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A Conceptual Hydrological Model of the Thermal Areas within the Northern Neovolcanic Zone, Iceland using Stable Water Isotopes

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ABSTRACT

Iceland is situated on the boundary between the European and American plates. The divergent plate boundary crossing Iceland is generally called the Neovolcanic Zone and is characterized by active volcanism, hydrothermal activity, seismicity and a graben structure. The Northern part of the Neovolcanic zone consists of five NNE-striking left stepping *en echelon* volcanic systems where a fissure swarm, a central volcano and high temperature hydrothermal areas characterize each system. The isotopic composition of the thermal waters varies considerably both within and between systems and thus reflects the complexity of both inflow and structure of the thermal areas. The origin of the deep thermal fluid in the areas that have been drilled into is precipitation, either local or from far away, and older groundwater with a pre-Holocene component. Observed oxygen shift is also highly variable from less than 1‰ to about 7‰.

In the paper the water isotopic characteristics of the thermal areas in the northern part of the Neovolcanic Zone in Iceland are reviewed and a conceptual hydrological model for the area constructed.

1. INTRODUCTION

The Northern Volcanic Zone (NVZ) of Iceland has a north-south direction and extends from the glacier Vatnajökull in the center of Iceland to the Tjörnes peninsula and Öxarfjördur bay in the north. It consists of five NNE striking left-stepping *en echelon* volcanic systems, with about 20-40 km spacing. The volcanic systems are characterized by central volcanoes, fissure swarms and geothermal activity, connected to recent magma intrusions and cooling magma bodies (Saemundsson, 1978). Two of the systems (Askja and Krafla) have developed calderas. Most of the volcanic rocks within the NVZ are tholeiitic basalts (Jakobsson, 1972) with minor amounts of acidic rocks (dacites and rhyolites) in the vicinity of the central volcanoes.

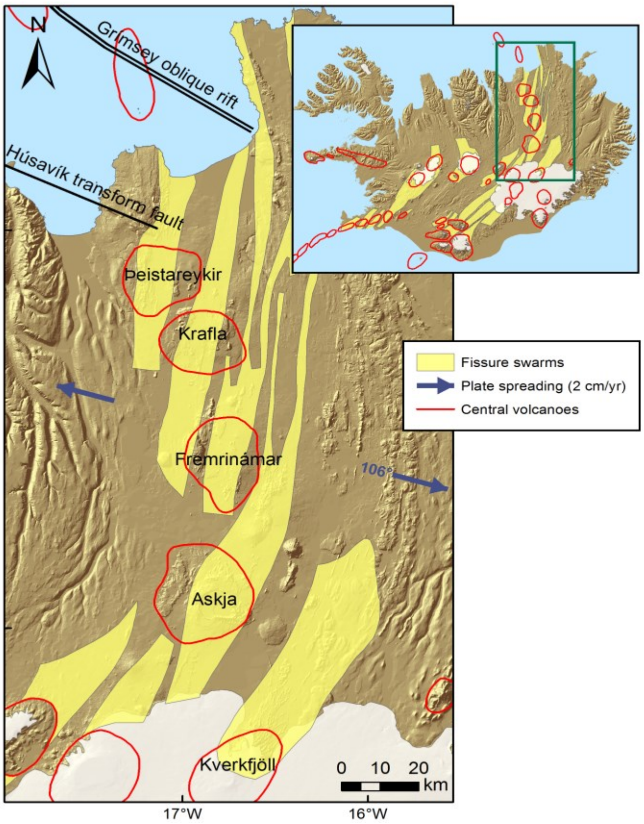

Figure 1: The five volcanic fissure systems across the Northern Volcanic Zone. The outlines of the fissure swarms and central volcanoes are according to Einarsson and Saemundsson (1987). Modified from Hjartardóttir et al. (2012).

The volcanic systems across the ca 50 km wide NVZ from northwest to southeast are: Theistareykir, Krafla, Fremrinámar, Askja and Kverkfjöll (Figure 1).

The water stable isotope technique has been applied to geothermal fluids from all but one system. Surface fumaroles and borehole deep fluids are available from the Theistareykir and Krafla fissure swarms, whereas only results for surface fumaroles are available for the Fremrinámar, Gjástykki and Kverkfjöll geothermal systems. No isotope results have been obtained for the hot water system in the Askja fissure swarm.

The 70-80 km long and 7-8 km wide Theistareykir fissure swarm is the northwesternmost (Figure 1). It is characterized by large normal faults (N22°E) with maximum displacement of 200-300 meters and rift fissures. To the north, the fault and fissure systems meet the NW strike slip Húsavík-Flatey Fault System (Magnúsdóttir and Brandsdóttir, 2011). The high temperature geothermal activity is connected to recent magma intrusions. The most recent volcanic activity in the area (Theistareykir lava) occurred some 2500 years ago (Saemundsson, 2007).

From 2002 to 2011 nine deep wells were sunk into the Theistareykir field, with depths ranging from 1723m to 2799m. The maximum rock temperature in 5 of the wells exceeds 300°C, with a maximum temperature of 380°C. However, chemical geothermometers show lower temperatures, generally in the range 270–300°C, which seems to reflect the measured temperatures of the major feed zones. Armannsson et al. (1986) divided the Theistareykir thermal area into 5 subareas (A,B,C,D,E) (Figure 2) on the basis of geology and geochemistry of fumaroles. The isotope composition of fumarole steam confirmed this division (Darling and Ármannsson, 1989).

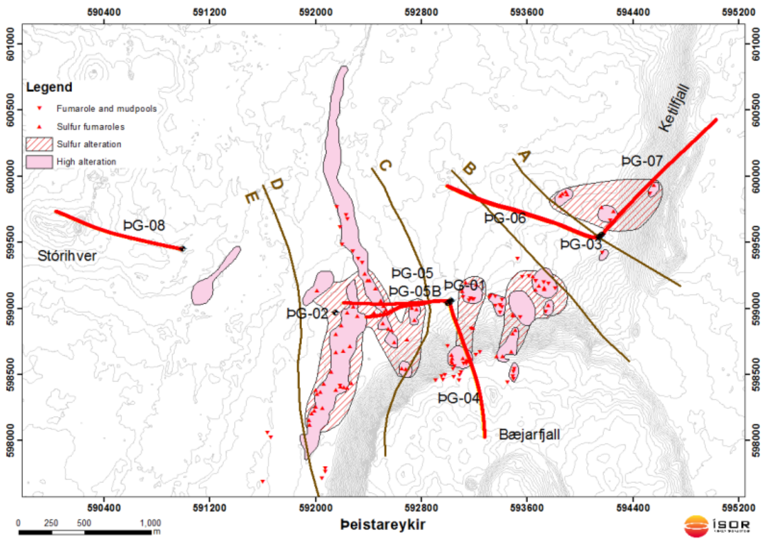

Figure 2: Locations and directions of drillholes and the division of the Theistareykir area into 5 sub-fields (Sveinbjörnsdóttir et al., 2013).

Gjástykki forms a large part of the Krafla fissure swarm north of Mt. Hrútafjöll. It comprises a graben 2-5 km wide and 40-50 m deep in which severl fissures and faults are found. One fumarole sample is available.

The Krafla volcanic system is located within an active caldera complex, which last erupted during the years 1975-1984. A shallow magma chamber at 3-7 km depth has been identified beneath the ca 8 km wide caldera by seismic attenuation studies (Einarsson, 1978). Analysis of ground deformation shows that deeper magma reservoirs are also present (Tryggvason, 1986), in accordance with Grönvold et al. (2008) that demonstrated that magma erupted from different magma reservoirs during the last eruptive episode (AD 1975-1984). The Krafla fissure swarm is about 90 km long and fractures are mostly oriented N to NNE with maximum width and throw of individual fracture of 40m and 42m respectively (Opheim and Guðmundsson, 1989). 40 production wells have been drilled into the Krafla geothermal system. The drilling has revealed temperatures in excess of 440°C at 2 km depth. The Krafla geothermal system has been divided into seven subfields as demonstrated in Figure 3. These are; Leirbotnar (Lower Leirbotnar, Vítismóar), Hvíthólar, Suðurhlíðar, Vesturhlíðar, Sandabotnar, Hvíthólar, Vestursvæði and Leirhnjúkur on basis of fluid chemistry and thermal characteristics (Ármannsson et al., 2015). Extensive isotopic studies have revealed distinct differences between subareas.

The Námafjall central volcano and hydrothermal system lies approximately 20 km SSA of the Krafla caldera and belongs to the Krafla fissure swarm. Drilling started in early 1950's for possible production of sulphur. Highest downhole temperature recorded is 320°C. In the Krafla fires, especially in the year 1977, when magma intruded towards south along the Krafla fissure swarm (Brandsdóttir and Einarsson, 1979) several wells in the Námafjall area were destroyed.

The Fremrinámar fissure swarm is the least investigated of the five NVZ fissure swarms. Surface thermal activity covers only about some 2 km^2 and is confined to the area close to the shield volcano Ketildyngja and the crater rows to the east and south of the volcano. The youngest volcanic activity occurred about 3000 years ago (Sæmundsson and Ólafsson, 2004). The maximum subsurface temperature estimated by gas geothermometers is about 300°C and the main upflow is connected to the youngest volcanic fissures (Sæmundsson and Ólafsson, 2004). The area is characterized by sulphur hummocks, often oriented in the same direction as fissures and faults in the area (NNE-SSW). Isotopic water analyses are limited to local precipitation and some fumaroles.

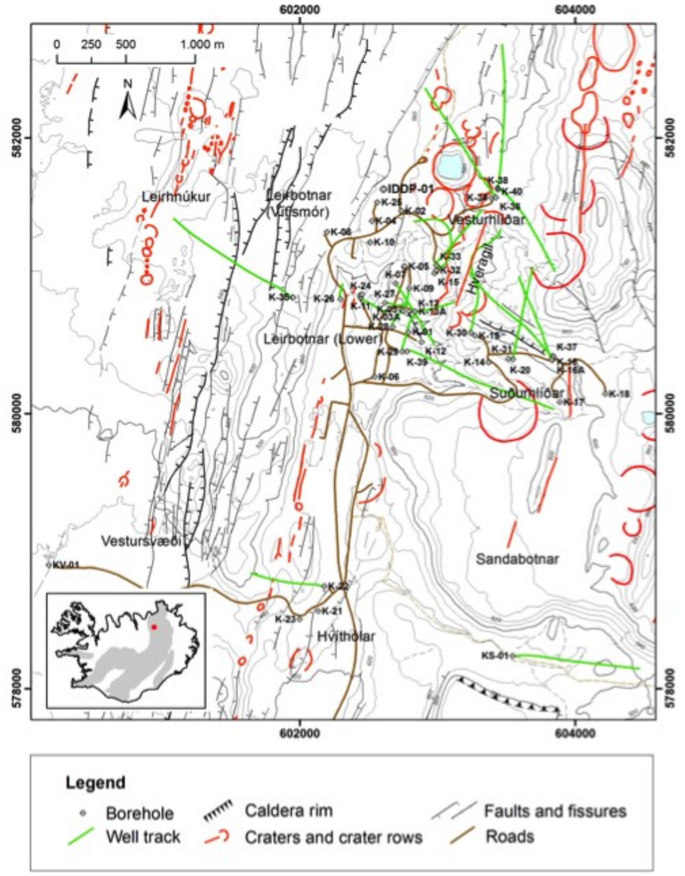

Figure 3: Map of the Krafla area showing tectonic features, the different wellfields and individual wells (from Ármannsson et al., 2015).

The Askja central volcano lies about 20 km south of the Fremrinámar thermal area. The Askja fissure swarm is the longest of the five NVZ fissure swarms and can be traced at least 120 km from Askja to the northern coast and about 30 km southward to Vatnajökull glacier (Saemundsson, 1974). The last major rifting episode in Askja occurred in 1874-1875 (Sigurdsson and Sparks, 1978a, 1978b). Minor episodes probably took place in 1920s and in 1961-1962 (Hjartardóttir et al., 2009). No drilling has been performed in the area and isotopic water analyses are limited to local precipitation and the caldera lake *Öskjuvatn*.

The Kverkfjöll volcanic system is the south-easternmost of the five NVZ volcanic systems. Its central volcano is located in the mountainous area on the northern edge of the Vatnajökull glacier and the fissure swarm extend some 60 km north of the central volcano (Hjartardóttir and Einarsson, 2012). Geothermal manifestations consist of fumaroles, mudpots and hot springs and cover some 25 km^2 (Ólafsson et al., 2000). Gas geothermometers indicate subsurface temperature of about 300°C. An extensive water isotope survey on fumaroles has been carried out in the area (Ólafsson et al., 2000).

2. ANALYTICAL METHODS

Isotopic analyses of samples were carried out at Science Institute, University of Iceland. The results are defined in the conventional δ-notation in ‰, relative to the VSMOW standard. Prior to 2007 the analyses were performed on a Finnigan MAT 251 mass spectrometer. Oxygen was extracted from the water samples by the method of Epstein and Mayeda (1953) and hydrogen isotope analysis were based on the H_2-water equilibration method using a Pt-catalyst (Horita, 1988). After 2007 the analyses were performed on a Thermo Delta V continuous flow mass spectrometer, with a gasbench device. In both cases the accuracy of the measurements is better than 0.08‰ for oxygen and 1‰ for hydrogen.

3. ISOTOPIC CHARACTERISTICS

3.1 Deep fluid disharge

Of the five fissure swarms discussed in this paper production wells are only available from the Theistareykir and Krafla swarms. The isotope composition of the deep fluid discharges as calculated from the steam and water isotopic composition in accord with the steam/water ratio of the sample at the well head, calculated from the measured discharge enthalpy and the reservoir temperature as estimated by geothermometry are given in Figure 4.

Distinct differences are observed for the subfields within the Theistareykir swarm. The wells discharging from area D (Tjarnarás) give the most ^{2}H enriched isotopic composition (-103 to -105‰) and about 2‰ oxygen shift. Bæjarfjall and the southern part of area C (Theistareykjagrundir) discharging deep fluids are slightly more depleted with discharging deep fluids with δ^2H -112 and -108‰ respectively. The hydrogen isotope ratio for well 7 is -126‰ and the oxygen shift is 6.5‰. The most depleted fluids are observed in area A (Ketilfjall) (-135‰) and the northern part of area C (Theistareykjagrundir) (-141‰). Oxygen shifts for these waters are 4.5 and 5.5 ‰ respectively.

There are also distinct differences observed for the subfields in the Krafla area as shown in Figure 4. The most enriched water is found within the Leirbotnar field, with δ^2H ranging from -85‰ to -89‰, which is very close to present local precipitation. These waters show variable oxygen shift up to 1.5 ‰. The waters discharging from wells from Sudurhlídar, Hvíthólar and Vesturhlídar are slightly more depleted with δ^2H around -93‰, with oxygen shift up to about 2‰. The waters discharging from the Námafjall area, some 20 km south of the Krafla caldera is still more depleted with δ^2H ranging from -94 to -101‰ and oxygen shift up to about 4.5‰. The only sample available from the Sandabotnar subfield is very different from other waters within the Krafla fissure swarm, with δ^2H around -115 ‰ and oxygen shift of about 7‰.

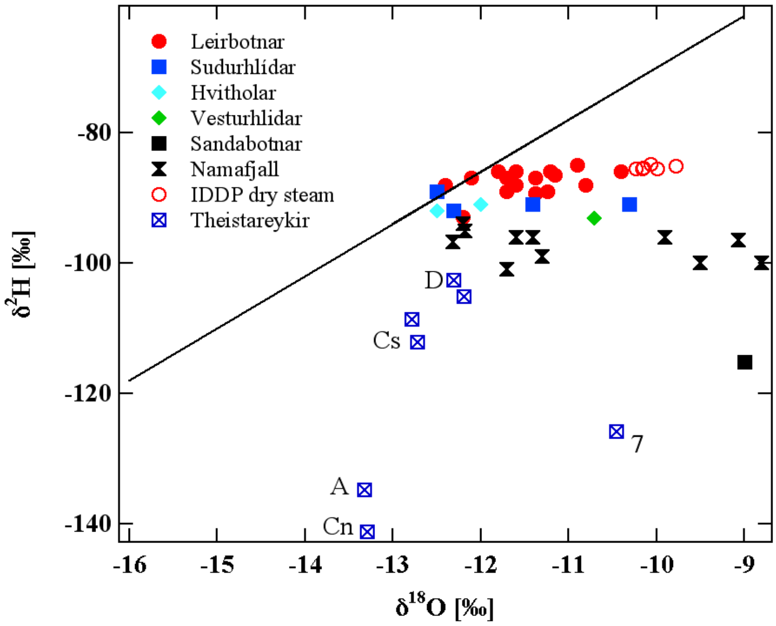

Figure 4: Isotope composition of the total discharge of latest samples from Theistareykir and Krafla/Námafjall production wells

3.1 Fumaroles

Figure 5 shows the isotope composition of fumarole condensates from the Theistareykir, Krafla, Fremrinámar and Kverkfjöll fissure swarms. For the Theistareykir area the groupings of the subfields are clear as well as for the Krafla area with the Námafjall area very different from other areas within the Krafla swarm. The water isotope composition of a fumarole condensate sample from Gjástykki suggests that the geothermal system may be fed by local groundwater.

The samples from the Fremrinámar fissure swarm indicate a ^{2}H depleted source compared to local precipitation and some of the samples from Kverkfjöll indicate a very depleted source (pre-Holocene), while others show some similarities to the Námafjall samples.

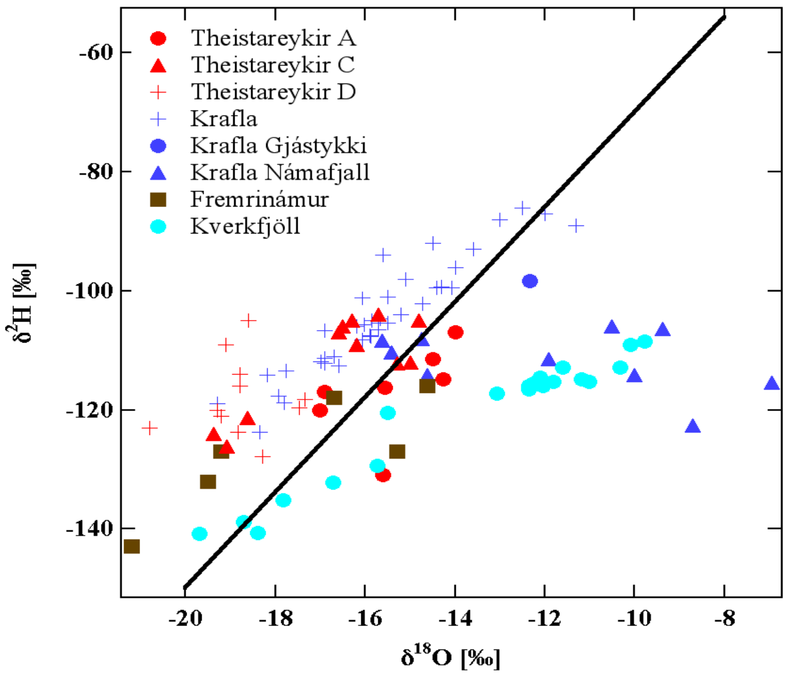

Figure 5: Isotope composition of steam fumaroles from the Theistareykir, Krafla, Fremrinámar, and Kverkfjöll fissure swarms.

4. ORIGIN OF FLUID AND CONCEPTUAL MODEL OF GROUNDWATER FLOW

The present results show that the isotopic compositions of the circulating fluids within the NVZ fissure swarms are very heterogeneous. On basis of the water isotopes a conceptual hydrological model is suggested on Figure 6, assuming different mixing of at least three components. These are 1) local precipitation, 2) groundwater originating from precipitation at higher elevation and further away, and 3) groundwater with a component of a pre-Holocene precipitation.

The deep thermal inflow into the Theistareykir swarm is depleted, compared to local precipitation, ranging from about -105‰ to about -140‰ in δ^2H. The most depleted precipitation in Iceland under the present climate regime is from the northern part of the ice cap in central Iceland, -106‰ (Árnason, 1976). If the annual mean temperature decreases by 1°C, the δ^2H decreases by about 6‰ (Arnason, 1976). Therefore the most depleted thermal water at Theistareykir suggests a cooling of at least 7°C, far more than the last 12000 years, the Holocene, has experienced. The Theistareykir thermal water or at least part of it must therefore originate as past precipitation from the last glaciation.

With reference to the isotope composition it is suggested that area A and the northern part of area C are closest to the source of the deep inflow into the Theistareykir high temperature field. The fluid probably originates to the south of the area and has a component of pre-Holocene precipitation. Considerable oxygen shift is observed for the deep undisturbed flow. The discharges of wells within the southern part of C, D and the Bæjarás area are more mixed with local and more recent precipitation. The fluid from well ThG-7 is distinctly different from that of the other wells both in oxygen isotope composition and chemistry (Óskarsson, 2012). Further sampling is needed to fully understand how it fits into the conceptual model of groundwater flow in the area.

The isotope hydrology of the Krafla fissure swarm is complex, with at least four distinct groundwater flows. The circulating fluid in the Leirbotnar area is isotopically homogeneous and has similar isotopic characteristics as the local precipitation with varying oxygen shift up to 1.5‰. Slightly more depleted are the fluids circulating the Suðurhlíðar, Hvíthólar, and Vesturhlíðar subfields suggesting some mixing with more distant water. The feed zone for the Sandabotnar subfield is however very different with about 20‰ more ^{2}H depleted water. This can only be explained by mixing with pre-Holocene groundwater. The fluids discharging from wells in the Námafjall-Bjarnarflag area show a considerable isotope range suggesting mixing of local groundwater with distant water to varying degree.

It is suggested on basis of the isotopic results for fumarole condensates that the inflow into the Fremrinámar and Kverkfjöll fissure swarms is partly of a pre-Holocene origin.

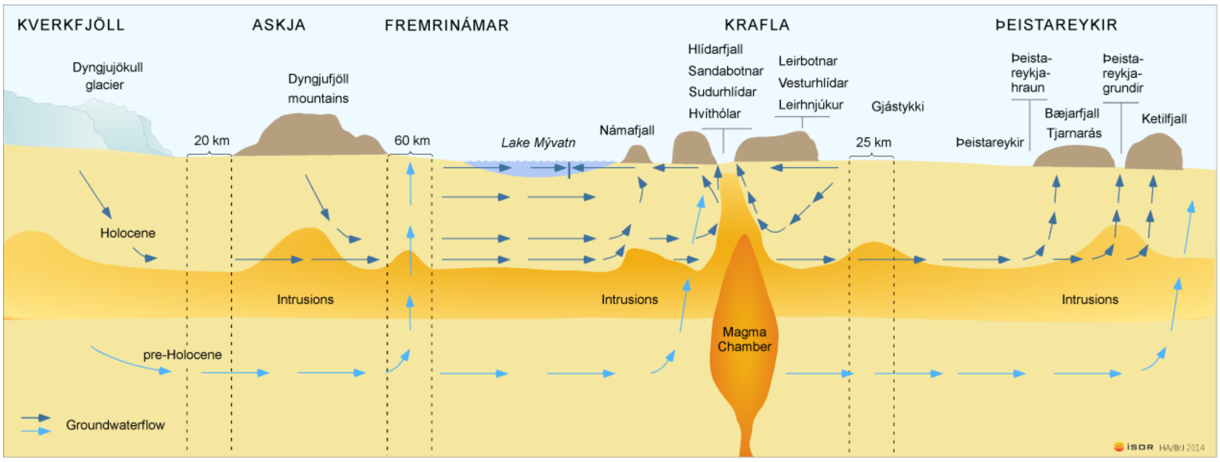

Figure 6: A Conceptual hydrological model of the thermal areas within the Northern Volcanic Zone. Modified from Hjartarson et al., 2004.

5. CONCLUDING REMARKS

The high temperature fields within the NVZ seem to be complex in terms of both inflow and structure as reflected in the subdivision of the drilled areas into several subfields, and the heterogeneous isotope characteristics of fumarole condensates. In all of the fissure swarms in which isotopes were studied there is evidence of a Pre-Holocene component.

REFERENCES

Ármannsson, H., Fridriksson, Th., Benjamínsson, J., and Hauksson, T.: History of chemical composition of geothermal fluids in Krafla, northeast Iceland, with special emphasis on the liquid phase. *Proceedings World Geothermal Congress,* (2015), Melbourne, Australia, 19-25 April, 2015.

Ármannsson, H., Gíslason, G., and Torfason, H.: Surface exploration of the Theistareykir high-temperature geothermal area, Iceland, with special reference to the application of geochemical methods. *Applied Geoche*mistry, (1986), **1**, 47-64.

Árnason, B.: Groundwater systems in Iceland traced by deuterium, *Societas Scientiarum Islandica*, (1976), **42**, 236pp.

Brandsdóttir, B., and Einarsson, P.: Seismic activity associated with the September 1977 deflation of the Krafla central volcanoin Northeastern Iceland, *J Volcanol Geotherm Res,* (1979), **6**, 197-212.

Craig, H.: Isotopic variations in meteoric waters, *Science*, (1961), **133**, 1702-1703.

Darling, G., and Ármannsson, H.: Stable isotope aspects of fluid flow in the Krafla, Námafjall and Theistareykir geothermal systems of northeast Iceland, *Chemical Geol*ogy, (1989), **76**,197-213.

Einarsson, P.: S –wave shadows in the Krafla Caldera in NE-Iceland, evidence for a magma chamber in the crust, *Bull Volcanol,* (1978), **41**, 187-195.

Einarsson, P., and Saemundsson, K.: Earthquake epicenters 1982-1985 and volcanic systems in Iceland (map). In: Sigfússon, Th.I. (ed) Í hlutarins edli, Festschrift for Thorbjörn Sigurgeirsson, Menningarsjódur, Reykjavík, (1987).

Epstein S., and Mayeda, T.K.: Variation in ^{18}O content of waters from natural sources, *Geochimica Cosmochimica Acta, (*1953), **4**, 213-224.

Grönvold, K., Halldórsson, S.A., Sigurdsson, G., Sverrisdóttir, G., and Óskarsson, N.: Isotopic systematics of magma movement in the Krafla Central volcano, North Iceland, In: *Goldschmidt Conference*, Vancouver, Canada, (2008), A331.

Hjartardottir, Á.R., and Einarsson, P.: The Kverkfjöll fissure swarm and the eastern boundary of the Northern Volcanic Rift Zone, Iceland, *Bull Volcanol,* (2012), **74**, 143-162.

Hjartardottir, Á.R., Einarsson, P, Bramham, E., and Wright, T..: The Krafla fissure swarm, Iceland, and its formation by rifting events, *Bull Volcanol,* (2012), **74**, 2139-2153.

Hjartardottir, Á.R., Einarsson, P., and Sigurdsson, H.: The fissure swarm of the Askja volcanic system along the divergent plate boundary of N Iceland, *Bull Volcanol,* (2009), **71**, 961-975.

Hjartarson, A., Sigurdsson, Ó., Gudmundsson, Á., Ármannsson, H. and Karlsdóttir, R. 2004: A computer simulation of the Námafjall geothermal system and forecast about its future state upon production of 90 MW electricity from Bjarnarflag (In Icelandic). Report No. ÍSOR-2004/009, ÍSOR, Reykjavík, 119 pp.

Horita, J.: Hydrogen isotope analysis of natural waters using an H_2-water equilibration metod: A special implication to brines, *Chemical Geology* (Isotope Geosciences Section), (1988), **72**, 89-94.

Jakobsson, S.: Chemistry and distribution pattern of recent basaltic rocks in Iceland, *Lithos*, (1972), **5**, 365-386.

Magnúsdóttir, S., and Brandsdóttir, B.: Tectonics of the Theistareykir fissure swarm, *Jökull*, (2011), **61**, 65-79.

Opheim, J.A., and Gudmundsson, Á.: Formation and geometry of fractures, and related volcanism, of the Krafla fissure swarm, northeast Iceland, *Geol Soc Am Bull,* (1989), **101**, 1608-1622.

Ólafsson, M., Torfason, H., and Grönvold, K.: Surface exploration and monitoring of geothermal activity in the Kverkfjöll geothermal area, central Iceland, *Proceedings World Geothermal Congress 2000,* Kyushu-Tohoku, Japan, May28-June 10, (2000), 1539-1544.

Óskarsson, F.: Chemical analyses of samples from well ThG-7 in 2012, Iceland GeoSurvey report, ÍSOR-2012/066, (2012), 30 pp.

Saemundsson, K.: Evolution of the axial rifting zone in Northern Iceland and the Tjörnes Fracture Zone, *Geo Soc Am Bull,* (1974), **85**, 495-504.

Saemundsson, K.: Fissure swarms and Central volcanoes of the neovolcanic zones of Iceland. In: Bowes D.R., Leake, B.E. (eds) *Geological Journal special issue*, Seal House, Liverpool, (1978), 415-432.

Saemundsson, K.: The geology of Theistareykir (In Icelandic), Iceland GeoSurvey report, ÍSOR-07270, (2007), 23 pp.

Saemundsson, K., and Ólafsson, M.: Fremrinámar Research 2003, *Isor-04105,* (2004), 10pp. (In Icelandic).

Sigurdsson, H., and Sparks, R.S.J.: Rifting episode in North Iceland in 1874-1875 and the eruption of Askja and Sveinagjá, *Bull Volcanol,* (1978a), **41**, 149-167.

Sigurdsson, H., and Sparks, R.S.J.: Lateral magma flow within rifted Icelandic crust, *Nature,* (1978b), **274**, 126-130.

Sveinbjörnsdóttir, Á.E., Ármannsson, H., Ólafsson, M., ´Oskarsson, F., Markússon, S., and Magnúsdóttir, S.: The Theistareykir geothermal field, NE-Iceland. Isotopic characteristics and origin of circulating fluids, *Procedia Earth and Planetary Science,* (2013), **7**, 822-825.

Tryggvason, E.: Multiple magma reservoirs in a rift zone volcano-ground deformation and magma transport during the September 1984 eruption of Krafla, Iceland, *J Volcanol Geotherm Res,* (1986), **28**, 1-44.