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Hvalfjörður Tunnel: Questions on geological indications of danger

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This text is intended to clarify some questions that Lars Olsson on behalf of Geostatistik AB sent to us by fax in late May 1996. We choose to answer the questions in the same order as they are posed in the fax.

1. Temperature

Q: *What is the expected temperature along the tunnel?*

A: We plotted Figure 1 to answer this question. The Figure shows a cross section of the proposed tunnel route and is digitized from Fossvirki drawing no. VS.001.103. Also projected on the Figure are the three core wells already drilled in the vicinity of the tunnel, i.e. the vertical and the inclined wells at Hjarðarnes and a vertical well at Hólabrú. We draw the wells at the NW and SE shoreline of the tunnel route, which is reasonably accurate.

The temperature contours shown in Figure 1 are based on A) measured temperatures in the three wells, B) a 5 °C annual mean temperature at the land surface and at the seafloor and C) a linear, horizontal temperature gradient at 250 m u.sl. between the deep well at Hjarðarnes and the projected well temperature at Hólabrú (defined by the linear temperature gradient of that well). These data together provide a frame based on "known" temperatures around the tunnel route. A contouring routine in the GMT package of Wessel and Smith (1995) was finally used to contour this data in a 20x20 m grid.

The thermal gradient of the vertical Hjarðarnes well is 18.2°C/100 m and that of the Hólabrú well is 12.0°C/100 m. The higher value is abnormal, suggesting nearness to a geothermal anomaly. This is also evident from a well at Saurbær, 800 m to the SW of the Hjardarnes well. A thermal gradient of 21-22°C/100 m is observed there. The Hólabrú value, on the other hand, is close to the regional average in this part of Iceland, suggesting the absence of convective water systems in its vicinity.

It should be noted that the temperature influence of the Hvalfjörður sediments is not fully known in the cross section. Our approach simply was to assume similar thermal characteristics as in the underlying rocks, neglecting both possible temperature perturbations due to cooler climate more than 10.000 years ago and a higher thermal conductivity of the consolidated sediments. These assumptions are supported by recent drilling of wells into young sediments at the southern lowlands of Iceland.

Q: *Can normal variations from the expected tunnel temperature be predicted and when does the temperature signal a danger?*

A: We tried to estimate this temperature sensitivity by varying the depth to the "known", horizontal temperature gradient between Hjardarnes and Hólabrú, and also by varying some parameters in the GMT contouring routine. As an example we obtained a 22-28 °C temperature range for the deepest part of the tunnel. Temperature gradients are less sensitive, due to the linear contouring assumptions used in the model. Gentle temperature variations on the order of ± 3–5°C from the model should therefore be taken as normal.

Q: *How fast does the temperature change when you are approaching a waterbearing fault, dike, etc. connected to hot (geothermal) or cool (sea) water?*

A: Here we can refer to our experience in thermal gradient drilling in Hvalfjörður, 15 km east of the tunnel route. In this area a powerful and convective geothermal system extends across Hvalfjörður. The measured, horizontal temperature gradients, perpendicular to this long and narrow anomaly, are typically in the range of 10-20 °C/100 m (as an example, a temperature of 80 °C is measured at 200 m depth in the center of this system). If we take Figure 1 as a reference, a normal temperature gradient of 0.5-0.8°C for every 100 m of the tunnel should be expected. This means that a water bearing fault, convecting either hot or cold water should deviate substantially in temperature from the model in Figure 1.

Q: *Measuring technique. Given that the waterflow into a drillhole is small, how long time will it take to obtain a stable temperature reading? What time is needed to predict the true formation temperature?*

A: As we suggested at our meeting earlier, well temperatures should normally only be logged during the few hours available between successive explosions in the tunneling work. Some of the exploratory wells dipping down (water filled) should be used for this purpose, preferably the longest one or the one of maximum flowrate. Note also that small leakages of water into the tunnel often show accurately the formation temperature. Considering the low, horizontal temperature gradient in Figure 1, it is obvious that your temperature sensors must be well calibrated (±0.05°C) in order to avoid false alarms caused by faulty electronics.

We feel that your people will soon pick up a proper way of measuring the temperature ahead of the tunnel phase, especially if the measuring tools are of good quality and the same personel routinely collects and stores the collected data.

Q: *Can one use temperature measuring equipment on the drill jumbo?*

A: Here we assume you are considering to install all the electronics in the drill jumbo and plug the respective sensors to it whenever needed. This is probably only a question of design and should not be a problem.

Q: *Geological explanations to finding water hotter than expected? Ditto for water colder than expected?*

A: In our opinion the primary permeability of the bedrock in Hvalfjörður has almost vanished due to geothermal alteration in the geological past. Therefore we think that the presence of water hotter than expected should be taken as a warning of vertical permeability ahead. Cooler temperature than expected is not as straightforward. The most probable explanation in that case would be nearness to the downward limb of a convective system along vertical flowpaths. This should go in hand with increase in salinity.

2. Salinity of groundwater

Q: *Can the expected salinity level along the tunnel route be predicted?*

A: No, we have no data other than our intuition and experience from other, near shore geothermal areas in Tertiary basalts. It is our belief that fresh groundwater should be expected for most parts of the tunnel route. The only exceptions could be where the distance between the tunnel and the ocean is less than say 20-40 m. We think that the mountains on both sides of Hvalfjörður dominate the regional groundwater flow and maintain the groundwater pressure higher than that of the seawater.

It is possible to check this theory of salinity by pumping fluid from the vertical well at Hjarðarnes for some weeks, or by measuring its salinity indirectly by a downhole cable. Note that temperature logs indicate minor downflow in the well from surface to the major feedpoint at 230 m depth. This means that only the 230-260 m depth interval may show the initial groundwater salinity. The new well at Hólabrú on the north shore also can be logged to check the deep salinity in that region.

Q: *How large is the predicted normal variation in salinity? When do the salinity readings signal a danger?*

A: At this moment we are not able to estimate accurately a reference value for the groundwater salinity. Our only estimates can be taken from geothermal wells in the vicinity. As an example, the chlorine in well 5 at Hrafnabjörg is 65 ppm and in well 10 in Hvammsvík 69 ppm (15 km east of the tunnel on opposite sides of Hvalfjörður). This water originates from feedzones at 700-1100 m depth. Other examples are from wells in the Seltjarnarnes area (west of Reykjavík) which have chlorine in the order of 500 ppm and in the island of Hrísey in N-Iceland where the chlorine is around 400 ppm. It is not clear if the higher chlorine in the latter two cases is due to direct infiltration of seawater or simply due to molecular diffusion. We only know that these areas are further away from high mountains than the Hvalfjörður cases. Therefore we conclude that a chlorine content in the range of 50-150 ppm in deeper part of the tunnel is normal.

As we belief that the salinity will decrease (abruptly) with depth, the presence of saline water should be taken very seriously as the tunnel deepens. The reason is that in order to allow downflow of seawater into the slightly overpressurized, fresh groundwater system in Hvalfjörður, one must have a vertical flowpath of very high permeability. This kind of structure may then unbalance the low density fresh water in the flowpath and high density, seawater intrudes.

Q: *What distance from a saltwater-bearing fault/dike can a change in salinity be registered?*

A: We are not able to answer this question properly as we have scarce data for estimating this. However, we can say that in general a permeable fault/dike most often has some horizontal permeability associated with it. Therefore we assume that a saltwaterbearing fault/dike will give a rise in salinity some tens of meters before encounter.

Q: *Measuring technique. Time to get stable readings? Taking of samples?*

A: Due to slow changes in tunnel temperature, conductivity measurements will be sufficient to monitor changes in the groundwater salinity. The salinity should preferably be taken from flowing water, or secondarily by submerging a probe into the downward dipping exploratory wells. The collected water samples should be stored and some of them analyzed for chloride and possibly silicia. The time to get a stable reading depends on your drilling technique. If the exploratory wells are drilled by air, some water may build up in the deeper end of the well after completion. This water can then be collected. If you, on the other hand, drill these wells with water, they are almost useless for salinity monitoring unless natural water flow occurs.

Q: *Geological explanations to an increase in salinity. Is it always seawater or can it be ancient salt water from closed aquifers?*

A: Our conceptual model of the tunnel route assumes that ancient saline water, that might have penetrated into the basement rocks during the late Pleistocene high sea level stand, will to a large degree have been swept away be the regional, groundwater flow. Abrupt changes in salinity should therefore always be taken as a serious warning of a hydraulic connection to the sea. However, as in the case of the temperature, possible occurrence of ancient salt water should produce smooth salinity anomalies whereas vertical flowpaths produce sharp ones.

3. pH of groundwater

Q: *What is the expected pH along the tunnel route?*

A: Close to normal at shallow depths but over 9 at greater depths for fresh water. In general increasing with depth.

Q: *How large is the predicted normal variation in pH?*

A: Between 8 and 9.5. Anomalies in the pH, for example a decrease with depth, should be taken as a warning of water that is associated with shallower depths, whereas increasing pH indicates the presence of deep water. Note also that the pH has limited value as the water salinity increases (ending in a constant pH value of the ocean).

Q: *Geological explanations of a change in pH.*

A: The basaltic origin of the Icelandic crust always leads to high values for the pH, both in cold and hot water reservoirs. Our chemists tend to say that a high pH value reflects mature water, i.e. the water has spent a considerable time in the subsurface.

4. Colour of drillwater

Q: *What different rock and sediment types give colour to the drillwater?*

A: The drillwater will normally be of different gray shades depending on the basalt types intersected, flows and dikes alike. A greenish tint may occur due to alteration products, particularly in the southern part of the tunnel route (clay minerals). Rhyolite may cause pink colour and rhyolite tuffs yellow to pink or greenish. Both are rather unlikely to occur. The thicker sedimentary beds of more than 1-2 m will yield brownish to blackish colouring (combined with high penetration rate). Thin interbeds will yield red colouring. Yellow coloring may also indicate a clay or opaline rich matrix, cementing fault breccias or filling faults.

Q: *If red or yellow coloured drillwater occurs, what is to be expected regarding water leakage and stability?*

A: The sediments are less stable than the basalt and may cause irregularities in the tunnel profile and some collapsing from the roof. Small water leakages may accompany the sedimentary beds, particularly in the vicinity of vertical permeability of secondary origin.

5. Drill penetration rate

Q: *Which geological structures (faults, scoria etc) can be expected to give a significant change in penetration rate, or other parameters that can be observed during drilling?*

A: The penetration rate will be different depending on the hardness of the rock. A significant change can be expected when drilling through sedimentary interbeds. Clay zones in faults may dampen the hammer.

6. Water leakage

Q: *Can very large inflows of water (as in Ísafjörður) be encountered even though there is no connection to the sea (i.e. water from large aquifers, for example from*

Akrafjall)?

A: No, we can't foresee any fresh water aquifers large enough to sustain that amount of flowrate for years. A large inflow case would therefore most likely arise from seawater intrusion, which in turn would give a prewarning in the tunnel salinity. However, if an uncemented, hot water fault is penetrated, severe inflow rates may take place initially but slow off rapidly. The reason is that almost all geothermal reservoirs in the Tertiary basalts of Iceland only have water storage to sustain between 20-100 l/s production in the long run.

7. General

Q: *How can a dangerous zone be characterized compared to not dangerous ones?*

A: A dangerous zone (regarding inflow problems) can best be characterized as one with considerable higher or lower temperature **and** horizontal temperature gradient than predicted from the model in Figure 1. A large increase in salinity would also be of immediate concern.

Q: *Can such a zone be found and directly identified by probe drilling or must indirect indicators be used?*

A: Water leakage, temperature and salinity changes in probe holes are probably the only directly measurable parameters to identify a dangerous zone ahead. We see no indirect methods, geophysical or others that might help. Drilling of shallow gradient wells along the two coasts may relieve the agony of possibly intersecting a powerful geothermal system centered somewhere under Hvalfjörður.

Q: *Which combinations of indicators are a sure sign of danger?*

A: A high inflow from probe holes with rapid rise in temperature and rise in pH, or rapid drop in temperature and salinity increase would be a sure sign of danger.

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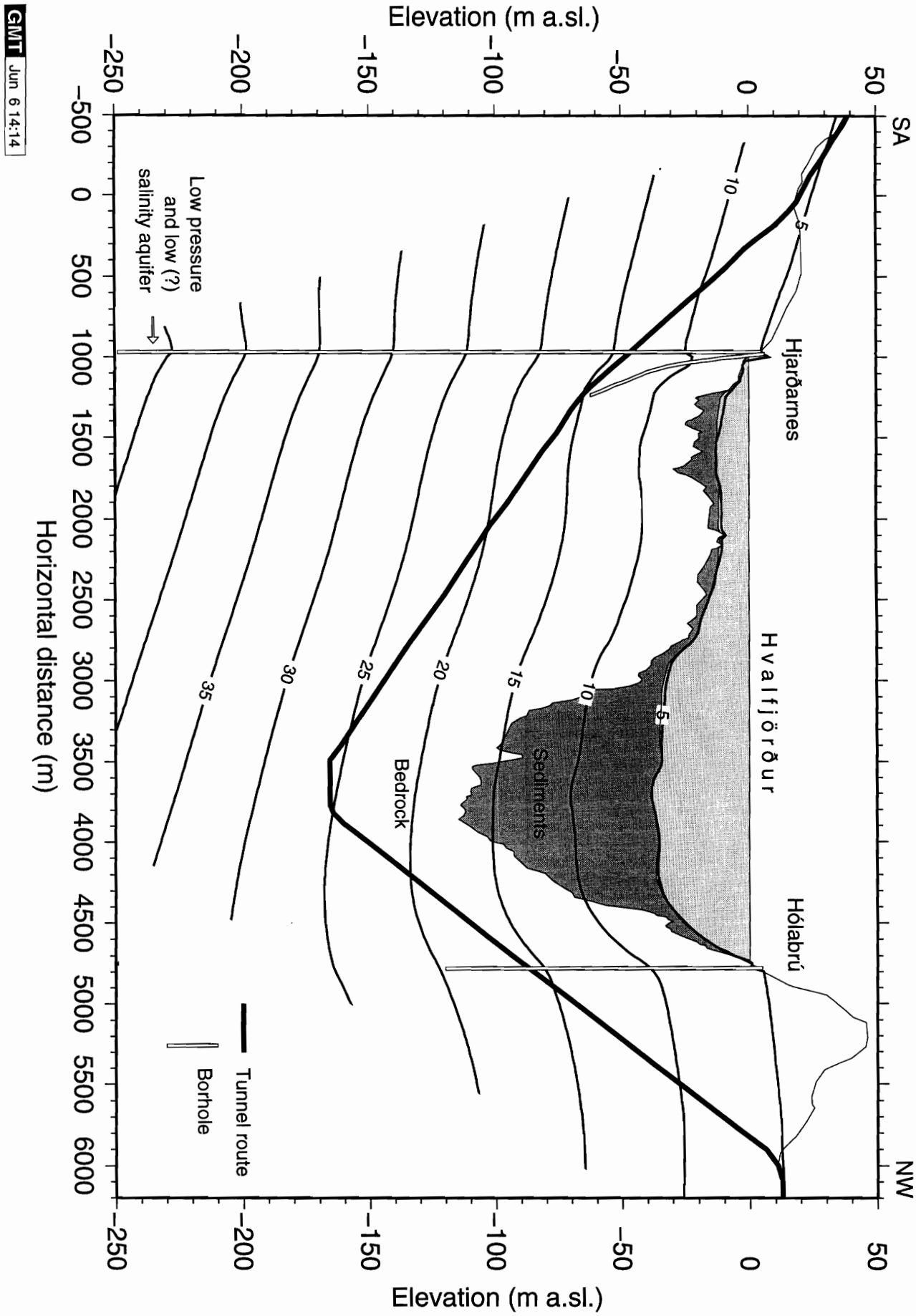

Figure 1: A schematic cross section of the Hvalfjörður tunnel and predicted temperature (°C)