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THE KERAUGA CAVE AND LÆKJARBOTNAVEITA IN SOUTH ICELAND – GROUNDWATER SAFETY AND HYDROGEOLOGY

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Abstract. This research looks at water protection of Lækjarbotnar and Kerauga springs in South Iceland. Discharge measurements show that Minnivalla- and Tjarnalækur streams lose 350 and 1350 l/s respectively into the ground. The equivalent amount springs to surface along the edge of the Þjórsá Lava and Búði Glacial Moraine in a few springs. Tracer tests indicate that lost surface water of Minnivallalækur transits partly along a fracture to Kerauga in 65 days and to Lækjarbotnar in 125 days through the Þjórsá Lava over a similar distance of about 5 km. Hence the lost surface water of Tjarnalækur in the east is unlikely to travel past this drainage divide west of the fracture to Lækjarbotnar but more likely to drain into Ytri-Rangá. Thus a proposed poultry farm in that area proposes minimum direct risk to water safety of Lækjarbotnar. As a result of this connection Kerauga is not a safe source of drinking water. The aquifer is considered unconfined, heterogeneous and anisotropic. It is recommended to define inner and outer protection zones for Lækjarbotnar further north and to springs of Minnivallalækur respectively. It is hypothesized that Kerauga cave is manmade.

Keywords: *Aquifer, groundwater system, Kerauga, poultry farm, water safety.*

Introduction

The Great Þjórsá Lava covers the surface of the research area. It came over the area some 8700 years ago. The Þjórsá Lava has a plagioclase porphyritic basalt composition and is on average about 20 m thick in this region. The Great Þjórsá Lava is believed to be the largest lava flow in Iceland and the largest lava that is known to have erupted on Earth in a single eruption after the Ice Age or last glacial period. The lava was stopped by the Búði Glacial Moraine Sequence (Fig. 1) in this area found near the water extraction site of Lækjarbotnar in Landsveit, South Iceland.

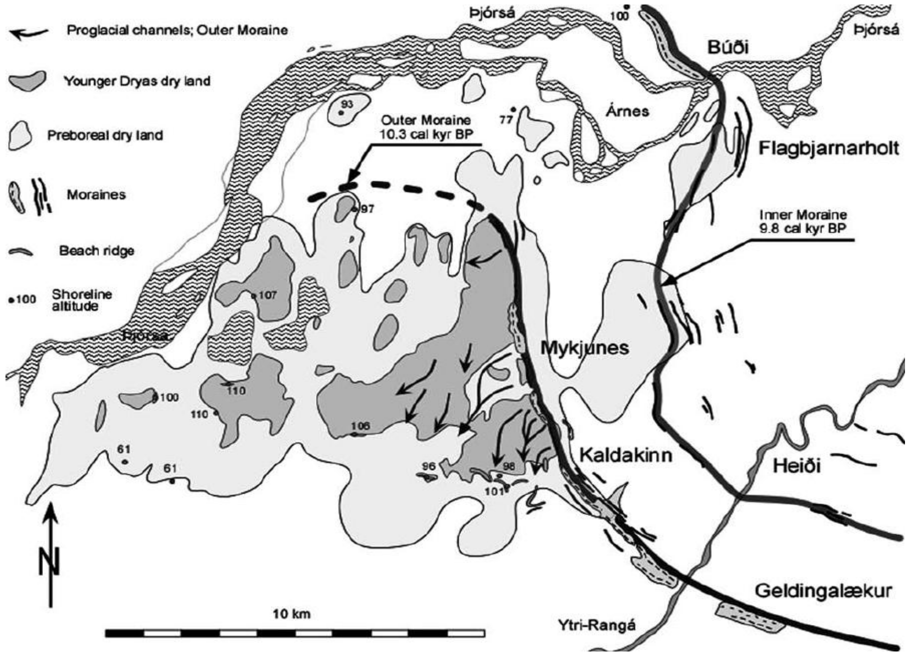

Fig. 1. An illustration of the Búði moraine (Ingólfsson *et al.*, 2010). The area is between Flagbjarnarholt, Mykjunes and Heiði.

The Búði Moraine forms hillocks in the landscape with marine sediments, glaciofluvial sediments and soils on the sides (Hjartarson, 1991). Generally, the moraines are about 10–20 m high and reach 75–100 m.a.s.l. (Geirsdóttir *et al*., 1997). The Búði Moraine consists of three types of sections: stratified diamictite, fine grained silty-sandstone and diamictite with dropstones. Investigations indicate that the Búði Moraine is thought to be 9800 years old (Ingólfsson *et al*., 2010). Several springs can be found at the border of the moraines and the Þjórsá Lava indicating that the moraines serve as a lateral barrier boundary and shape internal flow directions in the lava. The stream Bjallalækur follows the Búði Moraine Sequence south from its springs near Lækjarbotnar and Kerauga before it joins the river Ytri-Rangá. In the north of the research area Mt. Skarðsfjall rises above the Þjórsá Lava, formed under glacier not far from Mt. Hekla. North of Skarðsfjall the glacial river Þjórsá flows.

The Kerauga cave has been explored by a few divers and a few articles describe their dives. It can be seen that the water table level at the entrance of Keraugahellir is in Þjórsá Lava. The divers then dive down a few meters to enter a tight restriction with basaltic rock and alluvial sandstone in the roof but possibly rocks at the bottom. After passing through the restriction Dungal describes a tube 2–3 m in width and 2 m in height (Hróarsson, 1991) (Fig. 2).

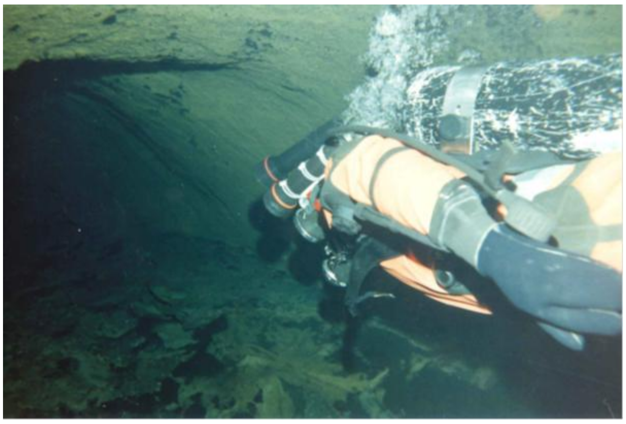

Fig. 2. Photograph from one of many diving expeditions of Pálmi Dungal and Kristinn Einarsson up the Kerauga cave. A selection of photos were scanned clearly indicating a round shaped roof about 2–3 meters in width and height 2–4 meters.

At the end of that chamber (100–300 m inwards) the divers describe a ceiling collapse with boulders of basaltic rock (Chowdhury, 1996). In 1332 it is known that at Kýraugastaðir, near Kerauga, a house of prayer had been established. Around the area six man-made caves are known. They are about two to three meters in diameter and about two meters in height. The longest one is 20 m. There are known about 80 man-made caves in Rangárvallasýsla. The largest one, Hellnahellir, is 50 m long, dug into the mountain Skarðsfjall. In the longest one there are remnants of religious signs which possibly Irish monks carved out before the Vikings settled in the area (Guðmundsson, 1998). An overview is given of known man-made caves in Iceland in Hjartarson *et al.* (1991).

In 1851, the river Stóruvallalækur was dammed by 56 men over two days, led by Sæmundur Guðbrandsson from Lækjarbotnar to prevent sand erosion going further west. The constructed dam is still visible south of Dráttarhóll, which redirected the stream north and made it a tributary river to Þjórsá, percolating into Þjórsá Lava, just like Tjarnalækur is today (Jón Árnason, 1967). Several hydropower plants can be found along that river. One is being planned close to Mt. Skarðsfjall, referred to as Hvammsvirkjun hydropower plant. Several fractures have been mapped by Khodayar *et al.* (2007). After the Ice Age the glacier retreated, leaving e.g. the Búði Glacial Moraines and gradually decreased in size forming an outwash plain of glacial sediments deposited by meltwater. This aolian sandstone is thought to underlie the Þjórsá Lava in the research area (Hjartarson, 2001).

The study area is within a transform fault zone with overall left-lateral transform motion whereas the individual earthquakes and surface faulting show N-S striking planes with right-lateral faulting (Einarsson, 2010). All larger earthquakes in the zone appear to occur in sequences where the largest events are located in the eastern part followed by smaller events further west. These types of sequences have been documented in 1630–1633, 1732–1734, 1784, 1896, 2000 and 2008 and similar sequences also occurred in 1294, 1339 and 1389–1391. Along the 15 km wide, 70 km long, E-W trending seismic zone widespread evidence of Holocene faulting is visible both in the glacier eroded surfaces, alluvial plains and postglacial lava flows (Einarsson, 2008). Prominent characteristic features of en-échelon type are exposed on the surface and form fracture arrays due to the strike-slip faulting in the area. The most identified fault ruptures in South Iceland are associated with right-lateral faulting and left-stepping fractures. Along with the en-échelon so called push-up structures are frequently found within the arrays where they bridge the gap between the tips of adjacent extensional fractures. They have the form of small hillocks where they vary in height, from tens of centimeters to a few meters. Where the soil covers an open fracture, sinkholes are formed due to smaller depressions in the ground (Einarsson, 2010; Angelier *et al*., 2004).

Hydraulic conductivity has been estimated to be 10^{-1}–10^{-3} m/s, effective porosity 15% and hydraulic gradient of 1/200 (Hjartarson, 2008). Pálmarsson (2010) presented a numerical model from Vatnaskil of the catchment area. Pálmarsson estimates that groundwater flow is in a NW direction towards Þjórsá River north of Bjallalækur but goes SE towards Ytri-Rangá between Tjarnalækur and Kerauga. Both have chosen similar values for hydraulic conductivity.

The aim of this study is to investigate the need for water protection for this aquifer which serves on average 2–3 l/s of untreated drinking water from two waterwells at the edge of the Þjórsá Lava. The municipality suffered from shortage of drinking water during droughts before inauguration of the Lækjarbotnar pumping station in year

2011. The aquifer is a stable and reliable source of high quality drinking water and serves the rural region with untreated drinking water on a daily basis and is a reserve area for the town Hella during droughts and possible contamination of their main water supply. The study particularly takes into account possible effects of a proposed poultry farm. Discharge, temperature and conductivity measurements were taken in addition to surveys conducted in Hellnahellir and around Kerauga cave. To estimate groundwater flow an extensive tracer test was conducted.

Legal Framework and National Policy

The Icelandic Drinking Water Regulation was introduced in year 2011 in accordance and with adaptation of the European Drinking Water Directive. Water governance has recently been implemented into the Icelandic legislation where the objective is to protect water and aquatic ecosystems as well as restore contaminated water bodies to its original state (Gunnarsdóttir, 2012). The Water Framework Directive (2000/60/EU) was adapted with Act No. 36/2011 (Water Act) and subsequent regulations. According to Art. 24 the aim is to prevent the status of water bodies, supplying drinking water to deteriorate.

States have different regulations for the protection zones due to various hydrological conditions. In Iceland water protection zones are defined in Art. 13 of regulation No. 796/1999 with subsequent amendments for protection of drinking water against contamination. In the regulation it is stipulated that three protection zones shall be defined based on geological, hydrological and geographical conditions in the area and its importance and contamination risk, see Fig. 3. This has been formulated into best practices as reviewed in Pálmarsson (2014).

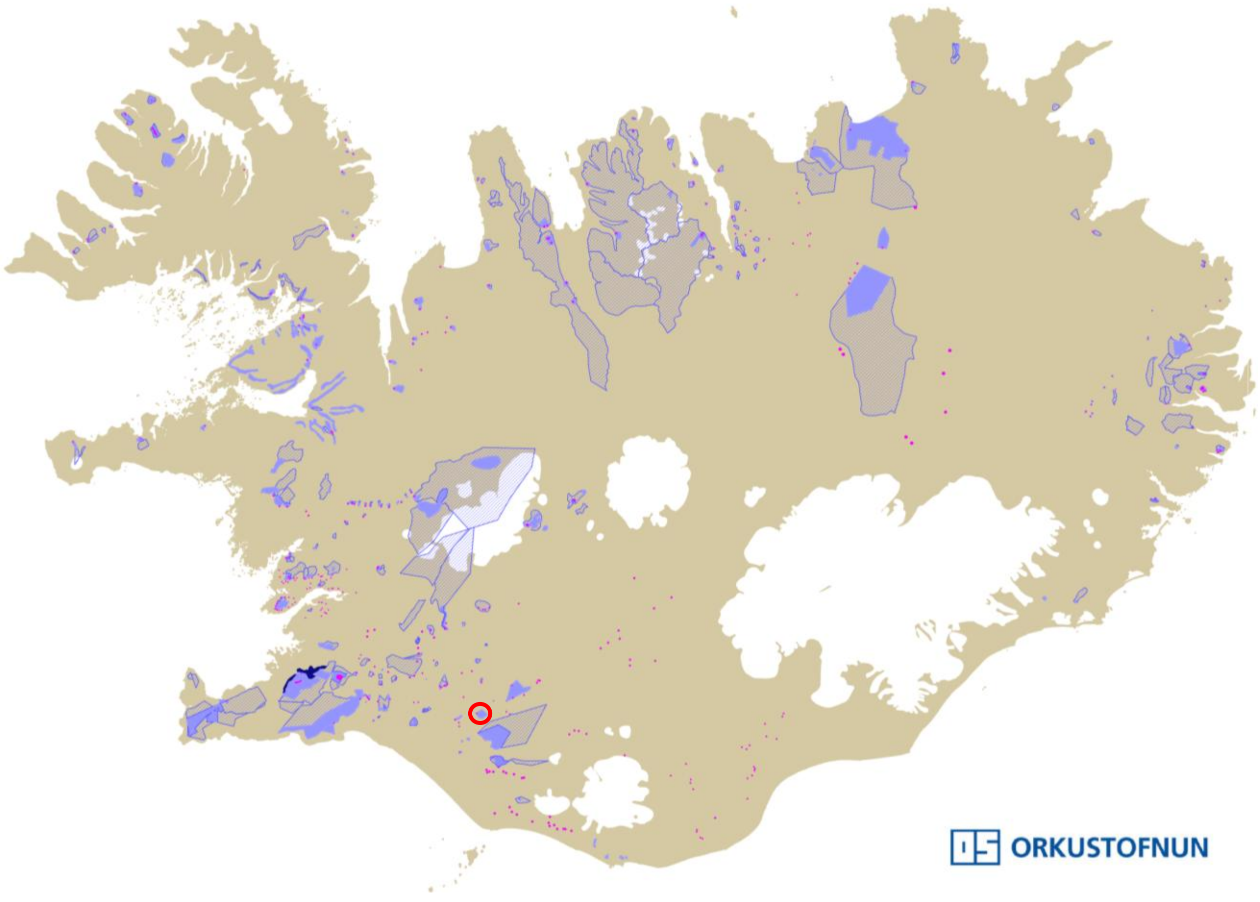

Fig. 3. Water Protection Zones in Iceland (Georgsdóttir, 2016). Study area is within the red circle. Protection zones illustrated for IS1 in pink, IS2 in light blue, IS3 with a hatch and IS4 in dark blue. As can be seen the size of protection zones varies greatly.

Protection Zone 1 (IS1). This area shall be completely protected from unauthorized traffic and constructions other than those relevant for the waterworks. Boundaries typically about 50–200 m from extraction.

Protection Zone 2 (IS2). When establishing IS2 the size, shape and geological and hydrogeological factors shall be taken into account. Within this area all use of dangerous substances and storage of such substances is strictly forbidden, i.e. use of oil, gasoline and related substances, toxic chemicals for insects and vegetation and other chemicals that can be harmful for the groundwater body. New buildings, summerhouses and other new activity is forbidden. Laying new roads or the use of fertilizers shall be under strict surveillance. Boundaries typically 50–100 transit days upstream or at 1 km from IS1.

Protection Zone 3 (IS3). Outside zone IS2 the zone IS3 shall be defined. Where known fractures are, special care shall be taken in storage and use of substances mentioned in IS2. The Local Health Committee can give further instructions in regards to traffic in the area and approval for new buildings. Typically referring to a one year transit time.

The Regional Plan for Rangárþing ytra municipality defines IS1 and IS2 around Kerauga. However IS3 is not defined and the zones are designed for Kerauga, not Lækjarbotnar. Hence, there is a need to amend the Regional Plan. The water protection zone in question is based on an estimated 50 day transit time for Kerauga with an added safety factor of four from the estimated hydraulic conductivity of a porous media using the Darcy equation and compensating for anisotropy with a higher effective porosity.

Material and Methods

In order to measure discharge of rivers and creeks, a stream meter with a spinning propeller was used to measure the velocity as further reviewed by Claesson and Collett (2016). The measurements were done over a cross-section in the river where the flow was smooth, steady and even (Fig. 4). Discharge measurements were performed in the following rivers and brooks; Tjarnalækur, Minnivallalækur, Bjallalækur, Kálfhagalækur, Grófarlækur and Tjörvastaðalækur in addition to several spring measurements by estimating surface velocity with a buoyant material for Tvíbytnulækur, Kálfhagalækur, Ytri Rangá and along Tjörvastaðalækur before the confluence of Bjallalækur. The measurements were done in April and May 2016. The electrical conductivity and temperature were measured.

Hydraulic conductivity and transit time was determined by tracer tests as further reviewed in Hjartarson (2016). In total five tracers were injected after being poured into 1000 liters of warm water. The location and type of tracer can be seen in Fig. 6, 7 and 14. Daily samples were taken at springs at Kálfhagalækur and Kerauga in addition to samples taken from the tab water in the pumping station and a few samples taken at Húsagarður. After that samples were taken every second day. In May it was decided to add two more injection sites straight into two streams that contribute surface water into the aquifer at Minnivallalækur and Tjarnalækur. After the injection in May samples were taken after 4, 6, 8, 10, 14, 18, 24, 30, 40, 50 hours and then daily for the first 20 days. Water samples were analyzed by Iceland GeoSurvey in a HPLC (High Performance Liquid Chromatography) to measure the amount of compounds in a sample (concentration) to find the tracers.

Relative elevation was surveyed in autumn 2016 around Kerauga and Hellnahellir cave using a laser distance sensor and a elevation laser level to determine relative elevation of survey points. The laser emitter to estimate elevations changes was equipped with a self-leveling. For comparison purposes photographs were taken in Hellnahellir and photographs from previous diving expeditions were scanned and compared (see figs. 1 and 5).

Fig. 4. Discharge measurements in the river Bjallalækur. The Búði Glacial Moraine can be seen in the distance.

Fig. 5. Top: Kerauga at present (to the left) compared to the entrance in 1990 (to the right) as seen in Hróarsson (1991). Below: Exploration of students of Hellnahellir cave showing effects of oxidation, overall shape of the cave and religious markings (photos from Andrina Janicke).

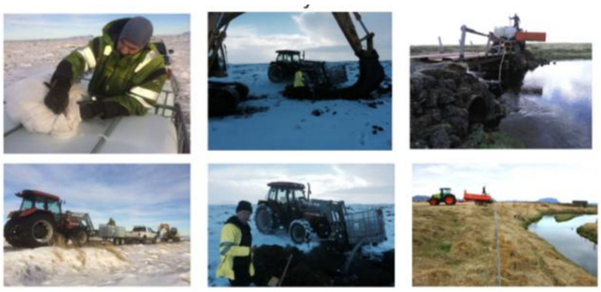

Fig. 6. Tracer injections onto Þjórsá Lava during winter after an excavator digs down below freezing and injections into the streams in spring. One can see the tracers in crystal form being diluted into about 1000 l of warm water prior to injection. Photos from Árni Hjartarson.

Fig. 7. Tracer sampling sites. From left: Kerauga spring, Kálfhagabotnar spring a tributary to Bjallalækur and tab water at the pumping station at Lækjarbotnar in addition to samples taken in the stream next to the station.

Results

The results of the discharge measurements show that Tjarnalækur and Minnivallalækur are losing streams with decreasing values downstream (TJ-1 1360 l/s, TJ-2 1120 l/s, TJ-3 905 l/s and MV-1 1640 l/s and MV-2 1290 l/s). Three right tributaries flow into Bjallalækur (BA-1) on the southern side. Bakkalækur (BA-1) 20 l/s, Veitustokkur (VE-1) 30 l/s and Grófarlækur (GR-1) 89 l/s, altogether provide about 140 l/s of surface run-off water. They are all from drainage systems outside the study area with high amounts of iron bacteria, and effectively do not enter the local groundwater system but influence the discharge measurements downstream. Discharge of Bjallalækur is measured in four cross-sections with increasing values BJ-1 316 l/s, BJ-2 793 l/s, BJ-3 1010 l/s, and BJ-5 1830 l/s. Three left tributaries flow into Bjallalækur on the southern side all from springs at the edge of Þjórsá Lava. The springs at Lækjarbotnar contribute 296 l/s, springs of Tvíbytnulækur 447 l/s, springs of Kálfhagalækur 217 l/s and springs of Tjörvastaðalækur 600 l/s (Fig. 8). Three right tributaries flow into Ytri-Rangá directly, all from springs close by to the edge of Þjórsá Lava, in total discharge 100 l/s from the lava aquifer. Húsagarður (ÞJ-1) on the SW-lateral boundary discharges 70 l/s into Ytri-Rangá as further reviewed in Claesson and Collett (2016).

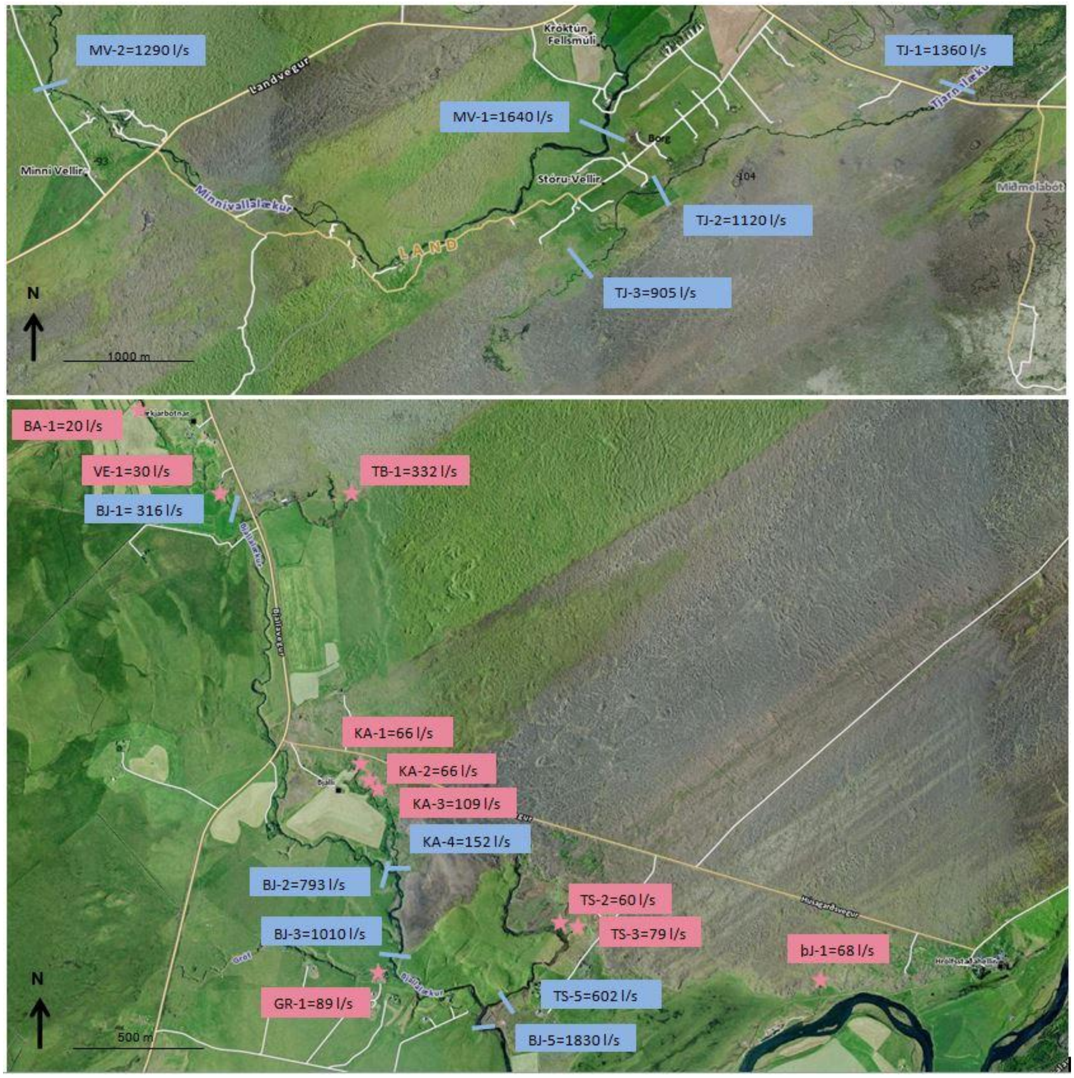

Fig. 8. Results of discharge measurements in the area for Minnivallalækur and Tjarnalækur on top and for Bjallalækur below (Claesson, Collett, 2016). Satellite image courtesy of Loftmyndir ehf.

In Minnivallalækur the electrical conductivity have similar values of 130 and 131 µS/cm and a temperature of 8.7°C and 5.3°C. Tjarnalækur has generally higher electrical conductivity than Minnivallalækur, 141 µS/cm. TJ-1 and TJ-3 have temperature values decreasing from 9.3°C to 6.6°C between the sites. Along Bjallalækur the temperature is steadily increasing downstream in BJ-1–BJ-5 from 6.2–7.2°C. Their electrical conductivity vary between 143–147 µS/cm. The springs that flow directly from the lava have in general lower electrical conductivity, 116.1–135.4 µS/cm, than the rivers (described previously). GR-1, which is located in Grófarlækur, has the highest value of electrical conductivity, 275 µS/cm, and the stream water had a reddish color, due to high amount of ferric precipitates and iron bacteria growth. Precipitation data from Iceland Met Office indicated that average annual precipitation for the past 15 years is 1351 mm. June is the driest month with an average of 65 mm whereas September is the richest in precipitation with an average of 154 mm. Generally, the seasonal variations show that in late spring and summer precipitation is lower than in the autumn and winter. Evapotranspiration was estimated to be 462 mm on an annual basis (Einarsson, 1972). It remains unknown how much of the measured rain has evaporated and hence how much infiltrates into the groundwater system.

The results of the tracer test indicate a different flow direction than previously estimated. Tracers injected in February have yet to be sampled however the tracer injected into Minnivallalækur was sampled in most of the sites. At Kerauga 65 days later and at the pumping station about 125 days later. Samples measured below significance at Lækjarbotnar and at pumping station earlier (Fig. 9).

Surveying of Hellnahellir illustrates a level of complexity in the cave with restrictions and chimneys e.g. for light (Figs. 5 and 10).

Results of a relative elevation survey around the Kerauga cave reveal that the regional sandstone layer under the Þjórsá Lava, but visible on surface south and east of the cave entrance, is about 1m higher than surface of the water in the cave. The divers claimed to have dived down a few meters through a tight restriction.

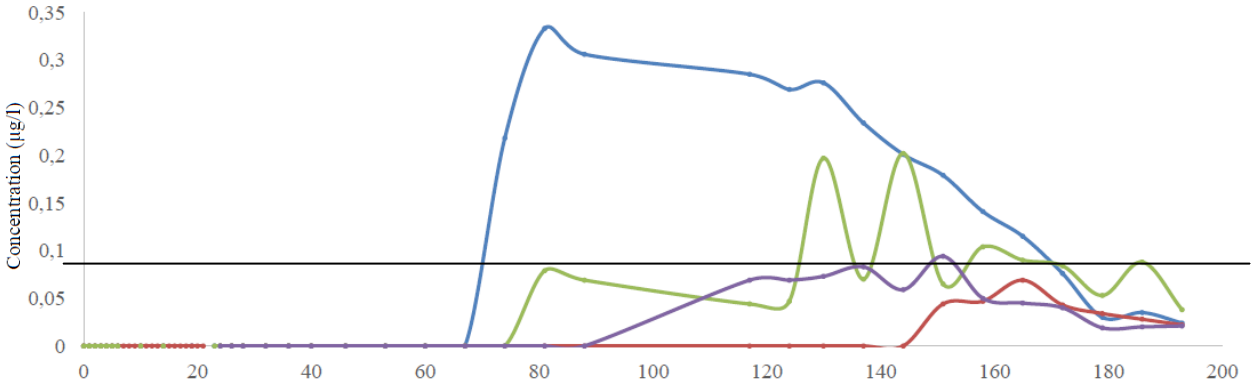

Fig. 9. Concentration of the tracer injected into Minnivallalækur (µg/l) against days at the four sample sites. Blue for Kerauga sampling site, green for the tab water in the pumping station, purple for the stream near the pumping station and red for the springs of Kálfhagalækur. The concentration is statistically significant when higher than 0.1 µg/l. Further reviewed in (Hjartarson, 2016c).

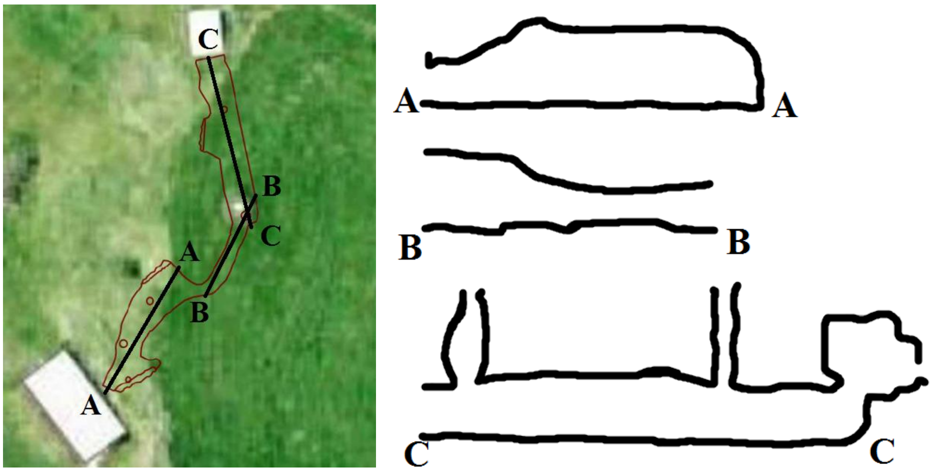

Fig. 10. Results of surveying the Hellnahellir cave in autumn 2016 conducted with assistance from students. Based on a map from Hjartarson et al. (1991). On left an aerial view of the cave superimposed on a satellite image from Loftmyndir ehf. and on right three cross sections as shown on the aerial view to the left. Another cave near Efrihvoll is closer to the description of the Kerauga cave as drawn in Hjartarson et al. (1991).

Fig. 11. It is hypothesized that Kerauga cave is a man-made cave based on interpretation of the description given by the divers. Water pressure was at maximum 0.5 bars indicating a 5 m depth from water surface. Tight restriction described in the mouth of Kerauga cave. Then a long tube until a tighter restriction divides the cave into two chambers. Then Pálmi Dungal and Kristinn Einarsson refer to a collapse at the end of the cave which Bernie Chowdhury claims he was able to pass and sit on top of and breathe air inside with a strong current in the rubble. He claims he could see a third chamber which he didn't survey similar to the previous ones. The length of the cave is unknown but thought to be extensive (100–300m).

Taking the above into account it is very likely that the cave is in fact in the alluvial sandstone a few meters below the Þjórsá Lava. From this it is hypothesized that the Kerauga cave is manmade and that the entrance to it is through a collapsed ceiling a few meters inwards from the original entrance (Figs. 11 and 12). The supporting factors are:

1) Several photographs from the diver Pálmi Dungal clearly illustrate a rounded ceiling made of sandstone. From a geological point of view it is difficult to explain the shape of the ceiling to have been naturally formed. Land surveying revealed that the regional sandstone found west and south of the cave is about a meter above the surface of the water in the cave ruling out the possibility it being a lava tunnel in the front. Oxidation of the sandstone has occurred which is typical when in contact with air. When reviewing the geological settings between the cave and the Tjörvastaðalækur stream it is plausible that one is looking at a collapsed area. The tubular spring of Kerauga indicates the water is flowing out of an underground cavern (Fig. 7).
2) Tracer tests indicate that surface water of Minnivallalækur transits over a distance of 5 km to Lækjarbotnaveita and Kálfhagalækur in over 125 days relatively but only takes about 65 days to transit to Kerauga spring which is a few hundred meters further away. Known fractures and recent seismic activity is shown in Fig. 13. It is hence hypothesized that the mapped Minnivallasprunga from year 1630 transits the water along the fracture in order to explain the transit time difference and also how water came into the cave after it was dug out before year 1630.
3) There are numerous man-made caves in this area. Some of them are extensive and have similar dimensions and shape as Kerauga cave being about 2–3 meters in dimensions. Comparison to Hellnahellir and in particular Efrihvoll as described in Hjartarson et al. (1991) reveal great similarities in dimensions.
4) Kýrauga refers to a porthole. The ruins of Akurgarðar where the springs of Tvíbytnulækur were dammed for irrigation within Kýraugastaðir indicate a level of intuition. Sandstone is on surface west of the Kerauga entrance were ruins can be seen 40–70m away. It is possible that Kerauga was connected to those ruins serving as a tunnel between which then collapsed on both sides just like Hellnahellir but water in the cave has supported the structure since and through the centuries was forgotten just like Akurgarðar.

Discussion

The groundwater model of Kerauga aquifer reveals a strong input of surface-runoff loosing streams entering into the aquifer upstream. The approximately equivalent amount of water surfaces downstream in several springs. Minnivallalækur (350 l/s) and Tjarnalækur (1350 l/s) are the two rivers upstream that together give this volume of water. They are termed influent streams and they are constantly losing water at the base of the river into the groundwater below. Over about 4 km Tjarnalækur feeds the groundwater with about 400 l/s until it has completely seeped into the ground. The water infiltrates and percolates down approximately 10 m in elevation through the unsaturated part of the Þjórsá Lava where the groundwater table is estimated to be about 85–90 m.a.s.l.

Fault structures and fracture zones with N-S strike-slip faults are known in the research area. Recent seismic activity is shown in this study in connection with these known fractures. It shows movement on Skarðsfjallssprunga south of where it has been mapped on surface (Fig. 13). In Iceland, fractures are known to effect flow patterns greatly. Fault displacement creates new paths for groundwater flow. Historically, springs and river runoff have been greatly influenced by large earthquakes, such as the one in year 1896 (Einarsson and Eiriksson, 1982).

The results of the tracer test indicate that some of the surface water of Minnivallalækur that seeps into the ground surfaces at the Kerauga spring over two months later. This indicates that the water Tjarnalækur loses into the ground is more likely to appear in the stream Ytri-Rangá than in Kerauga and that flow directions follow the

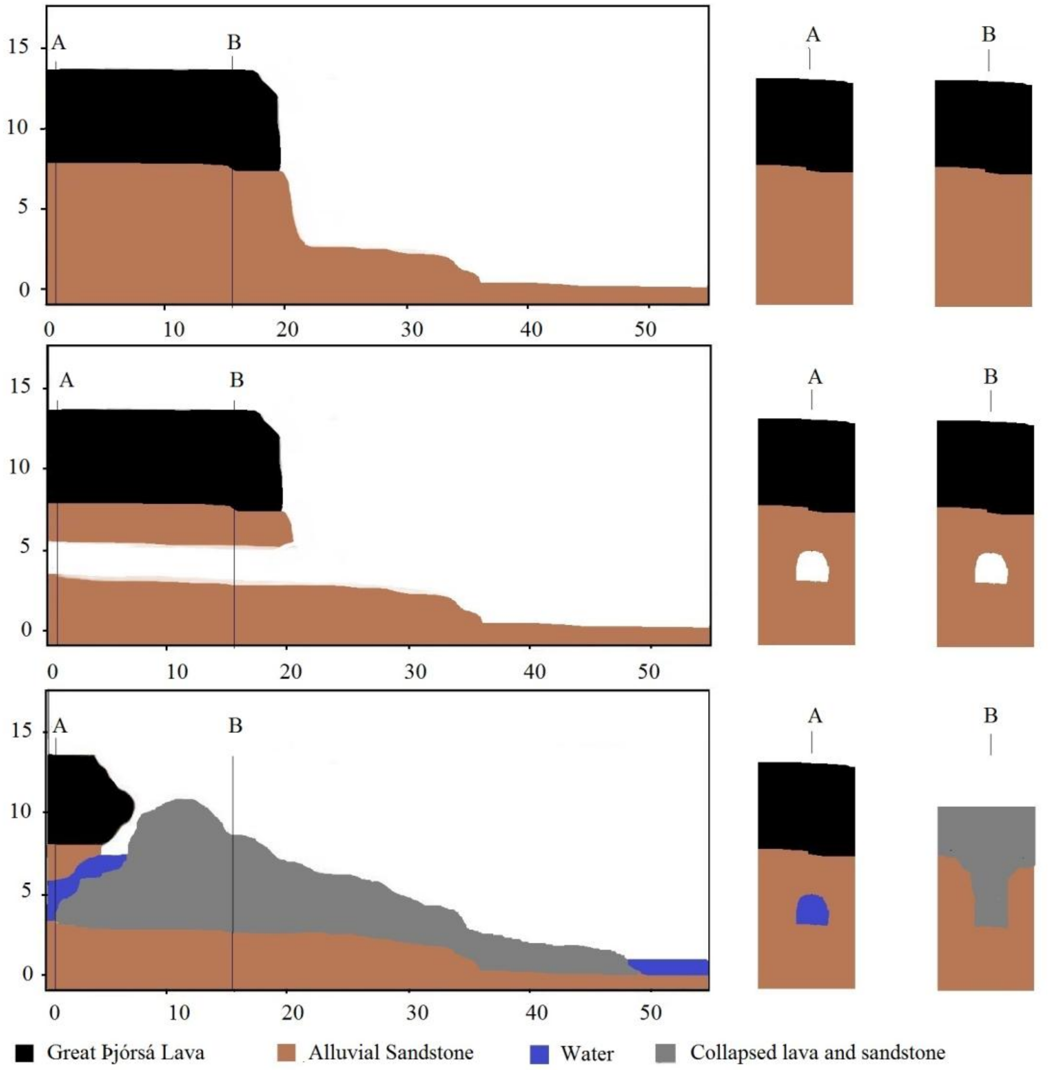

Fig. 12. The Kerauga cave in natural settings (top), after the cave was dug out (middle) and after the entrance caved in (bottom). Land surveying conducted by students in autumn 2016 for scale in terms of relative elevation and distance shown in meters on the graphs. Cross sections estimated.

orientation of fractures in the area. These results lower the water safety level of Kerauga as a source of drinking water in the future since the surface stream Minnivallalækur passes a road, number of farms and summerhouses and most importantly is subject to waste water from a large fish farm at Fellsmúli. Understanding the physical characteristics of the Kerauga cave is fundamental in revealing overall aquifer characteristics to explain the linkage of influent streams in the north and the springs in the south and hence water safety in the area as evident with results of the tracer tests conducted.

The moraine sequences observed in the area, suggest that there are possibly additional moraines under the Þjórsá Lava affecting the flow pattern of the groundwater which can be investigated further. The hillocks in the area could reflect where the moraines are. As an example, the travel path of Bjallalækur is within the Búði Moraine Sequence and is shaped by it. They are located on both sides of the stream before joining the stream Tjörvastaðalækur, which is supplied with water from the Kerauga spring. Where the moraine ends the two rivers join together and continue down to Ytri-Rangá. Minnivallalækur, previously named Stóruvallallækur, used to disappear into the lava in a similar way as Tjarnalækur does today, before it was dammed 165 years ago. These old river channels point towards Lækjarbotnar but could also have disappeared into e.g. Minnivallasprunga on its way directing the water south as is evident with the tracer of Minnivallalækur surfacing in Kerauga.

In comparison to previous discharge measurements in the area, in Hjartarson and Sigurðsson (2000) and (2008), similar values have been found. Kerauga is similar to measured values in this study (0.5m^3/s, in April 2000 and 0.6m^3/s in April 2016). Tjörvastaðalækur a discharge of 2.1 m^3/s in April 2000, whereas in this study it was measured to be 1.83 m^3/s in April 2016.

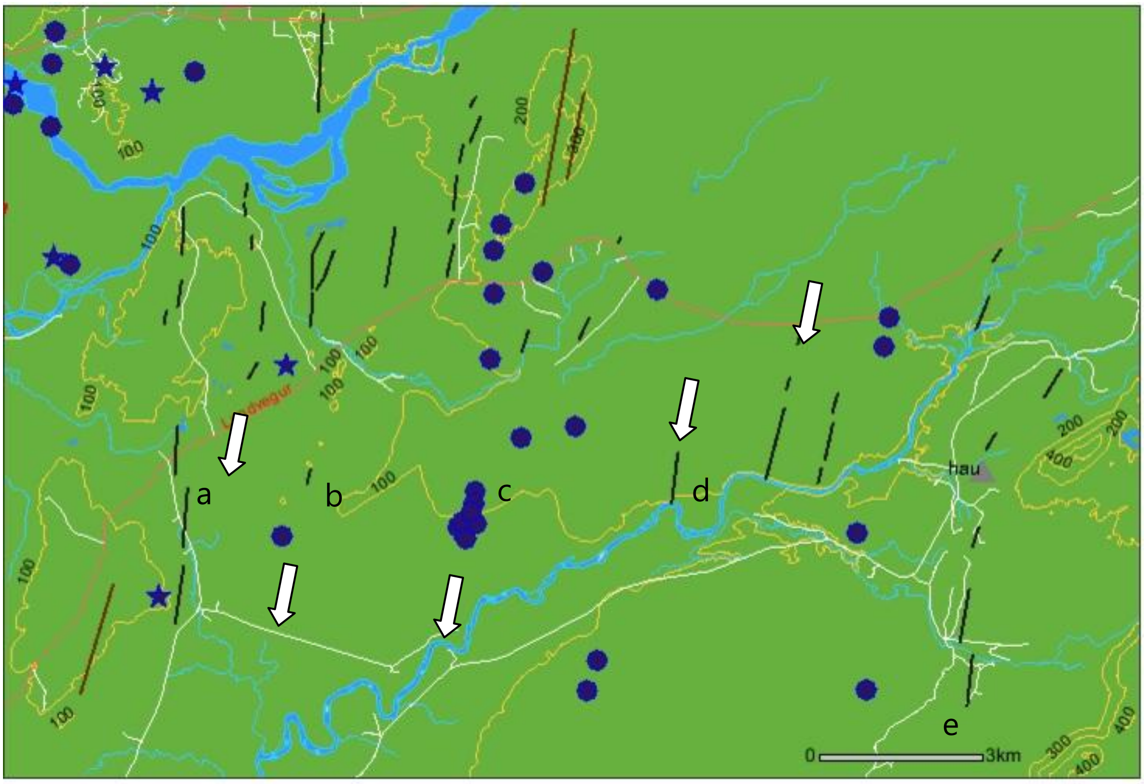

Fig. 13. Estimated epicenters of seismic tremors in the research area for the period 2010–2016 from Iceland Met Office database. A star depicts an earthquake of magnitude 3 or more, circle of magnitude 2–3. Known surface fractures are mapped by Einarsson (2010). Labelled fractures: a) Lækjarbotnasprunga (1896), b) Minnivallasprunga (1630), c) Skarðsfjallssprunga, d) Réttarnessprunga and e) Selsundsprunga (1912) white arrows indicating possible groundwater flow directions in fractures.

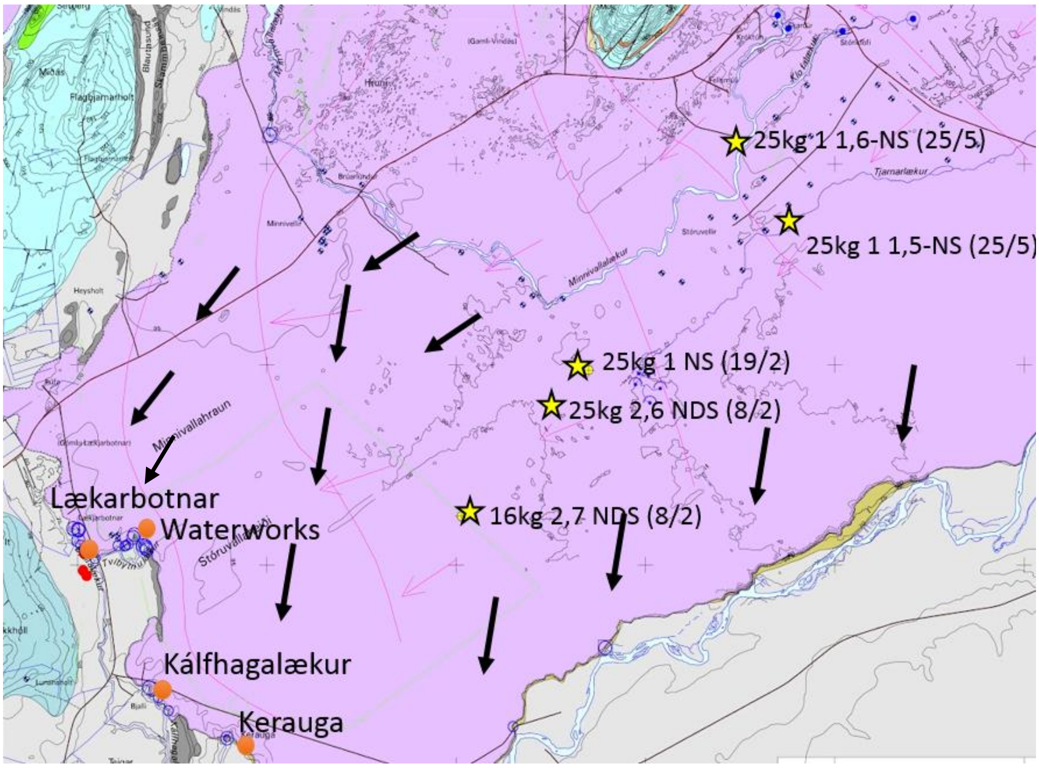

Fig. 14. The geological map of the area from Iceland GeoSurvey (Hjartarson, 2016a) and added sites of tracer injections with date and amount indicated and sample sites. Added are the black arrows suggesting a different orientation of groundwater flow after taking into account the results of the tracer test. This can be compared with the mapped fractures in Fig. 13 and recent seismic activity.

The electrical conductivity generally increases upstream in Bjallalækur. The higher amount of electrical conductivity can be caused by geothermal activity and inflowing water from tributaries to the west. The springs at Ytri-Rangá have lower hydraulic conductivity than the springs connected to Bjallalækur. This can be interpreted to that the groundwater is much purer and flows faster from e.g. Tjarnalækur to the spring outlets linked to Ytri-Rangá via fractures in the N-S direction.

In comparison to previous investigations by Vatnaskil (Pálmarsson, 2010) with a numerical model and the geological map from ÍSOR from Hjartarson (2016a) it is proposed that the groundwater is more controlled by fractures than has previously been proposed. This can change completely the protection zones for Lækjarbotnaveita which then needs to extend north. That could impact land use in that area which today is where a gravel mine is located for road works and excavators and trucks are stored when not in use.

At the Kerauga spring, where the divers entered, the sandstone is observed in the ceiling of the cave. Outside the cave sandstone can be seen below the lava. Hence it is hypothesized in this paper that the cave is man-made in similarity to several other man-made caves that exist in the area, e.g. cave near Efrihvoll, and that water then entered it through e.g. the mapped Minnivallasprunga which can explain why the tracer injected into Minnivallalækur surfaced at Kerauga. The claimed length of the cave poses questions.

It can be argued that the outer protection zone (IS3) for Lækjarbotnaveita should extend to the springs of Minnivallalækur and that the inner protection zone (IS2) be extended beyond Landvegur in the north. The proposed poultry farm in viscinity of Tjarnalækur does not propose a threat to Lækjarbotnaveita although it can have a negative effect on Kerauga. However, taking into account that it only took the tracer two months to go from the injected site close to the fish farm at Fellsmúli the Kerauga spring can be ruled out as a reliable and safe source of drinking water. For the waterworks the proposed poultry farm hence does not propose a threat to water safety. It can however influence the quality of the water in the stream Ytri-Rangá which was not investigated. Care should be taken in distributing manure from the poultry farm taking into account numerous fractures in the area which though are more likely to effect Ytri-Rangá than springs at Lækjarbotnar.

Future studies

It is recommended to study the Kerauga cave to explore further the hypothesis in this paper that the cave is manmade. In particular the area west of the Kerauga cave were ruins can be seen and possibly a second entrance can be found into the cave. Further investigation could be done on the effects of the proposed Hvammsvirkjun hydropower plant taking into account the N-S direction of fractures is also recommended. This could be done with further tracer tests and by incorporating the presented information into the numerical model of the area.

Conclusion

The aim of this study was to characterize the aquifer and establish its properties for water safety purposes. The major conclusions are:

It is proposed that Minnivallasprunga directs surface water from Minnivallalækur to Kerauga spring. Hence the surface water of Tjarnalækur is unlikely to travel past this drainage divide west of Minnivallasprunga to Lækjarbotnar springs. The proposed poultry farm east of Minnivallasprunga is hence unlikely to reduce water quality at Lækjarbotnar west of Minnivallasprunga. It could have an effect on water quality at local water wells for Húsagarður and Hrólfstaðahellir farms.

It is hypothesized that Kerauga cave is manmade. The main supporting argument are the photographs illustrating sandstone in the rounded ceiling in addition to the land surveying illustrating that visible regional sandstone is one meter above the surface of the water in the cave and the fact the spring is tubular indicating a connection to an underground cavern. The claimed length of the cave does pose questions which needs to be further investigated.

The gravel mine which is 1 km north of the water wells proposes a higher risk to water safety than the proposed poultry farm.

The results of the tracer test justify stretching water protection for the outer zone to the springs of Minnivallalækur and north towards and possibly past Landvegur. It is recommended to put road signs at protection boundaries at Landvegur and Bjallavegur after redefining them.

The draft tube of the proposed hydropower plant Hvammsvirkjun could have an effect since it crosses several faults before the tail water joins Þjórsá River.

It is proposed to explore the feasibility of establishing water works at the springs of Tjarnalækur as a future source of untreated water to be developed at a later stage, e.g. in years 2030–2050.

It is recommended to no longer aim at having a waterworks at Kerauga taking into account that it only took about two months for the surface water near Fellsmúli fish farm to appear in Kerauga. This rules out Kerauga as a source for reliable and safe drinking water in the future particularly since there are plans for building houses in the vicinity of Minnivallasprunga that would increase contamination risk.

The aquifer is considered unconfined, heterogeneous with strong influence of anisotropy both in the Þjórsá Lava and in the alluvial sandstone below which could drain into Ytri-Rangá or disappear into the bedrock.

The mapped moraines observed in the area, may indicate that there are possibly additional moraines under the Þjórsá Lava affecting the flow pattern of the groundwater that could also explain why the tracer injected into Minnivallalækur surfaced at Kerauga.

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