# FINAL REPORT

**Deep roots of geothermal systems**

Project ID: ISOR 13-0333

Coordinator: Hjalti Franzson

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# 1 Project summary

This study aims at understanding the concept of water rock interaction in the fossil and exhumed geothermal system surrounding and driven by a gabbro heat source at Hrossatungur (HTG) within the 5,5-4 Ma Hafnarfjall-Skarðsheiði central volcano in W-Iceland. A close study of the interaction of the magma (and volatiles) with the surrounding groundwater was of particular interest. The gabbro intrusion itself was formed by a repetitive accumulation of basaltic cone sheet injections into a trap between a steeply dipping basalt succession and a pyroclastic caldera filling (c.f. figure 1). The gabbro, which was emplaced at 700-1200 m depth, is the last intrusive phase in this part of the volcano. The gabbro is coarse grained except being doleritic at the outer contact. There is evidence of crystal fractionation within the gabbro possibly reaching dioritic composition near the roof of the intrusion, and this indicates a gradual long term uninterupting cooling process. The geothermal system developed during the cooling of the gabbro renders it as the youngest in that area only to be succeeded by a zeolite regional alteration. The geothermal system probably succeeds an earlier high-T system related to the caldera margin to the south and west of the gabbro. The gabbro contact shows a contrasting relation with the surrounding rock and relation with surrounding groundwater. A zone of hornfels up to 20m thick is found at the gabbro/lava contact showing strong evidence of forming simultaneously to the intrusion. Hornfels is also observed overlying the gabbro. However, hornfels is insignificant at the contact of the gabbro/pyroclastic caldera filling to the north. There we find ample evidence of quenched pathways of intruding groundwater into the gabbro along with areas of brecciation and probable steam explosive activity. The resulting hydrothermal activity associated with the gabbro heat source also shows a large contrast. High alteration (quartz – epidote – actinolite – hornblende – wollastonite – garnet - calcite assemblages) resides within the lava succession to the south and west, with additional aggressive calcite rock alteration above the intrusion in the northwest. Hydrothermal alteration is very limited at the gabbro/pyroclastic contact showing low rock alteration and deposition of zeolites and minor quartz. This scenario has been interpreted as indicating heat transfer by conduction at the lava/gabbro boundary and where the conducted heat is being mined by the geothermal system outside the gabbro, while a rapid inflow of ground water into the gabbro from the water rich pyroclastic caldera filling to the north presents a very effective heat mining and where the groundwater flow towards the gabbro prevents the alteration of the pyroclastic caldera filling. Hydrothermal alteration within the main gabbro body is low suggesting a very limited water/rock interaction during and succeeding the consolidation of the

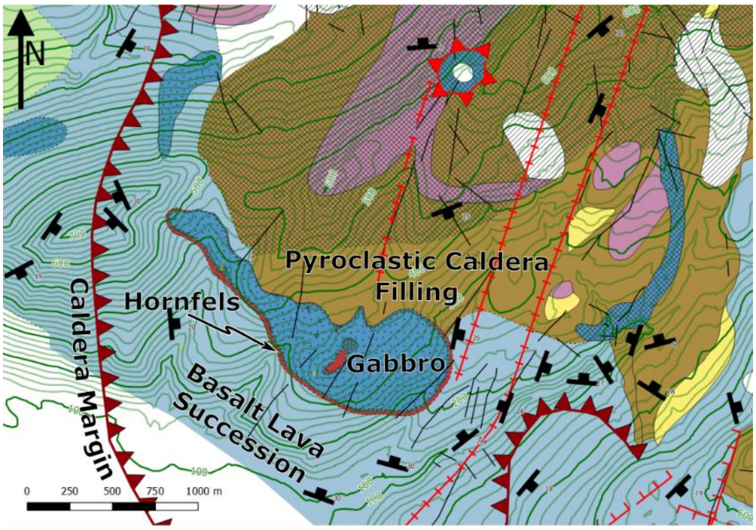

*Figure 1. A simplified geological map of the Hrossatungur Gabbro (HTG) and the surrounding basalt and pyroclastic caldera filling*

magma body. An exception to that is near the explosive fluid intrusion where extensive alteration is observed with hornblende alteration of pyroxene.

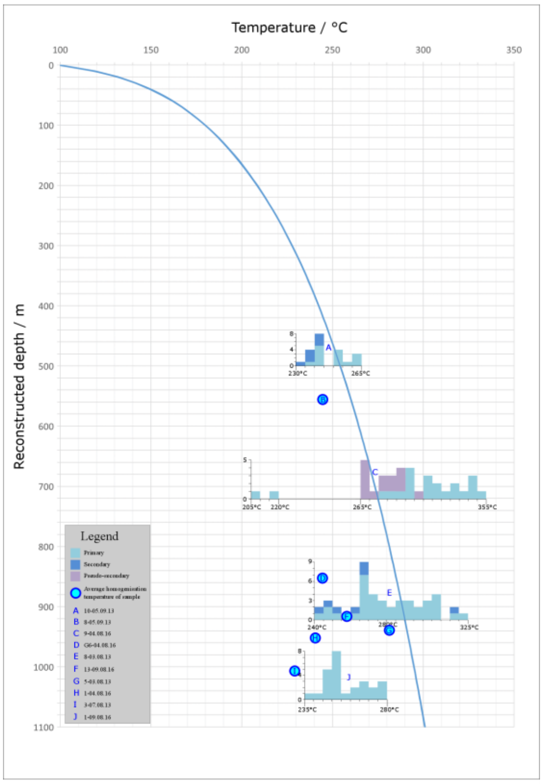


*Figure 2. Th fluid inclusion temperatures plotted against depth related to boiling point curve*

Fluid inclusion studies show a thermal range of 196 - 338°C in the geothermal system surrounding the gabbro, in particular within the lavas south of the intrusion while zeolites and low rock alteration presides within the pyroclastic caldera filling north of the gabbro. Fluid inclusions Th values taken in a quartz/platy calcite vein system at 700 m elevation which are indicative of boiling conditions provide depth constraints of the geothermal system as shown on the figure 2.

A detailed MSc study on the pyroxene hornfels shows conclusively how the conductive heat causes expulsion of the water and volatiles (LOI), by the recrystallization of the hydrothermal minerals into water deficient minerals (Figure 3). This recrystallization involves ortho- and clinopyroxenes, plagioclase and oxides. Figures 4-6 show the compositional range of these minerals, and these compositons are within the same range as those found within fresh basalts. That explains to some extent that ICP analysis of about 30 samples of hornfels fall in general within the primary compositions found within the products of the central volcano. One of the reasons for the chemical analysis of the hornfels was to evaluate metasomatic influence from the gabbro. The results do not show such effect, though there is a minor overall increase in lead, Zn, Cu and Ni which probably relate to minor sulfide diffusion across the gabbro boundary. Confined areas of high sulphide contents break through the hornfels which infer late stage volatile excape from the gabbro. The chemical rock analysis show a marked change which infers that rock dissolution has taken place which may have created the permeability needed for the volatile excape through the hornfels. SEM analysis of these sulfides in the rock show elevated lead, copper, zink, arsen and even gold and silver. Further research is needed to confirm these and other similar sulfide zones present within the hornfels. $CO_2$ is another magmatic volatile that may provide a heat input into the geothermal system. Calcite is indeed a major mineral component in the alteration assemblage and appears to be present at temperatures much higher than found within active high temperature systems (<300°), even near the hornfels. The cause of the extensive presence of calcite are probably several

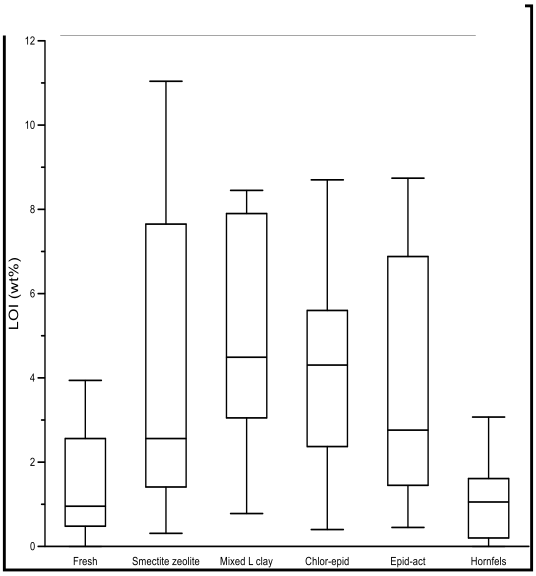


*Figure 3. Comparison between loss of ignition (wt%) of different alteration zone in Icelandic rocks and LOI of the hornfels around HTG. Solid line within the boxes indicate median value, horizontal lines in the boxes represent 25, 50 (median) and 75% value.*

(e.g. heating of groundwater, boiling, volatile excape) and further more detailed studies are needed to resolve these, e.g by fluid inclusion measurements.

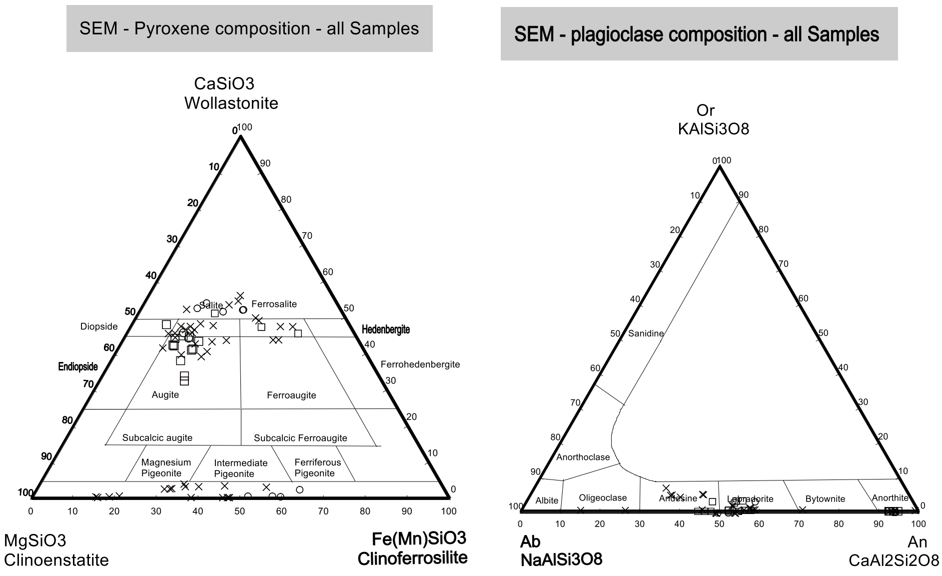


*Figure 4. SEM analysis of pyroxene and plagioclase within the hornfels. Microprobe analysis of same samples show similar analytical distribution.*

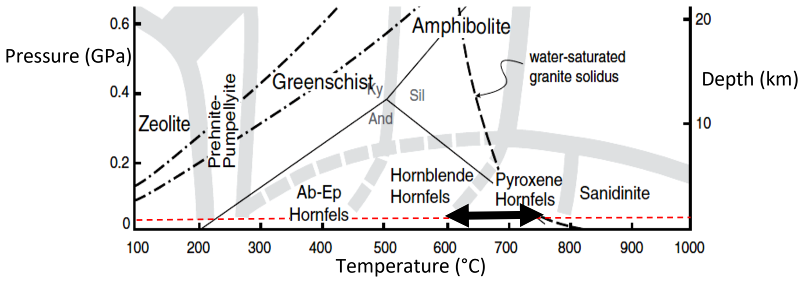


*Figure 5: Temperature- pressure diagram showing the general limits of various metamorphic facies. Boundaries are approximate and gradational (Winter, 2014). The dotted line at the bottom of the figure indicates the approximate pressure expected around the gabbro during the hornfels event and the double arrow the position of the HTG hornfels.*

The HTG is unique in many respects. On the northern side an aggressive intrusion of groundwater is observed, with a probable connection to an overlying caldera lake, into the gabbro causing steam brecciation and extreme thermal mining. On south side the access of water is limited which results in the formation of a protective near impermeable coat, where the heat conduction is the dominant thermal exchange to the surrounding and to the adjacent geothermal system. The HTG is also somewhat anomalous because it is emplaced at a very shallow level (700-1200 m depth) and can therefore hardly be considered to represent a deep roots to a geothermal system which is expected to lie >2 km and even much further down as evidenced by seismicity. This is in particular important with respect to the higher probability of a shallow heat source (HTG) connecting to a water resource.

If we look at the distribution of aquifers found within our drilled high temperature systems, then there is a general decrease of permeability below about 2 km. This decrease would diminish the probability of an interaction between a fluid and a deep magma source. This would also infer that the simultaneous formation of “impermeable” hornfels coating and dominating thermal conduction from the magma into the surrounding is more likely to occur at deeper levels.

One of the aims of the project was to relate HTG to situation the presently active high temperature systems. Many of the fossil relatively deeply eroded central volcanoes (e.g Hafnarfjall and Geitafell) which have developed calderas show that larger intrusions and magma chambers become relatively shallow which may relate to the gradual elevation with time of the deeper crust (L2/L3 interphase). This agrees well with Krafla and its high level magma chamber(s), while a shallow magma chamber has not been located at Hengill (though its precursors at Stardalur and Hvalfjörður developed to that stage) nor any of the Reykjanes systems. The apparent direct connection of a geothermal system to a larger “parental” intrusion is therefore probably quite varied and based on individual systems, and it must be taken into consideration to what extent the heat exchange is controlled simply by the general high thermal gradient present below the high-temperature systems. This higher gradient is certainly as a result of the higher proportion of intrusions where each of them are conducting heat to the surrounding.

Intrusions intersected by boreholes within the geothermal systems are often recognized by the contact alteration at their outer margins. These range from being negligible with minor oxidation to an extreme where the rock has been completely transformed into hornfels. In this project a collective sample was taken at about 1500 m depth in well HE-42 at Hellisheiði along a dyke margin. The detailed SEM/EMP analysis of the mineralogy is quite similar, or even more extreme, to that found at the HTG hornfels. Such mineralogy has also been found at depth within the Reykjanes high temperature field.  This type of alteration is therefore considered to represent a recrystallization due to a heat conduction transfer from the magma into the adjacent rocks and indicative of thermal recharging the rocks within the geothermal system. The extreme hornfels found at the dykes margin at Hellisheiði is also an indication of that the heat intensity is related to the time factor of the magma moving along the dyke (magma feeder to an eruption). The intrusions which form the base of most of the high-temperature systems are therefore transporting the thermal heat up towards the water resource to be eventually mined there.

Several studies within the high temperature systems have shown a close relationship between intrusions and permeability. It has also been proposed that renewed heating has occurred associated with historic eruptions at Reykanes, Eldvörp and possibly Nesjavellir. The feeder dykes are inevitably a direct connection to the deeper crust but may at the same time be the pathway for the downflow of fluid. An appropriate questions would then arise: does this downflow mine the heat from the molten dyke intrusion?, could it extend all the way to the “magma chamber” at lower crust?, or does it just extend to depths where crustal temperatures are “400-600°C” and mine from there?

The HTG is anomalous in that it presents a last volcanic and geothermal phase in this part of the volcano and the gabbro thus has the opportunity for a gradual conductive heating of its surroundings during cooling and consolidation uninterrupted by later tectonics and magmatic episodes. This gabbro therefore only describes the water/rock relationship associated with this particular one time volcanic and tectonic event. If we assume that a geothermal system is active for >$10^5$ y one must assume that several large intrusions will occupy the deep roots, each of them taking >$10^3$ y to consolidate and during that time to be intersected and interrupted by several magmatic and tectonic events, some of which will re-open a connection to a water resource and recreate heat mining as may have been the case in Geitafell in southeast Iceland (Friðleifsson 1983).

## 2 Project Management

*The project was managed by Hjalti Franzson and ISOR. A good cooperation was with Enikö Bali and Guðmundur Heiðar Guðfinnsson, both at University of Iceland. The sampling and mapping was mainly done by HF along with James Brett, Moneer Altenhary and Guðmundur Ómar Friðleifsson. The samples, mapping data and petrographic thin sections are and will in future be used by all parties at will.*

*The project had initially somewhat a different organization. Enikö Bali intended to cooperate in the project through grant proposals, the first one a Marie Curie and the second one through Rannis, but neither of them were awarded. This then lowered Enikö´s participation for a time. She has now a position within the UI and is actively taking part as supervisor to a student who´s projects includes a BSc thesis and a forthcoming MSc project, both on the HTG aureole. Another MSc study is now at it´s final stage, which initially had not been planned and is done by Moneer Altenhary and supervised by HF and Guðmundur H. Guðfinnsson at UI. Guðmundur Ó. Friðleifsson participated in the project in the intial stage. We hope that the HTG will continue to be a source for increased knowledge of geothermal systems.*

## 3 Student involvement

One BSc dissertation has be completed on the garnets found within the geothermal system to the south and west of the HTG (Haraldur Sigurjónsson, 2016) and two MSc thesis are under way; one by Haraldur Sigurjónsson and supervised by Dr Enokö Bali at UI, which will deal with the hydrothermal alteration and fluid inclusions (Th and Tm) south of the HTG. The other is a close study of the hornfels on the southern side of HTG done by Moneer Alnethary and supervised by Hjalti Franzson at ISOR and Guðmundur H. Guðfinnsson at UI. The latter thesis, which is near completion, presents results based on geochemisty (ICP) and mineralogy (petrography, SEM, EMPA) of the hornfels. James Brett an MSc geologist from England, joined ISOR for about 8 months in 2016 for an apprenticeship where he got aquainted with the various sides of geothermal science. He participated enthusiastically in this project where he took part in the fieldwork, figures and maps draughting and did also most of the fluid inclusion work of the project.

## 4 Publications and disseminations

A peer reviewed publication has not materialized yet. We, however have presented the results in various ways; firstly through the various GEORG workshops but also at 2016 Spring Meeting at the Geol Soc of Iceland. The work is still underway with regard to master projects, and we fully intend to publish results, which already are significant, hopefully next year.

# 5 Cost statement

*The cost of the work involved fieldwork, work in the lab and analytical cost. The cost of the student work was partly financed by the project but otherwise by the University of Iceland, the UNU Geothermal Training Programme, the apprentice and personal work by HF.*

*The overall book keeping will be made by ISOR.*