ORKUSTOFNUN
NATIONAL ENERGY AUTHORITY

STAÐUR

HYDROLOGICAL INVESTIGATIONS
PREFEASIBILITY REPORT

Orkustofnun
Vatnaskil Consulting Engineers
Prepared for Iceland Salmon Ltd.

OS-84096/JHD-43 B December 1984

ORKUSTOFNUN
Grensásvegi 9, 108 Reykjavík

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Our date	Our ref.
1984-12-14	STH/gb
Your date	Your ref.

Iceland Salmon, Ltd.
Suðurlandsbraut 32
105 REYKJAVÍK

Re: HYDROLOGICAL INVESTIGATIONS AT STADUR

The first phase of the investigation of the fresh water and sea water supply for a proposed aquaculture complex at Stadur is now completed. This work was carried out according to the plans submitted by the National Energy Authority 30 August, and your approval dated 6 September.

The prefeasibility report consists of four separate sections:

1. Hydrogeology and groundwater.
2. Hydrological Investigations.
3. Water analysis.
4. Drilling of Observation Wells.

The results are summarized separately in front of the main text. This report presents the preliminary results, and was compiled shortly after completion of the field work. Further evaluation is planned and will be included in the final report to be submitted in February.

Sincerely yours,

Sverrir Thorhallsson

Sverrir Thorhallsson, group leader.

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SUMMARY

SUMMARY OF RESULTS

1 FRESH WATER INVESTIGATIONS

1.1 The Stadur area is a part of a groundwater basin stretching south to the coast from the central parts of the Reykjanes peninsula. It is bordered on both sides by rows of hyaloclastite mountains, some rising above the lava field, some buried beneath it. The groundwater flows predominantly along scoracious contacts between or in the lava-flows, so the bedrock is very permeable. This permeability is enhanced by numerous tectonic fissures, running SW-NE.
The extent of the basin is approximately 10-12 km in SW-NE direction and approximately 6 km NW-SE. The proposed location for extraction of sea water is at the fissure Stadargja, 0.4 km from the shore, and the proposed fresh water site at the fissure Lambagja 1.4 km from the coast.

1.2 Because of anisotropy in the Lambagja area the permeability is greatest in SW-NE direction and has the value 0.32 m/s.
The permeability at the coast is 0.05 m/s, which is also high and corresponds to the permeability of fine gravel. Due to the high permeability strong tidal response is observed reaching 60% at the Stadargja and 30% at Lambagja. The tidal amplitude at the coast is 2-4 m.

1.3 The groundwater in this basin is influenced by the geothermal fields, in the east by Svartsengi, and the west by Eldvörp, both causing some increase in temperature. At the coast an elevation in the temperature of the groundwater has been measured between Husatoftir and Grindavik (temperature above 10°C due to effluent from Svartsengi) and on Stadarberg (effluent from Eldvörp, temperature above 8°C).

1.4 The equivalent thickness of the freshwater lens in the Lambagja area is 22 m and 17 m in the vicinity of Stadargja. In the center of the peninsula the thickness is 50 m.
Maximum permissible drawdown in Lambagja is 6 cm. The results of the investigation indicate that 350 l/s can be pumped from Lambagja without danger of seawater intrusion (upconing).

1.5 The chloride content increases towards the coast. It is 40-70 ppm Cl- in the central part of the region, 200 ppm in Tóftakrókar 2 km NW from Lambagja (t: 7-7.5°C), about 700 ppm Cl- in Lambagja (7°C) and 1,000-3,000 ppm Cl- west of Stadur (below 7°C). The chloride content in Lambagja, which is 9 m deep, was before the pumping test approximately 700 ppm Cl-. The chloride content in the pumped water was 800 to 1400 ppm Cl- fluctuating due to tidal effects, and an increase in the salinity gradient. The pump test was at 150 l/s for 10 days. Pumping of 350 l/s might increase the salinity further.

1.6 Water samples were collected in the open fissures and observation wells. Samples were taken at the surface and down-hole, and during the pumping test. The results are displayed in tables, but the data has not been interpreted further.

2 SEAWATER INVESTIGATIONS

2.1 The temperature of the seawater in a 60 m deep observation well SH-8 by Lambagja was about 8,0°C. 1 In a 50 m deep obs. well SH-2 by Stadargja it was 7-7.5°C in early October but had fallen to about 5.5°C at the beginning of December.

2.2 To ensure that the salinity of the pumped seawater is greater than 5000 ppm Cl- (10 o/oo salinity), roughly 150 l/s must be withdrawn from each site at the coast. With the estimated permeability of 0.05 m/s at least 2-3 m3/s of saline water can be pumped from Stadargja. The permeability at the coast must be determined by pumping test before the yield can be calculated. This test is to be carried out later.

PART I

HYDROGEOLOGY AND GROUNDWATER

Freysteinn Sigurdsson
Snorri P. Snorrason

National Energy Authority

CONTENTS

LIST OF FIGURES

1 INTRODUCTION

This part of the text deals with that part of the groundwater research at Stadur in Grindavik which was carried out by the Hydro Power Division, Geological Mapping Department, of the National Energy Authority of Iceland (NEA), and is concerned with the hydrogeology of the area, temperature and resistivity loggings of wells and certain aspects of the groundwater basins and groundwater quality. It was carried out by the following expert staff, all geologists; Freysteinn Sigurdsson, Chief of the Department, Snorri P. Snorrason and Bessi Adalsteinsson. Extensive use was made of Jon Jonsson`s excellent geological maps of the area, as well as his numerous recommendations on this matter. Use has also been made of the author`s former work in this area, including well-logs measured for Hitaveita Sudurnesja (Sudurnes Regional Heating) and other related data. The work was done in close cooperation with the other scientists working on this project, especially from NEA`s Geothermal Division and Vatnaskil Consulting Engineers Ltd.

2 HYDROGEOLOGY

2.1 Stratigraphy

The western half of the Reykjanes peninsula is largely covered by post-glacial basaltic lavas, originating in this area. They can be classified into volcanic systems (Sigurdsson, F., 1984). Each system is composed of one or more shield volcanoes, producing voluminous olivine-tholeiitic-lavas, and several eruption fissures, producing tholeiitic lavas and usually grouped together on relatively narrow strips. The volcanic systems lie obliquely along the Reykjanes peninsula constituting a volcanic zone. The eruption centres on the western part belong to two systems, known as the Reykjanes and Grindavik systems.

Submarine and subglacial eruptions have piled up mountains composed of pillow lavas and hyaloclastites (móberg in Icelandic) formed in subaerial eruptions. The moberg mountains have much the same orientation as the post-glacial eruption centres. Eruption fissures and moberg ridges have generally a SW-NE trend.

The largest single lava in this area is from the shield volcano Sandfellshaed (D-6, see Jonsson, J. 1978). It reaches the shore on both sides of Reykjanes eastwards to Grindavik, and enters the sea at Stadur. The western part of the Stadur lava field is covered by a large lava flow from the crater Raudholl (H-15, H-17, Jonsson, J., 1978; same, pers. comm. 1984). It has been partly covered by another lava, from the eruption fissure Eldvörp (H-16, Jonsson, J., 1978), considered to be about 2000 years old (Jonsson, J. 1982). The Sandfellshaed lava is by far the oldest. Nearly all visible fissures in Stadarhverfi are in this lava, while such tectonic features are practically absent in the younger lavas. At the time of eruption of this lava, the sea level was probably lower than at present. At any rate, its edge now reaches 4-5 m below sea level. It is likely, that the part of the lava flowing into the sea and cooling subaquatically is in some ways different from other parts of it. It could be more massive, which would have an effect on its permeability. The lava from Raudholl (H-15/17), on the other hand, ends in cliffs at the shore on Stadarberg. Off the coast, there are many rocks and skerries from the Sandfellshaed lava, but a notable abrasion has taken place there during the last centuries (Bryniolfsson, G., 1974).

The groundwater table elevation is low everywhere in the Stadur area. It probably lies in the Sandfellshaed lava in the whole area, except where the younger lavas reach the shore. It is not known how far below sea level the Sandfellshaed lava reaches. At the Grindavik harbour, it probably reaches at least 15 m below sea level, and the same seems to be the case in Hafnir and other places where it reaches the shore. In the exploration boreholes in the Stadur area, (SH-2, SH-8) olivine-tholeiites are found down to depths of 40-50 m below sea level (see Part IV), but those may not be part of Sandfellshaed lava. They may have originated from an older shield volcano.

Geological evidence indicates that there is a former valley northeast from Stadur on the west side of the mountain Thorbjorn, filled with basaltic lavas (Sigurdsson, F., 1984). NW of Eldvörp some moberg mountains rise above the low lava fields (Sandfell, Thordarfell, Stapafell). Geological factors, the state of the groundwater, geomorphology and geoelectrical resistivity soundings suggest that some moberg mountains lie beneath the lava fields in the area between the abovementioned mountains and the crater row Eldvörp. This moberg mountain may eventually reach to SE of Eldvorp. There possibly exist one or more older shield volvcanoes covered by Sandfellshaed, or at least near it, probably dating from the last interglacial period. They may be the source of the olivine tholeiites in the lower part of the boreholes at Stadur.

2.2 Tectonics

The tectonic structure is characterized by SW-NE fissure swarms. At the borders of the volcanic zone, these swarms have a WSW-ESE orientation. This is easily seen at Stadur, where the open fissures south of the road to Reykjanes have a more westerly direction. In the Stadur area, fissures are almost exclusively to be found in the Sandfellshaed lava, where there are many open ones, 1-2 m wide. Most of them are largely filled with blocks and stones fallen from the walls, or represent a narrow graben. Some of the fissures can be traced for more than 1 km, but they are not open everywhere. Most of them are interrupted or arranged in echelons. The intervals between the open fissures are usually some hundred meters although some narrow fissures occur in between, but they are often hidden by vegetation or the weathered surface layer of the lava. To the NW from Stadur and S of Toftakrokur, the fissures are filled with wind-blown sand. There the groundwater is nowhere visible in the fissures.

2.3 Permeability of the rocks

The rocks in this region can be classified according to permeability as follows:

1. "Móberg" (hyaloclastites with pillow lavas): Permeability often in the range 10E-4-1CE-2 m/s.
2. Interglacial basalts (found at the surface only in the northern part of the region): permeabilities often 10E-3-10E-1 m/s.
3. Olivine-tholeiites from the shield volcanoes: Often thick layers, dense and belted. Some openings at joints and belting planes. Permeabilities often 10E-2-10E-1 m/s.
4. Fissure lavas (tholeiites): In thin layers (2-20 m), often porous and with thick zones of scoria at the contacts of the layers. Permeabilities often 10E-2-10E-0 m/s.

On a broad regional basis widespread fissures influence the groundwater flow of an area. This "tectonic permeability" is comparable to a true permeability ranging between 10E-3-10E-1 m/s. Various methods can be used to estimate this "tectonic permeability" such as: comparison with other areas, local observations such as investigations of tidal effects, well tests and hydrological modelling (Ingimarsson, J. & Elíasson, J., 1980, Sigurdsson, F., 1984).

The permeability in the research area can be estimated from observations of the geology, the groundwater layer and the regional tectonic structure. N and NW from Eldvörp móberg can be expected in the groundwater layer, at least partially, resulting in permeabilities within the range 10E-3-10E-2 m/s. Towards NE from Stadarhverfi, the lava series probably have permeabilities as high as 10E-1-5 . 10E-1 m/s, possibly as far NE as 5-6 km. Similiar permeabilities may be expected between Mölvík and Raudhóll. Between Eldvörp and the coast in Stadarhverfi-Stadarberg, the groundwater layer is most likely in the Sandfellshaed lava, or other shield volcanoes, with permeabilities of 10E-1 m/s. There is some probability that th lava at the coast, and off it, some hundred metres out, is more massive and less permeable than elsewhere. Some tightening might also result from infillings through littoral and offshore sediments, especially from Stadarmalir to Arfadalsvik, where Sandfellshaed lava (D-6) reaches the farthest into the sea and the shore is sandy, as compared to the boulder walls and cliffs elsewhere.

In the young lavas almost no fissures can be seen, so the "tectonic permeability" must be estimated through comparison with better-known areas. Around Eldvörp and farther to NW, it is perhaps 10E-3-5. 10E-3 m/s. From there to the coast in Mölvík and Stadarberg, it is probably higher or near 10E-2 m/s. In Stadarhverfi proper and northeast from it, the "tectonic permeability" is probably still higher, or 5 . 10E-2 - 10E-1 m/s. The "tectonic permeability" causes some anisotropy in the permeability of the area, turning the groundwater flow everywhere towards the SW-NE direction. The structure of the lava layers results in the highest permeability along the horizontal bedding planes, thus causing a horizontal-vertical anisotropy. this is important in regard to the possible upwelling (coning) of seawater by excessive pumping.

3 GROUNDWATER

3.1 Freshwater layer

On the western Reykjanes peninsula, the fresh groundwater is floating on the seawater below, like an oil film on water. The bedrock is highly permeable in this region. The fresh groundwater therefore flows very easily towards the sea, preventing the fresh water lens from becoming thick. Centrally in this region, it is approximately 50 m thick. Measurements of the groundwater level in Tóftarkrókar, conducted for Hitaveita Sudurnesja (Sudurnes Regional Heating) in 1976-1978, indicate that the freshwater lens there has a thickness near 25 m or a little more. Temperature and resistivity logging in wells show that the lens has a thickness of perhaps 25 m, or somewhat less, at Lambagjá (SH-8), perhaps 15 m at Stadargjá (Sh-2) and somewhat less than 20 m at Húsatóftir (well 3A5). These thicknesses all refer to the thickness of a fresh water lens in a floating equilibrium with the heavier seawater below.

Not the whole fresh water lens is "fresh". For human consumptions, the maximal salinity in fresh water is set at 200-250 ppm Cl- in many national and international standards. In the centre of the western Reykjanes peninsula, the fresh water layer has a thickness of 25-35. Beneath it is a mixed layer, 15-25 m thick, with steadily increasing salinity downwards. Below it is pure seawater.

In Tóftakrókar and the fissure Badstofa the fresh water has reached this upper limit of salinity (200 ppm Cl-), but the thickness of the freshwater layer there is probably 20-25 m. Still closer to the coast, the "freshwater" layer is already saline (brackish), or up to 20% seawater. Still it appears as a definite layer above a mixed layer.

The groundwater finally flows out at the coast. It is in most places bordered by cliffs, rocks or boulders, where the outflow cannot be observed. Yet it can be estimated at a few places. Such an estimation is of course a very rough method. In Arfadalsvík, by Húsatóftir, the outflow is estimated as 0.1 l/s pr. m shore (l/s. m) but only 0.03 l/s.m at Stadarmalir. It is not known whether or how much fresh water flows into the sea below sea level.

In the Stadur area the groundwater is thought to originate, at least partially, in the area north of Eldvörp. This groundwater current is probably most significant in the western part of the area. A stronger current probably enters the area from the central parts of the region and from the area surrounding the geothermal field at Svartsengi. This current is regarded as dominant in the eastern part of the area, especially in the neighbourhood of Húsatóftir. Of course the groundwater flow in the Stadur area proper is increased through the precipitation falling in the area itself. The groundwater current down to Húsatóftir is thought to be notably stronger than the one to Stadur.

3.2 Well-logs, temperature and resistivity.

In the Stadur-area water is accessible in some places, in the most cases in open fissures, as well as in a number of boreholes, some of them having been drilled in connection with the present investigation (boreholes SH-1 - SH-8). These water places have been logged for temperature and electrical resistivity in the groundwater. The resistivity is measured as conductivity and converted to resistivity at 25°C. For various reasons, especially of instrumental nature, the accuracy og the absolute values of resistivity is somewhat uncertain, but in a relative sense they are seemingly accurate enough. The absolute values of the temperature may have an error as great as +/- 0,2°C, or even more in extreme cases, also of an instrumental nature. In a single profile, the relative error is thought to be less than +/- 0.1°C in most cases. The conductivity of the water depends on its chemical contents. It has in most cases a composition comparable to diluted sea water. Through comparison of chemical analysis and the resistivities it is possible to estimate the chloride content from the resistivity values, although only roughly.

In many profiles a clear layering in the groundwater can be recognised. Besides the distinction between a "freshwater layer" and a "mixed layer", there is some layering apparent in the freshwater. In some cases it appears in almost constant values of temperature and resistivity for a notable distance on the profile. This is thought to indicate a strong groundwater-flow in an aquifer as it often appears in connection with scoracious horizons. In other cases the values change gradually over some length of profile. This layering is regarded as an expression of the horizontal/vertical - anistropy in the permeability of the rocks, the horizontal component being much stronger.

Some of the resistivity- and temperature logs are shown in figs. 4 and 5. Names, letters and numbers refer to fig. 1. The most important parametres of the logs (thickness of principal layers, temperature, resistivity, estimated chloride content) are given in table 1.

The most northerly waterplace is borehole E-1, close to the crater row Eldvörp. It shows two distinct freshwater layers, both with a temperature of 8.8°C, the upper one about 8 m thick and having a resistivity of 34 ohmm. the lower one is at least 9 m thick and has a somewhat lower resistivity (27 ohmm), i.e. higher chemical content. This indicates a similiar chemical content as in the central parts of the region, i.e. 40-70 ppm Cl-1.

In the area of Tóftakrókar, 2 km NE from Lambagja, water has been found in three fissures. (It should be noted that the place names in this desolate area are somewhat uncertain). For the sake of convenience the fissure Badstofa by Húsatóftir is included in this area. One of the fissures ("Miðgjá", fissure T) has a water depth of 23 m. Sometimes a fall in resistivity has been observed at the bottom if it, together with a slight rise in temperature, indicating that the boundary between the freshwater layer and the mixed layer is at a depth of approximately 21-25 m. The temperature in the water in all fissures is 7-7 1/2°C and the chloride content near to or just above 200 ppm Cl-.

Two wells have been drilled on Stadarberg, SH-5 and SH-6. The "freshwater" in them probably has a chloride content of 1000 - 2000 ppm Cl-. The temperature is relatively high, about 7 1/2°C in SH-5 and 7 1/2 - 8 1/2°C in SH-6. This perhaps points to a warm groundwater current from the geothermal field in Eldvörp down to Stadarberg, probably with the axis west of SH-6.

West of Stadur, the temperature is generally decreasing towards the coast, while the salinity increases. With the exception of Lambagja/SH-8 the chloride content is most likely everywhere higher than 1000 ppm Cl- in the "freshwater" layer, reaching perhaps 3000 ppm Cl- in SH-3. In SH-8 by Lambagjá the seawater had a temperature of 8°C in the beginning of October. Unfortunately the casing in the borehole was damaged somewhat later preventing further logging. In SH-2 (by Stadargja) the seawater had a temperature of 7-7.5°C at the same time, but only near to 5.5°C at the beginning of December. This fall of temperature follows the probable temperature in the ocean of the coast, at least to some degree. The temperature of the ocean water has thus most likely a strong influence on the temperature of the sea water below Stadargja. Perhaps some transfer of water takes place, which would indicate, that the seawater below Stadargja is not stagnant, at least not totally.

According to the resistivity profiles there is a gradient of salinity in the water in the fissure Lambagja, the salinity increasing perhaps 100-120 ppm Cl- from the surface down to a depth of 9 m. This refers to natural conditions. During the pumping test, at the end of November, this gradient had increased to 500-600 ppm Cl- (estimated from resistivity), but was down to 200 ppm Cl- on the same day as the pumping test was finished (Dec. 7). The mean chloride content along this 9 m profile increased perhaps from 700 ppm Cl- to 900-1000 ppm Cl- and rapidly fell to 700-750 ppm after the end of the test.

From Húsatóftir eastwards to Grindavik the freshwater is warmer than at Stadur. In the well 3A5 the temperature is 10°C and the chloride content in the uppermost 10 m probably 500-1000 ppm Cl-. The seawater below has a temperature of 10 1/2°C, increasing with depth as far as known. It is not certain, whether it reaches the salinity of ocean water and its chemical composition is not known either. It is therefore possible that it was more or less influenced by a hot brine current from the geothermal field by Svartsengi, where the brine has a chloride content corresponding to 60-65% sea water. In any case that geothermal field must be regarded as the ultimate source of the higher temperatures at Husatoftir.

3.3 Water quality

The temperature of the groundwater is determined by two main factors: meteorological conditions, influencing the temperature of precipitative water percolating down to the groundwater, and geothermal influences, geothermal areas being widely present in this region. The chemical contents of the groundwater have their origin partly in the precipitation, above all as marine salt particles, partly in the reactions with the rocks and soils, partly in geothermal inflow and partly from mixing with seawater (Sigurdsson, F., 1977, 1984, Sigurdsson, F. & al., 1978).

In the northern part of the western Reykjanes peninsula, the temperature of the groundwater is 3-5°C. It increases towards the geothermal field at Svartsengi and is also high from there and down to the coast, often near or above 10°C. In Tóftakrókar and the Stadur area, the temperature is usually 7-7.5°C in the "freshwater" layer. In a single profile from a borehole (E-1) close to Eldvörp, the temperature was measured as just below 9°C. The temperature in the Stadur area is possibly influenced by geothermal fields higher upstream (Eldvörp).

The chemical contents are also lower in the northern part of the region. Expressed in (Cl-) they are only 20-30 ppm. The precipitation on that side of the peninsula has probably a lower salinity content, perhaps corresponding to 15-30 ppm Cl-, compared with the precipitation at the south side with perhaps 40-100 ppm Cl-.

Inhomogenities in the aquifers may cause some disturbances in the groundwater flow at the bottom of the groundwater layer, which, together with diffusion through the freshwater /seawater boundary, probable result in some mixing of seawater into the groundwater. At the south coast, the tidal effects can be traced some km inland. The groundwater layer rises and falls with them. Some seawater probably remains in pores and cavities in the rocks, thus adding salinity to the freshwater, in a manner comparable to pumping of seawater into the freshwater twice a day for long periods. This effect is probably proportionate to the height of the tidal rise, which is an exponential function of the distance from the coast. Each tidal pulse thus adds some salinity to the fresh water, the more so, the nearer to the coast it occurs. The number of pulses increases with time as the groundwater approaches the coast. This will not be dealt with closer here, but it should be mentioned that the chloride contents (in ppm Cl-) as a function of the tidal effect (in %) approximates a straight line on a log x lin scale for values from the strip of land from Toftarkrokar down to Stadarmalir, which is in a good accordance with the theory. In any case, the salinity of the "freshwater" increases strongly towards the coast. The "freshwater" layer often has a remarkably constant temperature and resistivity along the measured profile, while the temperature and the resistivity usually change steadily through the mixed layer, the resistivity increasing in accordance with increased salinity.

Generally speaking, the chemical content of the groundwater increases towards south in this region. In the central parts it corresponds to 40-70 ppm Cl-. Around the geothermal area at Svartsengi, and from there down to the south coast, it is higher than 100 ppm Cl-. In Tóftakrókar it is near to or above 200 ppm Cl-, and in Lambagjá it probably reaches 500-800 ppm Cl-. West of Stadur it is some thousand ppm Cl-. There it is no longer relevant to the criteria of "freshwater". The "freshwater" layer contains about 2,000 ppm Cl- or more. Still this layer is present as can be seen in the relatively small changes in temperature and salinity in it along a profile, as compared to the steady and strong changes in the mixed layer below. The "freshwater" layer seems to thin out rapidly close to the shore, yet it appears as a brackish coastal outflow by low tide. The salinity of this "freshwater" also seems to increase near the coast where no strong groundwater currents are present. At the same time, the temperature decreases.

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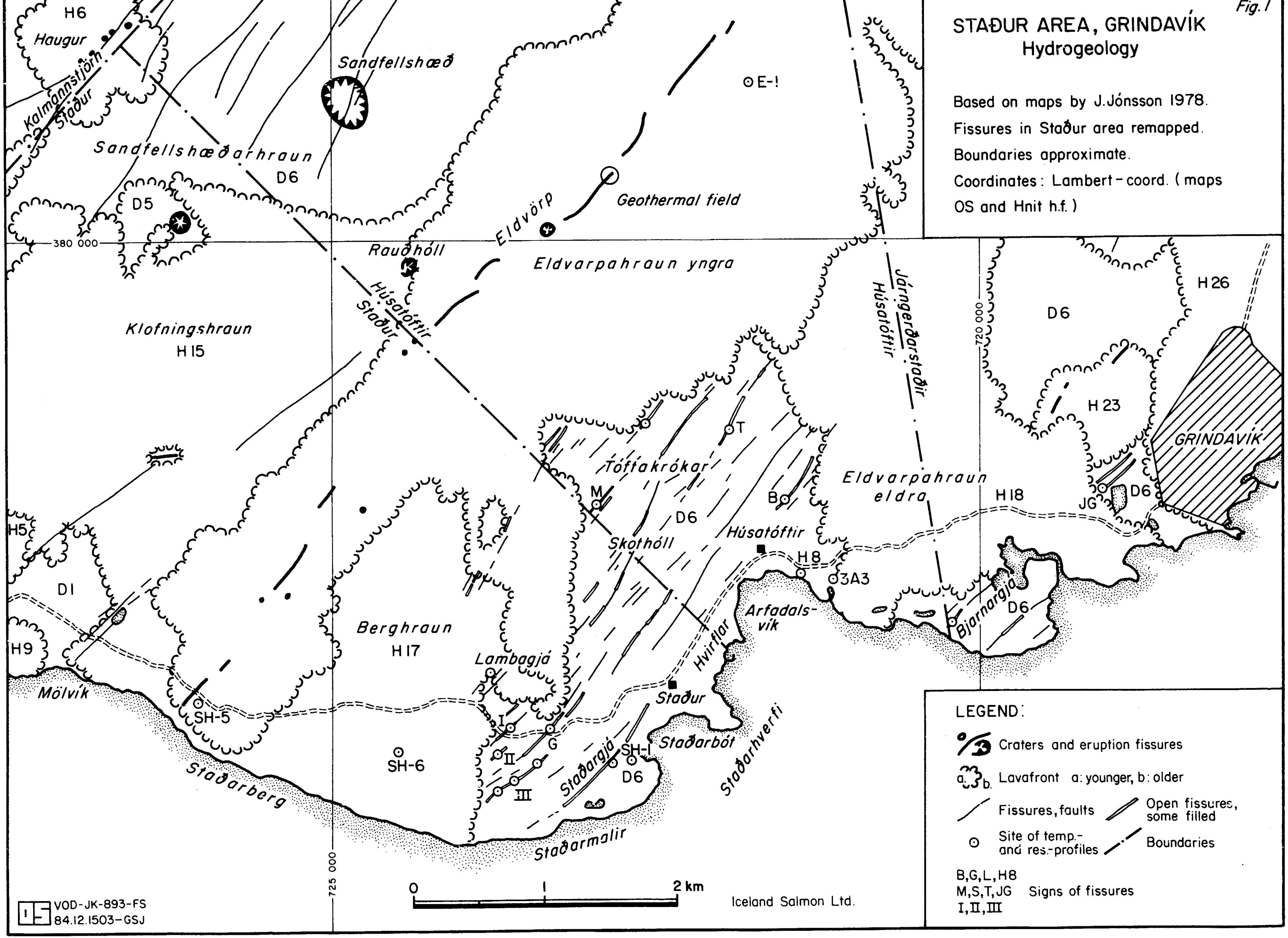
<u>Table 1</u>

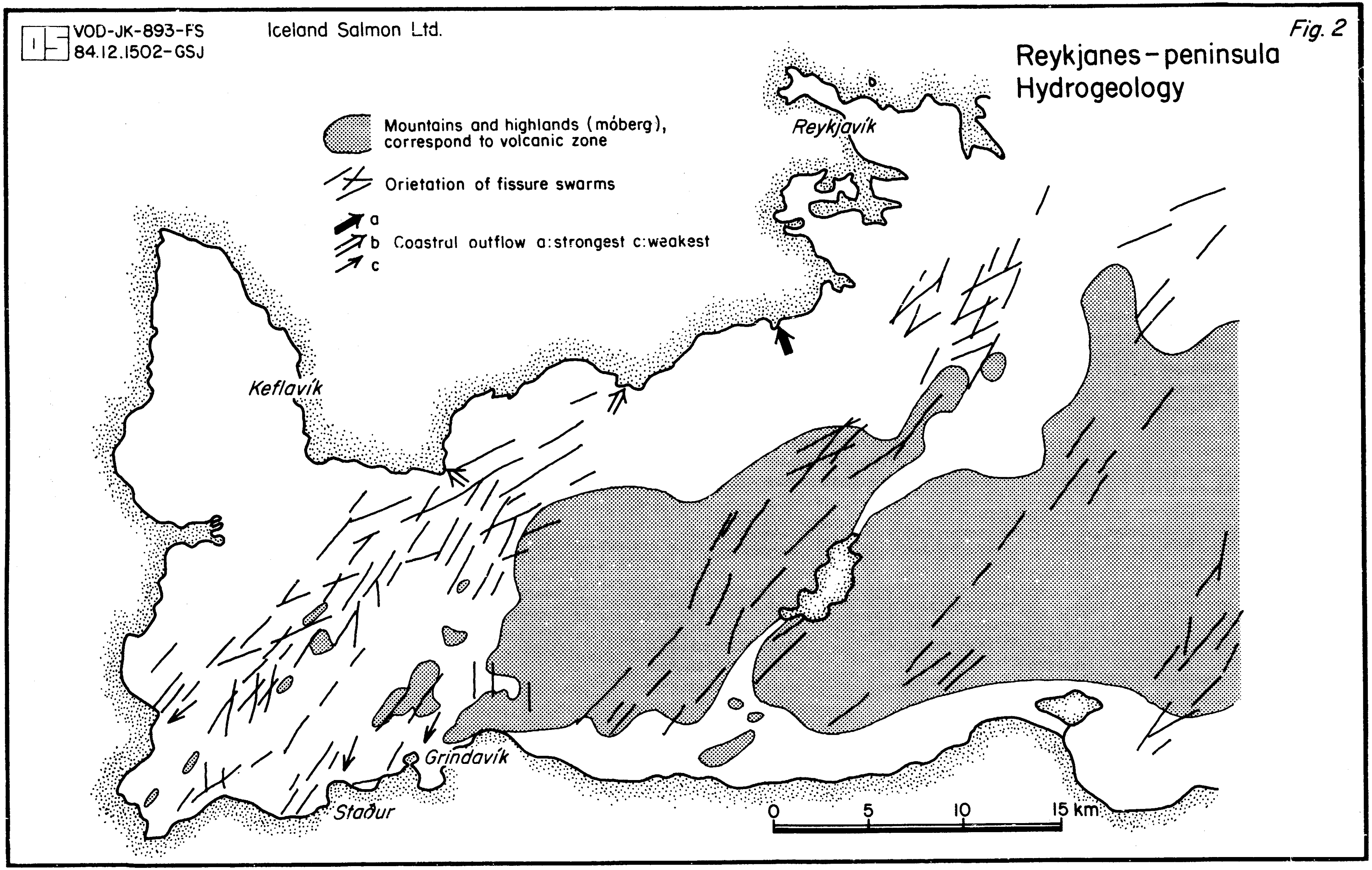
Stadur area and Grindavík.

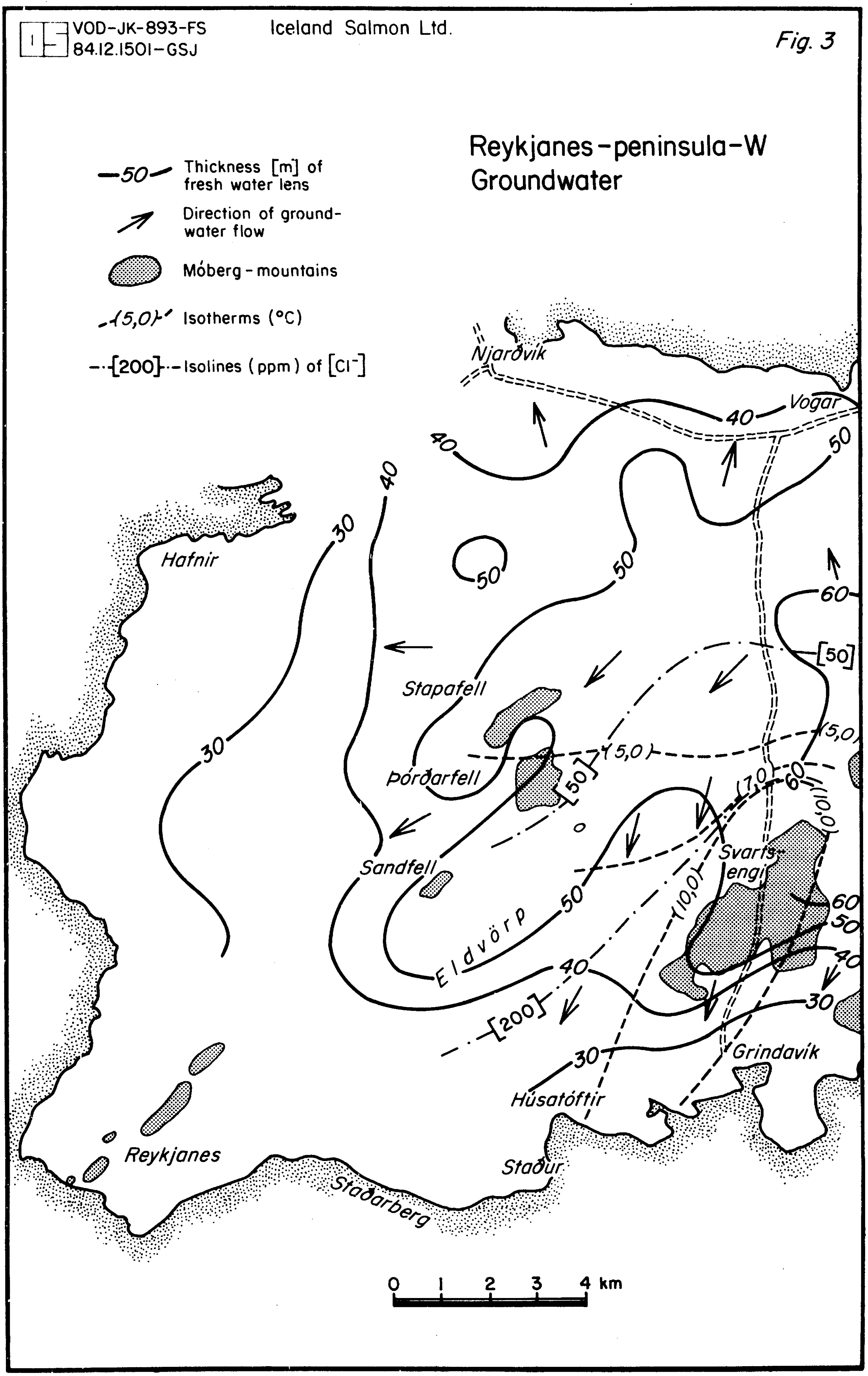
Temperature- and resistivity measurements.

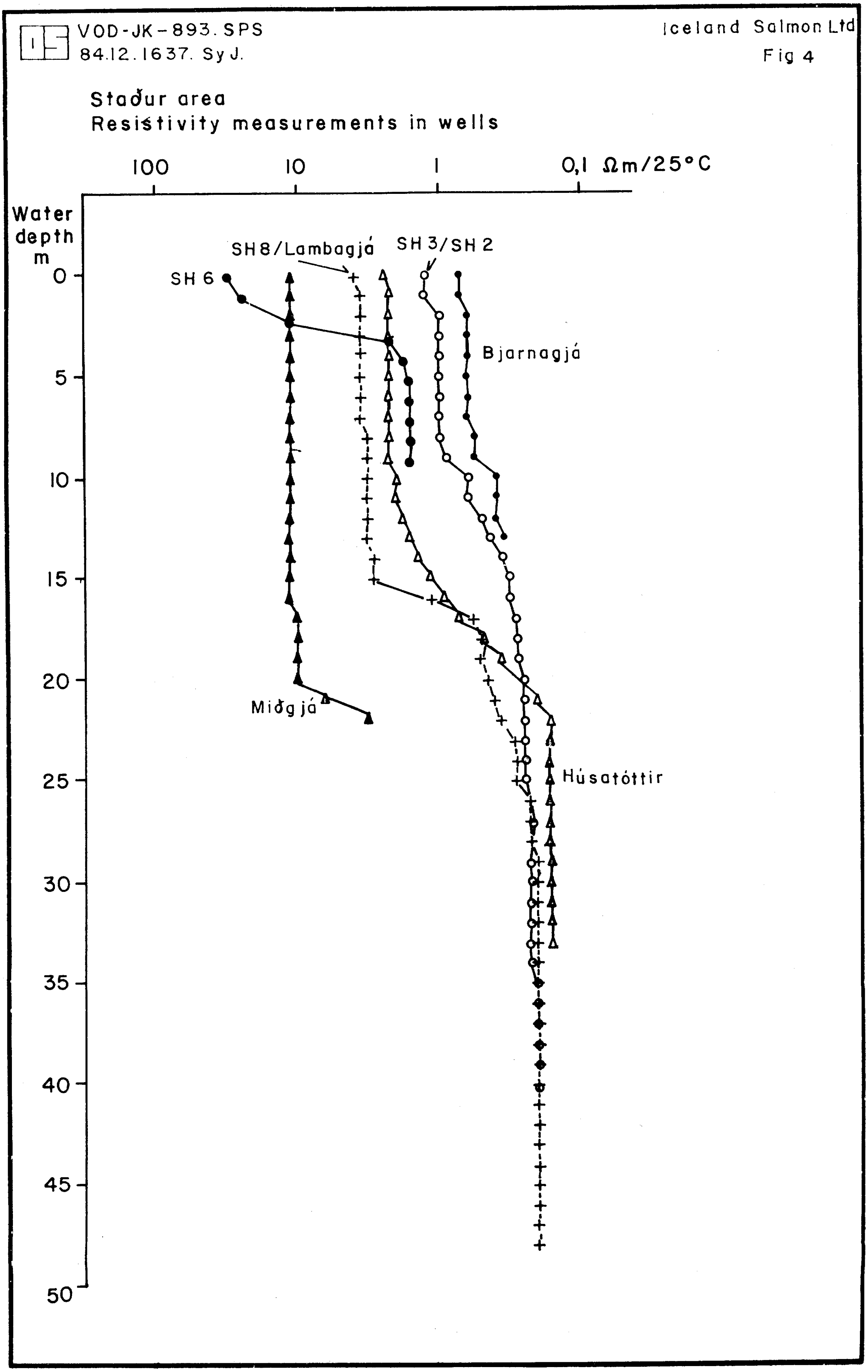
Location Borehole no.	"Freshwater" layer Thickness m	Temp. °C	Resist. Ωm	$[Cl^-]$,estim. ppm	Mixed layer Thickn. m	Temp. °C	Res.,min. Ωm	Sea water Temp. °C
Eldcörp, E-1	≥18	8.8	34-27	40-70			S.W: Seawater	
Tóftarkrókar, Fissure M (map)	≥ 5	7.0	7	≃ 200			1	
" " G "	≥ 5	7.0	7	≃ 200				
" " T "	22-23	7.4	7-9	150-200	≧ 1	7.6	2.5	
" " B "	≥11	7.4-7.8	7	≃ 200				
Stadur, Lambagjá/SH-8	17	7.0-7.3	2-3	600-800	9	7.2-8.0	S.W.	8.0-8.2
" SH-4, Fissure (I)	10	6.9	1.5-2	≃ 1.000	≥ 2	6.9-7.0	1	
" Graenagjá	≧ 2	6.9-7.0	≃ 1.5	1.000-1.500				
" Fissures S of road (II)	7	6.8	≃ 1.2	1.500-2.000				
" " " " " (III)	6	≥ 6.5	≃ 1	≃ 2.000	≥ 1	6.6	0.7	
" SH-3/SH-2	7	7.4-6.7	≤ 1	2.000-3.000	16	6.6-6.1	S.W.	6.9-7.6/5.6-5.3
" SH-1	3 ?	6.5	-	-	≥ 11?	6.6-6.7	0.25	
Stadarberg SH-5	10	7.5	≃ 1	≃ 2.000	≥ 3	7.6-7.8	0.5	
SH-6	≥ 9	8.2-8.4	1-2	≃ 1.500				
Húsatóftir, 3A5	16	10.0-10.2	1-3	500-2.000	9	10.3-10.5	S.W.	10.7
Járngerdarstadir Bjarnargjá	7	10.0	≃ 0.5	≃ 4.000	≥ 10	9.8-9.2	0.25	
" Fissure (JG)	≥ 5	9.3	≃ 1	≃ 2.000				

Fig. 1


STAÐUR AREA, GRINDAVÍK
Hydrogeology
Based on maps by J. Jónsson 1978.
Fissures in Staður area remapped.
Boundaries approximate.
Coordinates: Lambert-coord. (maps OS and Hnit h.f.)
LEGEND:
Craters and eruption fissures
Lavafront a: younger, b: older
Fissures, faults
Open fissures, some filled
Site of temp.- and res.-profiles
Boundaries
B,G,L,H8 M,S,T,JG I,II,III Signs of fissures
H6
Haugur
Kalmannstjörn
Staður
Sandfellshæð
Sandfellshæðarhraun
D6
D5
380 000
Geothermal field
E-1
Eldvörp
Rauðhóll
Eldvarpahraun yngra
Húsatóftir
Staður
Klofningshraun
H15
Járngerðarstaðir
Húsatóftir
720 000
H26
D6
H23
GRINDAVÍK
JG
D6
Eldvarpahraun eldra
H18
Tóftakrókar
T
M
B
D6
Skothóll
Húsatóftir
H8
3A3
Arfadalsvík
Bjarnargjá
D6
H5
D1
H9
Mölvík
SH-5
Berghraun
H17
Lambagjá
I
II
III
G
SH-6
Staðarberg
Staðargjá
SH-1
D6
Staðarbót
Staður
Hvirflar
Staðarhverfi
Staðarmalir
725 000
0
1
2 km
Iceland Salmon Ltd.
VOD-JK-893-FS
84.12.1503-GSJ


VOD-JK-893-FS
84.12.1502-GSJ
Iceland Salmon Ltd.
Reykjanes – peninsula
Hydrogeology
Mountains and highlands (móberg), correspond to volcanic zone
Orietation of fissure swarms
a
b Coastrul outflow a:strongest c:weakest
c
Reykjavík
Keflavík
Grindavík
Staður
0
5
10
15 km
Fig. 2

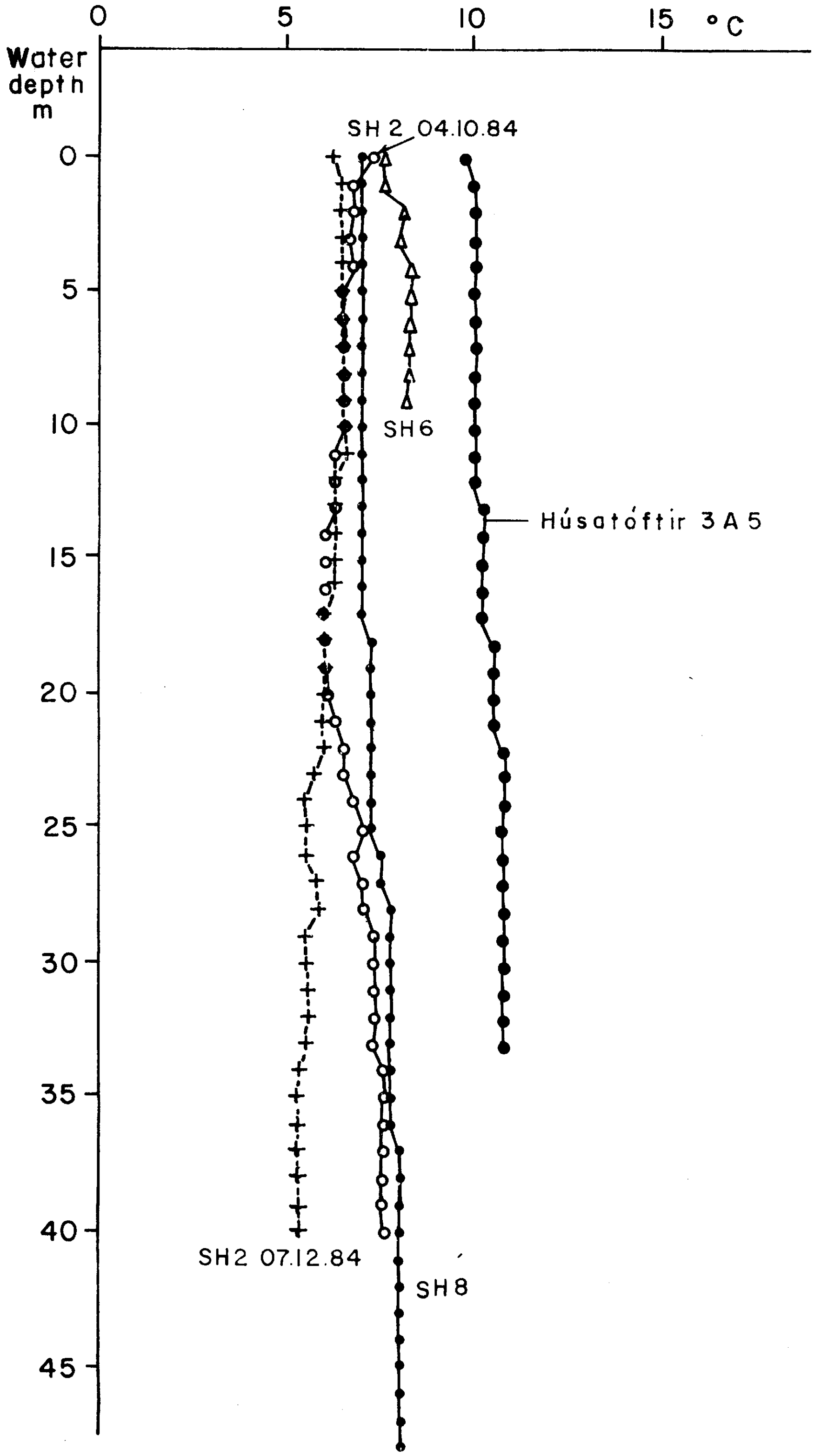

VOD-JK-893-FS
84.12.1501-GSJ
Iceland Salmon Ltd.
Fig. 3
Reykjanes-peninsula-W
Groundwater
Thickness [m] of fresh water lens
Direction of groundwater flow
Móberg-mountains
Isotherms (°C)
Isolines (ppm) of [Cl⁻]
Njarðvík
Vogar
Hafnir
Stapafell
Þórðarfell
Sandfell
Eldvörp
Svartsengi
Grindavík
Húsatóftir
Reykjanes
Staður
Staðarberg
0 1 2 3 4 km


VOD-JK-893. SPS
84.12.1637. SyJ.
Iceland Salmon Ltd
Fig 4
Staður area
Resistivity measurements in wells
100
10
1
0,1 Ωm/25°C
Water depth m
0
5
10
15
20
25
30
35
40
45
50
SH 6
SH8/Lambagjá
SH 3/SH 2
Bjarnagjá
Miðgjá
Húsatóttir

VOD-JK-893.SPS
84.12.1637. SyJ.

Iceland Salmon Ltd
Fig. 5

Staður area
Temperature measurements in wells



PART II

HYDROLOGICAL INVESTIGATIONS

Vatnaskil Consulting Engineers

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LIST OF TABLES

LIST OF FIGURES

LIST OF DRAWINGS (in separate cover)

1 TIDAL RESPONSE

Tidal response has been recorded in all the wells and fissures in the area, see location map (drawing no 8419-01). An example of the response is shown on figs. 1-9. Amplitude ratio and timelag is given in table 1. As can be seen from the table and figure 10 the amplitude ratio decreases with increasing distance from the shore and timelag increases as expected. The diffusivity, T/S, is shown in the table estimated both from the amplitude ratio and the timelag. The diffusivity is small at the coast indicating smaller permeability than in the Lambagjá area.

Measured groundwater level at Staður has been transformed corresponding to the mean level for the last six years by using continuous measurements of the groundwater level in Lágar area at Svartsengi. The results are shown in table 2. The transmissivity (T) is shown in the table calculated from the diffusivity in table 1 for two different porosities (S). By using the mean groundwater level to estimate the thickness of the freshwater lens the permeability is calculated for the different wells as shown in table 2. The permeability is apparantly lowest at the coast. The permeabilities are on the whole very high the lowest being almost the same as for fine gravel.

TABLE 1 Results from tidal response analysis

Observation well	Amplitude ratio %	Timelag hours	T/S from amplitude ratio m^2/s	T/S from time lag m^2/s
SH-1	63.1	1.32	21	10
SH-2	58.9	0.95	33	39
SH-3	50.6	1.43	20	17
SH-5	24.7	2.67	2	2
SH-6	37.5	1.65	19	25
Grænabergsgjá	40.8	1.90	107	91
SH-4	37.5	2.08	98	83
SH-7	29.2	2.03	85	120
Lambagjá	30.8	2.28	94	95

TABLE 2 Estimated permeability

Observation well	Transmissivity m^2/s porosity 1%	porosity 10%	Mean groundwater level m a.s.l.	Permeability porosity 1% m/s		porosity 10% m/s
SH-1	0.16	1.6	0.41	0.01	-	0,1
SH-2	0.36	3.6	0.49	0.02	-	0.2
SH-3	0.19	1.9	0.43	0.01	-	0.1
SH-5	0.02	0.2	0.53	0.001	-	0.01
SH-6	0.22	2.2	0.46	0.01	-	0.1
Grænabergs-gjá	0.99	9.9	0.45	0.06	-	0.6
SH-4	0.91	9.1	0.39	0.06	-	0.6
SH-7	1.03	10.3	0.49	0.05	-	0.5
Lambagjá	0.95	9.5	0.49	0.05	-	0.5

2 THICKNESS OF FRESHWATER LAYER

An example of the results from the the salinity and temperature logs is shown on figs. 11 and 12 where the calculated density is given. The density profile on fig. 12 is in SH-8 near Lambagjá and the other one is in SH-2 at the coast. As can be seen there is a relatively sharp interface in the Lambagjá area whereas at the coast there is a more diffused profile and of course higher salinity. The groundwater flow model used in the following assumes a sharp interface. Thus it is just in the immediate vicinity of the coast where that assumption breaks down.

The equivalent thickness of the freshwater lens in SH-8 is 22 m and 17 m in SH-2. As the uppermost part of SH-2 is cased off the results of the logging of SH-3 is used instead to estimate the thickness of the freshwater lens at the coast.

Logging results in Lambagjá before the pumping test show that there is a salinity gradient in the fissure as could be expected. The salinity of the pumped water therefore corresponds most likely to the salinity at some depth in Lambagjá.

3 EVALUTATION OF METEOROLOGICAL DATA

Because of the limited storage capacity of the field, it is important to analyse the effect of extreme drought on the waterbalance. In that respect it is important to see if the thickness of the freshwater lens is constant or if the interface takes part in the rapid fluctuations of the water table. As a first estimate of the stability of the interface, resistivity logs from well HSK-11(see location map, drawing 8419-01), are used for the past six years. According to the resistivity profile the thickness of the freshwater lens is calculated and shown on fig. 12 for the period 1978-1982. The average thickness of the lens is 50.1 m and the standard deviation is 1.0 m. By using measurements within the same month to estimate the standard deviation of each measurement a value of 0.95 m is obtained. Because there is a very little difference between the standard deviations there is no reason to believe that the interface has moved during the past six years. Before final recommendations can be submitted it is necessary to verify this result by timedependent calculations of the groundwater level.

4 HYDROLOGICAL EVALUATION-GROUNDWATER MODELLING

The basis for the groundwater modelling is the hydrogeological map in the report prepared for the Suðurnes Regional Heating "SVARTSENGI I. Grunnvatnsrannsóknir vegna ferskvatnsöflunar fyrir varmaorkuver", Orkustofnun 1980. In cooperation with Mr. Freysteinn Sigurðsson, geologist, the original hydrogeological map has been revised at the Staður area. The main difference from the original map is the more tighter formations at the coast. This was confirmed by the results of the tidal response calculations and permeability estimates. The permeability in the model is estimated by matching the model calculations with the mean groundwater level given in table 2. The results are listed in table 3 where the well numbers are used for reference.

The results agree reasonably well for porosity around 5%. The result of these calculations is shown on drawing 8419-02. The following four cases have been calculated:

1) Pumping of 100 l/s from Lambagjá
2) Pumping of 350 l/s from Lambagjá
3) Pumping of 700 l/s from Lambagjá
4) Pumping of 350 l/s from Lambagjá and 150 l/s from Húsatóftir area.

The results are shown on drawings 8419-03 - 8419-06.

TABLE 3 Permeability estimates

Observation well	Permeability from tidal response porosity 1%		Permeability from tidal response porosity 10%	Permeability from model calculations m/s
SH-1	0.01	-	0.1	0.05
SH-2	0.02	-	0.2	0.05
SH-3	0.01	-	0.1	0.05
SH-5	0.001	-	0.01	0.005
SH-6	0.01	-	0.1	0.02
Grænabergsgjá	0.06	-	0.6	0.32
SH-4	0.06	-	0.6	0.32
SH-7	0.05	-	0.5	0.32
Lambagjá	0.05	-	0.5	0.32

The maximum regional drawdown should be less than 6 cm to ensure that no significant changes in the salinity occur. The following two conclusions can be drawn for the prefeasibility study.

1) 350 l/s can be pumped from the area without danger of seawater intrusion (upconing).

2) Pumping of 150 l/s at Húsatóftir has very small effect on the groundwater level at the Staður area.

The calculated groundwater outflow at the coast is 570 l/s at Húsatóftir and 480 l/s at Staður.

5 WELL TESTING OF LAMBAGJÁ

The testing of Lambagjá was conducted in the period from November 24 to December 7 1984. Due to great variation of the watertable from tides and infiltration it was very difficult to analyse the results although the pumping test was conducted at either high or low tide. Preliminary results of the pumping test show about 1 cm drawdown in the fissure for 150 l/s pumping rate. The expected drawdown calculated by using the permeability from table 3 is approximately 1.5 cm. Further calculation of the pumping test data will be given in the final report.

The available chloride analysis are given in table 4. The temperature of the pumped water was fairly constant about 7^{o} C. The tidal fluctuations in Lambagjá during the testing period are given on fig. 14. The chloride content is also shown on the figure. Figure 15 shows the groundwater elevation in Lambagjá versus chloride content in ppm. For higher tides and pumping rates the chloride content will exceed 1400 ppm. In order to decrease this entrainment process due to the pumping it would be wise to partly fill the fissure with gravel. The undisturbed chloride content decreases linearly with the tidal amplitude ratio. Tidal amplitude ratio of 15% corresponds to 200 ppm undisturbed chloride content. According to fig. 10 this ratio is reached at a distance of 2300 m from the coast.

TABLE 4 Chloride content of pumped water in ppm.

Date	Time	Cloride content ppm	Salinity o/oo
84.11.24	15.05	964.8	1.8
84.11.26	10.30	1165.8	2.0
84.11.26	11.30	1234.0	2.3
84.11.26	14.08	1113.3	2.1
84.11.26	14.35	1068.2	2.0
84.11.26	17.35	1039.5	1.9
84.11.26	22.09	1246.7	2.3
84.11.27	10.55	1324.9	2.4
84.11.27	17.00	1040.7	2.1
84.11.28	13.45	1142.0	2.2
84.11.28	22.35	1031.6	2.1
84.11.29	12.00	1130.6	2.1
84.11.29	23.00	918.4	1.9
84.11.30	13.15	1007.3	1.8
84.11.30	15.00	984.5	1.8
84.11.30	17.00	874.4	1.7
84.12.01	00.50	874.0	1.8
84.12.01	12.00	829.5	1.7
84.12.02	00.05	790.6	1.7
84.12.02	12.30	793.2	1.7
84.12.03	13.06	813.3	1.7

6 SEAWATER INVESTIGATIONS

In the investigation plan for the seawater at Staður it was proposed to clean the fissure "Staðargjáin" to allow sampling of the water, tidal response measurements and possibly pump testing. One of the main objectives was to determine the permeability in the area. The permeability at the coast has now been determined approximately by tidal measurements and groundwater model calculations. The results are given in the following table for the available observation wells.

TABLE 5 Estimated permeability and mean groundwater level

Observation well	Mean groundwater level	Permeability from tidal response			Permeability from ground-water model
		porosity		porosity	
	m a.s.l.	1%	m/s	10%	m/s
SH-1	0.41	0.01	-	0.1	0.05
SH-2	0.49	0.02	-	0.2	0.05
SH-3	0.43	0.01	-	0.1	0.05
SH-5	0.53	0.001	-	0.01	0.005
SH-6	0.46	0.01	-	0.1	0.02

The results agree reasonably well . The difference in permeability in SH-2 and SH-3 is possibly due to the smaller depth of SH-3. These estimates are not very accurate and a more reliable method to estimate the permeability is necessary in order to calculate the capacity of the area. It is therefore recommended to proceed with our original plan, and place a pump in the fissure for establishing the quality of the seawater and estimate the yield of the fissure. The results of these rather inexpensive tests should be used to determine whether it is necessary to perform more expensive pumping tests in deep 24" diameter wells.

The pumping tests should be performed at low tide in order to avoid direct intrusion of the seawater.

To ensure that the salinity of the pumped water is greater than 10 o/oo just about 150 l/s must be taken from each site. With the estimated permeability of 0.05 m/s at least 2-3 m^3/s of saline water can be pumped from Staðargjá.

7 RESULTS

Results of the prefeasibility study can be summarised as follows:

1) Because of anisotropy in the Lambagjá area the permeability is greatest in SW-NE direction and has the value 0.32 m/s, which is very high but not unexpected for scoriaceous fractured lavas in Iceland. The permeability at the coast is 0.05 m/s, which is also high and corresponds to the permeability of fine gravel.

2) The equivalent thickness of the freshwater lens in the Lambagjá area is 22 m and 17 m in the vicinity of Staðargjá. For comparison the freshwater lens is 50 m thick in the Lágar area. Maximum permissible drawdown in Lambagjá is 6 cm. Without danger of seawater intrusion (upconing) 350 l/s can be pumped from the fissure. The chloride content of the pumped water could exceed 1400 ppm. At a distance of 1.5 km north-east from Lambagjá the salinity of the water can be expected to correspond to approximately 200 ppm chloride.

3) To ensure that the salinity of the pumped water at the coast is greater than 10 o/oo about 150 l/s must be taken from each pumping site. With the estimated permeability of 0.05 m/s at least 2-3 m^3/s of saline water can be pumped from Staðargjá. The permeability at the coast must be determined by pumping tests before the seawater yield can be finally estimated.

VERKFRÆÐISTOFAN VATNASKIL V 8419 - 07
84.11.01. SLH/RS

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ICELAND SALMON LTD

TIDAL RESPONSE IN WELL SH-1
12.- 13. OCTOBER 1984

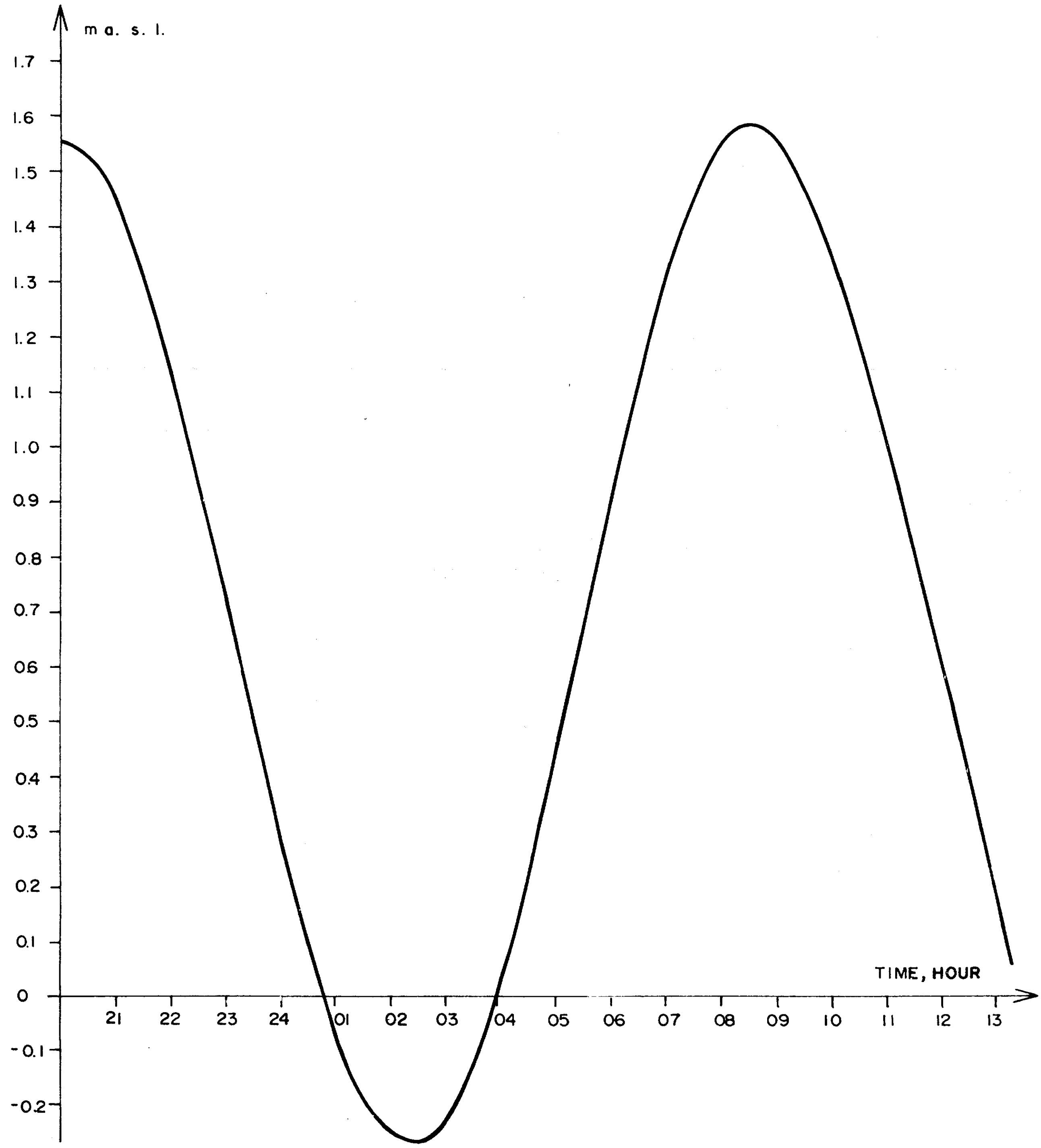

FIG. 1

VERKFRÆDISTOFAN VATNASKIL V 8419 - 08
84. 11. 01. SLH / RS
ORKUSTOFNUN

ICELAND SALMON LTD.

TIDAL RESPONSE IN WELL SH-2
20. OCTOBER 1984

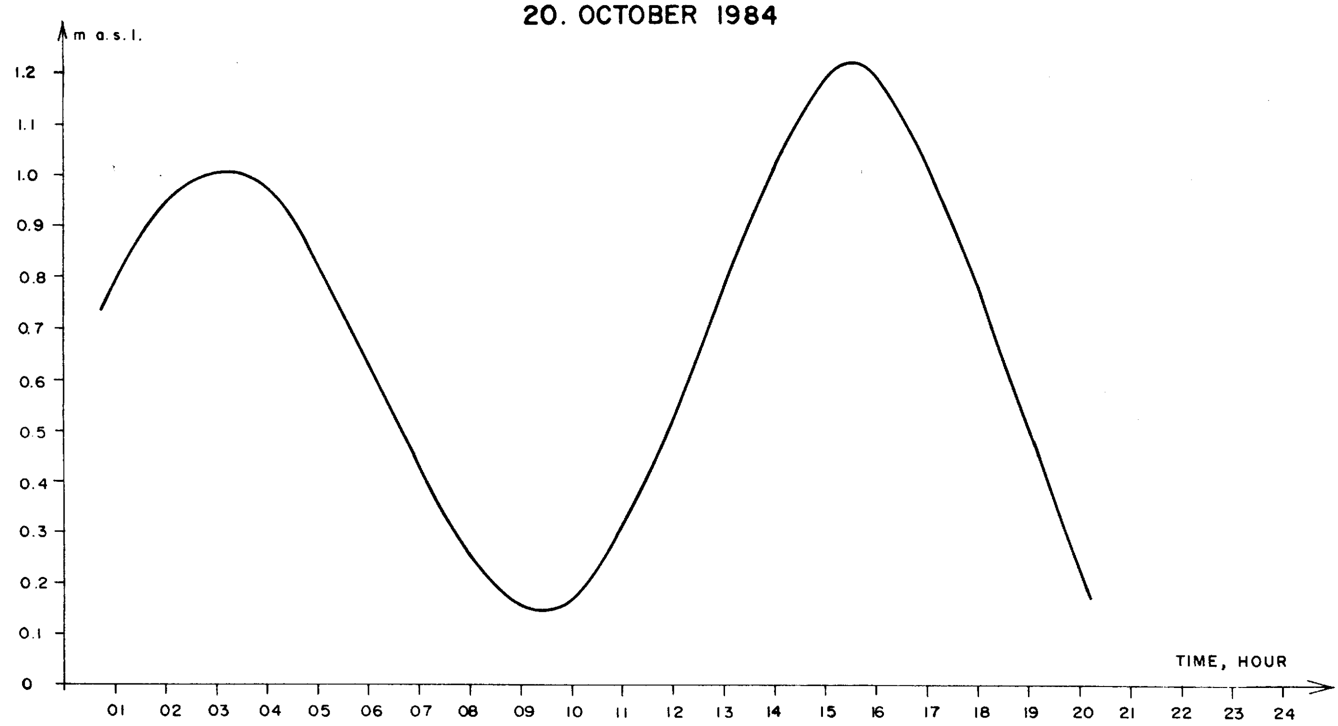

FIG. 2

VERKFRÆDISTOFAN VATNASKIL V 8419 - 09
84. 10. 31. SLH / RS
ORKUSTOFNUN

ICELAND SALMON LTD.

TIDAL RESPONSE IN WELL SH-3
16.-17. OCTOBER 1984

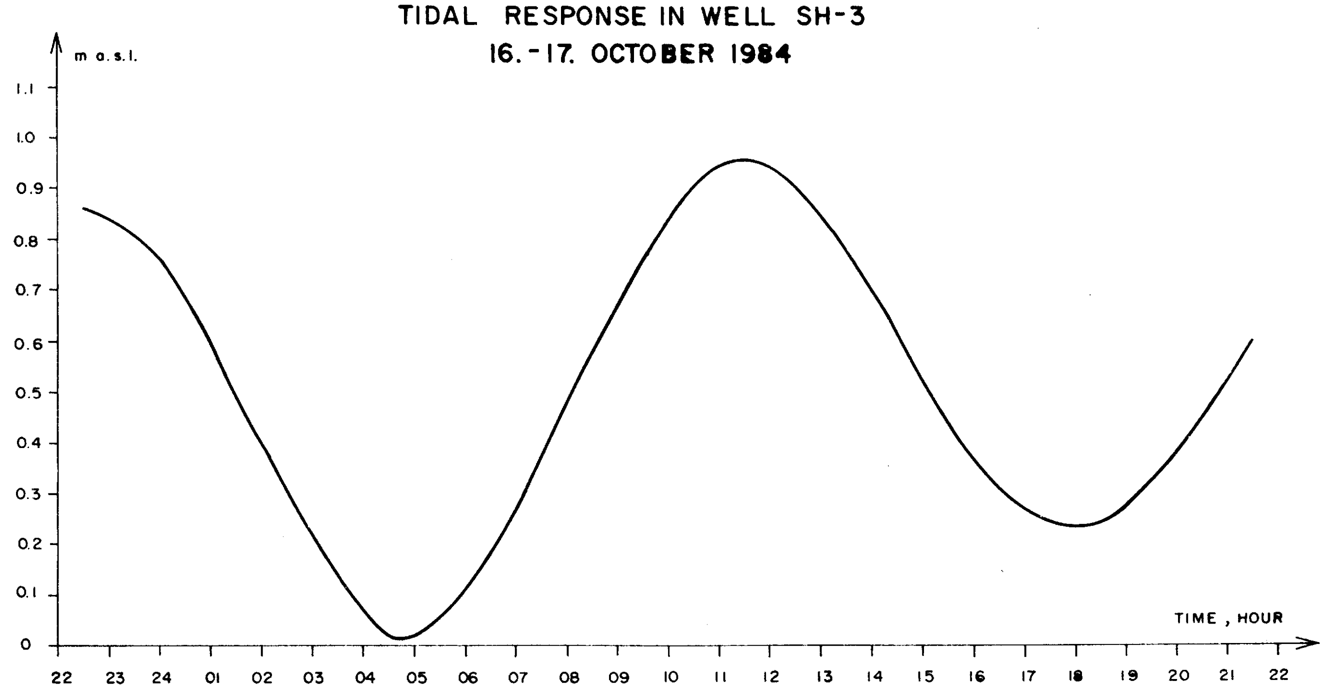

FIG. 3

VERKFRÆÐISTOFAN VATNASKIL V 8419 - 10
84.10.29. SLH/RS

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ICELAND SALMON LTD.

TIDAL RESPONSE IN WELL SH-5
28.- 29. SEPTEMBER 1984

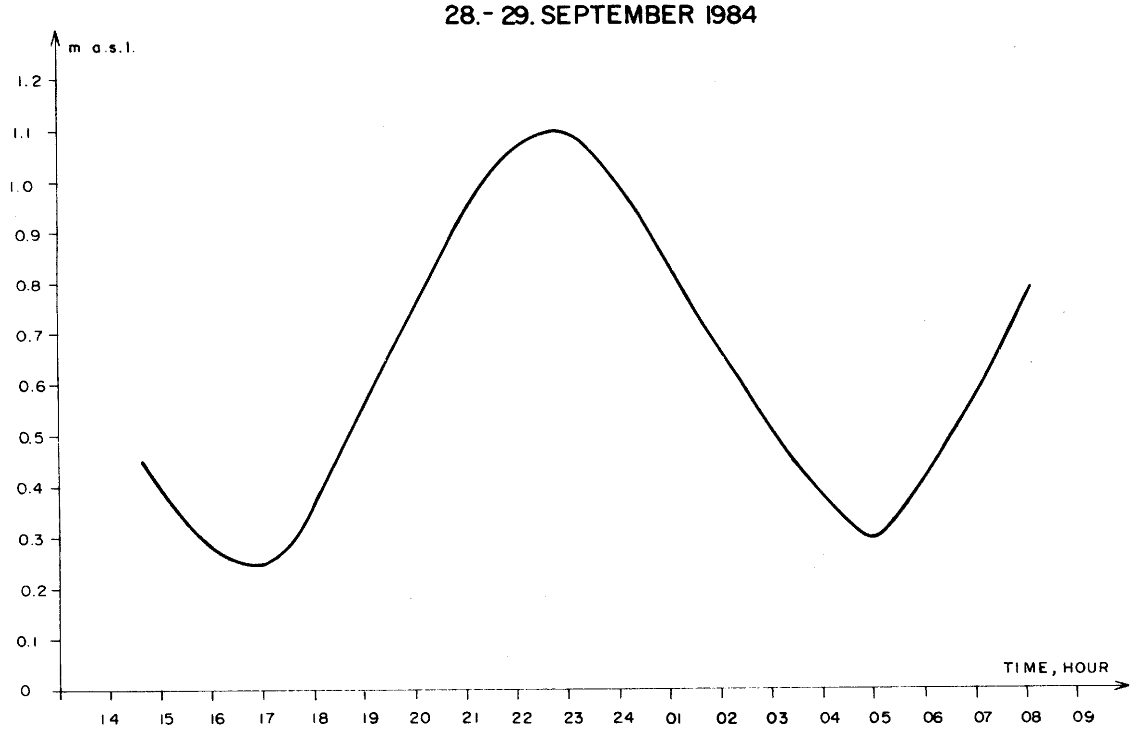

FIG. 4

VERKFRÆÐISTOFAN VATNASKIL V 8419 - 11
84.10.29. SLH/RS

ORKUSTOFNUN

ICELAND SALMON LTD.

TIDAL RESPONSE IN WELL SH-6
30. SEPT. - 1. OCT. 1984

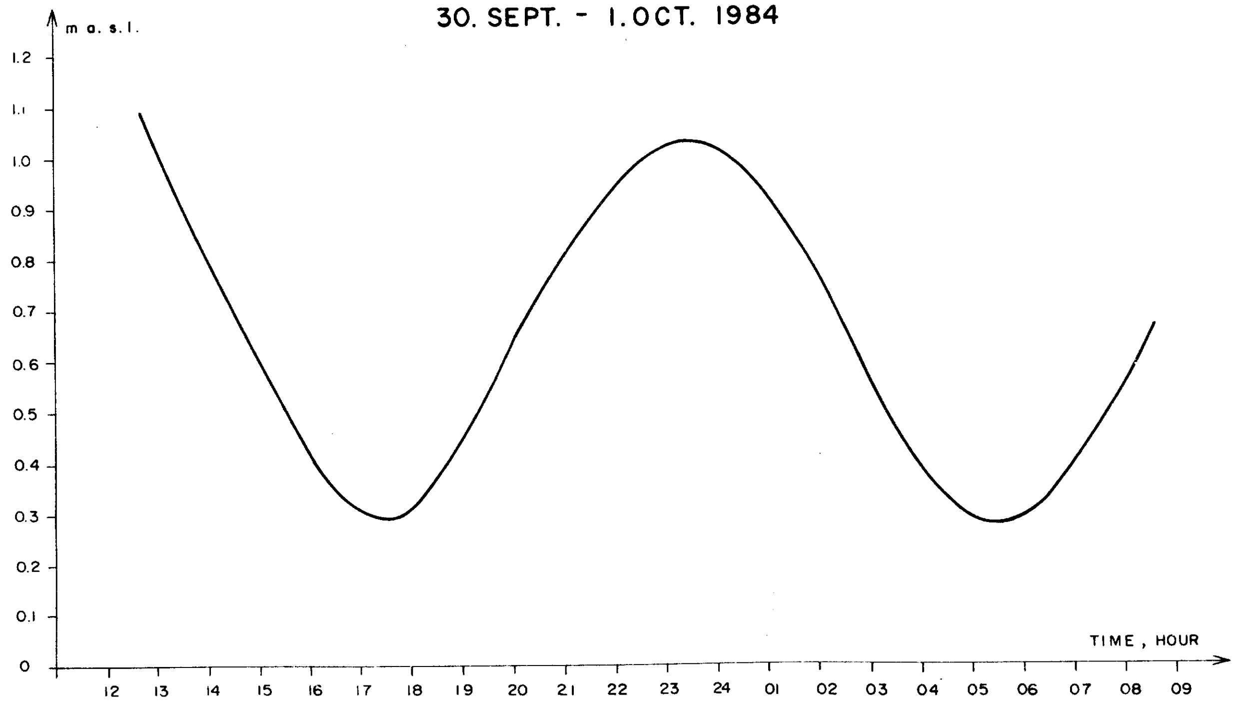

FIG. 5

VERKFRÆDISTOFAN VATNASKIL V 8419 - 12
84.12.11. SLH / RS

ICELAND SALMON LTD.

ORKUSTOFNUN

TIDAL RESPONSE IN WELL SH-4
8.- 9. OCTOBER 1984

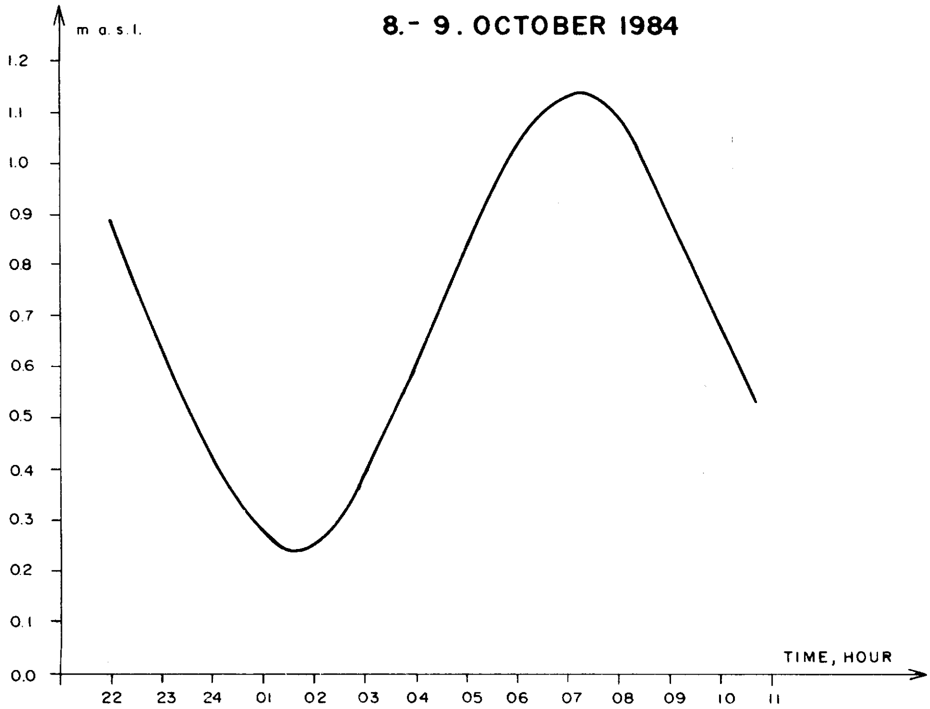

FIG. 6

VERKFRÆDISTOFAN VATNASKIL V 8419 - 13
84.12.11. SLH / RS

ICELAND SALMON LTD.

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TIDAL RESPONSE IN GRÆNABERGSGJÁ

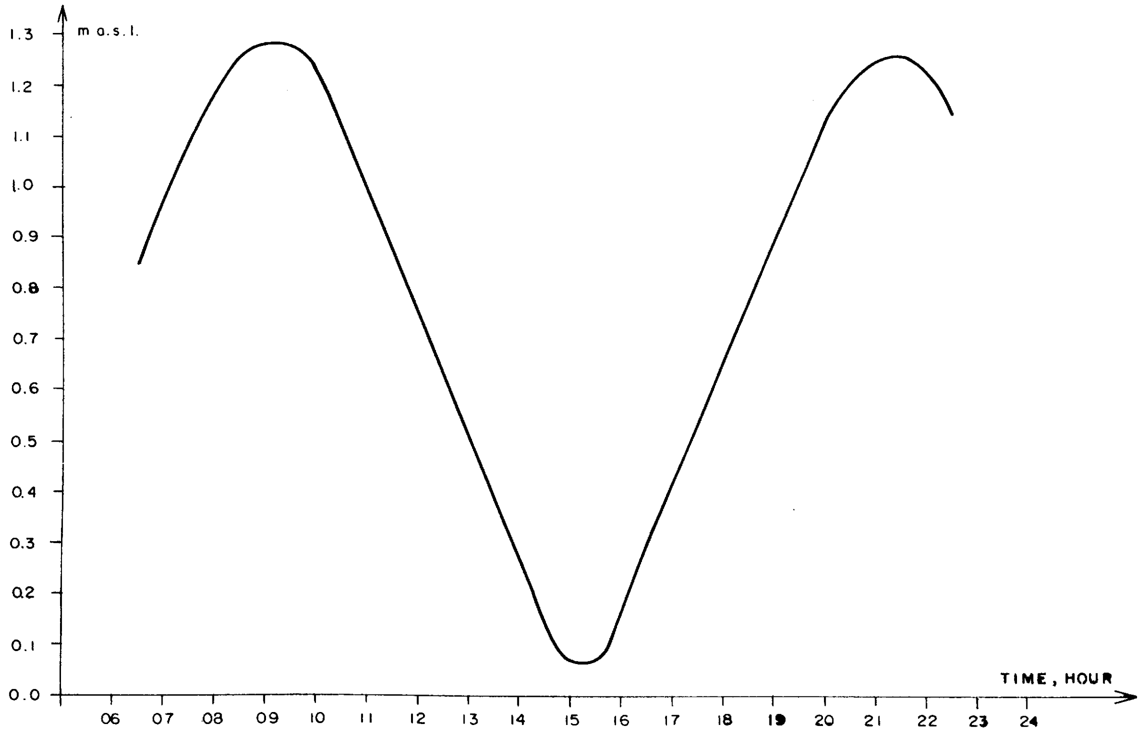

FIG. 7

VERKFRÆDISTOFAN VATNASKIL V 8419 - 14
84.10.29. SLH / RS

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ICELAND SALMON LTD.

TIDAL RESPONSE IN WELL SH-7
28.- 29. SEPTEMBER 1984

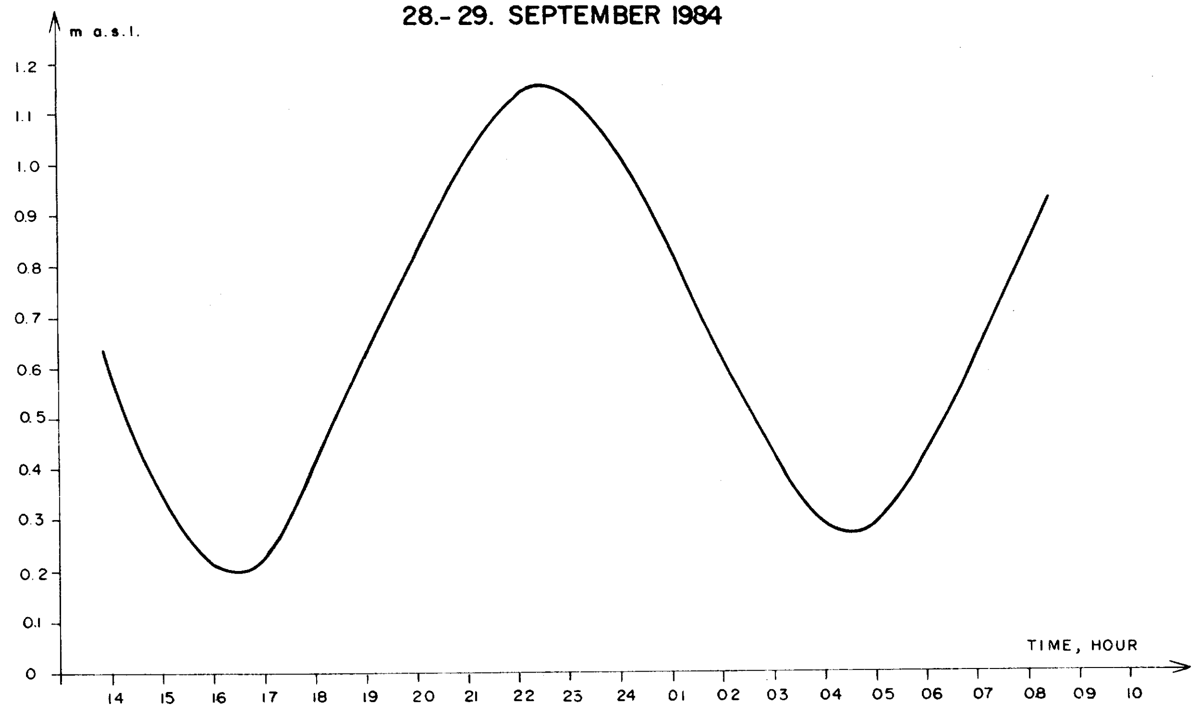

FIG. 8

VERKFRÆDISTOFAN VATNASKIL V 8419 - 15
84.12.11. SLH/RS

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ICELAND SALMON LTD.

TIDAL RESPONSE IN LAMBAGJÁ

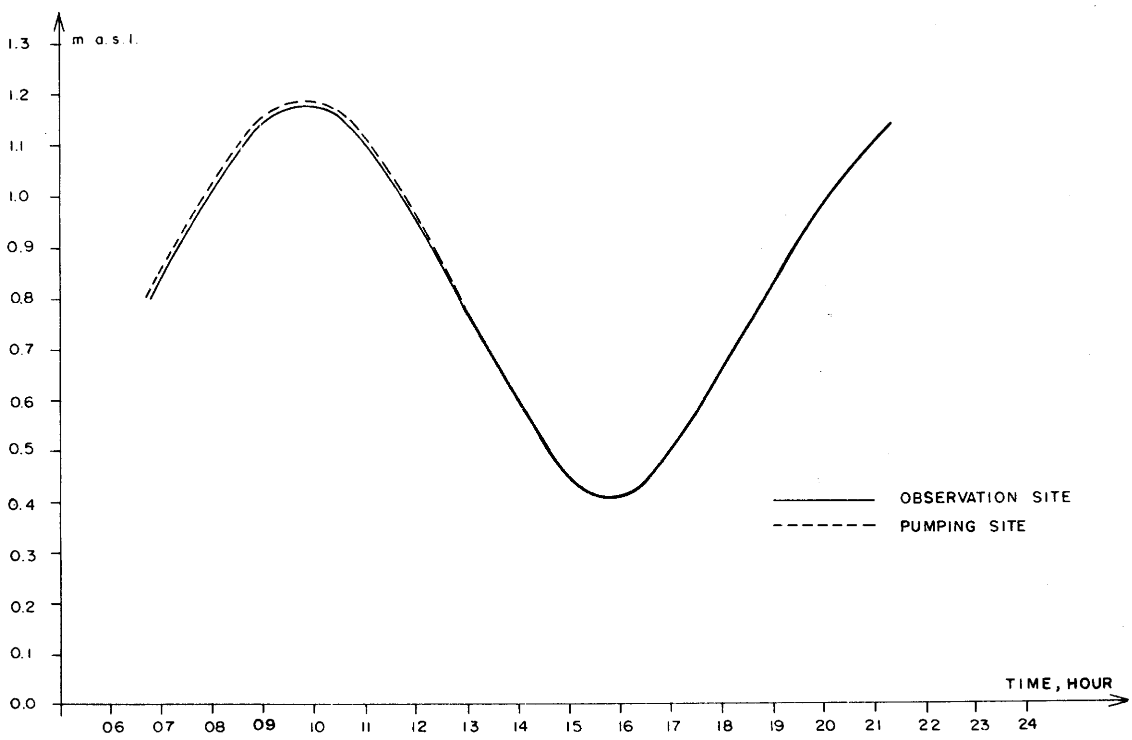

FIG. 9

VERKFRÆDISTOFAN VATNASKIL V 8419-19
84.12.14. SLH/RS

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ICELAND SALMON LTD.

DECREASING TIDAL AMPLITUDE FROM THE COAST

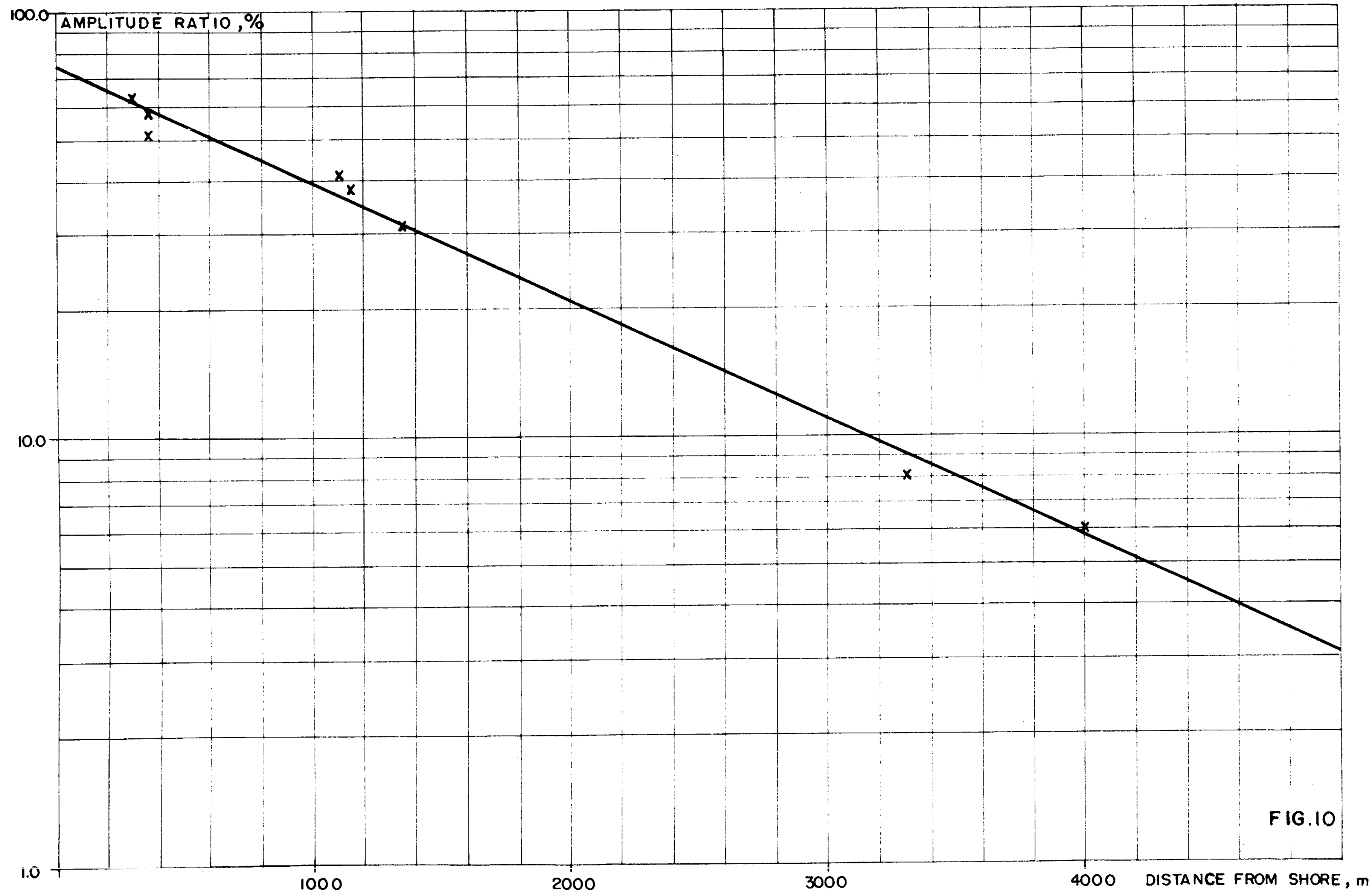

FIG.10

VERKFRÆÐISTOFAN VATNASKIL V 8419 - 16
84.12.10. SPK / RS

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ICELAND SALMON LTD

DENSITY PROFILE IN WELL SH-2

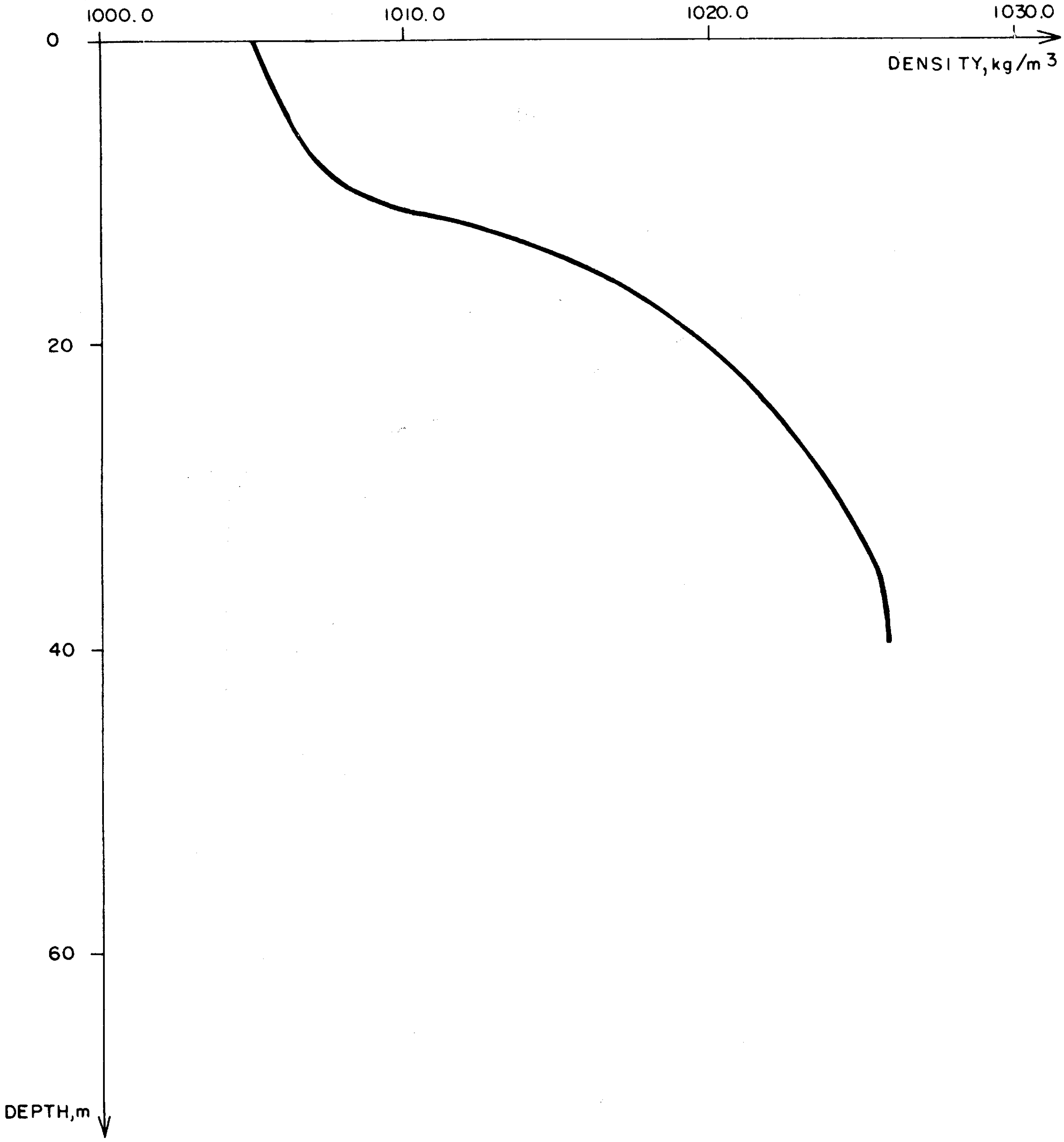

FIG. 11

VERKFRÆDISTOFAN VATNASKIL V 8419 - 17
84.12.10 SPK/RS

ICELAND SALMON LTD

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DENSITY PROFILE IN WELL SH-8

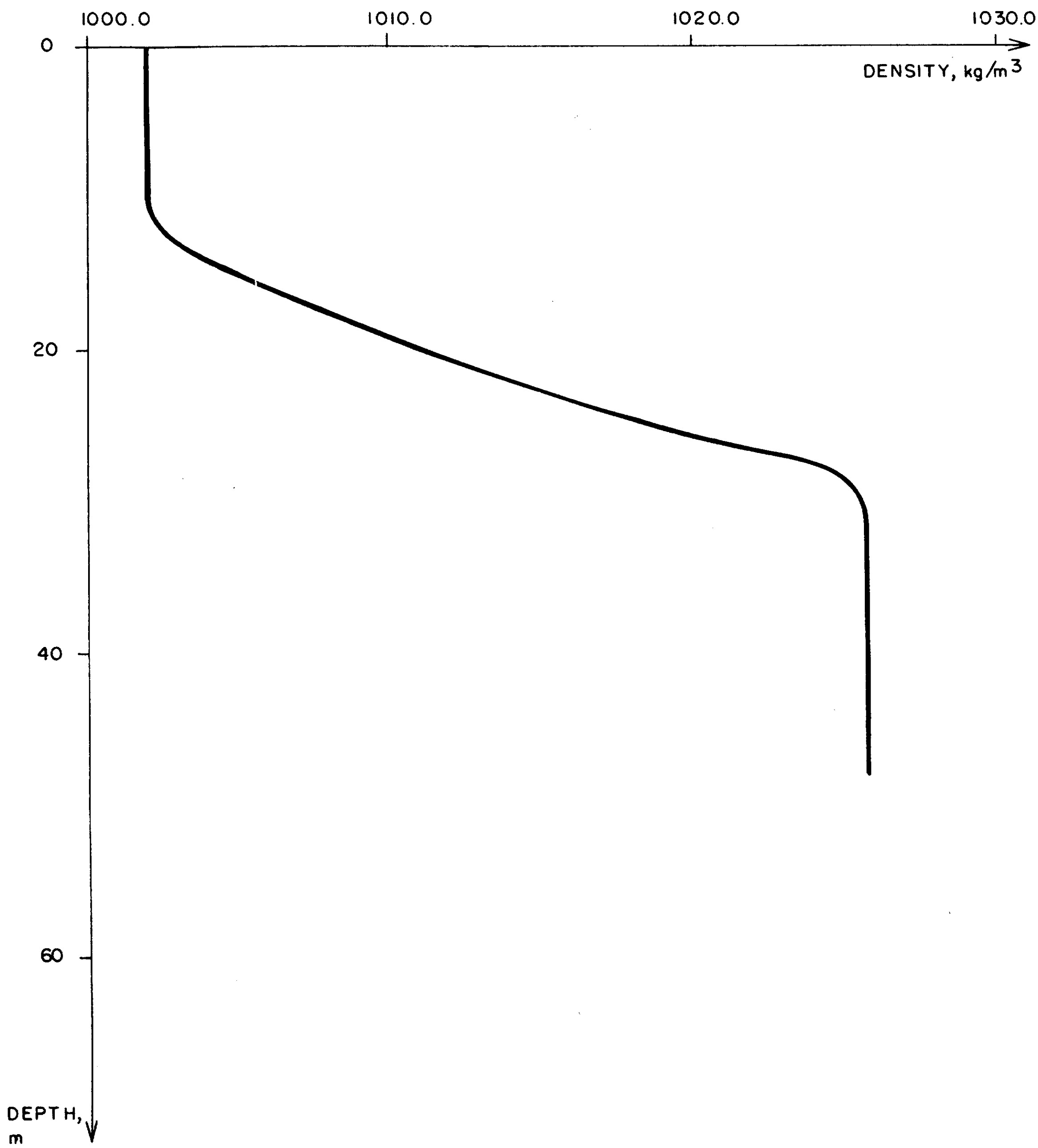

FIG. 12

VERKFRÆÐISTOFAN VATNASKIL V 8419 - 18
84.11.12. SPK / RS

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THICKNESS OF FRESHWATER LENS IN HSK-II

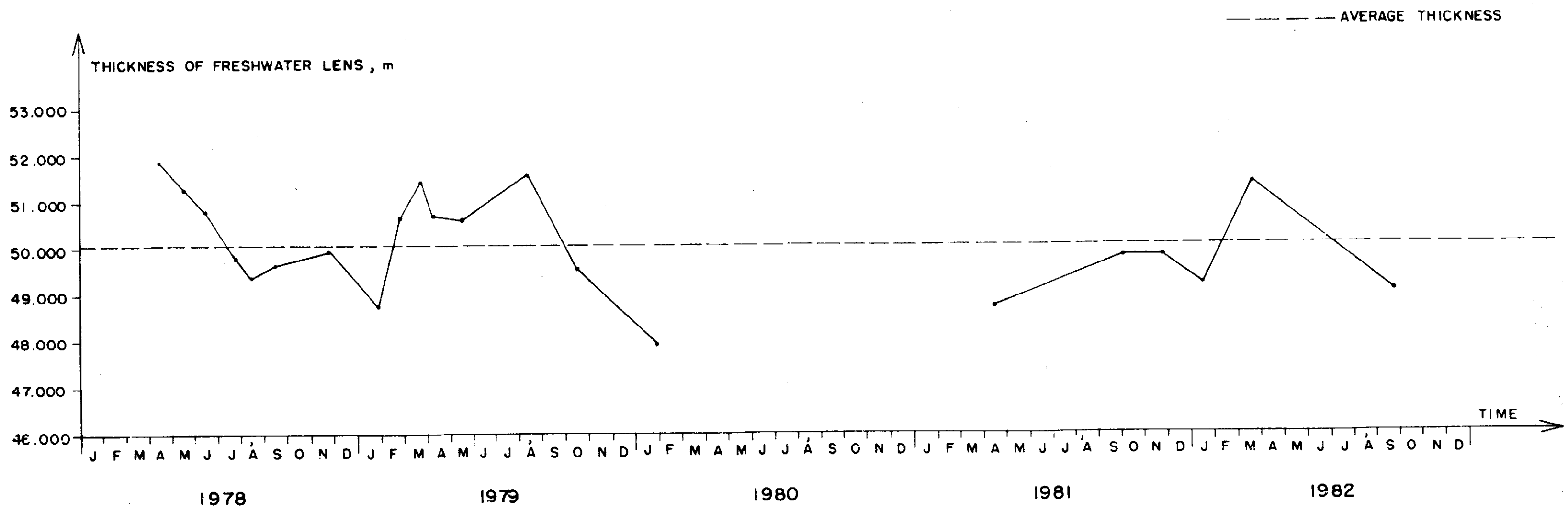

FIG. 13

VERKFRÆÐISTOFAN VATNASKIL V 8419 - 21 84.12.14. SLH/SPK/RS

ICELAND SALMON LTD

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CHLORIDE CONTENT OF PUMPED WATER AND TIDAL RESPONSE IN LAMBAGJA'

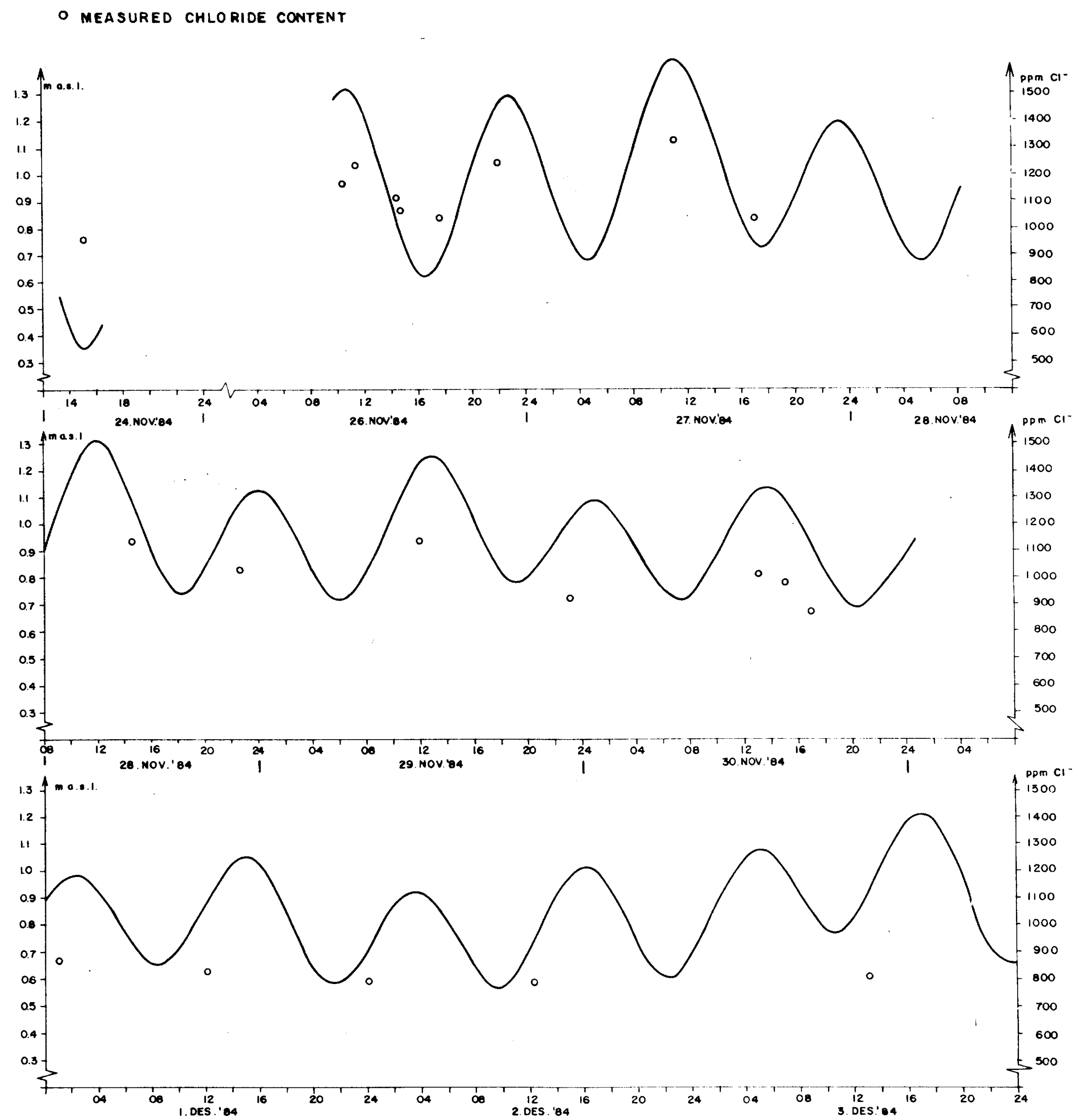

FIG. 14

VERKFRÆÐISTOFAN VATNASKIL V 8419 - 20
84.12.13. SLH/RS

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ICELAND SALMON LTD

GROUNDWATER ELEVATION IN LAMBAGJÁ AND CHLORIDE CONTENT OF PUMPED WATER

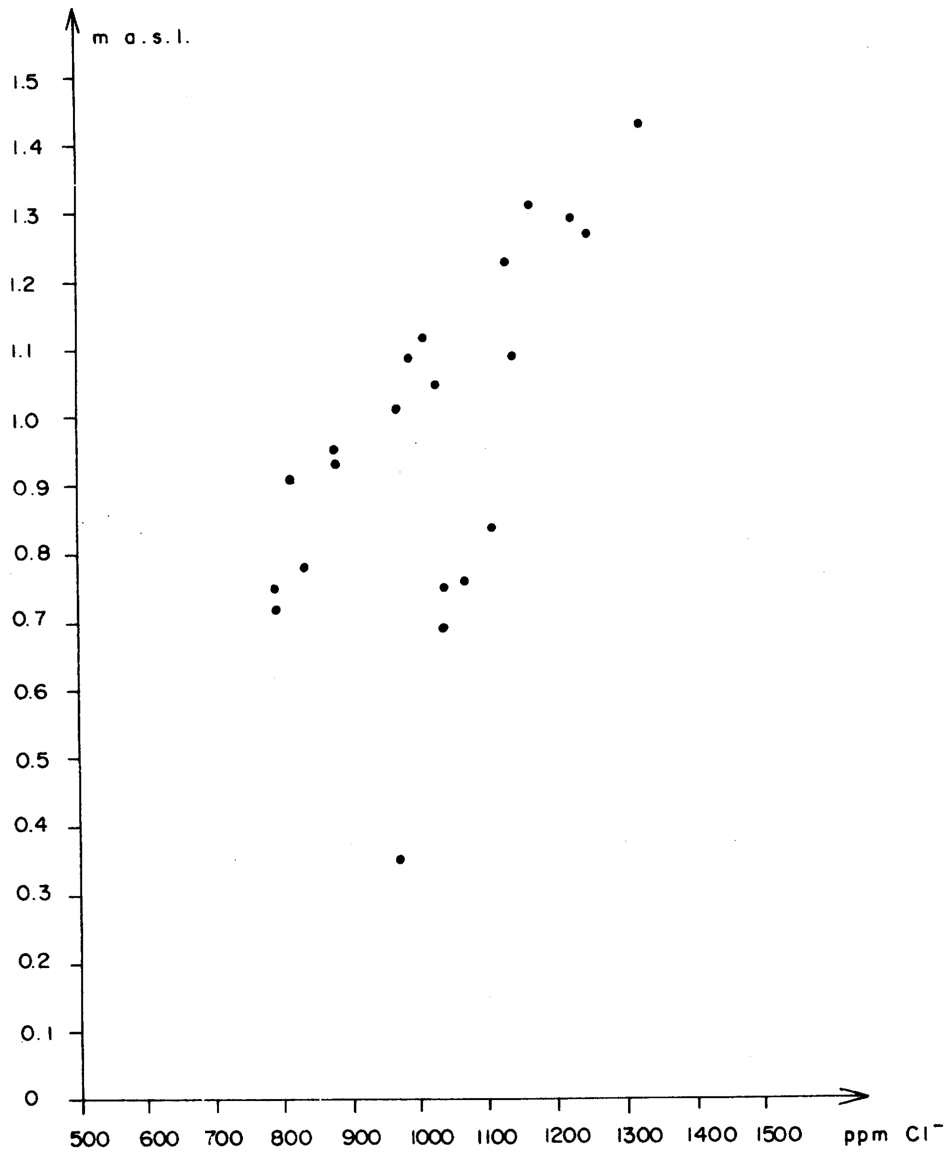

FIG. 15

PART III

WATER ANALYSIS

Kristján H. Sigurdsson
Hrefna Kristmannsdóttir

National Energy Authority

ANALYTICAL METHODS USED FOR
ANALYSES OF SAMPLES OF THE
FRESH AND SALINE WATERS AT STAÐUR:

pH is measured by a pH-meter with a glass electrode.

Dissolved O_2 is measured with a Chemét test kit based on reaction with rhodazine D.

Total carbonate as CO_2 is measured by titration with 0.1N HCl using a pH-meter (from pH 8.2 to pH 3.8).

Conductivity is measured by a conductivity meter.

Salinity is measured by a conductivity meter.

Na is measured by atomic absorption spectrophotometric methods.

K is measured by atomic absorption spectrophotometric methods.

Ca is measured by atomic absorption spectrophotometric methods.

Mg is measured by atomic absorption spectrophotometric methods.

Cl is measured by ion chromatography.

SO_4 is measured by ion chromatography.

F is measured by an ion sensitive electrode.

SiO_2 is measured spectrophotometrically as yellow silicomolybdate complex or reduced to molybdenum blue complex (1).

Fe is measured by atomic absorption spectrophotometry (graphite furnace).

Al is measured by fluorimetric spectrophotometry with lumogallion (2).

Cu is extracted by dithizone in chloroform (3) and measured by atomic absorption spectrophotometry.

Zn is extracted by dithizone in chloroform (3) and measured by atomic absorption spectrophotometry.

Cd is extracted by dithizone in chloroform (3) and measured by atomic absorption spectrophotometry.

Pb is extracted by dithizone in chloroform (3) and measured by atomic absorption spectrophotometry.

Hg is collected into $KMnO_4$ solution and measured by flameless atomic absorption spectrophotometry (4).

NH_3* is measured with indophenolblue in autoanalyser (5).

NO_2* is measured by azodyecolorometric method in autoanalyser (5).

NO_3* is transformed to nitrite by Cu - Cd reduction and analysed by azodyecolorometric method in autoanalyser (5).

Note: * Performed at the Icelandic Marine Research Institute.

References

(1) Standard Methods for the examination of Water and Wastewater, 1980. 15th ed. AP HA-AWWA-WPCF.

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Table 1. Freshwater analyses.

Sampling Site	Lambagjá fissure 1m depth	Lambagjá fissure 7m depth	Grænabergs-gjá fissure	Fissure near well SH-4	Lambagjá fissure Pump test 1	Lambagjá fissure Pump test 2
Sample no.	840096	840097	840098	840099	840103	840107
Sampling date	84-11-06	84-11-06	84-11-06	84-11-12	84-11-12	84-12-07
pH /°C	7.30/22.1	7.33/22.1	7.53/22.1	7.48/21.5	7.62/21.8	7.59/20.2
Conductivity (micro-S at 21.0°C)	2200	2300	4810	4410	3450	3190
SiO2(mg/l)	15.1	14.8	14.2	13.9	15.8	15.8
Na+ (mg/l)	354	372	809	737	556	518
K+ (mg/l)	14.1	14.8	34.0	30.7	21.1	19.7
Ca++ (mg/l)	35.1	36.4	55.8	51.5	48.2	44.9
Mg++ (mg/l)	44.2	46.2	96.1	89.5	67.0	63.8
Total carbonate (as mg CO2/l)	21.0	21.9	28.9	26.3	25.4	23.4
Br- (mg/l)	2.4	2.5	5.3	5.1	3.9	3.4
SO4-- (mg/l)	80.6	87.0	194	180	134	121
Cl- (mg/l)	674	718	1557	1416	1034	957
O2 (mg/l)	n.m.	n.m.	4.5	7	9	9
NH3 (as micro-mol N/l)	0.3	0.4	0.4	0.5	0.3	0.1
NO2- (as micro-mol N/l)	0.1	0.1	0.1	0.1	0.1	0.1

NO2- + NO3- as micro-mol N/l)	5.0	4.9	3.9	4.3	5.4	4.6
Fe (total) (micro-g/l)	15	31	25	90	38	38
Al (total) (micro-g/l)	40	10	n.m.	n.m.	10	15
Cu (total) (micro-g/l)	2.8	3.0	n.m.	n.m.	1.7	1.5
Zn (total) (micro-g/l)	13.3	22.8	n.m.	n.m.	4.7	3.1
Pb (total) (micro-g/l)	<1	<1	n.m.	n.m.	<1	<1
Cd (total) (micro-g/l)	<1	<1	n.m.	n.m.	<1	<1
Hg (total) (nano-g/l)	<10	<10	n.m.	n.m.	<10	<10

n.m. = not measured

Table 2. Seawater analyses.

Sampling site	Seawater well SH-2 10m depth	Seawater well SH-2 40m depth	Seawater offshore
Sample no.	840100	840101	840102
Sampling date	84-11-12	84-11-12	84-12-25
pH /°C	6.92/21.5	7.83/21.5	7.96/21.5
Conductivity (micro-S at 21.0°C)	10900	38500	45500
SiO2 (mg/l)	11.6	4.3	1.5
Na+ (mg/l)	1996	8247	9717
K+ (mg/l)	89.2	361	415
Ca++ (mg/l)	95.6	323	381
Mg++ (mg/l)	235	1021	1223
Total carbonate (as mg CO2/l)	53.1	87.5	103.0
Br- (mg/l)	13.2	54.8	67.9
SO4-- (mg/l)	508	2122	2531
Cl- (mg/l)	3784	15985	18037
O2 (mg/l)	4.5	2	n.m.
NH3 (as micro-mol N/l)	4.7	1.4	1.5
NO2 (as micro-mol N/l)	3.1	0.4	0.6
NO2- + NO3- (as micromol N/l)	9.1	10.1	11.8
Fe (total) (micro-g/l)	75	35	10

n.m. = not measured

PART IV

DRILLING OF OBSERVATION WELLS

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DRILLING OF OBSERVATION WELLS

Drilling Equipment. All wells were drilled with Ingersoll Rand ECM 350 drillrig and Atlas Copco 750 ft3 compressor. Drillbits were 2.5 inch Sandvik Coromant.

1.1 Observation wells for seawater investigation

Three wells (SH-1 to SH-3, table A) were drilled for the seawater investigation. Locations of these are shown in Fig. x. The wells have a diameter of 64 mm and are cased with 50 mm PVC pipes, partly perforated below ground water table. Each well has 1 m galvanized steel casing cemented at the top. Detailed drill logs are shown in Fig. y1. Wells SH-1 and SH-3 are 17.5 m deep whereas SH-2 is drilled to 46 m depth.

All wells penetrate the same compound lava flow originating from the shield volcano Sandfellshaed. The rock is olivine tholeiite basalt, fresh, coarse grained, finely vesicular and with columnar jointing. The lava is made of several, gently dipping flow units of different thicknesses lying on top of each other. The contacts between units are usually very porous and scoriaceous. These are indicated by the hatched areas in the drill logs. Individual cavities and pockets of scoriaceous rock are also common within the layer as shown in the logs. The presence of a loose scoria at the bottom of well SH-2 (preventing further drilling) may represent the lower limit of the flow.

Excavation of the lava would be by drilling and blasting. To obtain maximum efficiency in blasting, the charges should be placed in the massive basalt, but not in the porous and scoriaceous rock. In order to do so, the drilling must be closely observed. Excavation below seawater imposes a costly problem. The overall feasibility of a pumping scheme during excavation will be established by the pumping test results.

1.2 Observation wells for freshwater investigation

Five wells were drilled for the investigation of freshwater (SH-4 to SH-8, table A). The well diameter and type of casing is identical to those of the seawater wells. Well locations are shown in Fig. x and detailed drill logs in Figs. y1 and y2.

Well SH-4 penetrates the same compound lava flow as SH-1 to SH-3 with several scoriaceous flow-unit contacts. Well depth is 17.6 m.

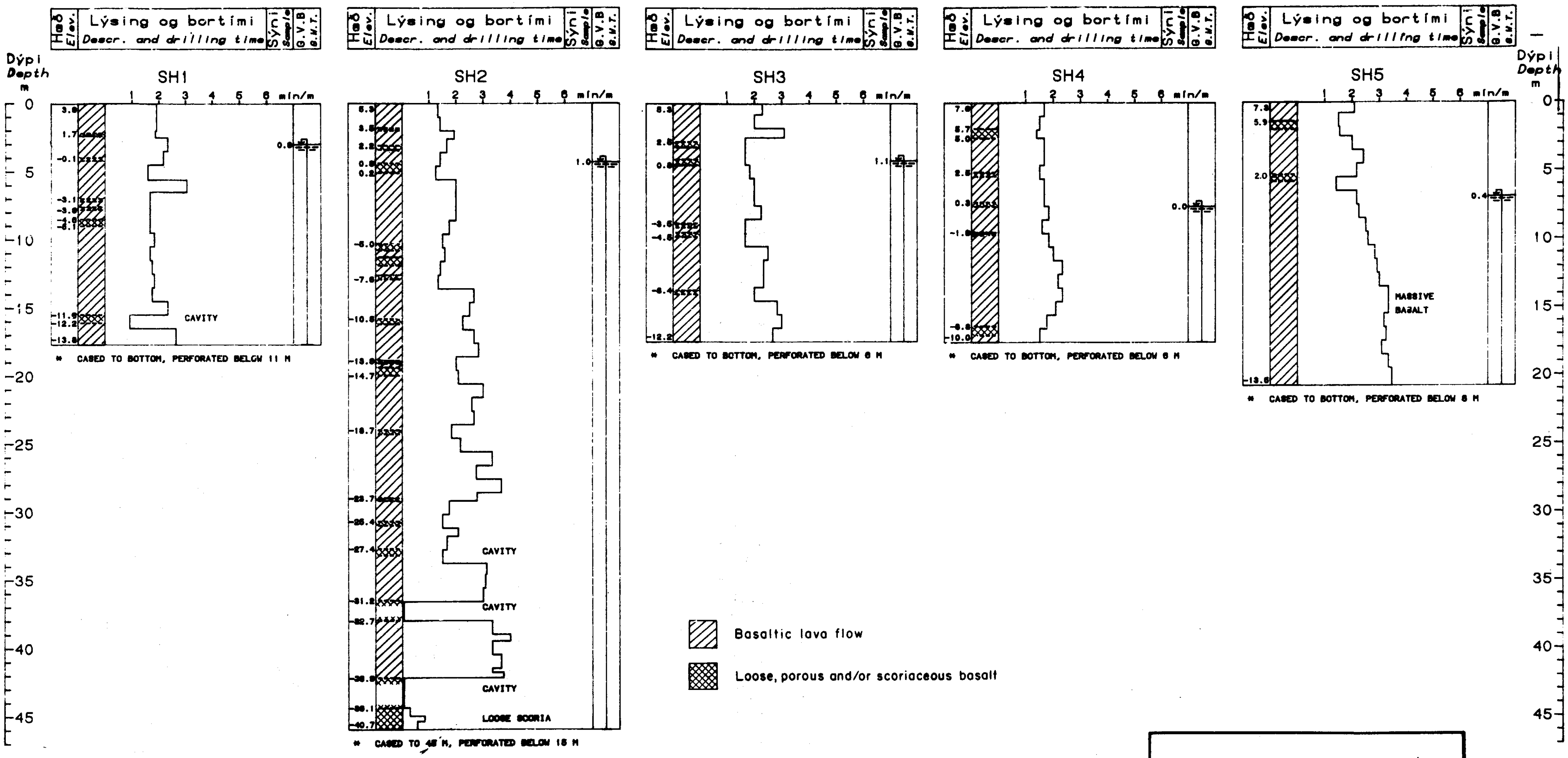
Well SH-5 is situated in the younger Eldvörp lava, about 2.5 km west of SH-4. The rock is tholeiite basalt, fresh and relatively fine grained. Only two vesicular and scoriaceous zones were encountered in the well. Below 6 m depth, the rock is massive and homogeneous. Well depth is 20.8 m.

Well SH-6 is located about 1 km west of SH-4 in a basaltic flow called Berg lava of uncertain origin. The rock is tholeiite, fresh and relatively coarse grained. The rock is homogeneous in the well down to a depth of 23 m. Below that, the well penetrates three loose and scoriaceous zones which may represent the lower limit of the flow (see drill log in Fig. y2). Well depth is 26.7 m

Wells SH-7 and SH-8 are situated close to the Lambagjá fissure, roughly 320 m NNW of SH-4. The top 0.5 to 2.0 m are very loose and scoriaceous. This rock is believed to represent the Berg lava flow in this area. Below is the thick Sandfellshæd lava flow, the same as in SH-1 to SH-4. The rock is fresh, coarse grained with 1-2% plagioclase phenocrysts and finely vesicular. Both wells penetrate a scoriaceous flow-unit contact with cavity at 2-3 m depth. Another major scoriaceous contact is at depth 16-18 m. Well SH-7 is 20.5 m deep and SH-8 is 61.6 m deep. Eight scoriaceous belts were observed in SH-8 below 18 m depth, but no certain flow contacts could be established (see drill log Fig. y2). Suspended drill cuttings were observed in the Lambagjá fissure while drilling both wells. The PVC casing in SH-8 is damaged at depth 4.5 m, and care should be taken when logging the hole.

TABLE A Well location, elevation and depth

Well number	Coordination x-north	Lambert y-east	Elevation m a.s.l. Ground	Casing	Well depth (m)
SH-1	722749.51	376046.62	3.95	4.88	17.7
SH-2	722837.38	376026.37	5.31	6.42	46.0
SH-3	722893.73	376031.74	5.27	6.31	17.5
SH-4	723707.78	376408.00	7.55	8.75	17.6
SH-5	726123.51	376588.83	7.33	8.62	20.8
SH-6	724681.18	376148.64	18.73	19.78	26.7
SH-7	723831.19	376704.15	11.22	12.18	20.5
SH-8	723830.13	376701.24	11.07	12.05	61.6



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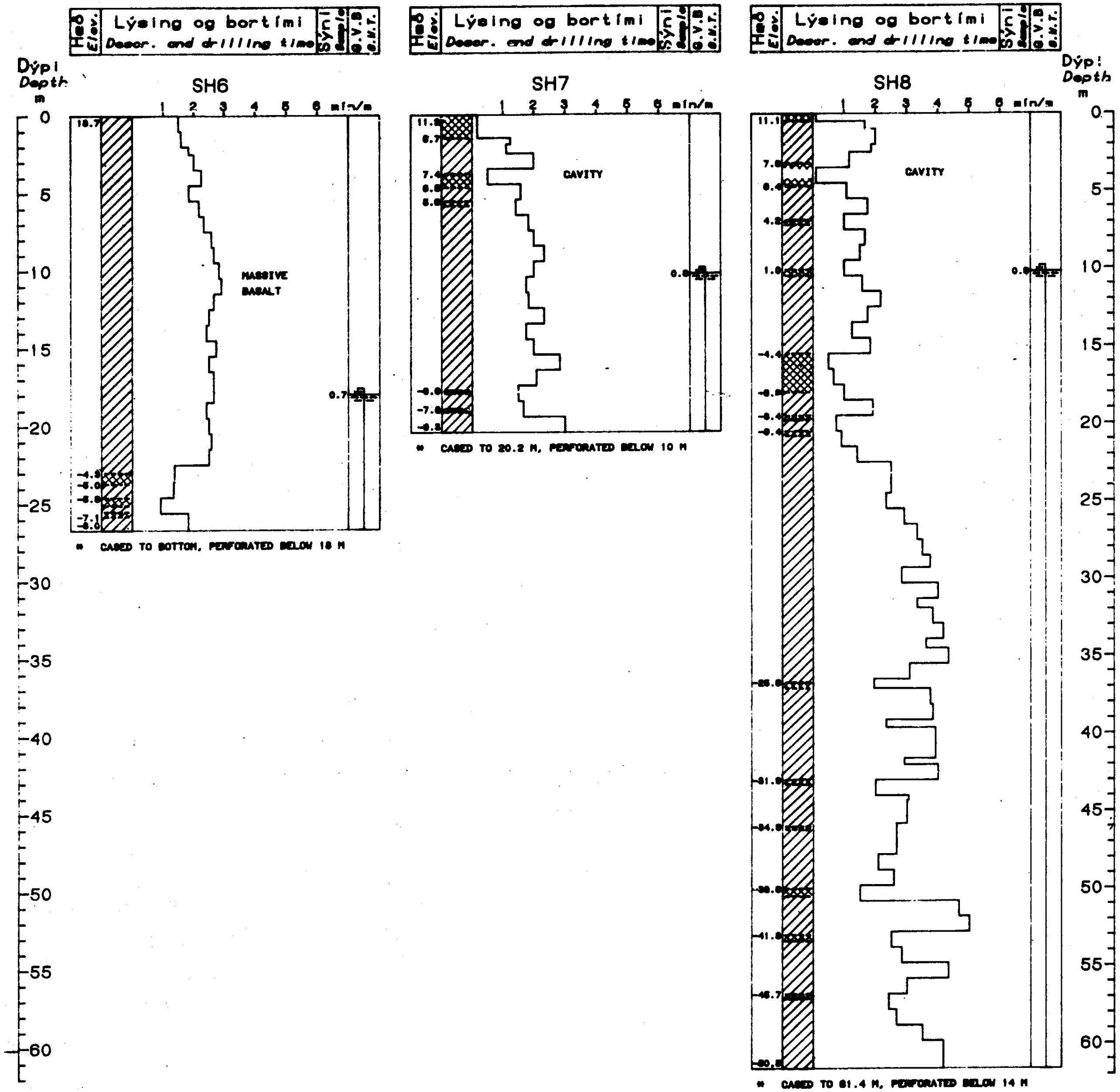
PROPOSED AQUACULTURE COMPLEX
AT STADUR

DRILL LOGS SH-1 TO SH-5



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PROPOSED AQUACULTURE COMPLEX
AT STADUR

DRILL LOGS SH-6 TO SH-8