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THE GEOTHERMAL EXPLORATION OF THE ÖXARFJÖRDUR HIGH-TEMPERATURE AREA, NE-ICELAND

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ABSTRACT

The Öxarfjördur lowlands in NE-Iceland are characterized by sediments from a glacial river and by fissure swarms from active central volcanoes further inland. A major graben is associated with the recently active Krafla fissure swarm in the central part of the area, where the sediments may be up to 1000 m thick. Rather insignificant surface geothermal activity in the form of warm springs and warm ground is encountered at a few locations within the fissure swarm. A systematic geothermal exploration in the eighties and the nineties has confirmed the existence of high-temperature geothermal activity within the Krafla fissure swarm. Resistivity soundings have outlined an area of at least 10 km^2 with a very low resistivity, 1-5 Ωm. The low resistivity surrounds a high-resistivity body which is associated with alteration minerals forming at or above 250°C. Another low-resistivity area is seen near the coast. Geochemical analysis and calculations based on mixing models indicate temperatures above 200°C. This has been supported by studies of alteration minerals in samples from shallow exploration wells. Seismic refraction measurements also show a high-velocity an omaly associated with the high-temperature activity as well as anomalously high seismic noise.

1. INTRODUCTION

The Öxarfjördur bay in NE-Iceland (Fig. 1) is located at the intersection of the active zone of rifting and volcanism, which crosses Iceland from southwest to northeast, and a fracture zone which offsets the plate boundary to west (Saemundsson, 1974). While most of the volcanic zone is characterized by volcanic products of some sort, the Öxarfjördur lowlands are chiefly a N-S trending 25 km broad down-faulted trough with no indica tions of volcanic activity. The lowlands are flat and dominate d by the delta of the Jökulsá glacial river, flanked by the Tjörnes peninsula to the west and highlands to the east. The trough is filled by shallow marine fjord sediments and glacial outwash from the Jökulsá river, which originates in the Vatnajökull glacier in the central highlands. Jökulsá has meandered all over the lowlands in Holocene time using different outlets to the sea from one time to another. During this century, the main flow has been in the Bakkahlaup outlet and to a lesser extent in the Sandá outlet (Fig. 1).

Scientific interest has focussed several times on the geothermal activity in the Öxarfjördur region (Stefánsson, 1977; Georgsson et al., 1989; Georgsson et al., 1993a). The nature of the geothermal systems has been debated as the sedimentary stratigraphy of the area is unusual in Iceland. In this paper we give an overview of geothermal exploration and drilling in the Öxarfjördur region and the status today, focussing on the hig h-temperature areas outlined here. Drilling of the first deep w ell, BA-2 at Bakkahlaup, was completed in late 1999.

2. GEOLOGY OF THE ÖXARFJÖRDUR AREA

The Öxarfjördur region is located at the junction between the North Volcanic Zone (NVZ) of Iceland and the Tjörnes Fracture Zone (TFZ) (Fig. 1), a right lateral transform zone connecting it to the Kolbeinsey Ridge spreading axis further north. Sedimentary depressions commonly develop at such junctions. The thickest known sedimentary sequence in Iceland is found within the Tjörnes Fracture Zone, both on land and off-shore. It covers a 50 km wide area from Eyjafjördur in the west to th e Melrakkasletta peninsula in the east, for a distance of 150 km. The sequence is up to 4 km thick and may have been accumulating since Miocene times. The eastern boundary of the basin is unknown, but the basin predates the Tjörnes horst just west of Öxarfjördur, and may underlie Öxarfjördur itself.

A simplified geological map of the area and a schematic lithological section crossing Tjörnes and Öxarfjördur are shown in Fig. 2. The lithological section is based on current ideas on the tectonic settings, and data from the deepest borehole (455 m) in the area, and geophysical surveys. The Öxarfjördur regi on is presently within the North Volcanic Zone. This plate boundary is characterized by localized central volcanoes and extensional fissure swarms coupled with subsidence and volcanism (Fig 1). The thickest marine sediments exposed on land in Iceland (of Pliocene and Pleistocene age) are found on the Tjörnes tectonic horst. East Tjörnes rises in 4-6 prominent steps to an altitude of 300-400 m in the north and 600-700 m in the south. The present-day tectonic setting dates back about 1 Ma when the Öxarfjördur area became the active spreading axis. Prior to that the North Volcanic Zone and the Kolbeinsey Ridge were coupled by the Húsavík transform fault, and a more westward lying spreading axis in early Pleistocene (Saemunds son, 1974; Ólafsson et al., 1993). Accordingly, the Öxarfjörd ur basement could consist of Miocene, Pliocene and Pleistoc ene lavas, hyaloclastites and sediments, yet to be confirmed b y drilling.

Three active northerly trending fissure swarms, parts of active volcanic systems further inland, cross the Öxarfjördur region (Fig. 1). The Krafla fissure swarm extends for tens of kilometres from the active Krafla central volcano, through the central part of the Öxarfjördur depression. The Theistareykir fissure swarm extends into the western margin of the area, and the Fremri-ná mar fissure swarm is found at the eastern margin. Intense volcanic and rifting activity was experienced within the Krafla central volcano in 1975-1984, usually referred to as the Krafla fires (Björnsson, 1985). Magma was fed into a shallow chamber in its central part. Episodically the pressure was reli eved by feeding of the magma into the fissure swarm, which was accompanied by intense rifting and intrusive/eruptive acti vity within the fissure swarm, with different parts active in different episodes. On 3-4 occasions big changes were record ed in Öxarfjördur, associated with this rifting and movement of magma. However, no magma reached the surface in the lowlands and seems not to have done so in Holocene times. Most of the surface geothermal activity is confined to the gravel plain and the Krafla fissure swarm.

The deepest well in the area, AER-4, was drilled in 1991 to 455 m depth (Ólafsson et al., 1993) in the Skógalón geothermal field at the sea shore (Fig.1). It was originally targeted to penetrate a 700-800 m thick sedimentary sequence, in order to seek a potential source rock for organic gases of thermogenic origin, but had to be abandoned. The well encountered deltaic, lacustrine and marine sediments of Holocene age, down to 365 m depth, and glaciomarine sequence of late Pleistocene age below that depth to the bottom. Knowledge on the deeper part of the basin is deduced from the geophysical surveys. The well, however, indicates an exceptionally high sedimentation rate in Holocene times, on the order of 3.5 cm/year.

The geothermal systems in Öxarfjördur are replenished by enormous amounts of cold fresh groundwater flowing along the fissure swarms and porous lava fields towards the lowlands. At the surface the geothermal systems are covered by the water-s aturated sandur of the Jökulsá river delta, which is unconsolidated down to about 50 m depth. Artesian springs e ast of Jökulsá and the sandur in Öxarfjördur yield about 6 m^3/sek, and the springs west of the Jökulsá river yield about 30 m^3/sek. Many shallow wells have been drilled for cold and war m groundwater close to the coast, east of the Skógalón geothermal field (Georgsson et al., 1989; Fridleifsson et al., 1995). Most of them are artesian, yielding several tens of l/s per well. Undoubtedly, this enormous ground water supply will prove beneficial to future exploitation of the high-temperature geothermal systems in the area.

3. GEOTHERMAL ACTIVITY

3.1 Surface manifestations

Surface geothermal manifestations in the Öxarfjördur region are meagre, mainly in the form of warm springs and warm ground within the active fissure swarms. Geothermal manifestations are known at 13 locations (Fig. 1) which can be divided into 3 groups (Georgsson et al., 1993a).

The Krafla fissure swarm includes the most significant sites. During the Krafla fires the geothermal activity increased considerably, but recently it has gradually decreased again. The most important locations are:

Skógalón where water at shallow level with temperatures up to 100°C is found in an area covering several hundred squ are metres. Before the Krafla fires, the temperature was 7 0-80°C.

Bakkahlaup with warm ground spread over a wide area, a nd temperatures up to 80°C in the uppermost metre, which were considerably lower before the Krafla fires.

A few geothermal locations are found within the Theistareykir fissure swarm in the western part of the Öxarfjördur area, the most important one being at Ytra Lón, close to the coast, where temperatures of 50°C have been measured recently, though old records stated temperatures above 80°C. Two geothermal sites are found outside active fissure swarms (Fig. 1).

3.2 Boreholes

Several shallow wells have been drilled in the area, as mentioned above, most of them are for fresh water, warm water and sea water to be used for fish farming, or as thermal gradient wells. Wells at Bakkahlaup and Skógalón (Fig. 1) were drilled as exploration/production wells.

BA-1 at Bakkahlaup, which is 81 m deep, was drilled in 1987 as a reconnaissance well to confirm high-temperature activity. It recorded temperatures of 107°C at the bottom, and alteration related to high-temperature activity (Georgsson et al., 1993a).

In 1988, a production well, AER-3, was drilled into the Skóga lón field to get hot water of low-/intermediate-temperatures fo r space heating and/or fish farming. Well AER-3 was drilled t o 322 m depth and yields 45 l/s of 96°C hot water mainly fro m aquifers at 140 m depth. The temperature at the bottom is a pprox. 130°C (Georgsson et al., 1989). It is now the producti on well for the Öxarfjördur Heating Services, and supplying h ot water for heating purposes to the village of Kópasker (Fig. 2) with population of 170 inhabitants, and to farms and minor industries along the coastline (Georgsson and Fridleifsson, 1 996).

The highlights of the drillings at Skógalón was the first ever discovery in Iceland of "thermogenic" organic gasses in the water. Well AER-4, was especially aimed at investigating this. Its temperature is 150°C at the bottom and it yields about 10 l/s in free flow (Ólafsson et al., 1993; Ármannsson et al., 1998).

4. GEOCHEMISTRY

Numerous cold and warm water samples from the Öxarfjördur area have been analysed for all major elements, some trace elements and the stable isotopes of hydrogen and oxygen. The geothermal sites are shown in Fig. 1 and representative analyses in Table 1. The chemical composition of the water varies, wit h TDS in the range of 100-6500 mg/l and temperatures from 4°C to 100°C for the hot springs. Highest temperatures and TDS are found within the Krafla fissure swarm and the highest chlorine content in hot springs and wells at Skógalón. Geothermometry calculations are based on data from the Skógalón field, as good representative samples were not available from the other areas .

The δD - δ^{18}O relationship for waters in the Öxarfjördur area is shown in Fig. 3. The Bakkahlaup sample is from Jökulsá river According to the plot, cold water, river water and most of the thermal waters fall on or close to the meteoric line, indicating their origin from precent day precipitation. A significant positive oxygen shift is though observed for the thermal waters from Skógalón, which applies both to hot springs as well as waters from boreholes AER-1, AER-3 and AER-4. The thermal waters at Skógalón are Cl-rich, but chemical and isotopic measurements indicate that the salinity is not caused by direct mixing of geothermal water with recent seawater. Similar oxy gen shift observed in geothermal water in the Southern Lowlands of Iceland (Arnórsson et al., 1993) is best explained either by a relatively long residence time of the water or that the water dates from the last glacial period, i,e, isotopically much lighter precipitation.

Geothermometry calculations based on the silica concentration of the thermal waters indicate a subsurface temperature of 160 and 180°C according to chalcedony and quartz, respectively. The highest temperature encountered in well AER-4 was 150°C at 450 m depth. Calculations based on the gas composition of fluid (Arnórsson and Gunnlaugsson, 1985) from well AER-4 indicate subsurface temperatures of 190-260°C and the methane/ethane ratio in the gas (Darling and Talbot, 1992) in dicates a temperature of 200-220°C. Subsurface temperatures based on the silica-enthalpy mixing model (Fournier 1977) have also been estimated (Fig. 4). Two mixing lines were calculated. Line a is a best-fit line through all data points and gives the equilibrium temperature with quartz as 200°C, but line b assumes mixing between cold water and water from well AER-4 and gives a temperature of 230°C.

5. RESISTIVITY STRUCTURE

5.1 Measurements, interpretation and resistivity maps

About 70 Schlumberger resistivity soundings have been carried out in the Öxarfjördur region, concentrating on the central part and the Krafla fissure swarm (Georgsson et al. 1993a and b). The maximum AB/2 of these soundings is 1000-1780 m. The older soundings are irregularly distributed, covering more or less the whole area of interest, while the more recent ones were measured along distinct lines from west to east across the fissure swarm. All the soundings were first interpreted by 1-D inversion. 2-D interpretation was then done along the E-W cross-sections by the program FELIX developed and written a t Orkustofnun. Interpretation of other soundings was then modified based on the 2-D interpretation.

Fig. 5 shows the resistivity distribution in the Öxarfjördur area at 500 m b.s.l. It shows a N-S elongated low-resistivity anomaly, at least 10 km^2 in size, located within the Krafla fissure swarm. It coincides with the Bakkahlaup thermal anomaly (Fig. 1). Along the central part of the anomaly, higher resistivity is recorded at deeper levels. This high-resistivity anomaly clearly outlines the centre of the geothermal activity. This is well demonstrated in the 2-D cross-section A-A' in Fig. 6 (for location see Fig. 5). It shows clearly how the low-resist ivity rocks appear like a coat around the resistive inner core, a similar structure to what has been found in many Icelandic hi gh-temperature systems. A smaller low-resistivity anomaly is also found close to the sea shore at the Skógalón geothermal f ield. The main low-resistivity anomaly is flanked by zones of higher resistivity, which coincide with the active fracture zone s bordering the active zone of subsidence within the fissure s warm. Inland, outside the Krafla fissure swarm, the resistivity is generally rather high, 50-200 Ωm, except in the eastern par t of the region, where it is somewhat lower.

5.2 Geothermal activity and resistivity of rocks

Correlating the resistivity of rocks in Iceland with other geophysical parameters (Flóvenz et al., 1985; Árnason and Fl óvenz, 1992) shows that together with temperature and salinit y of the fluid, it is the surface conduction along fracture walls (interconnected pores) that dominates the electrical conductio n of water-saturated rocks. Hence, variations in the electrical resistivity of rocks are mainly due to different fracture porosit y, temperature and alteration minerals lining fractures.

Geological circumstances in Öxarfjördur differ from other parts of the volcanic zone in Iceland. The hot water flows up through sediments which are 0.5-1 km thick according to gravity and seismic measurements. Thus, comparison with other geothermal fields can be misleading. However, the low resistivity, 1-5 Ωm, measured within the Krafla fissure swarm and the high-resisti vity core are difficult to explain except by high-temperature g eothermal activity. The high-resistivity is thought to originat e from changes in mineralisation at deeper levels, from clay m inerals which have loose ions and hence low resistivity, to the more resistive high-temperature alteration minerals, like epid ote and chlorite. The change generally happens at temperatur es around 250°C. This may not necessarily be representative f or the present temperature conditions in the geothermal syste m, but it has at least reached such temperatures during its lifet ime. Shallow exploration drilling has confirmed the existence of alteration related to high temperatures at shallow levels, su pporting this theory. Therefore, we propose that a high-tempe rature geothermal system is associated with the Bakkahlaup g eothermal field. Using the 5 Ωm isoline at 500 m b.s.l. to del ineate it, the area is at least 10 km^2 in size. Though the geothe rmal manifestations on the surface are meagre, this can be exp lained by the abundant mixing of cold groundwater at shallow depths and the high sedimentation rate. However, it is not un likely that recent intrusions may also contribute to higher resis tivity at the deepest levels, e.g. from the intrusive episodes of the Krafla fires.

Another result of interest is the high resistivity flanking the m ain low-resistivity anomaly, coinciding with the active fractur e zones. Here cold, ground water has easy access to deeper le vels through the open fractures, leading to cooling and hence relatively high resistivity in the uppermost kilometre. Close t o the coastline, at Skógalón, this is reversed. The low-resistiv ity anomaly here is associated with upflow. The warmest hot springs are found here on the active fracture zone defining the eastern flank of the Krafla fissure swarm.

The resistivity is generally rather high outside the Krafla fissure swarm and similar to values found in coastal areas of the volcanic zone away from high-temperature activity. The low resistivity in the northeast part of the research area is probably due to warm brackish ground waters and high porosity (Fridle ifsson et al., 1995, Georgsson and Fridleifsson, 1996).

6. SEDIMENTARY FORMATIONS

Sedimentary formations are generally characterized by low gravity values and low seismic velocity, in contrast to the higher values of denser rocks, such as the more common basaltic layers in Iceland. To get a quantitative information on the thickness of sediments in the Öxarfjördur lowlands, a survey combining gravity measurements and seismic refraction was carried out in the delta area in the late eighties. The latter was done in cooperation with Russian geophysicists from the University of Moscow and the Leningrad Mining University. Two refraction profiles were measured. The main profile (S-1) is across the l owlands from west to east, but the other (S-2) between the geothermal field at Bakkahlaup in south and the coast in the north.

Fig. 7 shows a Bouger gravity map of the Öxarfjördur area and the location of the main gravity and seismic profiles. The grav ity map shows a prominent gravity low over the Öxarfjördur tr ough with a marked minimum within the Krafla fissure swarm. This reflects the thick sedimentary formations in the area and especially within the Krafla fissure swarm.

The 2-D interpretation on profiles S-1 and S-2 included both the seismic data and the gravity data. Fig. 8 shows this combined interpretation for both profiles (location Fig. 7). The profiles show 2-3 low-gravity (1.6-1.9 g/cm^3) and low- velocity (1.6-3.0 km/s) layers reaching down to a depth of 400-500 m. These layers certainly correspond to the sedimentary formations. An intermediate layer is seen below this (3.5 km/s, 2.0 g/cm^3) and reaches down to 600-1000 m depth, thickening towards the coastline. This higher velocity and gravity indicates that the layer may correspond to underlying young basalt formations, possibly interbedded with sedimentary formations. The high seismic velocity (5 km/s) and gravity (2.7-2.8 g/cm^3) in deeper layers probably reflect altered basaltic layers. Here they are found at shallower depth than elsewhere within the active rift zone, which may suggest that old basaltic crust underlies the sediments. Profile S-2 shows a gradual thickening of the seismic layers towards the coastline.

It is of interest to note that the high-velocity/gravity layers seem to “reach upwards” in the central part of the Krafla fissure swarm, indicating locally increased alteration. This supports the existence of high-temperature geothermal activity there.

7. SEISMIC NOISE

In association with the seismic refraction, data was collected on seismic noise (Rykounov et al., 1992; Árnason and Flóvenz, 1992). Fig. 9 shows the combined results of the seismic noise in reference to the resistivity at 500 m below sea level and the active fracture zones. Well defined areas of seismic noise at 1800 m depth are noticed on both sides of the active fractures of the eastern flank of the fissure swarm in the Bakkahlaup area. One of the maxima is located directly below the resistivity anomaly, ssuggesting that the noise is of geothermal origin, may be boiling within the reservoir or cracking due to thermal contraction of cooling rocks.

8. HIGHLIGHTS AND CONCLUSIONS

A geological model based on the tectonic settings and geophysical data indicates that the Öxarfjördur sedimentary trough is younger than ca 1 Ma and may reach a thickness of up to 1 km at the shore inside the Krafla and Theistareykir fissure swarms, thinning southwards, where the sediments are expected to be more frequently interbedded with lavas and hyaloclastites. It also assumes that high-temperature geothermal activity can be associated with both fissure swarms, represented by the 200°C isotherm (Fig. 2).

Distribution of geothermal activity in the Öxarfjördur region is controlled by the active fissure swarms with the main fields located within the Krafla swarm. The intense tectonic and intrusive activity during the Krafla fires in 1975-1984 was followed by a considerable increase in surface geothermal manifestations, but a decreasing trend has been noted since.

Geothermometry calculations indicate reservoir temperatures in excess of 200°C at Skógalón and possibly as high as 230°C. On the other hand, geological and geophysical evidence shows that the Bakkahlaup field is the centre of geothermal activity in the area, and it is postulated that higher subsurface temperatures will be met there.

Resistivity measurements show an area within the Krafla fissu re swarm including the Bakkahlaup geothermal field, at least 10 km^2 in size at 500 m depth, with a resistivity structure typical for high-temperature systems in Iceland. It shows a low-resist ivity coat around a resistive core, representing the centre of th e system. This high resistivity is associated with alteration minerals such as chlorite and epidote, that form at temperatures around 250°C. This is also supported by the local high-velocit y/gravity anomaly in this area.

Also of interest is the high resistivity coinciding with the active fracture zones where cold, ground water can penetrate to deeper levels, leading to cooling and, thus, relatively high resistivity. The clearly defined areas of seismic noise are associated with the active fracture zone at the eastern flank of the Bakkahlaup field, and may partially reflect boiling within the reservoir and partially cracking due to cooling of rocks.

The geothermal exploration indicates that the geothermal fields at Bakkahlaup and Skógalón should both be classified as high -temperature systems, where temperatures reach 200°C in the uppermost kilometre. The heat source of the systems is presumably intrusives, which are periodically rejuvenated in association with volcanic, rifting episodes of the Krafla volcanic system and flow of magma along the fissure swarm. The high sedimentation rate and enormous cold groundwater flow undoubtedly cause the lack of conventional high-temperature geothermal manifestations on the surface especially at the Bak kahlaup field. Drilling of the first deep exploration well into t he larger Bakkahlaup field was completed in October 1999.

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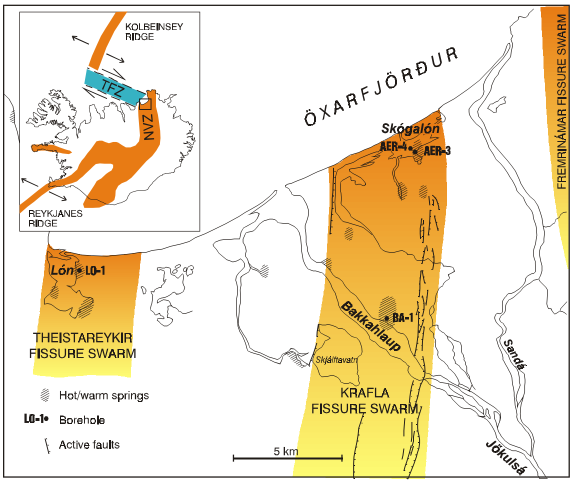

Figure 1. Öxarfjördur region, tectonics and geothermal activity

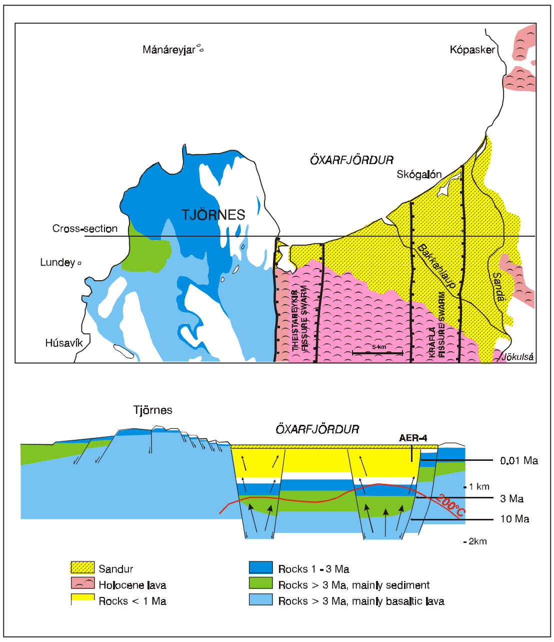

Figure 2. Geological map of the Öxarfjördur region and a conceptual model section through the region

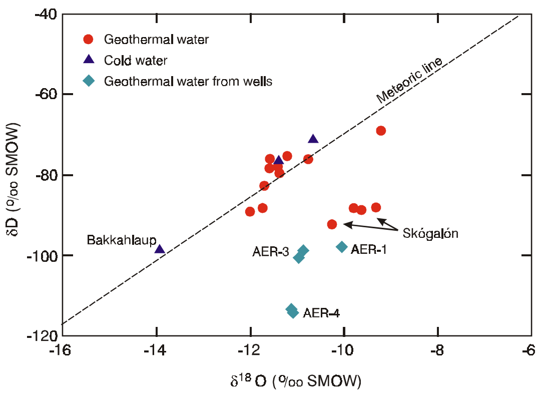

Figure 3. Distribution of δD and $\delta^{18}O$ in cold and geothermal waters in the Öxarfjördur region

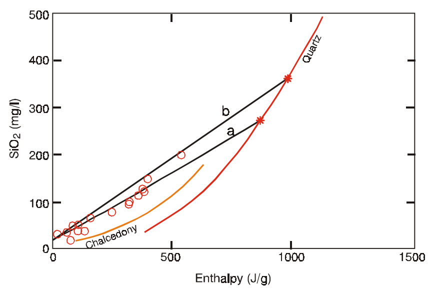

Figure 4. The silica mixing model applied to Öxarfjördur waters

Table 1. Chemical composition of representative samples from the Öxarfjordur region (isotope values in ‰ SMOW)

Location	T (°C)	pH/ °C	SiO_2 (mg/l)	B (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	CO_2 (mg/l)	SO_4 (mg/l)	H_2S (mg/l)	Cl (mg/l)	F (mg/l)	Br (mg/l)	TDS (mg/l)	δD	$\delta^{18}O$
Skógalón	95.7	7.3/16	148.0	1.77	1818	98.2	400	7.14	30.3	232	0.05	3539	0.41	12.1	6401	-87.8	-9.28
Skógakíll	92.0	8.7/19	122.7	1.40	950	54.5	186	0.07	30.6	85.9	0.05	1807	0.33	6.2	3326	-88.5	-9.59
Bakkahlaup	78.5	8.4/16	100.3	0.53	427	41.1	17.0	1.47	30.8	46.1	<0.05	658	0.59	2.2	1283	-90.0	-11.98
AER-3	96.0	7.9/24	129.1	1.00	833	43.5	154	0.42	24.3	96.6	0.07	1534	0.27	5.3	2709	-100.4	-10.93
AER-4	132	8.6/22	214	1.36	1222	67	185	0.63	5.1	150	<0.03	2110	0.12	8.23	4085	-114.1	-11.05
Jökulsá	2.9	7.8/14	16.8	-	19.8	1.4	6.1	3.62	42.1	7.9	<0.03	6.9	0.16	-	104	-98.7	-13.90
Sea water	4.0	8.1/22	1.6	-	10113	396	378	1162	105	2545	<0.03	18288	0.70	-	36110	-7.1	-0.79

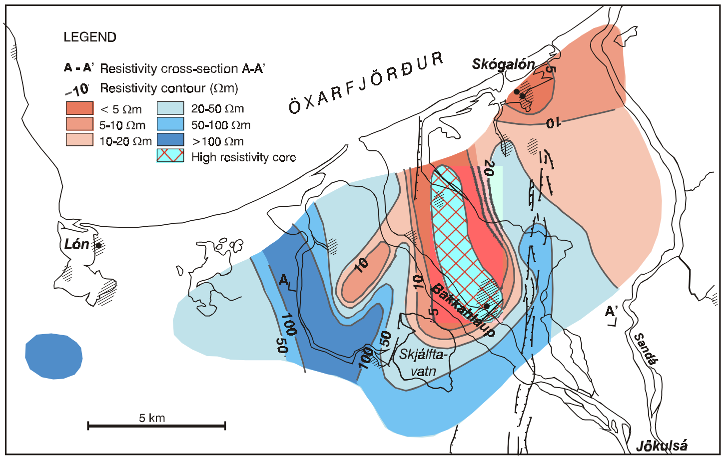

Figure 5. Resistivity at 500 m below sea level in Öxarfjördur

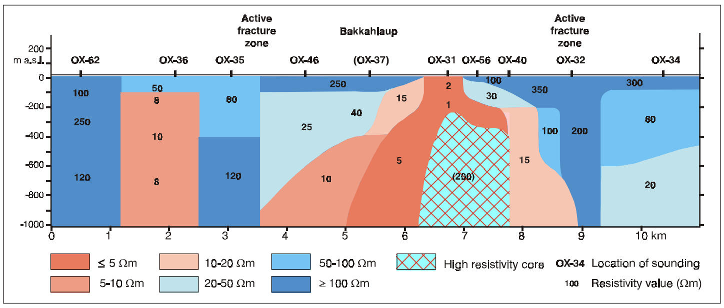

Figure 6. 2-D resistivity cross-section A-A'

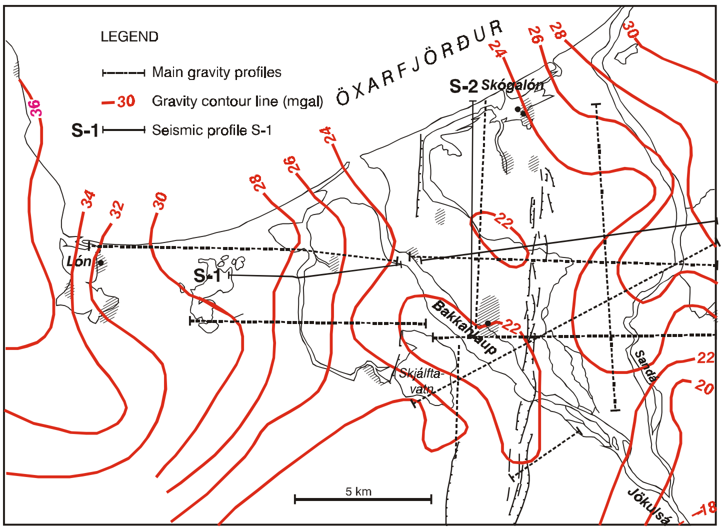

Figure 7. Bouger gravity map of the Öxarfjördur region

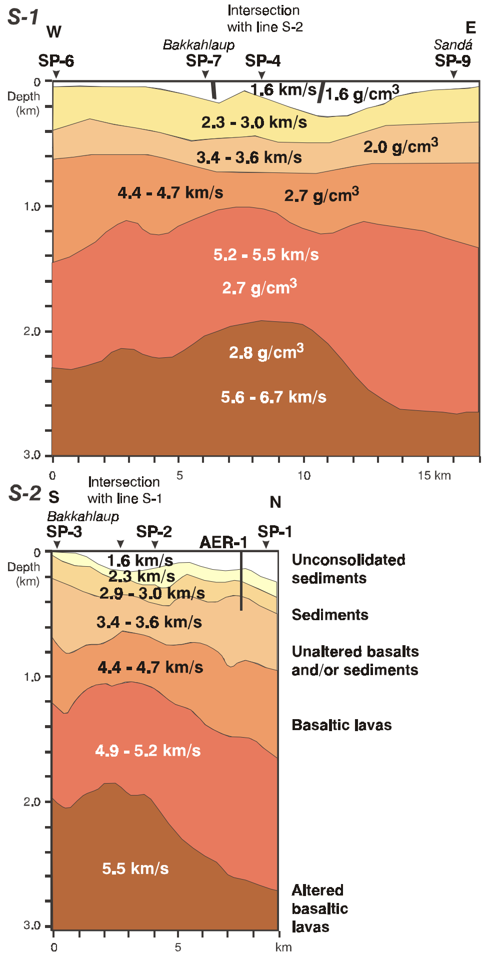

Figure 8. 2-D seismic and gravity cross-sections

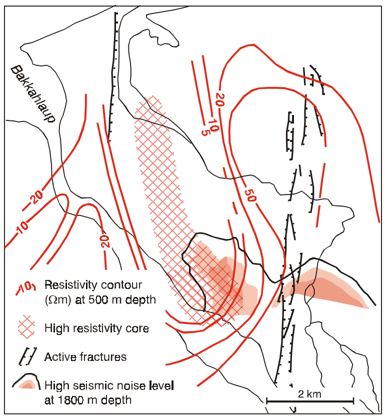

Figure 9. Seismic noise in the Bakkahlaup field