Bjarnarflag and Þeistareykir Geothermal Areas, 2024 update. *Landsvirkjun* **LV-2024-085** (2024), 30 pp.

Guðnason E.Á., Ágústsdóttir Þ., Magnússon R.L. and Gunnarsson K.: Seismic Monitoring in Krafla, Þeistareykir and Námafjall: November 2023 to November 2024. *Landsvirkjun* **LV-2025-008** (2025), 39 pp.

Gudnason, E. Á., Drouin, V., Yang, Y., Sigmundsson, F., Ágústsdóttir, Th. and Mortensen, A. K. (2024). Changes in seismicity and observed deformation related to inflation at the Theistareykir high-temperature geothermal field, NE Iceland, in 2023-2024. *EGU24-19913, EGU General Assembly 2024,* Vienna, Austria. https://doi.org/10.5194/egusphere-egu24-19913.

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

Mortensen, A.K., Grönvold, K., Gudmundsson, Á., Steingrímsson, B., Egilson, T.: Quenched silicic glass from Well KJ-39 in Krafla, north-eastern Iceland. *Proceedings*, World Geothermal Congress (2010), Bali, Indonesia, 1284.

Lanzi, C., Drouin, V., Sigmundsson, F., Geirsson, H., Hersir, G.P., Ágústsson, K., Parks, M.M., Hreinsdottir, S., Guðmundsson, Á.: Pressure increase at the magma-hydrothermal interface at Krafla caldera, North-Iceland, 2018–2020: Magmatic processes or hydrothermal changes? *JVGR*, **440**, (2023), 107849.

Zierenberg, R.A., Schiffman, P., Barfod, G.H., Lesher, C.E., Marks, N.E., Lowenstern, J.B., Mortensen, A.K., Pope, E.C., Bird, D.K., Reed, M.H., Friðleifsson, G.Ó., Elders, W.A.: Composition and origin of rhyolite melt intersected by drilling in the Krafla geothermal field, Iceland. *Contrib. Mineral. Petrol.*, **165**, (2013) 327-347.