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Bókasafn Orkustofnunar

ORKUSTOFNUN
NATIONAL ENERGY AUTHORITY
GEOTHERMAL DIVISION

Magnús Ólafsson
Guðmundur Ómar Friðleifsson
Jón Eiríksson
Hilmar Sigvaldason
Halldór Ármannsson

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ON THE ORIGIN OF ORGANIC GAS IN ÖXARFJÖRÐUR, NE-ICELAND

OS-93015/JHD-05
Reykjavík, March 1993

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Translated by G. Ó. Friðleifsson, J. Eiríksson and H. Ármannsson

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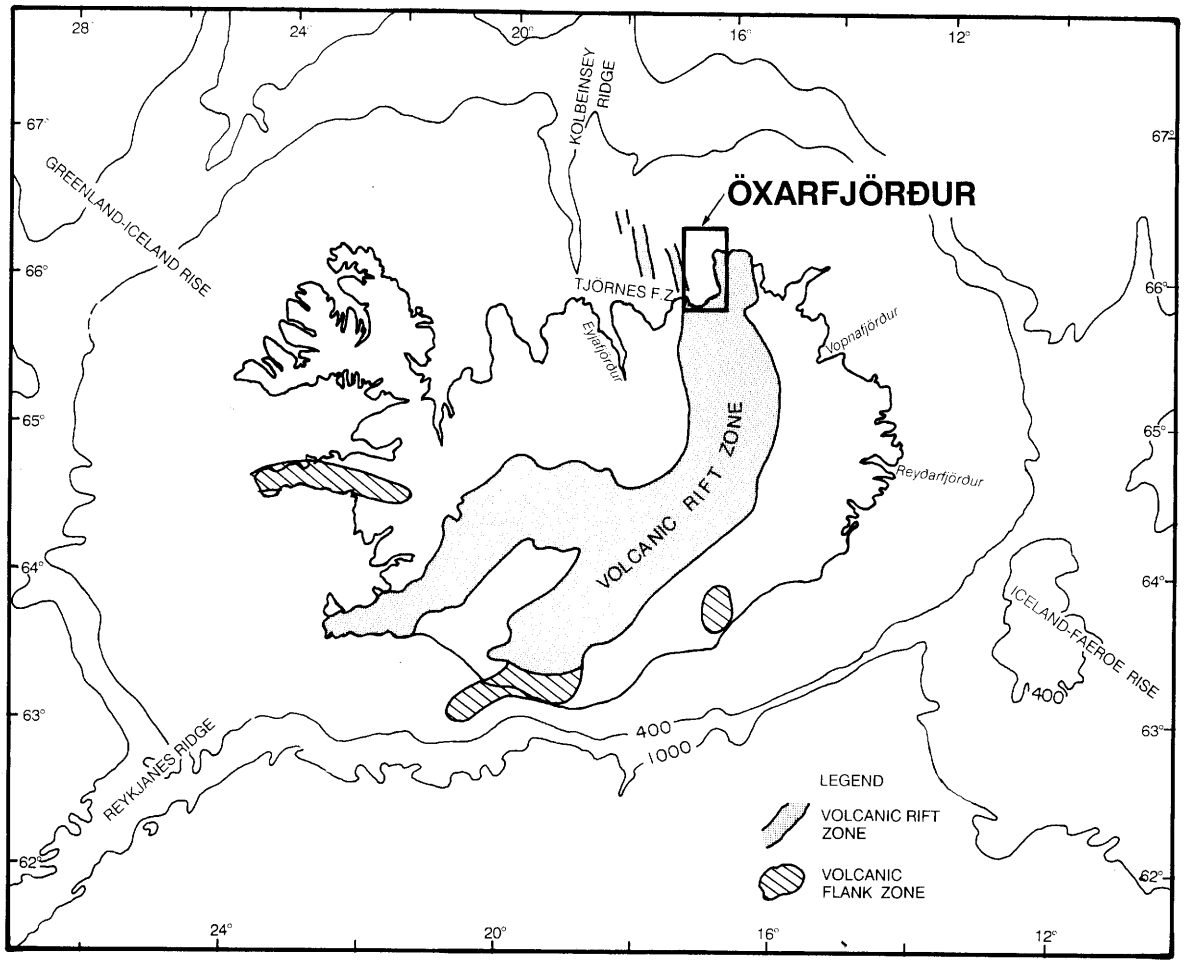
ÖXARFJÖRÐUR
KOLBEINSEY RIDGE
GREENLAND-ICELAND RISE
TJÖRNES F.Z.
Eyjafjörður
Vopnafjörður
Reyðarfjörður
VOLCANIC RIFT ZONE
ICELAND-FAEROE RISE
REYKJANES RIDGE
400
1000
LEGEND
VOLCANIC RIFT ZONE
VOLCANIC FLANK ZONE
28°
24°
20°
16°
12°
67°
66°
65°
64°
63°
62°

EXTENDED ABSTRACT

(This report is a translation of an Icelandic report from Orkustofnun (OS-92031/JHD3, July 1992) with a few additional explanatory remarks).

In 1987 and 1988 a feasibility study for aquaculture was completed by Orkustofnun in the Öxarfjörður region in NE-Iceland. One of the results showed a fraction of the geothermal gases in two research wells in the Skógalón geothermal area to be organic. This first finding of "oil associated" gases in Iceland resulted in the study presented here.

Well-4 was drilled with the aim to core-drill the lower portion of a 700-800 m thick sedimentary sequence in order to seek a potential source rock for the organic gas. Initially Orkustofnun (The National Energy Authority of Iceland) planned to set a temporary casing to 320 m depth in well-3 and core-drill it from there to approximately 700 m depth. This plan had to be abandoned for several reasons and well-4 was drilled instead. The drilling operation was, however, only partly successful in the fact that a final depth of only 450 m was achieved instead of the planned 700-800 m. Rotary drillbits were used for the upper 325 m of the well, which was cased off with a 3 1/2" casing, and a total of 123 m of drillcore was recovered from the lower portion of the well.

To investigate the origin of the organic gases a closer study of the following was planned:

a) Analyses of the type, quantity and and maturation of organic remains

b) Gas analyses

c) Sedimentary analyses

Oil and gas develop from kerogen in sedimentary sequences. Usually the processes are considered to take millions of years. However, recent studies have shown that oil may develop during a much shorter period of the order of a few thousand years, given the right geological environment in geothermal systems. High organic production in surface waters and anoxic conditions at bottom layers favour the production of high quality (lipid rich) oil source rock in sedimentary basins.

Little is known about the kerogen content of sediments on land or on the insular shelf around Iceland. In Icelandic waters the production rate of organic matter is amongst the highest encountered in the world. It is therefore possible that kerogen rich sediments may have accumulated at some stage during the geological history of Iceland. On the other hand it is more speculative whether anoxic conditions have developed or lasted long enough to favour gas- or oil-prone source beds in the sedimentary sequences off-shore. Today the bottom waters around the island are near oxygen saturation. Major climatic changes during Pleistocene might for instance have changed the paths of ocean currents and possibly the oxygen cycle. It is also possible that major explosive eruptions or large glacial bursts carrying large volumes of ash, silt and clays might have caused temporal anaerobic conditions on the underlying ocean bottom.

Öxarfjörður is located at the junction between the NE-SW spreading zone, which crosses Iceland, and a right-lateral transform zone, the Tjörnes Fracture Zone (TFZ). 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 an area from Eyjafördur in the west to Melrakkaslétta in the east, about 140 km long and at least 40 km wide. The sequence is up to 4 km thick and may have been accumulating since the

Miocene. The eastern boundary of this basin is unknown, but the basin pre-dates the Tjörnes horst just west of Öxarfjörður, and may underlie Öxarfjörður itself. Older sediments, probably of Mezozoic age or older, are known to exist on the Jan Mayen ridge which extends towards the Northeastern shelf of Iceland. It is not known how far south this crustal segment reaches.

The uppermost section of the sediments in well-4 in Öxarfjörður, extending down to 65 m depth, consists of unconsolidated layers of coarse sand and conglomerates from an outwash delta of the glacier river Jökulsá á Fjöllum. Below this, extending down to 140 m depth, are fine consolidated sandy layers considered to have piled up in deeper water. Marine fossils and some shell fragments are found within these layers. Next in the sequence are layers of mud and silt as well as thin layers of fine sand, thought to have been transported along the sea floor with turbidity currents.

Core sampling began at 325 m depth, below which the sedimentary analysis is more accurate than in the section above. The uppermost part of the core consists of fine-grained sand and silt mixed with single boulders, with numerous signs of turbidity currents, mudflows and slumping. Further down more complex layering ensues, indicating an unstable environment. At 365 m depth the first indication of glaciation is seen in the sedimentary formation in diamictite, formed on a sea floor below an ice sheet. Three such beds are seen from 365 to 385 m, below which muddy turbitity sediments are found down to 415 m, deposited ahead of a delta. The interval between 415 m and 420 m is composed of brown silty/clayish sediment suggesting a calm environment some distance off-shore. The lowermost part (down to 450 m) is composed of conglomerate and diamictite, formed during glaciation, intervened by silt layers. Occasional marine fossils and some shell fragments are found in the sedimentary succession in the cored part of the well.

The oldest sediments are probably no more than a few hundred thousand years old, whereas the first sign of glaciation was found at 350 m depth. The sequence above suggests a transgression first followed by regression where the glacial river built up a delta. Most likely this part of the sequence (i.e. above 350 m) was formed during the last 10.000 years.

TOC (Total Organic Carbon) was measured in all potential layers down the well. The TOC-value was invariably low (<0.02-0.05%). Thus, further analyses of organic remains were not attempted. The origin of the organic gas has consequently not been located and is most probably to be sought at deeper levels, as indicated by the presence of organic gases in the geothermal fluid from an aquifer (normal fault) at 360-370 m depth.

Part of the secondary mineral assemblages and homogenization temperatures of fluid inclusions in calcite (200-250°C) suggest that the geothermal system is more akin to a high-temperature system than the low-temperature one assumed sofar. An evolutionary sequence is believed to be present involving early assemblages of low-temperature zeolites ($\leq$100°C) and smectite succeeded by mixed layer clays of smectite-chlorite and quartz and wairakite ($\geq$200°C), followed by apparently stable assemblages of mordenite, clinoptilolite and calcite. This sequence indicates heating and subsequent cooling.

The core is fairly jointed, especially near the fault at 360-370 m depth. On average 1-2 joints are observed per meter of core. The width of the veins is from <0.1 mm to 7 mm. Approximately 70% are less than 1 mm across and about 90% less than 2 mm. Three types of joints are recognized, i.e. regular joints, faults and tension cracks. All types seem to be formed in the same stress field of rifting and subsidence.

The highest temperature observed in the drillhole is about 150°C, at 370 m depth, and the estimated well yield is about 10 kg/s of 100°C hot water. The temperature in the geothermal system at Skógalón, as indicated by chemical geothermometry, ranges from 160° to 190°C. The

geothermal system is thermally layered. About 100°C hot water is found from the surface down to 150 m depth. From 150-190 m a horizontal aquifer shows temperatures between 30-40°C. Below that depth the temperature rises sharply to 80-90°C and gradually to 150°C at 370 m. The geothermal water is brackish and therefore not suitable for direct use.

The caliper-log of well-4 from the 3 1/2" casing at 325 m downwards shows the walls to be smooth from 325 to 365 m but caved below that depth. The hole diameter everywhere exceeds 6", and measures up to 10", despite being drilled with a NQ corebit (3").

Total porosity of the sediments calculated from neutron-neutron values proved to be variable ranging from 26% to 62%, being highest in the diamictite at 360-370 m depth near a feed zone in a fault. Effective porosity also turned out to be fairly high, or 25-42%, mostly between 36-40 %. The permeability is generally close to 0.03-0.07 mD, but an order of magnitude higher in the 410-415 m depth interval. Grain density ranges from 2.65 to 3.0 g/cm^3. The density of the core straight from the well ranges from 1.5 to 2.7 g/cm^3.

Gas detected in boreholes at Skógalón is primarily nitrogen, while total measured volume of methane is 2-6 % and that of organic gases other than methane 0.2-0.5 %. A small amount of CO_2 was found in the gas from well-4 contrasting with that from wells-1 and 3 suggesting a higher temperature in well-4. The following hydrocarbons have been observed: methane, ethane, propane, iso-butane, n-butane, neo-pentane, iso-pentane, n-pentane, iso-hexane, n-hexane and benzene. In the organic gas fraction the percentage of hydrocarbons heavier than methane ranges from 4 to 17 %, and that of methane ranges accordingly from 87 to 96%. The isotopic ratios of the gas strongly indicate hydrocarbons of a thermogenic origin. According to classification schemes, the organic gas at Skógalón is either oil- or coal-gas, which implies that at least a considerable part of it has been subjected to high temperatures. Whether the gas is of marine or terrestrial origin is, however, not known.

The gas has been dated by the C-14 method and the result suggests that it is at least 20.000 years old and probably much older.

By the conventional methods described in the report, the organic gas has not been found to originate within the uppermost 450 m of the sedimentary succession in Öxarfjordur. In view of the data discussed the origin of the gas is probably to be sought in one of the following locations:

a) In marine sediments at a depth of between 450-700 m, i.e. above the lava basement

b) In a sedimentary succession of an unknown thickness below approximately 1000 m depth. It is not known whether these sediments are present at depth in Öxarfjörður. In view of the Tjörnes sedimentary succession and the sedimentary basin off-shore, their presence is, however, not unlikly.

c) In lignite beds of terrestrial origin, intervening lavas. Lignite is fairly common between lavas in the Tjörnes succession.

Dating of the gas in well-4, though inaccurate, suggests that the origin of the gas is to be sought below the depth of well-4, as the uppermost 350 m of the succession are younger than 10.000 years old.

In order to continue the investigation of the origin of the gas in Öxarfjörður, within the relevant financial constraints, the following plan is recommended:

To complete a drilling programme through the sedimentary succession down to a depth of 700-800 m.

Investigation of the natural gas emision in Öxarfjörður by grid sampling in shallow holes (1-3 m deep) and head space gas analysis of bottom samples, and/or total carbon analysis using a portable field monitor. This is a simple and inexpensive method to see whether the organic gas emission is restricted to hydrothermal surface manifestations or has a wider distribution.

Reprocessing and interpretation of multichannel off-shore reflection profiles obtained by Western Geophysical, and refraction profiles obtained by the USSR Academy of Science in 1987/1988. Interpretation of this data might throw light on the possible presence of a deep-seated sedimentary succession below the lava basement.

1. INTRODUCTION

1.1 Previous geothermal research in Öxarfjörður

In 1987 and 1988 Orkustofnun carried out a research project in cooperation with the local communities. The project, focussed on aquaculture was aimed at collecting basic data on groundwater (fresh and saline) and geothermal potential in the eastern part of Öxarfjörður (Georgsson et al. 1989).

The result revealed a large brackish geothermal system hidden below the outwash plain, most probably entailing a high-temperature (High-T) field. It also became clear that the geothermal system is hosted in a thick sedimentary succession making it unique amongst geothermal systems in Iceland.

According to geophysical data, lava successions are not to be expected above 700-800 m depth near the shore. Part of the research project involved the drilling of several research wells for seawater and hot water. Two of these, wells No 1 and 3, are located in the Skógalón hot spring area, near the farm Ærlækjarsel. The result of the drilling proved quite productive. Well 3, which is 322 m deep, yields artesian flow of 40-50 l/s of 96°C hot water (140-180 tn/hr).

Several water and gas samples were collected from the wells. The gas samples invariably included a trace of organic gases. Gas samples were sent to the BGS in UK for more detailed analyses confirming the presence of evolved hydrocarbons (C_{2+}) and thereby showing the gases to be different from normal geothermal gas. The discovery of this gas is unique in Iceland.

1.2 The purpose of the research drilling at Skógalón

Orkustofnun received a 8.5 MKr special appropriation in the 1991 fiscal year for investigating the origin of organic gases in Öxarfjörður. The appropriation was founded on a research proposal from Orkustofnun (Ólafsson et al. 1990). The proposal was based on deepening (core-drilling) of well-3 from 320 m to approximately 700 m. This approach was considered to be the least expensive way to discover the origin of the gas, provided it was to be found within the 700 m thick sedimentary succession. Due to reservations expressed by the drilling contractor and the local community, this plan had to be abandoned and a new well, No 4 (ÆR-04) was drilled instead (Fig.1).

The type, concentration and maturation of a) the potential sourcerock and b) the gases were to be analysed, and a detailed study of the sedimentary succession and its hydrothermal alteration was to be made. Gas emission during drilling was monitored and core samples collected for head-space gas analyses.

Analyses of organic remains in the core and cuttings, and porosity and premeability of plug samples were to be made by the Danish Geological Survey (DGU) in Copenhagen, specially contracted for the purpose. DGU sent a geologist (Jens Hendriksen) to the drill site at their own expense, a gesture much appreciated by Orkustofnun. W.G.Darling of the British Geological Survey (BGS) in Wallingford kindly completed the organic gas analyses from all wells at Skógarlón. His work is similarily appreciated by Orkustofnun.

The analytical results are published in this report. The main emphasis is put on the sedimentary succession, its hydrothermal alteration and the gas chemistry. It also containes a detailed literature review on the geological structure of the Öxafjörður region within the framework of the North-Iceland Volcanic Zone and the Tjörnes Fracture Zone and its sedimentary basin.

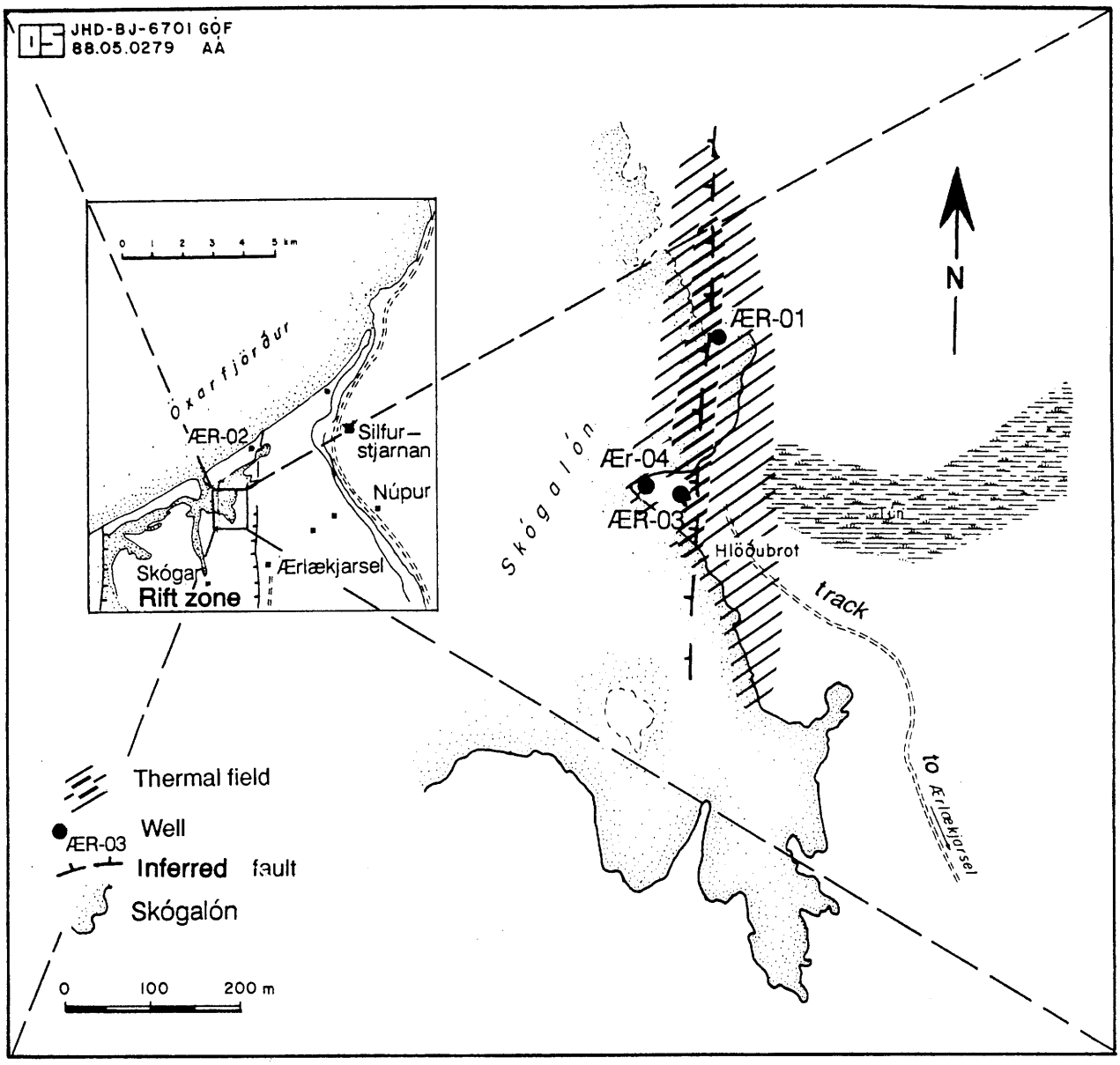

Figure 1. Location of drillholes and the Skógalón geothermal area

2. DEVELOPMENT OF OIL AND GAS

Geoscientists have for a long time been of the opinion that oil and natural hydrocarbon gas are formed by the breakdown and subsequent maturation of organic matter in thick sedimentary basins, over long periods of time. Oil has been considerd to form from the remains of marine organisms and gas from terrestrial organisms. This can be taken as the main rule regarding the formation of oil and gas. In many areas, however, oil and gas coexist. The process of oil and gas formation is a multi-stage one. The oil and the gas may subsequently be transported away from the source rock and collected into structural traps, often in exploitable quantities. The maturation process is generally assumed to take several million years.

Gas and oil are thus formed from organic matter contained in sediments. In the ocean photosynthetic algae are the main source of organic carbon. Their productivity depends mostly on solar radiation and the supply of nutrients. It is usually at maximum near the surface in shallow waters, where upwelling of nutrient-rich seawater takes place or where rivers carry nutrients to the sea. On land the climate, particularly precipitation, controls plant productivity with respect to organic carbon. Organic materials preserved in sediments are called kerogens. The necessary condition for their preservation is oxygen depletion, i.e. that oxygen uptake exceeds its replacement. Decomposition of organisms is mainly responsible for oxygen uptake, oxygen being transported by ocean currents. A negligible amount of kerogens is preserved in open air, but in stagnant waters extensive organic production can support the build-up of kerogen-rich sediments in an oxygen depleted environment.

2.1 On the origin of hydrocarbons

In geothermal systems gas is usually of a very different origin than the natural hydrocarbon gas discussed above. Its composition is to some extent controlled by the temperature of the geothermal system. In High-T systems the most abundant gases are carbon dioxide (CO_2), hydrogen sulphide (H_2S) and hydrogen (H_2), but in low-temperature systems it is nitrogen (N_2). Some other gases may occur, e.g hydrocarbons, particularly methane (CH_4).

Until now the interest in hydrocarbons contained in geothermal gas has centred around the concentration of methane, and the ratio of carbon isotopes in methane to those in carbon dioxide, as parameters in geothermometry, i.e. the estimation of subsurface temperatures in geothermal systems (e.g. Panichi et al., 1977).

Hydrocarbons with more than two carbon atoms in their structure (C_{2+}) were first reported in geothermal gas from Yellowstone Park (Gunter and Musgrave, 1971). More recent investigations have revealed their frequent occurrence in geothermal systems, especially those located within thick sedimentary basins (e.g. Nehring and Truesdell, 1978).

Non-geothermal gas is usually divided into two major groups according to its origin, viz. biogenic ("B") and thermogenic gas ("T"). Schoell (1980) has obtained isotope ratios in hydrocarbon gases from a large number of areas and classified them according to their origin as shown in Figure 2. Some of the gases he discusses do not fall into either main group and he classifies them as of mixed origin ("M") but concludes that some of them may be inorganic in origin. Schoell furthermore divides thermogenic gases into wet (oil gas, "T") and dry (coal gas, "TT") gases, and biogenic and dry thermogenic gases into those of terrestrial origin ("B(t)", "TT(h)") and marine origin ("B(m)", "TT(m)")). He argues that biogenic gas is usually formed in two steps: To begin with CO_2 is released from decomposing organic matter and H_2 from water by the action of non-methanogens. These then form methane with the assistance of methanogens:

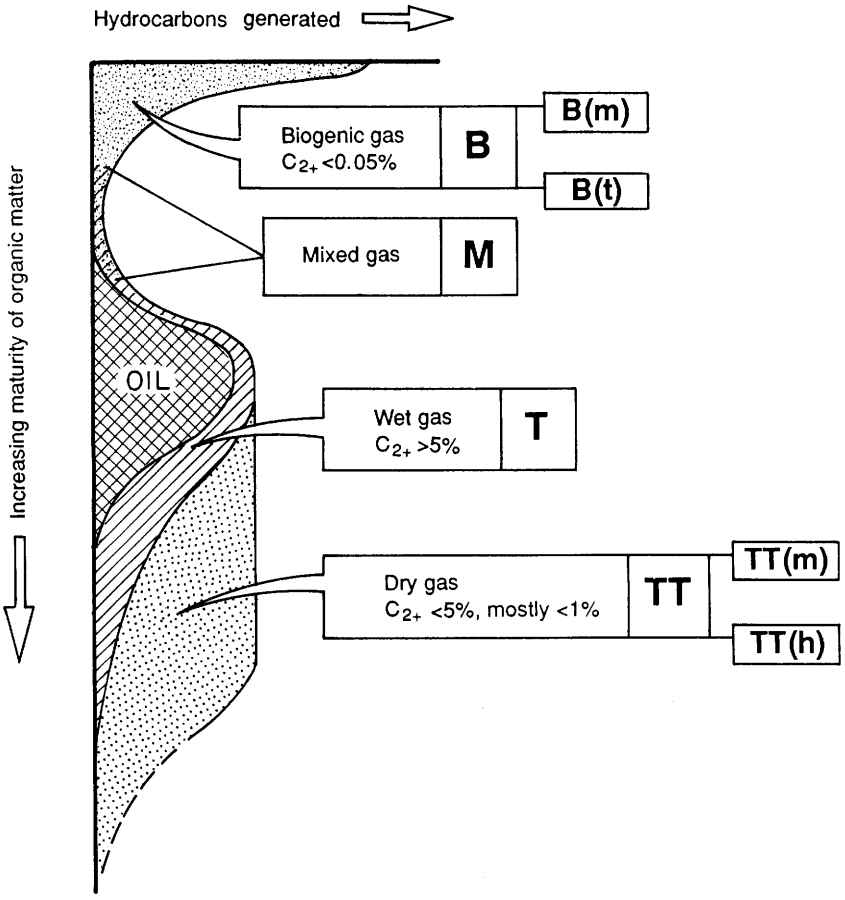

Figure 2. The classification of natural hydrocarbon gases

$$CO_2 + H_2 \rightarrow CH_4 + 2H_2O$$

Occasionally the free radical CH_3 is formed from organic matter and combines with H_2 originating from water.

$$CH_3 + 1/2H_2 \rightarrow CH_4$$

Pure methane that is thought to be formed by thermal cracking of organic materials, such as lignite exist in oil fields at great depths (Laier, personal communication, 1992). Small amounts of hydrocarbon gases found in granite in the Siljan Ring, Dalarne, Sweden are considered to be formed from CO and H_2, catalyzed by iron and magnetite (Laier, 1990).

$$(2n + 1)CO + (6n + 8)H_2 \xrightarrow{\text{(iron/magnetite)}} CH_4 + C_nH_{n+2} + (2n + 1)H_2O$$

Traces of hydrocarbon gases have also been found in dolerite at the same location. These are thought to be abiogenic, originating from carbon in the rock, probably constituting remnants of mantle gas emplaced by magma (Laier, 1990). Hydrocarbons found in gas from the submarine geothermal field at 21°N on the East Pacific Rise is considered to be of a similar origin (Welhan and Craig, 1983).

The most important characteristics of each group of gas, classified according to origin, are shown in Table 1.

Gold (1979) and Gold and Soter (1980, 1982) suggest that a large portion of the carbon that is transported to the earth's surface, originates in the mantle where there is thought to exist a source of primordial carbon compounds which constitutes the remnants of primordial carbon, mostly in the form of hydrocarbons. Primordial methane is thought to have been buried deep in the earth at high temperatures and pressures and to have formed complex carbon compounds. These can form methane which escapes to the surface via structural weaknesses. At high temperatures such as at plate boundaries and in active volcanoes, this methane reacts to form carbon dioxide which later is converted to carbonates, but in cooler areas methane may escape to the surface without reacting. Gold (1980) suggested that such upflows may take place in Iceland near the flanks of the volcanic region, such as in the extreme West and the extreme East. His opinion was that the gas upflow in Lake Lagarfljót was difficult to explain otherwise. Gold (1983) also concluded that the Siljan Ring in Dalarne, Sweden, was a promising prospect for revealing a gas upflow of this kind. As a result deep boreholes have been drilled in the Siljan Ring but little gas has been obtained. Studies on it and on gas from Lake Lagarfljót have not lent support to Gold's hypothesis (Laier, 1990; Ármannsson and Einarsson, 1987).

Table 1. The most important characteristics of natural hydrocarbon gases of different origins.

Group	ΣC_{2+}	$\delta^{13}C‰$ (PDB)	Heimildir
Biogenic	0	-100 - -55	Schoell (1980), Laier (1990)
Thermogenic, wet	>5%	-50 - -25	Schoell (1980), Laier (1990)
Thermogenic, dry	<5%	-50 - -25	Schoell (1980), Laier (1990)
Mixed origin	0.3 - 5%	-60 - -50	Schoell (1980)
Abiogenic, iron catalyst	30 - 90%	-40 - -20	Jeffrey & Kaplan (1988)
Abiogenic, rock inclusion	1 - 10%	-10 - -20	Jeffrey & Kaplan (1988) Welhan & Craig (1983)
Geothermal, from CO_2, CO	0	-40 - -25	Lyon & Hulston (1984) Ármannsson et al. (1989)
Geothermal from organic sedimentary matter	3 - 5%	-45 - -20	Des Marais et al. (1981a)
Abiogenic, primordial	trace	> -10	[1]

[1] This group has not been positively identified in any natural system and thus the values are theoretically predicted.

In many geothermal areas methane is thought to be formed via the reaction of H_2 with CO_2 or CO, catalyzed by iron compounds or bacteria, methane being the sole hydrocarbon formed in the reaction. In sedimentary geothermal areas, e.g. Cerro Prieto, Mexico and Yellowstone Park, USA, methane, that is not related to CO_2 but associated with several higher hydrocarbons including both unsaturated and aromatic ones (e.g. pentene, benzene), has been discovered (DesMarais et al., 1981a). It is thought to be a product of the cracking of organic matter (e.g. lignite) in the sediments. Gas with a similar composition has been formed during experiments where conditions in the geothermal reservoir are simulated. The origin of this gas is probably similar to that formed at great depths in oil fields but much younger. The higher hydrocarbons will probably disappear with time.

It has been known for a long time, that the rate of reaction leading to oil formation is primarily dependent on temperature. A few years ago it was discovered, that in certain conditions such a process can take a relatively short time, possibly only a few thousand years.

Studies on the Guyamas sedimentary basin in the Gulf of California (Didyk and Simoneit, 1989) have for instance shown that oil has been formed in a geothermal system within the sediment. The results of analysis show that the oil is only 5000 years old. The sediments are thought to have been formed during the last 150.000 years. This oil is similar to normal petroleum, but information on the extent of its occurrence and the quantity involved is scant. The temperature at the outlets of the geothermal system is about 200°C at 200 m depth. The porosity of the sediments is about 50% and the total concentration of organic matter (TOC) ranges from 0.2 to 2%.

In Iceland hydrocarbon gas has been found outside Öxarfjörður in Lake Lagarfljót and results of chemical analysis suggest that the gas there is biogenic (marsh gas) (Jónsson, 1967, Ármannsson and Einarsson, 1987). Similar gas is known to emerge in several other locations within the East Iceland flexure (Benjamínsson, 1985) which also encompasses Lón where asphaltic petroleum has been found (Jakobsson and Friðleifsson, 1989). Methane has been observed in Ísafjörður harbour and reported in Bolungarvík and some other locations in the Northwestern peninsula, Lake Haukadalsvatn and Lake Vesturhóp (Jónsson, 1967, Jóhannesson, H., pers. comm., 1992). Figure 3 is a map of Iceland showing some of the locations where hydrocarbon gas has been reported.

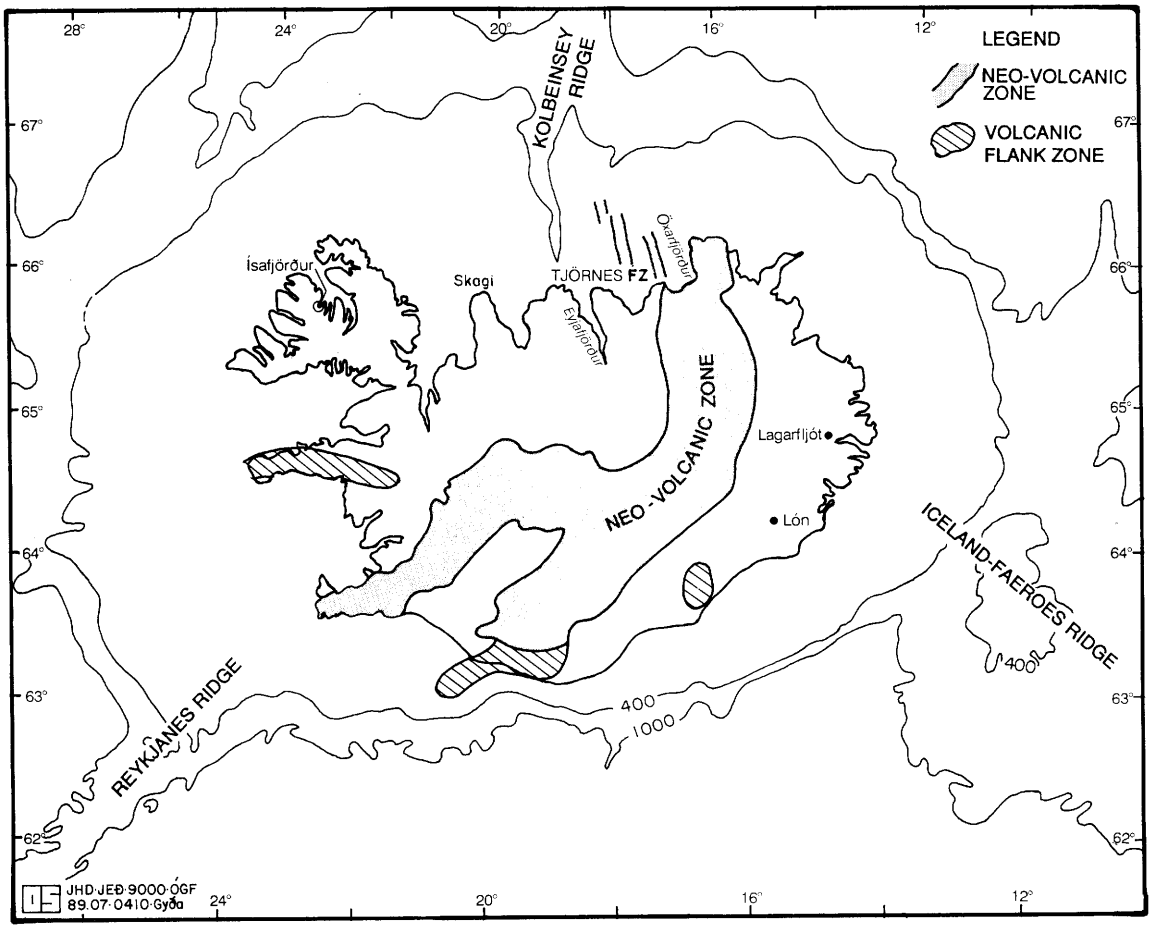

Figure 3. A map of Iceland and its shelf, depicting some of the location where hydrocarbons have been observed.

2.2 Oil and gas in Iceland

Oil reservoirs are generally confined to thick sedimentary successions and the first step in oil prospecting involves finding and delineating sedimentary basins. Although sedimentary rocks in the Iceland region are usually very thin, the existence of thick sediments off North Iceland has been verified (Chapter 3). Oil can only be generated in sediments that contain substantial amounts of organic material.

Very little is known about the amount of kerogen in Icelandic sediments, neither on land nor on the insular shelf. According to Allen & Allen (1990) the organic productivity in the seas around Iceland to-day is among the highest found in the world oceans, amounting to 500 $mg/m^2/day$. Sections on land contain Tertiary and Quaternary seams of lignite intercalated in lava successions as well as in thick sedimentary horizons. Among factors favouring high organic productivity in the seas around Iceland are sufficient insolation (latitude 65°N), abundant nutrients in the sea-water (the front between the North Atlantic Current and the East Greenland Current lies close to the north coast of Iceland), partly due to intensive runoff carrying vast amounts of suspended material and solutes to the sea, and wet, oceanic climate contributing to a surprisingly lush vegetation cover. These factors have probably not changed significantly throughout the geological history of Iceland. It may therefore be assumed that organic productivity has generally been high enough to produce substantial amounts of organic sediments. It is less clear, however, whether anoxic conditions have prevailed at any time preventing bacterial degradation of the organic components and oxidation, removing the potential for the formation of oil source rocks. The knowledge of palaeocurrents, morphology, and sedimentary basins is rather limited in the Iceland region. It is known that the oceanic currents in the North Atlantic have changed radically and repeatedly during the last few millions of years (Ruddiman and McIntyre, 1973; Jansen and Sjöholm, 1991). However, there is no data on past chemical and physical conditions of the deep water close to Iceland. The oceanography around Iceland may have been substantially different during periods when the North Atlantic Current did not reach the Norwegian sea. In addition to changes in the oceanic currents, the bottom topography around Iceland and on the shelf off North Iceland may have undergone tectonic changes leading to the formation of relatively isolated basins. Periodic environmental changes such as drastically increased input of terrestrial sediments due to climatic or topographic changes may also have favoured the conservation of organic sediments. The evaluation of these factors remains speculative while the mapping of the shelf and ridges around Iceland is in the initial stages and the stratigraphy largely unknown. It should be emphasized that most of the earth's oil is derived from marine source rocks. The best conditions for potential source rock formation prevail in semi-closed bays and fjords or on continental shelves where organic productivity is very high.

Oil or hydrocarbon prospecting has been very limited in Iceland and on the shelf around Iceland. A brief account of projects undertaken by Orkustofnun during the last decade will be given below, with the exception of some geophysical seismic reflection studies within the economic zone of Iceland ("continental margin").

In 1982 a 554 m deep research borehole was drilled on the island of Flatey in Skjálfandaflói, North Iceland. The project was instigated by a special committee on applied sea floor studies under the auspices of the Icelandic Ministry of Industry with the aim of evaluating the feasibility of oil reservoirs in the sedimentary succession beneath Flatey. The results were published in an Orkustofnun report (Gunnarsson et al., 1984). In short there were no indications of oil nor of organic sediments capable of yielding oil under any circumstances.

During the years 1983-1985 Orkustofnun studied gas emanations from lake Lagarfljót in Eastern Iceland. The aim of the study, which was initiated by the Sea Floor Committee of the

Icelandic Ministry of Industry, was to establish the origin of the gas. Previous studies had indicated that the emanations were composed of methane gas only. Thorough chemical analyses and isotopic studies (Ármannsson and Einarsson, 1987) confirmed earlier conclusions to the effect that the Lagarfljót gas consists of young and immature organic gas generated by biodegradation, but not of older gas related to oil formation.

During the summer of 1985 minor amounts of asphalt were found in amygdales enclosed by secondary minerals in South-East Iceland. This was indeed the first oil find in Iceland, and it was consequently thought appropriate to investigate the origin of this asphalt. It was concluded by Jakobsson and Friðleifsson (1989) that a seam of lignite intercalated between lava flows had been heated up by an intrusion to give off oil that was trapped in quartz infillings in lava amygdales above.

Organic hydrocarbons were found in gas during geothermal investigations in Öxarfjörður in 1988. The present report contains the results of a research project that followed.

It was stated above that gas and oil are generally formed and preserved in sediments. To locate the source rock it is necessary to look at the geological structure and tectonic history of the area in question. Sediments are to be found nearly everywhere on the earth's surface but they only attain substantial thickness in relatively restricted sedimentary basins characterized by prolonged subsidence. Many sedimentary basins are related to continental margins or extensive rift valleys. The geographic extent of the sedimentary basin off North-Iceland is comparable to that of many of the best known sedimentary basins on the earth to-day. Almost all economic hydrocarbons on the earth are located in sedimentary basins.

3. GEOLOGICAL SETTING

Detailed knowledge of the geological structure and tectonic history of sedimentary basins is important for the evaluation of their hydrocarbon potential. The organic gas in Öxarfjörður indicates that there are organic sediments buried under the coastal plain. Several hypotheses may be put forward to explain the origin of the gas. It might have been generated from relatively young organic sediments subjected to a high thermal gradient within the presently active Öxarfjörður basin. The sediments in Öxarfjörður are 700-800 m thick at the present coastline, and increase in thickness towards north (Flóvenz and Gunnarsson, 1991). It is also possible that the rocks beneath the 700-800 m reflector contain organic sediments that have generated gas. There is no data on the nature or origin of these rocks. Tertiary basalts covered by Early Pleistocene lava flows and sediments crop out in fault escarpments on the east side of the Tjörnes peninsula to the west of Öxarfjörður. The western margin of Öxarfjörður is characterized by step-faults with down-throw towards east. It is possible that the Early Pleistocene and Tertiary units have been down-warped and extend eastwards into the Öxarfjörður basin at a depth below 700-800 m. The Tertiary lava pile on Tjörnes contains lignites (Einarsson, 1958, Eiríksson, 1979). These rocks were dated at 7-10 Ma with K/Ar dating (Aronson and Sæmundsson, 1974, Albertsson, 1976, 1978). The Tjörnes beds, which crop out above the Tertiary lavas on the west coast of Tjörnes, contain numerous lignites as well as marine sediments which are at least 3-5 million years old. It is conceivable that a comparable unit of marine sediments and lignites has been conserved in the Öxarfjörður basin, although erosion due to repeated glaciations during the Upper Pliocene and Pleistocene has removed such rocks from the Tjörnes horst. Even older sediments have probably accumulated in the basin off Flateyjarskagi (Fig 5) at ca. 10 Ma (Jancin et al. 1985). The eastern boundary of this basin is unknown, but it pre-dates the Tjörnes horst. Finally it is possible that the gas is derived from rocks related to the Jan Mayen Ridge or its continuation towards Iceland. When Scandinavia was separated from Greenland at ca. 55 M.y. ago the rifting took place along the Ægir Ridge in the Norwegian Sea. At 27 Ma the Ægir Ridge became inactive and divergence set in along the Kolbeinsey Ridge which lies further west. The 100 km broad crustal segment between these two spreading ridges forms the Jan Mayen Ridge which is derived from the old Greenland continental shelf (Talwani and Eldholm 1977, Kristjánsson 1980). The segment may contain Palaeozoic and Mesozoic sediments (Gunnarsson, 1988). It is not known how far south towards Iceland this segment extends.

3.1 Geology of sedimentary basins

The formation of sedimentary basins is controlled by properties of and processes in the earth's crust and upper mantle. The plate tectonic theory is concerned with motion in these layers, which form a 100 km thick shell, the lithosphere, which is divided into a mosaic of plates. The probability of the development of sedimentary basins is highest at the plate margins. There are three basic types of plate margins: divergent plate boundaries, where new crust is generated, convergent plate boundaries, where crust is destroyed, and conservative plate boundaries, where plates move beside each other. Öxarfjörður and the shelf westwards to Kolbeinsey Ridge lie at a plate boundary which is partly divergent, and partly conservative. Sedimentary basins may be divided into three genetic groups. In the first group there are basins where the earth's crust is undergoing extension, secondly there are basins where the crust is being down-warped, such as along deep sea trenches, and finally basins along conservative plate margins where transform movement takes place. Subsidence is a key factor in the accumulation and conservation of substantial sedimentary successions. Most sediments accumulate below sea level or in coastal regions where the conservation potential is usually

much higher than on land, due to weathering and erosion. In a broad sense it is the interaction between landscape and climate which controls sedimentation. A few sedimentary environments occur frequently on the earth to-day, and it is generally assumed that the same types of environments have remained common throughout the geological history. Among the most important ones are deserts, alluvial plains, deltas, barrier reefs - lagoons, continental shelves, continental slopes, and pelagic environments. Sedimentological models have been defined to facilitate the interpretation of data from sedimentary successions. Among environments that are favourable for the accumulation of hydrocarbon source rocks are lakes, deltas, and submarine basins. Continental slopes and some fluvial plains (fens and swamps) may also be potential source rock environments.

3.2 The geology of Öxarfjörður and the surrounding areas

The geology of Iceland is characterized by plate boundaries that split the island between the North-American and Eurasian lithospheric plates. The boundary is by no means simple and consists of alternating segments of diverging and conservative plate margins (Fig 3).

A diverging plate boundary (North-Iceland Volcanic Zone, NVZ) runs northward from Vatnajökull along Öxarfjörður onto the North-Iceland shelf. The boundary is characterized by localized extensional fissure swarms coupled with subsidence and volcanism. A combination of processes involving these features has generated several active volcanic systems. The North-Iceland Volcanic Zone is offset westward and connected to the Kolbeinsey Ridge along the WNW-trending Tjörnes Fracture Zone (TFZ). The thickest marine sediments exposed in Iceland are located on Tjörnes which is a tectonic horst bounding Öxarfjörður to the west. East Tjörnes rises in 4-6 sharp, prominent steps to an altitude of 300-400 m in the north and 600-700 m in the south. The west side, on the other hand, is characterized by gentle slopes and there are no signs of step-faulting. Einarsson (1958) described large WNW-ESE trending faults across Tjörnes near the village Húsavík and estimated that the Tertiary basement to the north of the faults had been uplifted some 700 m. Einarsson et al. (1967) published an account of the geology of Tjörnes. They concluded that Tjörnes had been tectonically active since the Miocene, and that a series of N-S trending fault systems had formed a basin and range topography with several sedimentary basins. The final phase of tectonic activity had then been a 500-600 m uplift in SE-Tjörnes, decreasing towards north. Shortly before 1970 it was suggested that there were transform faults near the north coast of Iceland between Kolbeinsey Ridge and the North-Iceland Volcanic Zone in Öxarfjörður (Sykes 1967). The suggestion was based on earthquake studies on the shelf off North-Iceland. More detailed analyses of the earthquake activity supported Sykes suggestion (Ward et al., 1969; Ward and Björnsson, 1971), but it became clear that the transform movement was taking place along a a few tens of km wide fracture zone. Ward (1971) compiled what had been written about the geology and tectonics of North Iceland and concluded that the Húsavík faults were the only obvious signs of this fracture zone on land, and that they demarcated the southern limit of the Tjörnes Fracture Zone. As well as formulating ideas about a transform fracture zone, Ward (1971) published current ideas on past changes of the configuration of volcanic zones in Iceland. Sæmundsson (1974, 1978, 1980) presented geological data supporting the transform model. He argued (1974) that the Tjörnes Fracture Zone had become active at 4 Ma when the divergent plate margin jumped eastward to the present NVZ position. Previously the margin had extended northward from Reykjanes to Skagi. According to Sæmundsson (1974), relative transform motion along the Húsavík faults and their continuation westward amounted to 60 km during the next 3 m.y., accommodating spreading along the NVZ which extended only as far north as the bottom of Öxarfjörður, and along the Kolbeinsey Ridge spreading axis which

extended southward at least to the Grímsey shoal. He however pointed out that the Tjörnes Fracture Zone is not a simple structure. The only visible signs of transform faulting are the Húsavík faults and their continuation westward. The faults appear as a sharp break in the depth contours, and are also indicated by an eastward shift of the Grímsey shoal relative to Flatey Peninsula. The Tjörnes Fracture Zone is delineated by earthquake activity, and within it there are prominent N-S trending topographic lineations. From east to west there are Melrakkaslétta (high), Öxarfjörður (deep), Tjörnes (high), Skjálfandi (deep), Grímsey shoal (high), Eyjafjörður (deep), and Skagi (high). Sæmundsson suggested that the topography is related to faulting and volcanism. He considered the Öxarfjörður deep to be a clear extensional graben in direct continuation of the NVZ, featuring volcanism along both margins. As to the Eyjafjörður deep, which lies directly south of the Kolbeinsey Ridge, Sæmundsson suggested that it was a feature similar to Öxarfjörður formed during a period when the spreading axis of the Tjörnes Fracture Zone was located on the Grímsey shoal, until Öxarfjörður became the active spreading axis at 1 Ma. After that the Húsavík faults have been less active. Shortly after the geological scenario had been established, Pálmason (1974) published the results of gravity measurements over the shelf off North Iceland. The gravity field displays a prominent anomaly with a low around Flatey, extending WNW towards Eyjafjörður. Pálmason considered the gravity low to be related to the Húsavík faults and suggested that it indicated thick sediments off North Iceland.

Walker (1975) described the N-S trending landforms as an en echelon arranged sequence of volcanic spreading axes connecting the NVZ and the Kolbeinsey Ridge in a similar fashion as the Reykjanes Peninsula volcanic system. Walker's model was partly confirmed by data presented by McMaster et al. (1977) including magnetic, refletion, and bathymetric measurements coupled with sea floor sampling. Most of the TFZ was mapped by McMaster et al. and three main subsidence troughs separated by ridges were identified. They considered the topography to be controlled by tectonism and volcanism. This conclusion was based on very recent signs of both processes on a zone extending from Öxarfjörður westward north of Grímsey and to the Kolbeinsey Ridge. A normal polarity magnetic anomaly coincided with this zone, which has a NNW-SSE main trend. The Grímsey shoal and the area to the west of Eyjafjörður deep are characterized by reverse polarity anomalies. The volcanism was again described as a sequence of en echelon arranged N-S trending segments. Vogt et al. (1980) and Nunn et al. (1983) have published magnetic data that show a very similar general pattern, with details indicating a subdivision into N-S trending segments, coinciding with McMaster et al.'s volcanic ridges. McMaster et al. did not find any WNW-ESE trending faults other than a continuation of the Húsavík faults across sediments in Skjálfandi bay. The main results of Sæmundsson (1974), McMaster et al. (1977), and subsequent contributions to the geology of the TFZ, have been compiled in Fig. 4.

Sæmundsson (1978, 1980, 1986) has published a modified overview of the TFZ in light of new data and observations. Apparently the spreading axis in western Iceland became inactive at 6-7 Ma and was replaced by activity in the present NVZ. Tertiary lava sequences on Flatey Peninsula fall into two age groups, i.e. older than 9-10 Ma and younger than 5 Ma (Cotman, 1979; Sæmundsson, 1980).

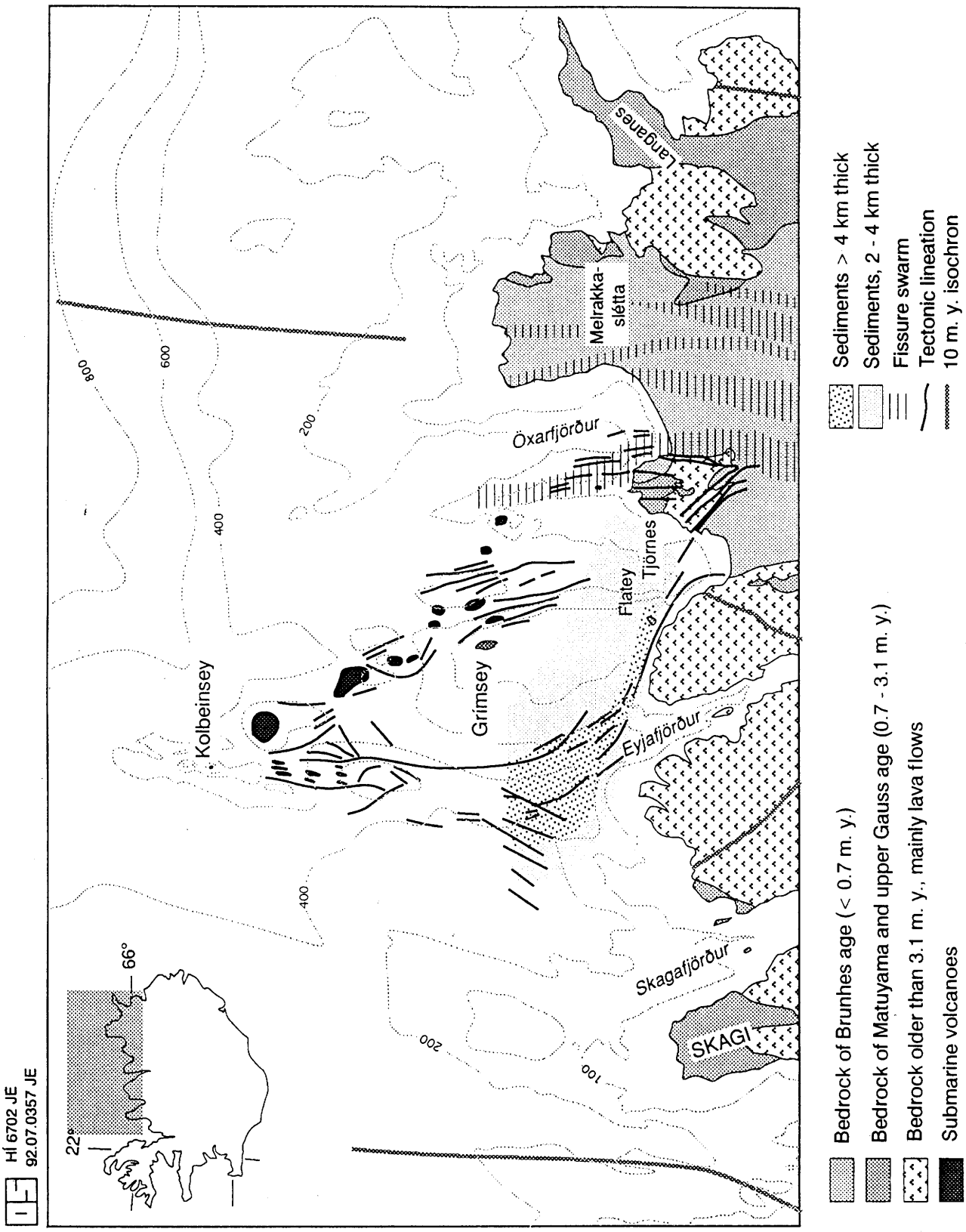

Figure 4. Geological map of the north coast of Iceland showing a simplified picture of tectonic and volcanic features, sediment thicknesses (where known) and chronology. (Ref. Kristján Sæmundsson, 1974, 1980; McMaster et al., 1977; Thors, 1982; Jancin at al., 1985; Flóvenz and Gunnarsson, 1991)

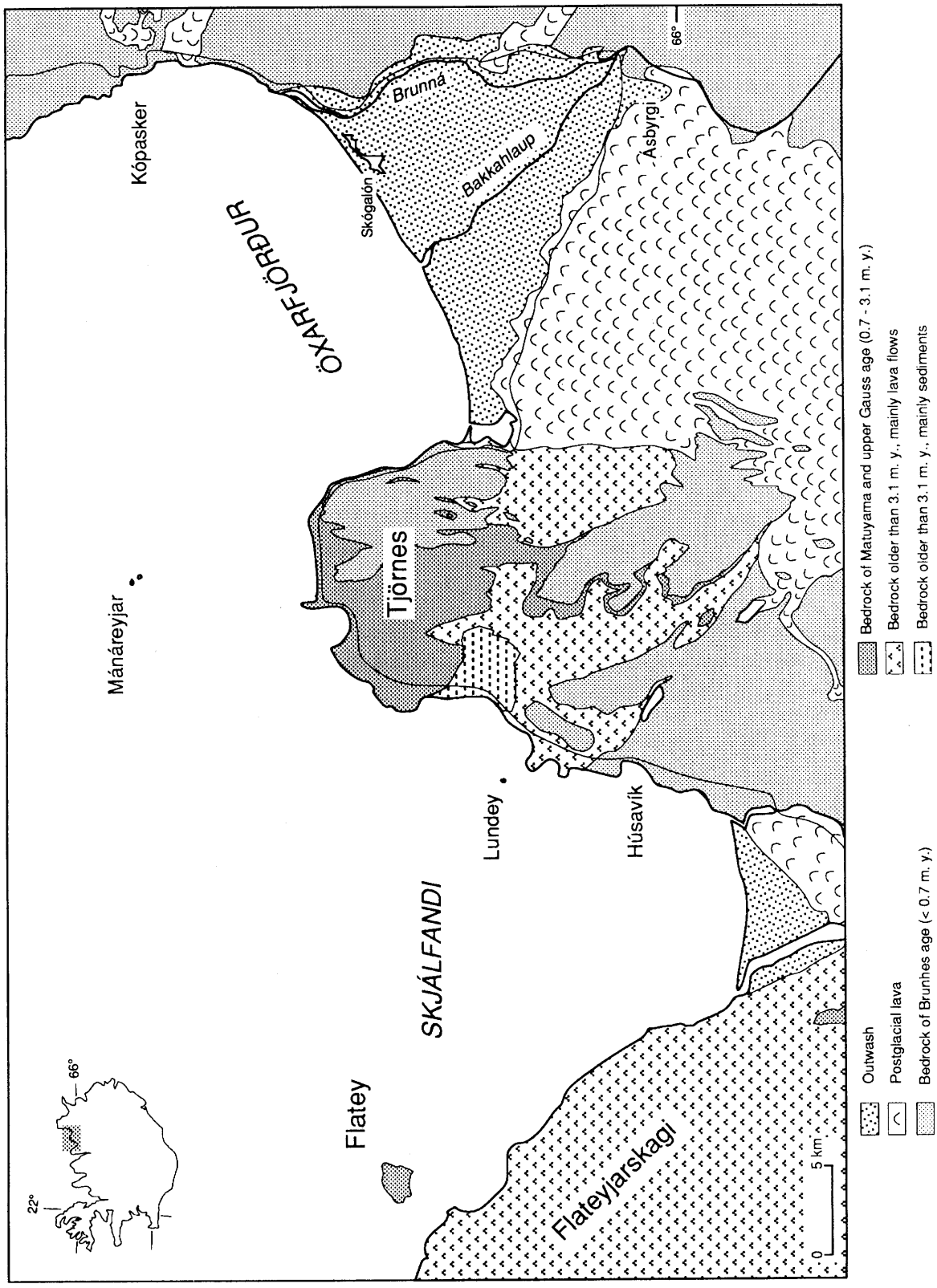

Figure 5. A geological map of the Tjörnes region (ref. Jóhannesson and Sæmundsson, 1989, (geological map); Eiríksson et al., 1987.

The TFZ was originally defined as a seismic zone (Sykes 1967; Ward, 1971). Further seismological studies have not resulted in a simple pattern. Studies of earthquakes in 1968 and 1969 (Einarsson 1976a) indicated a long, well defined seismic zone from the bottom of Öxarfjörður to the southern end of Kolbeinsey Ridge. Einarsson suggested that transform movement along the plate margin between Öxarfjörður and Kolbeinsey Ridge was currently taking place along two parallel transform zones, the Grímsey and Húsavík faults, and possibly partly along the third lineation across NE-Iceland towards the mouth of Skagafjörður. A very strong earthquake in 1963 probably originated on this lineation. This earthquake could be interpreted as resulting from right lateral WNW-ESE movement.

In subsequent review papers, Einarsson and Björnsson (1980; Björnsson and Einarsson, 1981) have expressed reservations about the strict relationship between the rather scattered seismic activity and definite faults. Continuing seismic monitoring coupled with improved positioning of epicentres has led to an improved knowledge about the nature and origin of the activity. Einarsson has published maps (Einarsson 1976b, 1976c, 1983, 1984) that indicate that the seismic activity is not evenly distributed along the Grímsey fault zone, but rather concentrated on N-S trending regions which display an en echelon configuration with respect to the general WNW-ESE trending broad zone. At least 5 such regions coincide with McMaster et al's (1977) volcanic ridges, and two additional ones occur on the east side of Grímsey Shoal and in the outer region of the Skagi Shoal. Seismic activity on the Húsavík-Flatey lineation may, on the other hand, be more easily related to definite faults, along which it is distributed.

Thors (1982) used sparker seismic to investigate the southern part of the TFZ in Skjálfandaflói, around the island of Flatey and westward to the mouth of Eyjafjörður. Gravimetric measurements had indicated a negative anomaly in this area (Pálmason 1974) and it was consequently thought that the upper part of the crust consisted of sediments. The sparker seismic profiles revealed a sharp contact between the Tertiary lava basement of Flatey Peninsula and a sedimentary sequence offshore. The contact is very steep and can be traced from the western part of Skjálfandaflói westward to the mouth of Eyjafjörður. The contact coincides with the eastward shift in depth contours cutting across the Grímsey Shoal. There can hardly be any doubt that the contact represents a major fault, the Flatey fault, which is probably a combination of a right-lateral strike-slip fault and a normal fault with a northerly downthrow. The sparker measurements also showed several faults on the bottom of Skjálfandaflói, cutting across Holocene and older sediments. Historical records of frequent earthquake activity in Skjálfandaflói between Húsavík and Flatey exist (Einarsson, 1976a; Björnsson, 1976; Björnsson and Einarsson, 1981). The youngest faults display an en echelon arrangement along an ESE-WNW trending zone where individual faults tend to strike NW-SE. This zone connects the Flatey fault and the Húsavík faults which display a similar pattern. Another, strikingly similar fault zone lies to the west of the Flatey fault, on the Grímsey shoal. On approaching the Skjálfandaflói deep, the faults become blurred. The topography of the sea floor of Skjálfandaflói is bifurcated by a central, N-S trending ridge, which may either be a tectonic feature or have been left there by glacial erosion on both sides. The ridge consists of volcanic rocks as far north as the fault zone, but is mostly covered by young sediments further north. Still farther north it appears to be carved out of sedimentary rocks. The thick marine sediments on Tjörnes peninsula rest on a Tertiary lava basement that can be traced on the sparker profiles some 5-10 km westward along the floor of Skjálfandaflói. This reflector displays strong topography, which is probably of tectonic origin and has been filled by sediments. Low-angle reflectors characterize the sedimentary rocks to the west, and Thors (1982) interpreted these features as a continuation of the Tjörnes sediments in a nortwesterly direction. The lava flows that form the top of the island of Flatey are seen on the sea floor covering an area roughly five times that of Flatey, apparently elongated in a WNW-ESE direction.

Geological mapping and dating as well as tectonic studies on Flatey Peninsula and on Tjörnes Peninsula have thrown new light on the origin and evolution of the TFZ, and in particular the Húsavík-Flatey fault system (Jancin et al., 1985; Young et al., 1985). Their main conclusion is that the rocks fall into two units of different age and composition. The older part is found on the northwestern part of Flatey Peninsula and consists mainly of tholeiitic lava flows from 9.5 - 13 Ma while the southeastern part is younger than 6.5 Ma and consists mainly of olivine tholeiites. According to Jancin et al. (1985), there are glacial vestiges in the uppermost part of the younger series. The older series is extremely tectonized, particularly close to the Flatey fault, where the dips approach 45°, and a systematic change towards an easterly direction of the strike of dikes and faults is observed coupled with intensified alteration of the country rock. Apparently, a 10 km wide zone to the south of the Flatey fault was severely deformed during the right lateral transform movement along the Húsavík - Flatey fault zone (Young et al., 1985). On the other hand, the younger series shows few signs of such deformation. Young et al. (1985) concluded that the right lateral displacement along the Húsavík - Flatey fault zone had been up to 20 km and lasted for 2 m. y., having taken place prior to 6-7 Ma. This conclusion means that a spreading axis must have been active in Northeast Iceland already before 6-7 Ma, probably roughly in the position of the present axis. The younger series on Flatey Peninsula was erupted within this spreading axis. K/Ar dates and palaeomagnetic data from the Flatey borehole show that the uppermost 550 m of lavas and sediments under Flatey accumulated during the Matuyama chron (0.7 - 2.5 Ma) (Albertsson and Eiríksson, 1989; Eiríksson et al., 1990).

Multichannel seismic profiling within the TFZ shows the presence of a basin with up to 4 km thickness of sediments (Flóvenz and Gunnarsson 1991). The westernmost part of the sedimentary basin is a southward continuation of the Kolbeinsey Ridge spreading axis, but the basin stretches eastward along the shelf towards Skjálfandaflói. Soviet geoscientists have measured p-velocities in the basaltic crust in North Iceland and in the Öxarfjörður spreading axis, and their results were discussed by Flóvenz and Gunnarsson (1991). The data from Öxarfjörður show that sediments in the Öxarfjörður graben become thicker towards north on approaching the TFZ, reaching a thickness of 700 - 800 m at the present coastline in Öxarfjörður. The p-velocity increases locally in a geothermal area in Öxarfjörður, possibly because of lowered porosity due to hydrothermal precipitates (Flóvenz and Gunnarsson, 1991). They pointed out that the TFZ is bounded by two sets of WNW-ESE trending transform fault zones, the Flatey zone in the south and the Grímsey zone (cf. Einarsson, 1989) in the north. Three major N-S trending tectonic valleys were observed on the TFZ: Eyjafjörður Deep, Skjálfandi, and Öxarfjörður. The Eyjafjörður Deep extends southward from the Kolbeinsey Ridge and forms a low in the North Icelandic shelf, marked on both sides by SW-NE trending faults. The eastern margin of this graben system curves ESE-wards towards the Flatey fault, and the Flatey sedimentary basin extends eastwards into Skjálfandaflói. The drilling in Flatey showed that the uppermost 550 m consist mainly of shallow-marine and nearshore sediments of Pliocene-Early Pleistocene age. The rate of subsidence in the basin has amounted to 0.5 - 1.0 mm/yr during the accumulation, but during the last 1 m. y. subsidence has come to a halt or even been reversed (Gunnarsson et al., 1984; Eiríksson et al., 1985; Albertsson and Eiríksson, 1989; Eiríksson et al., 1990).

Jónsson et al. (1991) have recently published a review of the magnetic anomalies in the Iceland region. The magnetic pattern gives many clues to the geological structure of Iceland, being roughly parallel with the spreading axes. The magnetic anomalies are interpreted as resulting from dipping units of volcanics with alternating polarity. Normal polarity anomalies coincide with the presently active volcanic spreading axes. The northernmost normal anomaly on land in Iceland runs from the Mývatn area northwards into Öxarfjörður, where a sharp change takes place. In Öxarfjörður, the magnetic anomaly is bounded by faults at Kópasker

and Húsavík. Jónsson et al. (1991) consider the magnetic pattern in the area to be disturbed by crustal deformation.

In summary the TFZ was originally defined as a seismic zone, and forms a 75-80 km wide and 140-150 km long zone on the North Icelandic shelf between Iceland and Kolbeinsey Island, and from Öxarfjörður to Skagi Shoal. Major earthquakes within the zone are related to right-lateral transform movement, spreading, and volcanism in the zone between the North Icelandic Volcanic Zone in Öxarfjörður and the spreading axis along Kolbeinsey Ridge.

The transform movement is currently accomplished by a zone where a series of NW-SE trending volcanic systems form an en echelon pattern of horsts and grabens on the shelf. The plate margin is very complex.

Previously the transform movement was confined to the much narrower Húsavík - Flatey fault zone, which has formed a substantial sedimentary basin.

It is generally assumed that the Húsavík - Flatey fault zone became active in response to an eastward shift of the spreading axis across Iceland at ca. 6-7 Ma. The northward propagation of the Öxarfjörður spreading axis has reduced the activity on the Húsavík- Flatey fault zone, and the current plate margin further out on the shelf took over. Apparently this happened at ca. 1 Ma, coinciding with the end of subsidence in the Flatey area. Sediments have accumulated further out on the shelf off Skjálfandaflói during the last 1 m. y.

Investigations on Flatey Peninsula indicate that the relatively young sediments under Flatey accumulated after the transform movement had ceased. The 20 km horizontal displacement along the zone of faults and deformation postulated by Jancin et al. (1985) took place during an active period of 2 m. y., before the development of the unconformity between the two lava series, i. e. before 6-7 Ma. However, the weakness caused by the preceding deformation and faulting contributed to continued subsidence and development of the Flatey basin until 1 Ma. or even longer. According to the Jancin et al. results, the Húsavík - Flatey fault system was active already at 9 - 10 Ma, possibly forming a trap for sediments.

The sedimentary environment in Northeast Iceland is related to the tectonic evolution of the area, in particular within the TFZ. The available data indicates that the coastline has not deviated significantly from the present one during at least the last 10 m. y. Tertiary and Quaternary sediments exposed in uplifted segments or penetrated by drilling in the area reveal shallow marine or near-shore sediments alternating with terrestrial sediments and volcanics (Bárðarson, 1925; Norton, 1974; Eiríksson, 1985). It is probable that the sediments in the Tjörnes Fracture Zone are a mixture of terrigenous volcaniclastic sediments derived from Iceland, and organic detritus of marine origin.

3.3 Sedimentary basins on conservative plate margins

Areas where spreading axes become shifted laterally are characterized by alternating basins and ridges. Individual faults may either be straight or curved, and although all the transform movement is sometimes accomplished by distinct faults, blocks and segments along such plate margins may often suffer considerable deformation. The major faults are generally sub-vertical and lie deep in the lithosphere, splitting up into subparallel fault swarms in the uppermost part, which generally consists of sedimentary rocks. Lateral movement along curved, subvertical fault planes is typically accompanied by a sequence of ridges and troughs forming pull-apart basins. The transverse topography along the TFZ may partly be due to such irregularities in the major faults connecting the spreading axes.

Even though the plate tectonic forces control the topography and tectonics at the plate margins forming the required conditions for the development of subsidence and sedimentary basins, the sedimentation is largely controlled by climate, weathering, biological factors, and erosion. During the past 4 m. y. sedimentation has equalled or surpassed the rate of subsidence in the nearshore transitional environments along the coast of Northeast Iceland. This is not uncommon where glacial erosion has contributed to a high rate of sedimentary input from land. The nature of the sediments away from the coastal areas is completely unknown at present, but recent geophysical measurements in Skjálfandi may throw some light on their distribution (Gunnarsson, 1985; 1988).

3.4 Origin and composition of the sediments in Öxarfjörður

The shelf off North Iceland between Skagi and Melrakkaslétta is characterized by alternating N-S trending segments that have either been uplifted or subsided. The only direct source of information on the nature of the sediments on the shelf are the borehole data from Flatey (Gunnarsson et al., 1984; Eiríksson et al., 1990) and the sedimentary sequences on Tjörnes (Eiríksson, 1981; 1985). Sediments dating from the Matuyama and Brunhes chrons in these sections show that the lowlands and shelf have repeatedly been glaciated during glacials separated by ice free interglacial periods. Older sediments are also conserved in Tjörnes with alternating shallow marine sediments and lignite seams of Pliocene and possibly Miocene age.

Although Öxarfjörður is probably the youngest of the North Iceland basins, it is quite possible that older sediments occur at deep levels in the Öxarfjörður sedimentary sequence. In particular, it is possible that an eastward continuation of the Húsavík - Flatey basin in Skjálfandaflói may have extended further east along North Iceland, accumulating Miocene and Pliocene sediments.

Subsidence is prominent in Öxarfjörður, and it is bounded on both sides by step faults. The uppermost stratigraphic units on both sides of the tectonic graben consist of young (Brunhes) lava flows, hyaloclastites, and sediments. On the eastern side these rocks crop out in mountains and fault escarpments on Melrakkaslétta and along the east coast of Öxarfjörður. On the western side, the Tertiary lava basement crops out at Fjöll and along fault escarpments extending northwards along the west coast of Öxarfjörður. These rocks are covered by Matuyama and Brunhes rock units. Postglacial lava flows reach the lowlands to the south of Kópasker and to the northwest of Hafrafell, and they cover much of the lowlands of Kelduhverfi. Most of these lava flows originate from the Þeistareykir volcanic system. Seaward of the lava plain, the glacial river Jökulsá á Fjöllum has built out an outwash delta plain with numerous shallow lagoons, dunes, and a coastal barrier.

Before the data from borehole 4 at Skógalón are interpreted, the present sedimentary environment in Öxarfjörður will be described, and a model for interpreting the core and cuttings is presented.

The connection between Kolbeinsey Ridge and Öxarfjörður along the TFZ has changed during the last few million years as the Öxarfjörður graben has propagated northward. Concurrently with this changed position of the plate margin, changes in tectonic subsidence and volcanism have taken place. Therefore it is very difficult without extensive seismic work controlled by coring, to estimate the age of the sediments in the Öxarfjörður basin. Possibly unconformities are hidden in the sequence, e.g. that the 700-800 m reflector on the coastline marks the beginning of the current phase of subsidence (assuming no unconformities even higher up in the sequence). Data from Tjörnes indicate that subsidence to the east of Tjörnes and an eastward tilting had begun already during the Matuyama chron (Eiríksson, 1985). This would indicate that the uppermost sediments in Öxarfjörður date from the Brunhes and Matuyama and that their accumulation has been affected byof intermittent glaciations of the

Matuyama and that their accumulation has been affected by intermittent glaciations of the area.

Sedimentation during the last ice age was strongly influenced by changes in the size of ice caps. Drastic environmental changes took place from glacials to interglacials. The glacial sedimentary environment may be defined in terms of a few zones with respect to the position of the ice margin. A central, subglacial zone is clearly very small during interglacials, and during past interglacials in Iceland it may have been no larger than the present Vatnajökull glacier. During glacials it may be assumed that the subglacial zone extended to the lowlands and into fjords and shelf areas beyond the present coastline. The subglacial zone is initially characterized by erosion and then by deposition of lodgement till and melt-out till towards the end of the glaciation, leaving an erosional unconformity and a layer of till.

The subglacial zone is bounded by an ice-proximal zone which may be either terrestrial or marine, leading to very different conditions for sedimentation. On land the ice-proximal zone is typically characterized by end moraine complexes and extensive glaciofluvial outwash plains. In the glaciomarine environment, the ice margin may develop morainal banks, especially if it is stationary for some time. These banks are typically deposited upon an erosional surface or a bed of subglacial till, and are built up of sediments that melt out of the basal ice at the ice margin, interfingering seawards with glaciomarine mudrocks and diamictites formed by ice rafting and sedimentation of suspended sediments carried into the sea by glacial meltwater. Meltwater currents, tidal currents, wave currents or other currents in the sea may cause local deposition of sorted material in the glaciomarine environment. The front of the marginal bank may well become oversteepened during continued sedimentation leading to frequent slumps, debris flows and turbidity currents extending seawards into deeper water. If the ice margin is calving off into the sea above the morainal bank, the proglacial sea bed may be covered by glaciomarine diamicton consisting of ice rafted debris that melts out of the icebergs. In other cases, an ice shelf may develop and extend into fjords and onto continental shelf areas. Sedimentation in such environments is characterized by deposition of till carried by basal ice rather than ice rafting. In arctic climates where cold glaciers extend into the sea, a third kind of glaciomarine environment may develop and form an ice shelf zone (Powell, 1984). Sedimentation in such an ice shelf zone is not very well documented, but the environment favours deposition rather than erosion, particularly from debris that is melted out of the basal ice. Various currents may cause sorting and bedding structures in the sediments. Debris flow tongues or lenses are also very probable, extending outwards from zones where the ice shelf meets grounded ice. These may be shoals on shelves or in fjords.

The distal part of a glaciomarine environment consists of a zone that is characterized by icebergs. Sedimentation from melting icebergs is characterized by dropstones and other debris. The conservation potential of these sediments is very good both during expansion and recession of glaciers. If calving takes place close to the limit of grounded ice, the ice rafted debris may interfinger with meltwater sediments and debris flow sediments and turbidites from the marginal zone.

The stratigraphy of the uppermost 325 m of the sediments in Öxarfjörður was investigated by means of boreholes at Skógalón in 1988 (Georgsson et al., 1989). Analyses of the borhole cuttings showed that the uppermost part consisted of coarse grained sediments, gravel and sand, which was interpreted as the bedload of the river Jökulsá á Fjöllum. This was underlain by fine grained marine sediments with fossil shells. A shell fragment at 70 - 80 m depth gave a ^{14}C age of 3000 BP. Basaltic rock fragments deeper in the borehole were interpreted as large boulders or even lava flows. It was estimated that the sediments penetrated by the borehole were younger than 10 000 BP.

4. THE DRILLING OF WELL 4

To continue the investigation of the organic gas in the Skógalón geothermal area, Orkustofnun originally planned to place a temporary casing in well 3 to 320 m depth and obtain a continous core from there to approximately 700 m depth, through a sedimentary succession of that thickness suggested by geophysical data. Well-3 was drilled as a geothermal production well in 1988 and yields 45 l/s of 96°C hot water in an artesian flow. The well was partly financed by the local community and thus in joint ownership with Orkustofnun. In the first proposal it was intended to install a 4" temporary casing in the well and spot-cement it at the shoe. The well was then to be core-drilled to the target depth, leaving the upper production part intact.

In discussions with the drilling contractor, Jardboranir ltd, in March 1991, the firm voiced strong reservations to deepening the well as planned, partly due to the poor foundation of the well-cellar. Instead the drilling contractor put forward a proposal to drill a new well. In addition, the local owners of well-3 were concerned that it might be damaged and opposed its deepening. The contractor's proposal for a new well was therefore approved, and a contract to the effect signed on June 7, 1991. Well-4 is 30 m west of well-3 (Fig 1).

The drilling of well 4 to 325 m depth, the casing (3 1/2") and the cementing were completed by a Wabco 2000 rig in August 1991. Core-drilling didn't begin until September 21-22, a month later than planned, as the Canterra CT-312 rig was delayed on other work. Below there is a brief description of the core-drilling operation below 325 m depth. More detailed descriptions are to be found in the contractor's drill-logs, and in notes and letters at Orkustofnun.

After alteration to and adjustment of the rig to fit it to the well-head and delays due to bad weather, the core drilling started on September 25th. Coring was successful for the first two days, the depth was 362 m on the evening of the 26th of September. Core recovery was nearly 100%. Below 360 m the temperature rose and water from an artesian aquifer started flowing. Drilling continued to 370 m, but at a slow rate, mainly because of inadequate equipment. A specially designed safety valve to fit the corebarrel didn't function properly due to a construction fault. Core recovery was poor in the 360-370 m interval. On the 28th of September the wireline broke at 371 m depth leaving the overshot in the well. In order to retrieve it the drill rods had to be taken up. To overcome wall collapses, the well and the artesian aquifer at 360 m depth were cemented up to casing depth on the 30th of September.

Re-drilling from 318 m depth started October 1. Drilling continued until the following evening down to 365 m when a safety pin in the overshot broke and the corebarrel stuck. The next day a gale force blizzard drove everybody off the drill-site.

After a crew break drilling proceeded slowly on October 8 down to 371 m depth - the same depth as on September 28. The following day additional 10 m were penetrated and on October 10 the drilling rate improved and so did the core recovery. At noon the next day the drillstring stuck again at 425 m depth and a drillpipe broke. After a delay the drilling continued down to 440 m depth on October 13. Core recovery improved from 390 m depth and was fairly good to 446 m depth, apart from an interval near 430 m depth. Descriptions of the core and the core recovery are given in chapters 5 and 6.

At this point the budget was more or less exhausted, including additional 2.7 mkr funding provided by the Ministry of Industry. In view of all the problems and the inadequate conditions of the drillrig the operation was stopped. On the last day, October 14th, 15 additional m were drilled and the final depth reached was 455.3 m. The last 9 m were never recovered because the drillstring broke again, this time at 420 m depth. A corebarrel, 35 m of

drillstring and a drillbit had to be abandoned in the well.

Figure 6 shows the actual versus the schedules drilling time for both rotary bit and core drilling parts of the operation.

Several geophysical well-logs were run with and without the rig on the hole. The heating-up period was monitored thoroughly. Samples for chemical analyses were collected during the discharge period of the well. The results of these are described in chapters 6 and 7. Finally the well was closed and the wellhead partly removed as it will become covered by water and ice every winter. General information on wells 1 to 4 is reported in Table 2.

Table 2. Drilling information on wells 1-4

Location No	Well No	Drilling from	period to	Depth m	Rig name	Drillbit diameter inches	Casing size inches	Casing depth m
62551	ÆR-01			23	Locals	Jetting	10	23
62551	ÆR-01	29-06-87	17-07-87	71.2	Hydreq G	7 7/8	5 1/2	69
62551	ÆR-01	07-08-87	07-08-87	71.2	Tractor	Jetting	2	69
62552	ÆR-02	05-08-87	18-08-87	101.6	Hydreq G	8 1/2	6 5/8	16
62552	ÆR-02	05-08-87	18-08-87	101.6	Hydreq G	8 1/2	5 1/2	101
62553	ÆR-03			30	Locals	Jetting	14	30
62553	ÆR-03	19-07-88	25-08-88	136	Wabco	12 1/4	9 5/8	119
62553	ÆR-03	19-07-88	25-08-88	322.3	Wabco	8 1/2	7	322
62554	ÆR-04			5.8		Tractor	14	5.8
62554	ÆR-04	24-06-91	02-09-91	78	Wabco	9 7/8	8 5/8	78
62554	ÆR-04	24-06-91	02-09-91	325	Wabco	6 3/4	3 1/2	325
62554	ÆR-04	20-09-91	19-10-91	455.3	Canterra	3		

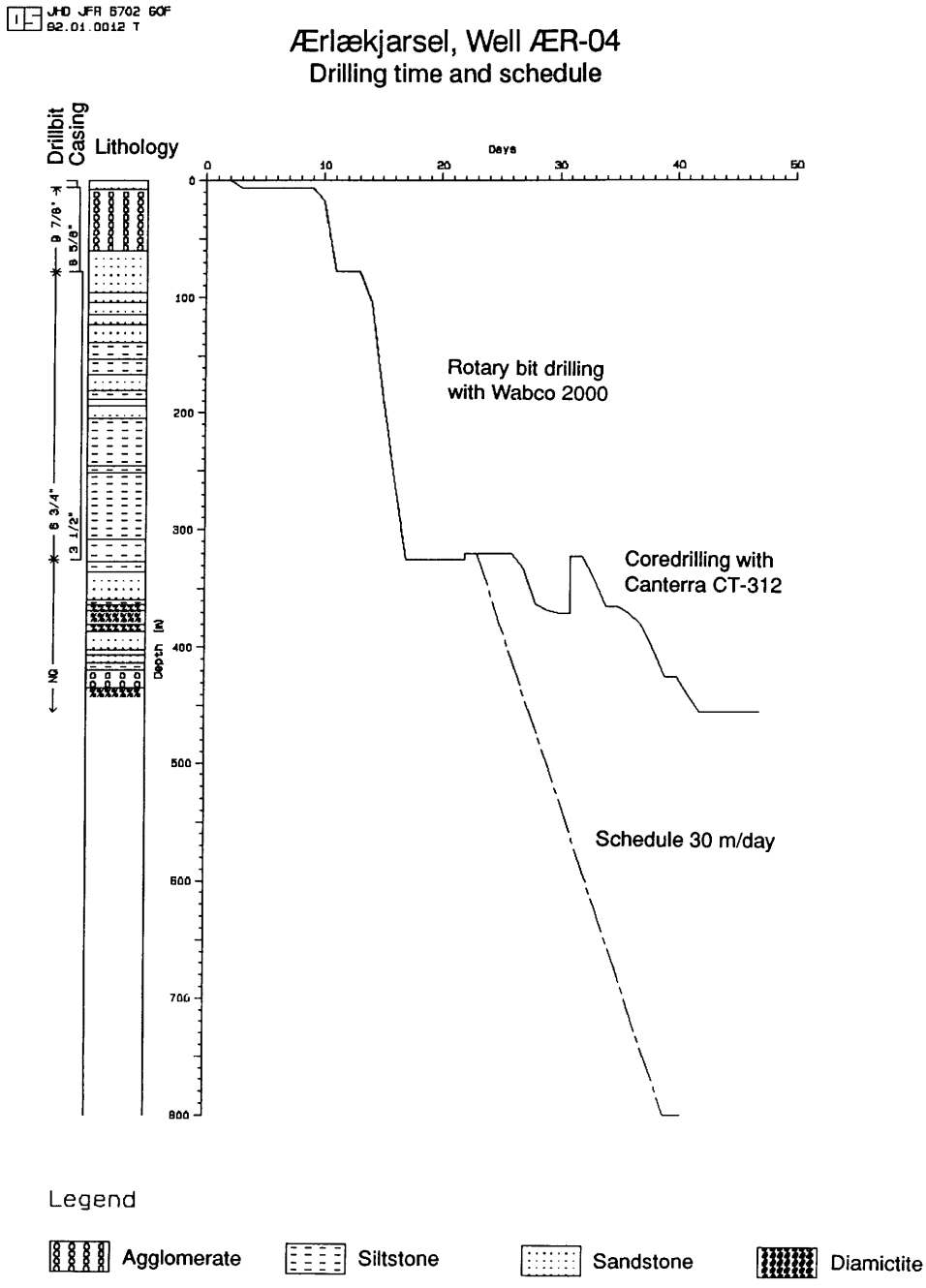

Figure 6. Actual versus scheduled drilling time for well-4

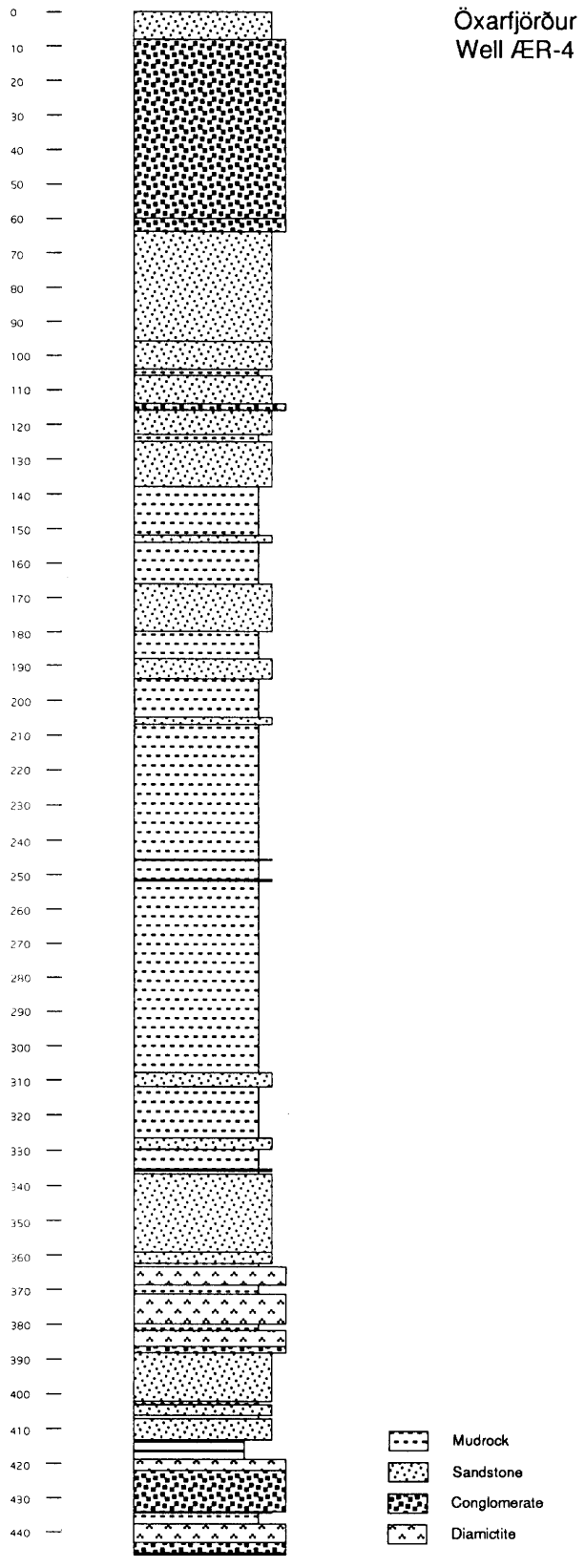

Figure 7. A simplified geological section based on cuttings and core from borehole 4, showing vertical changes in lithology and grain size.

5. GEOLOGICAL ANALYSIS

5.1 Analysis of cuttings and core

The drill-cuttings from well-4 were analysed in the same manner as were drill-cuttings from well-3 in 1988. Cutting samples were collected at 2 m intervals. The cuttings were washed clean in water in a fine sieve and analysed submerged in water under a binocular microsope. The result is similar to that from well-3. It is nevertheless quite supportive to analyse both wells, e.g. to evaluate wether basaltic cuttings belong to a lava flow or boulders. The same arguments hold for the sediments.

The drill-core was analysed under a microscope as it emerged from the well. Grain-size, structure, colour and other sedimentological features were noted along with other investigations and plug-sampling. In Table 3 the main characteristics and the classification of the sedimentary succession are compiled and the stratigraphic columns in Fig. 7. The same stratigraphic profile, the drill bit diameter, the casing sizes and the casing depths is depicted in Fig. 8.

The river Jökulsá á Fjöllum has built a delta into Öxarfjörður from the south. The topmost, coarse grained unit of the delta reaches a thickness of 65 m in borehole 4, and the relationship to the present environment is obvious. Below that the sediments become more fine grained, and marine fossils begin to appear. This change shows that the delta and the present coastline is currently being extended northward into the fjord. Öxarfjörður is broad and open enough to allow access of high energy waves which prevents the formation of a lobate delta. The bedload of the river is immediately dispersed by the sea and carried longshore away from the river mouth, which must cope with a bar extending eastward. A sequence of lagoons has developed behind the coastal bar. Some of these lagoons are seasonal in character, and may form traps for fine grained sediments such as sand and mud. The interval between 60-64 m in borehole 4 is characterized by alternating gravel and silt beds that may be interpreted as alternating beach and lagoon sediments.

Below 64 m depth there are considerable units of sand that have probably been deposited on the shoreface. A few marine fossils, in particular broken molluscs and foraminifera, are preserved in these units. It is not possible to be exact about water depth at the time of formation without special analysis of the fossil fauna. With respect to grain size and conservation state of fossils it is considered likely that the sand was deposited below the lower limit of wave erosion, perhaps at a depth of 30-50 m. The sand has probably been transported outward onto the shoreface by rip currents, wave currents, and tidal currents. The rather fine grained sand dominates down to a depth of 140 m in borehole 4, but below that there is an interval with alternating units of mud and sand down to a depth of 210 m. It is not possible from the cuttings to define the type of bedding. The sand units may either have been transported along the sea bottom with turbidity currents or other bottom currents, and the mud has either settled out of suspension or been carried with turbidity currents along the delta slope. Shell fragments and microfossils were found in these units.

In the depth interval 210-246 m the sediment consists of 50-75% silt, the remainder being fine sand. Below a very thin layer of gravel at 246 m the sediment becomes even finer grained with clayey silt extending down to 324 m, where coring was started. In the uppermost 12 m of the core (down to a depth of 336.7 m) the sediment is very fine grained. At the top of the core there are laminated sands and silts, which have been deformed by a dropstone. Fig. 9 shows the appearance of the sediment at a depth of 328.6 m, being a typical turbidite sediment with graded units of sand and silt. At the time of formation, the coastline of the Öxarfjörður delta has been several km further south inland than it is to day. Fluvial sediments carried to the sea

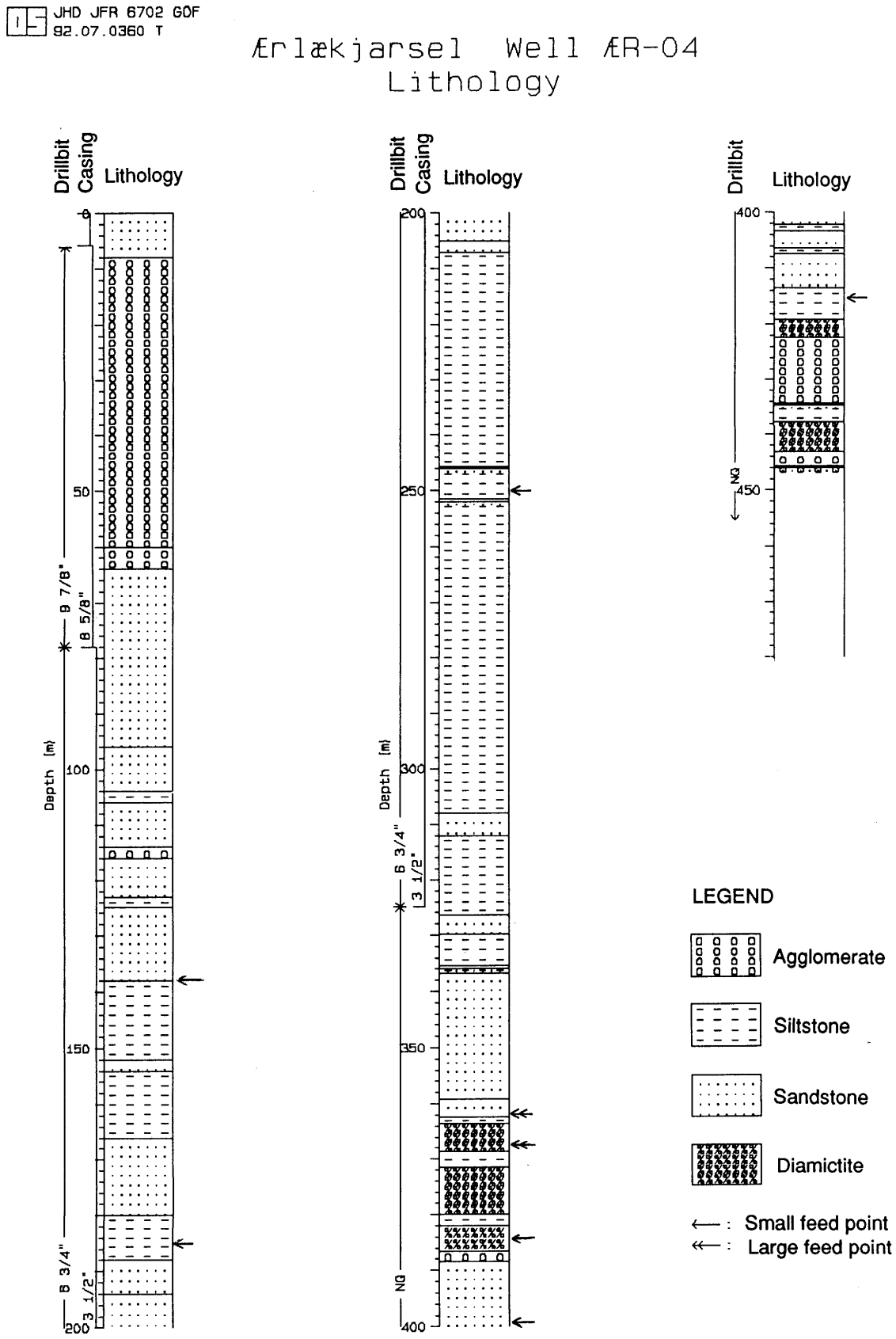

Figure 8. Lithology, casing and drillbit diameter of well-4.

have been deposited in the nearshore environment below the active wave base, where the bedload and the suspended sediments have built out a delta slope. Oversteepening due to continued sedimentation on the unstable slope, storm waves, floods, or even earthquakes may now and then have triggered slumps initiating debris flows and/or turbidity currents from the delta slope. The core displays signs of rapid sedimentation where each unit of sediment did not consolidate between events of sedimentation. There are few signs of quiet conditions in this interval, and the prodelta area must have been further north in a deeper part of the fjord. At a depth of 332 m the bedding becomes more complicated with intricate convolute bedding, indicating soft but coherent sediment deformation caused by slumping or shear stress from currents over the sediments (Fig. 10). Frequent load casts and ball and pillow structures also indicate rapid sedimentation and frequently reversed density gradients. The core becomes more coarse grained and sandy again at 336,7 m depth, but signs of slumping continue. There are many silty clasts in the core, indicating that the slumped sediments consisted of interbedded silt and sand. The sand has been cohesionless and liquid due to excessive pore water but the silt more cohesive (Figs. 11, 12). The increased grain size may reflect increased energy, perhaps due to increased runoff and sedimentary input leading to an advancing of the coastline. Lowered sea-level is another possibility. The latter possibility might explain increased signs of slumps involving semi-consolidated silts, because sediments that were deposited in relatively deep and quiet conditions became subjected to an increased rate of sedimentation and even erosion. The sediment remains sandy down to a depth of 363.5 m, where it is replaced by a very poorly sorted mixture of subrounded boulders, sand, and mud. The sediment is distinctly bedded, and contains shell fragments. In the lower part of this unit the mud appears to have settled out of

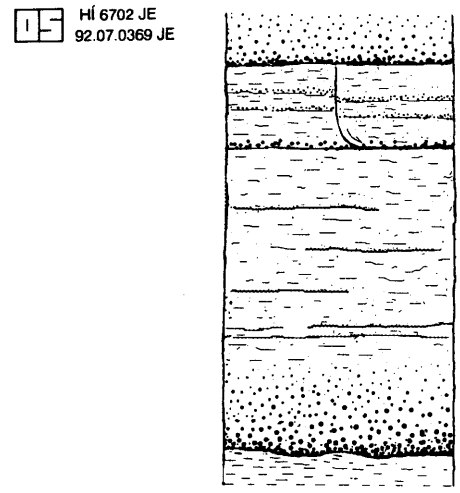

Figure 9. Turbidite units of sharp-based sand grading upwards into silt. Note minor, synsedimentary fault. Depth of 328 m.

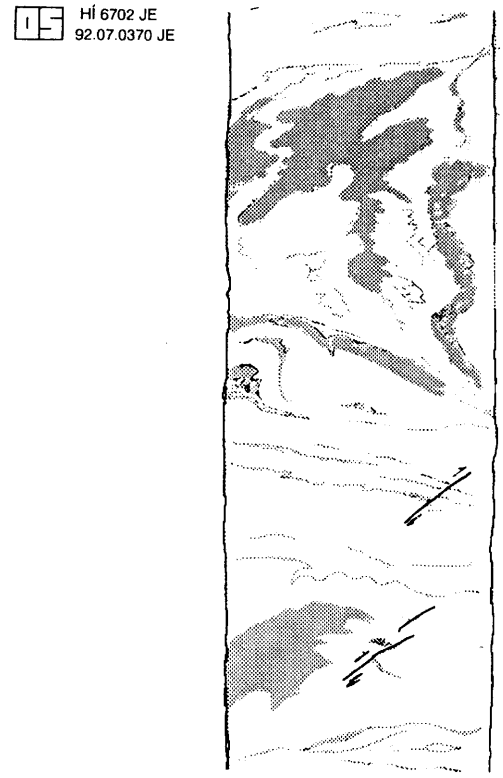

Figure 10. Bedding contacts between silt and sand at a depth of 333 m. The original bedding has been deformed by penecontemporaneous slumping at the water-sediment interface.

suspension, but higher up the matrix becomes sandy, with the sediment still matrix supported. This unit of diamictite was probably deposited under an ice shelf or in an iceberg zone off a glacier snout calving into Öxarfjörður. At shallower core depths there are only single dropstones that may have been carried out into the fjord during winter floods or glacial bursts from the river Jökulsá á Fjöllum. In the interval between 363-386.5 m there are three diamictite beds separated by two 2 m thick silt beds. Under the diamictite, from 386.5-413.5 m there is a unit with laminated, fine sand with silt laminae (Fig. 13), becoming gradually more coarse grained upwards, grading into a 3 m thick conglomerate at the top. This unit consists mostly of graded turbidites with frequent folding and convolute bedding in the finer grained parts (Fig. 14). No fossils were found in this interval of the core, and the sediment was probably deposited on a regressional delta slope. Such delta sequences are generally characterized by upwards coarsening sequences. From 413.5 down to 419 m the core consists of brown clay, indicating very quiet conditions, probably in the sea far from the coast. The lowest part of the core is rather coarse grained, consisting of two pairs of conglomerate and diamictite, separated by a siltstone bed at 435-438 m. The diamictite units are very similar to those found higher in the core, and have probably been deposited in water. The conglomerate forming the lower part of each pair is poorly sorted, but the pebbles are not separated by the matrix. Silty lenses in the conglomerate indicate variable current.

The uppermost signs of glacial influence in the Öxarfjörður lie buried at a depth of 350 m. The sediments above the glacial units show signs of transgression followed by regression where the Jökulsá outwash delta has been built out into the fjord across delta slope and prodelta sediments. It is probable that the uppermost 350 m were deposited during the last 10 000 years, but the diamictite beds may have been deposited at

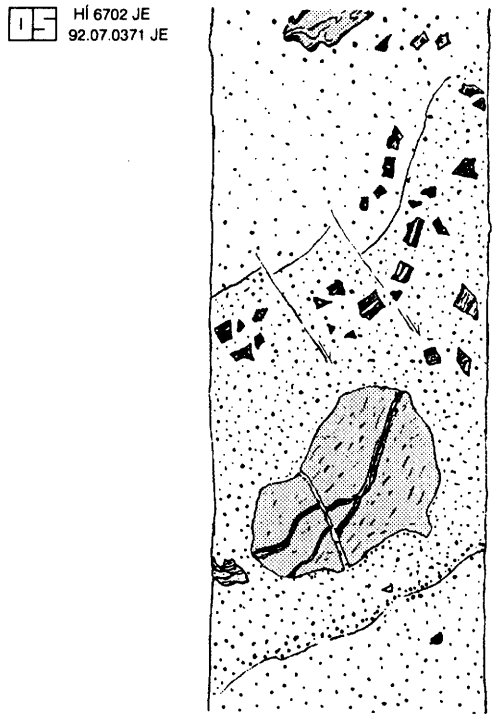

Figure 11. Brecciated silt beds (dark clasts) in a sandstone at a depth of 358 m. The silt has been deposited on waterlogged sand and crumbled later due to quicksand movements.

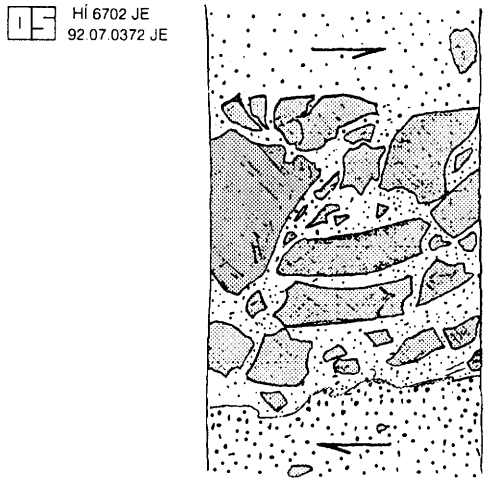

Figure 12. Brecciated silt clasts (dark) in fine grained sand at a depth of 358.5 m. The silt has originally formed a continuous layer which has been shattered after compaction. The fractures indicate horizontal shear stress, perhaps caused by a strong current or a slumping event across the bed.

some stage during or towards the end of the last glaciation (Weichselian). Fine grained units in between the diamictite beds indicate that some changes in the extent of glaciation took place, but it is not possible to estimate the extent of deglaciation. There is nothing to indicate that the lowest sediments in borehole 4 are older than at most a few hundred thousand years old.

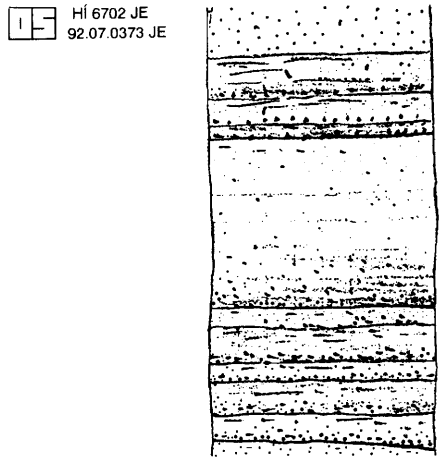

Figure 13. A unit of undisturbed sandstone at a depth of 409 m.

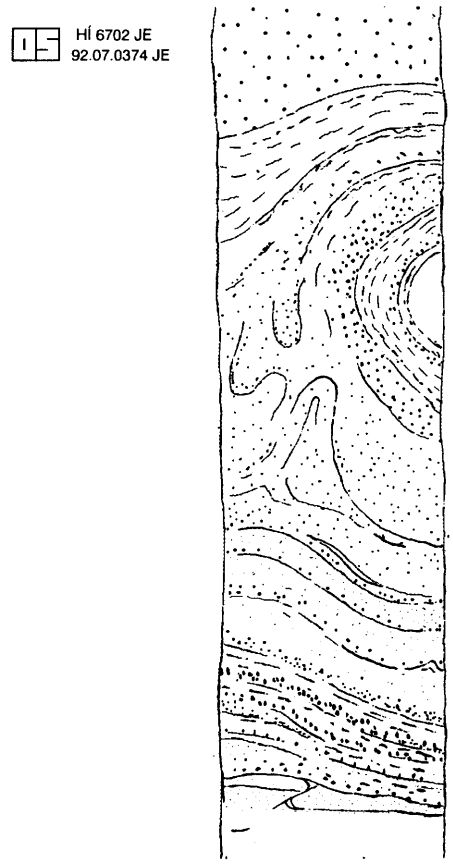

Figure 14. Folds in sandstone and siltsone at 409 m. The sediment has slumped along the bottom without losing cohesion.

Table 3. Stratigraphy of well 4

Depth (m) From	to	Facies[1)]	Rock type	Remarks
0.0	8.0	S	Sand	
8.0	60.0	G	Gravel	
60.0	64.0	G	Gravel	Alternating sandy gravel and silt
64.0	96.0	S	Sandstone	Lithified basaltic glass and minerals, some rock fragments. Intercalated silt layers
96.0	104.0	S	Sandstone	Sandstone and siltstone with mineral veins. Occasional fossil
104.0	106.0	F	Siltstone	
106.0	114.0	S	Sandstone	
114.0	116.0	G	Conglomerate	
116.0	123.0	S	Sandstone	Distinct layering. Shell fragments.
123.0	125.0	F	Siltstone	
125.0	138.0	S	Sandstone	
138.0	152.0	F	Siltstone	Fine sand at top, ca 50% diminishing downwards Foraminifera, Ostracode, and shell fragments (bivalves?)
152.0	154.0	S	Sandstone	Fine-grained, silty sandstone with shell fragments and foraminifera
154.0	166.0	F	Siltstone	Silt with shell fragments, coarse-grained in part
166.0	180.0	S	Sandstone	Fine to medium grained sandstone
180.0	188.0	F	Siltstone	Sandy siltstone with occasional black basaltic glass grains
188.0	194.0	S	Sandstone	Silty sandstone, middle part coarsest
194.0	205.0	S	Siltstone	Siltstone with shells
205.0	207.0	S	Sandstone	Fine-grained sandstone
207.0	245.7	F	Siltstone	Siltstone with shell fragments, finer grained in upper part
245.7	246.0	S	Sandstone	
246.0	251.5	F	Siltstone	Clayey silt, 10% sand grains, chiefly basalt fragments
251.5	252.0	S	Sandstone	Poorly sorted sandstone; brown clayey veins
252.0	308.0	F	Siltstone	Siltstone, shell fragments at 287 m
308.0	312.0	S	Sandstone	
312.0	326.5	F	Siltstone	Siltstone, lower part laminated with ca 2 cm sand layers with sharp upper and lower contacts. No grading. Boulder has sunk into a soft sediment and concaved its base
326.5	329.8	S	Sandstone	Graded fine sand layers, 5-25 cm, generally 10-12 cm. Laminated silt units with drop-stones. Sand layers with sharp base contact grading upwards to silt Synsedimentary faults, but no evidense of slumping
329.8	335.4	F	Siltstone	Laminated siltstone with a few fine sand layers Many drop-stones. Slump folds common. Drop-stone at 331.8 m has not submerged into the mud. Sand and siltlayers have coated this drop-stone
335.4	335.9	S	Sandstone	Poorly sorted lens at top (diamictite?), otherwise fine sand with up to 2 cm siltstone fragments
335.9	336.7	F	Siltstone	Faintly thin-layered to massive siltstone with distorted sandbands
336.7	359.2	S	Sandstone	Normally graded, to medium-grained at top Angular, siltstone fragments near top. Silt lenses in lower part. Drop-stones common at 345 m depth
359.2	362.4	S	Sandstone	
362.4	363.5	F	Siltstone	
363.5	368.7	D	Diamictite	
368.7	371.5	F	Siltstone	Siltstone with sparse sand grains. Fossils?
371.5	380.0	D	Diamictite	Diamictite, chiefly boulders in silt matrix; stones at 374-375 m and at 377m
380.0	382.0	F	Siltstone	Laminated silt- to sandstone
382.0	386.5	D	Diamictite	Large boulders in silty matrix

Continues on next page

Table 3, continued

Depth (m) From	to	Facies[1)]	Rock type	Remarks
386.5	388.4	G	Agglomerate	Normally graded, grain supported texture. Laminated fine-
388.4	402.2	S	Sandstone	to very fine sandstone. Upper part very thinly bedded, each layer grading to siltstone. Redbrown colour, sometimes most pronounced at the bottom in graded units
402.2	403.3	F	Siltstone	Thinly laminated siltstone
403.3	406.4	S	Sandstone	Medium- to thinly bedded fine sandstone. Drop-stones at 404,3 m Graded units of thinly bedded sandstone to silty claystone Several siltstone layeres are fragmented due to subsidence into the mud
406.4	407.4	F	Siltstone	Thinly laminated siltstone and very fine-grained sandstone Massive at base.
407.4	413.5	S	Sandstone	Very thinly laminated to laminated units of fine sand and silty claystone. Usually an erosion surface at each base Intraformational siltstones clasts occur, loadmarks in some units
413.5	419.0	F	Claystone	Brown claystone, interbedded silt layers Grades upwards to laminated coarse siltstone and claystone
419.0	422.3	D	Diamictite	Gray silt matrix, pebbles at 419 and 422 m. Probably marine fossils
422.3	434.3	G	Conglomerate	Poorly sorted, matrix chiefly sand, greenish upper part
434.3	434.6	S	Sandstone	Very fine-grained, laminated near base
434.6	437.8	F	Siltstone	Brown and gray silty claystone, (25 cm units), becomes coarser and more grayish near top, sand laminae in the top 10 cm
437.8	443.3	D	Diamictite	The bottom part is pebbly silt, presumably deposted in water More pebbly at top with sandier matrix upwards
442.6	445.8	G	Conglomerate	Poorly sorted
445.8	446.0	S	Sandstone	Coarse-grained
446.0	446.3	G	Conglomerate	Poorly sorted

[1)]: Facies explanation:

G: Gravel or conglomerate. Mean grain-size > 2.0 mm

S: Sand or sandstone. Mean grain-size 0.0625-2.0 mm

F: Silt or siltstone. Mean grain-size < 0.0625 mm. Mud includes silt and clay in any proportions

D: Diamictite. Poorly sorted mixture of boulders, stones, pebbles and sand grains in a silty matrix. Individual grains float in the matrix.

5.2 Hydrothermal alteration, organic remains and thermal conditions

The distribution of secondary minerals is shown in Fig 15. While the secondary alteration in drill-cuttings from the upper part of the well was analysed, the secondary mineral distribution within the cored part of the well was emphasized. Routine methods were applied, i.e. hand specimen analyses, with and without a microscope, thin section analyses and XRD (X-ray diffraction) analyses. In parallel with this, samples were selected for TOC (total organic carbon)analyses, the results of which are also shown in Fig 15.

The TOC was measured at DGU as mentioned earlier. The TOC-screening was carried out to select samples for further hydrocarbon analyses (EOM, GC, isotopes) in order to determine their origin, environment, evolutionary path and composition, distinguish between terrestrial or marine origin, and to relate them to the presently active hydrothermal system or to an older one. Normally it is useless to attempt EOM if the TOC value is below 1-2 % according to DGU. As seen in Table 4 and Fig 15 the TOC ranges from 0,02-0,05 %. Thus, further tests on the plugs were not attempted. The low TOC implies that the organic gas did not originate within the strata penetrated sofar. In addition, organic gas emission from the aquifer at 370 m depth suggests a deeper origin for it.

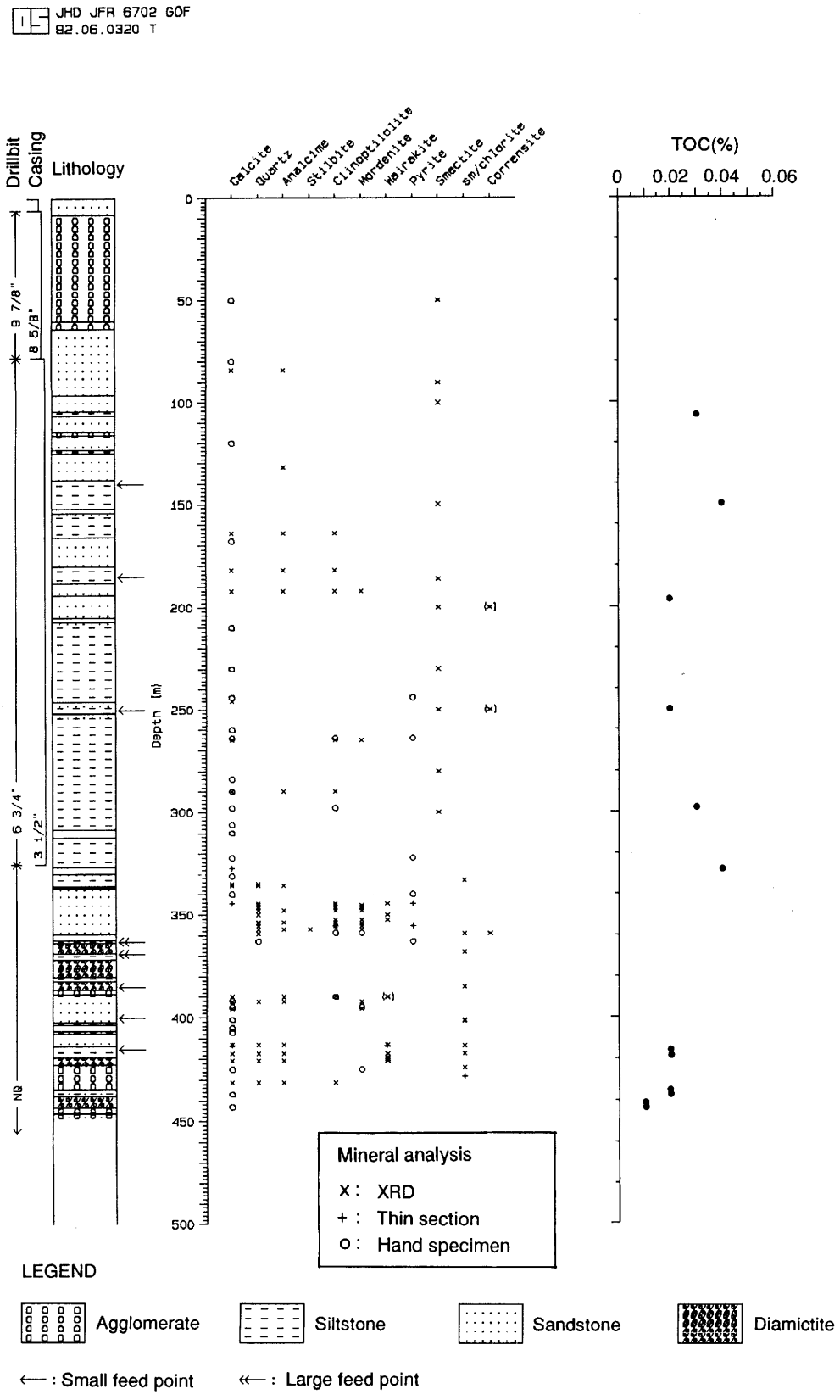

Figure 15. Lithology, secondary minerals and TOC in well 4.

Table 4. Total organic carbon (TOC) in selected samples.

Depth (m)	TOC (%)	Depth (m)	TOC (%)
106,0	0,0280	369,8	0,0281
150,0	0,0437	392,6	0,0472
196,0	0,0242	416,2	0,0176
250,0	0,0170	418,7	0,0183
298,0	0,0282	434,9	0,0203
327,8	0,0351	436,8	0,0220
330,6	0,0181	441,6	0,0139
333,1	0,0281	443,4	0,0138
342,6	0,0324	444,1	0,0187
353,6	0,0302	445,8	0,0140

The locations of aquifers (feed-points or -zones) in Fig 15 are shown by arrows. The locations of new aquifers and hydrothermal alteration are often compared because alteration intensity and/or the occurrence of new minerals commonly accompany new aquifers. Referring to Fig 15, hydrothermal alteration in the uppermost 200 m of the strata is limited. The top 50 m are unconsolidated and secondary minerals are rare. Below 50 m depth the consolidation of the sand is intense enough to speak of sandstone, the cementing minerals being smectitic clays and some iron-oxide (limonite, goethite ?). The first zeolite veins appear below 100 m; their intensity increasing at 130 m depth. The increase may be related to an aquifer at 135-145 m depth in well-3, which is 30 m east of well 4. Aquifers were noted at 132 m and 150 m (2.6 l/s) during drilling, inferred from circulation increases (artesian). Undoubtedly this feed zone is connected to an aquifer in well-3 at 135-145 m. At 208 m depth the circulation increase reached 8.8 l/s, while no further aquifers are noted down to 325 m. The temperature profiles indicate feed zones at 130-150 m depth, 180-190 m depth and at 240-260 m depth.

Chabazite and analcime, analysed by XRD, and a fibrous zeolite (thomsonite?) are the first zeolites found. These are formed at low temperatures and may be thermally stable at present as well as smectite. The clays were XRD-analysed at every 50 m interval. The chabazite and thomsonite distribution was investigated in detail, the results implying a restricted distribution (Fig 15). At 200 m depth the mineral assemblages change. Calcite in veins becomes common, the clays become more dark green and pyrite appears as well as clinoptilolite (an alkali rich variety of heulandite). Both smectite and corrensite (formerly swelling chlorite) are found by XRD analysis.

Close to 300 m depth the zeolite assemblage changes again. In hand specimens fibrous zeolites (scolecite/mesolite and mordenite), heulandite and laumontite all appear common, while that observation is not confirmed by the XRD analyses, which only show clinoptilolite and mordenite (Fig 15). The early zeolites may be pseudomorphed but a thin section study is needed to support that conclusion. According to the XRD data, a somewhat unusual zeolite assemblage dominates the sedimentary succession as shown in Fig 15 (i.e. compared to Icelandic hydrothermal systems which are predominantly hosted in volcanics). Four zeolite types dominate the vein mineral assemblages, i.e. analcime (an), clinoptilolite (cli), mordenite (mo) and wairakite (wai). The thermal stability of three of these is poorly known while the wairakite stability above 200°C is fairly well established. The present-day temperature in the cored part of the strata ranges from 120-150°C. Both clinoptilolite and mordenite appeared to be in the process of growing within the veins, which is some cases are only partly infilled.

In addition to the zeolites below 300 m depth, quartz (qtz), calcite (cc) and mixed layered clays (mlc) of chlorite-smectite (chl-sm) are common. Experience from active high-T fields in Iceland suggests that the wai-qtz-mlc assemblage only forms at T > 200°C. This implies that the formation temperature (T_F) within well 4 exceeded 200°C in the past, while the T_F is close to 150°C at 370 m depth today. This is an important conclusion implying that the geothermal system at Skógalón is more akin to a high-T system than a low-T system. A fluid inclusion study was done for support.

Successful measurements of the homogenzation temperatures (T_h) were done on calcite from two samples. (Fluid inc. were not found in the qtz. Wai contains a lot of fluid inclusions but suffers decrepitation upon heating). The T_h in primary inclusions from 413.2 m depth yielded 206°C and 238°C, and ranged from 230-240°C in 6 additional inclusions. In a sample from 421.3 m the T_h ranged from 228-248°C in 6 inclusions. Accordingly, the T_h below 400 m depth suggests that the calcite precipitated from a 200-250°C hot fluid, in good agreement with the temperature estimate from the wai-qtz-mlc assemblage. Before well-4 was drilled the Skógalón area was considered a Low-T system from the evidence of surface character and fluid composition; possibly a runoff from the Bakkahlaup High-T system located several km south of Skógalón; both are witihin an active fissure swarm. Hithereto the chemistry of the Skógalón thermal fluid has only shown Low-T characteristics, while the first signs of High-T character are seen in the deep fluid of well 4 (Ch 6).

The thermal effect on petroleum, assuming that the geothermal system is a High-T- rather than a Low-T system, will now be considered. Presumably the High-T activity relates to intrusive activity related to the Krafla volcanic system which started propagating northwards 1 m.y. ago (Ch 3). The frequency of rifting episodes may be 300 years by comparison with the last two rifting episodes in the Krafla system (Björnsson, 1985). During rifting episodes accompanied by volcanism, magma may have formed dykes in the Öxarfjörður fissure swarm at depth, far away from the volcanic orifices within the Krafla volcano. (Presumably such dykes are rootless, and this may be of importance for source rock maturation). During the Krafla rifting episode 1975-1984 the geothermal surface activity in Öxarfjörður increased.

High- or increasing temperature would speed up kerogen maturation considerably. Thereby, high-temperature activity could be one of the fundamental reasons for the development of organic gases at Öxarfjörður. Conversely, high temperatures, e.g. from a neighbouring a magma body, would lead to thermal cracking of the longer hydrocarbon chains in petroleum, leaving us with a dry gas field and graphite. An oil field would in that case change into a less valuable gas field.

Gas fields are catagorized as wet or dry, the wet fields being intermediate between oil- and gas fields. The result of isotope analyses of the Skógalón gas either catagorize it within the wet- or dry fields (Ch 7). That might imply that possible petroleum at depth may have suffered thermal cracking, and that undamaged petroleum might be preserved elsewhere within the area, had any large scale petroleum development taken place there in the first place. It is just as possible that the organic gas is developing from a "cooking" lignite bed, similar to that in SE-Iceland which resulted in minute petroleum formation (Jakobsson and Friðleifsson 1989). As yet unsuccessful attempts have been made to establish the origin of the gas because deposits of liquid or solid petroleum are still to be found.

5.3 Fracture analysis and porosity

The mineral vein intensity, inclination and thicknesses were measured during the secondary alteration study. Effective porosity was also measured from plug samples and compared with the neutron-neutron well-logging profile (Ch 6) which is a measure of the total water content in the rock formation.

In Fig 16 a histogram showing the fracture density is presented. The data depends on the core recovery (CR) shown. Accurate data on the fractures is only to be expected where CR is near 100%, i.e. from the 325-360 m, 390-400 m and 408-426 m depth intervals. The effective and total porosities are also shown in Fig 16.

The mean fracture density is 1.5 fracture/m from 325-360 m depth. Deeper in the well the fracture density appears similar though the core recovery is much poorer. Apparently 1-2 fractures are to be expected per metre of the sedimentary succession cored sofar.

The fracture widths (mineralvein widths) were also estimated or measured, and found to range from < 0.1 mm to 7.0 mm. About 44 % are <0.1 mm; close to 70 % < 1,0 mm, and about 90 % < 2.0 mm. Thus only 10% of the fractures are wider than 2 mm. All but one of the wider veins are found within the 344-355 m interval, just above the main feed zone in the well at 360-370 m depth.

The average thickness of all fractures above 360 m depth is slightly less than 1 mm, but from below 390 m just about 0,25 mm. Despite the 1-2 fracture/m average, Fig 16 also shows that the fracture density increases slightly close to 360 m depth. Thus the data suggests that both the density and the fracture widths increase close to the main feed zone at 360-370 m, which is a normal fault with a 70° dip. The fracture density and fracture widths increase slightly on the throw side.

The effect of fractures and fracture density on the permeation properties will now be considered. Porosity and permeability were measured in plug samples (Ch 6). The mean porosity turned out to be 38% and the mean permeability 0.1 mD (millidarcy), i.e. comparable to clay permeability which is poor. This probably relates to consolidation due to hydrothermal alteration, chiefly by clay minerals. Open fractures change the permeation property of a rock block considerably. For example, a 0.1 mm wide fracture has a 100 mD permeability, or 1000 times better than an unfractured rock matrix. A 1 mm wide fracture has a 100 D, or million times better than the rock, and a 5 mm wide fracture has a 10.000 D permeability. Thus it is evident that the total flux of fluid through a sedimentary succession multiplies as fracture density and widths increase. The permeability of each fracture is not all that important, however, unless the fractures are long enough to form a continous grid.

Three types of fractures (joints) are recognized, i.e. regular joints (dip 30-80°), faults (dip 65-85°) and irregular often discontinous tension joints (dip 70-90°). The former two are often wider than the tension joints. It is quite possible that all fracture types are cognate. A repeated joint pattern, for instance, is seen at 340-360 m depth, where the tension joints have formed next to a fault in a 2-3 m interval on both sides of the faults, while the regular joints occur in the interval between the tension joints. Furthermore, the strike/dip pattern of the regular joints is variable, and not uncommonly a 90° turn in strike from one joint to the next is seen in the same piece of core, few tenths of a cm long. Thus it appears inevitable that the joints form a continous grid.

The fault throw is small (mm-cm) except perhaps in the feed-zone fault between 360-370 m. Just above that fault an open space breccia is seen in the drillcore. In the partly infilled cavities a paragenetic sequence is seen, i.e. heulandite + scolecite -> mordenite. The breccia

appears to have moved twice, at least, as the younger cavities are only infilled by mordenite and a mineral resembling laumontite (presumably clinoptilolite according to XRD). Other circumstancial evidence of mineral paragenesis in mineral veins is found, but hard fact data like cross cutting joints were not seen. The following sequences may be mentioned. Calcite - wairakite -> calcite below 390 m depth; mordenite - wairakite -> calcite; two generations of calcite; red clay -> clay-zeolites -> calcite below 400 m. Overall, the mineral paragenesis appears to be : low-T zeolites (scolecite/mesolite, heulandite) -> quartz, wairakite, calcite, mordenite -> mordenite, calcite, clinoptilolite.

XRD analyses were carried out on a number of samples in the cored section of the drillhole (Fig 17). No conclusive difference was found between the different fracture types and the vein minerals, supporting the idea that the fractures have a common origin in a stressfield of extension and subsidence. A difference in vein mineral assemblages above and below the feed zone at 370 m is on the other hand found to exist.

The upper group is composed of mordenite - clinoptilolite - analcime - quartz, while calcite is not found except in one sample. The lower group is characterized by calcite - quartz - wairakite, while analcime, mordenite and clinoptilolite are less common. This seems to indicate that clinoptilolite, analcime and mordenite are closest to equilibrium with the feed-zone fluid, which may have been slightly undersaturated with respect to calcite during the vein mineral formation above 370 m. Presumably both quartz and calcite are older and from the time when the geothermal fluid was 50°C warmer than now or more.

Repeated faulting and fracturing next to the feed-zone-fault at 360-370 m must have resulted in episodic increases in fracture permeability. At present most of the fractures are more or less infilled by vein minerals which again decrease the fracture permeability. The feed-zone-fault is, however, obviously quite permeable.

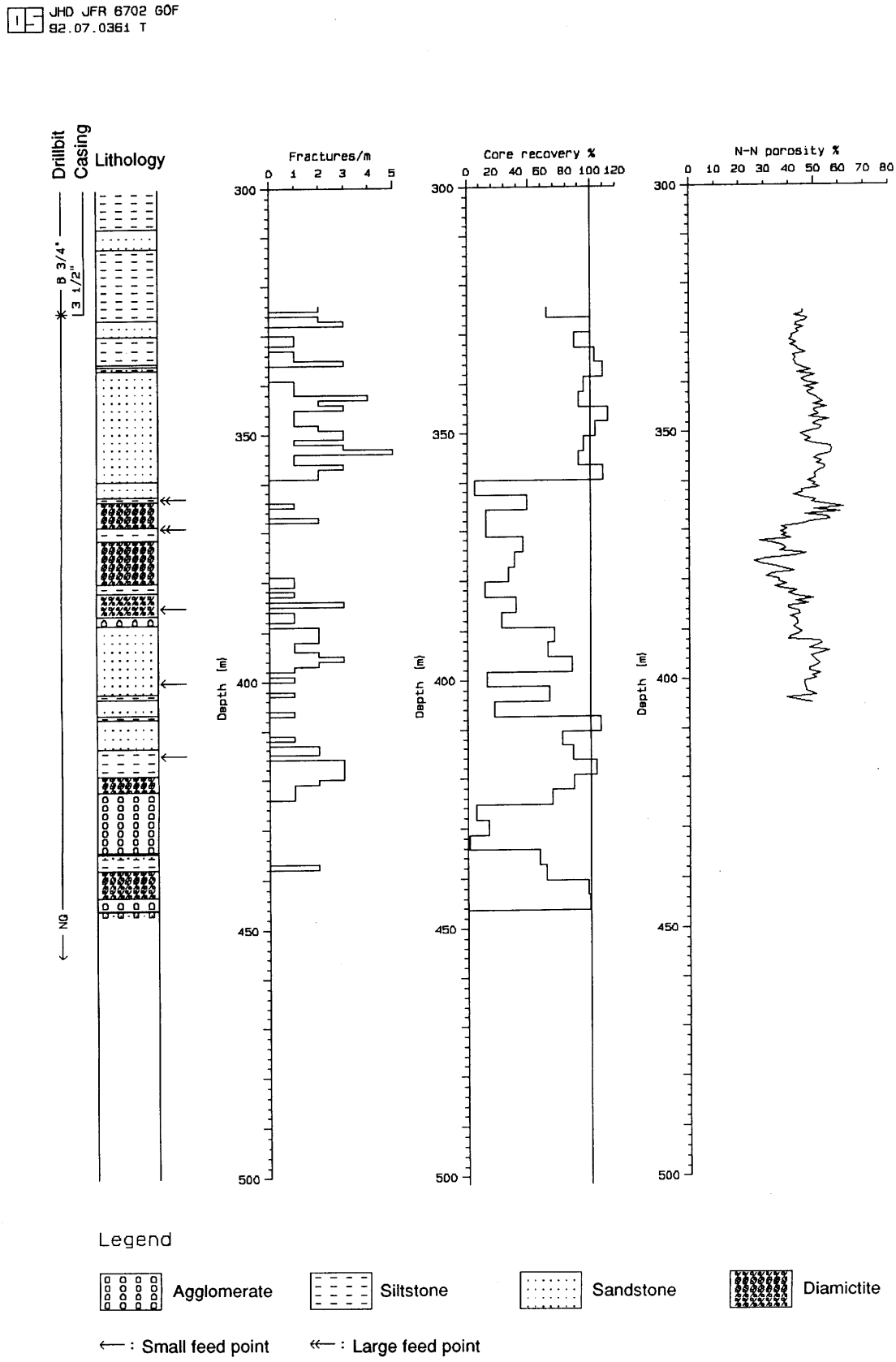

Figure 16. Fracture density, core recovery and porosity.

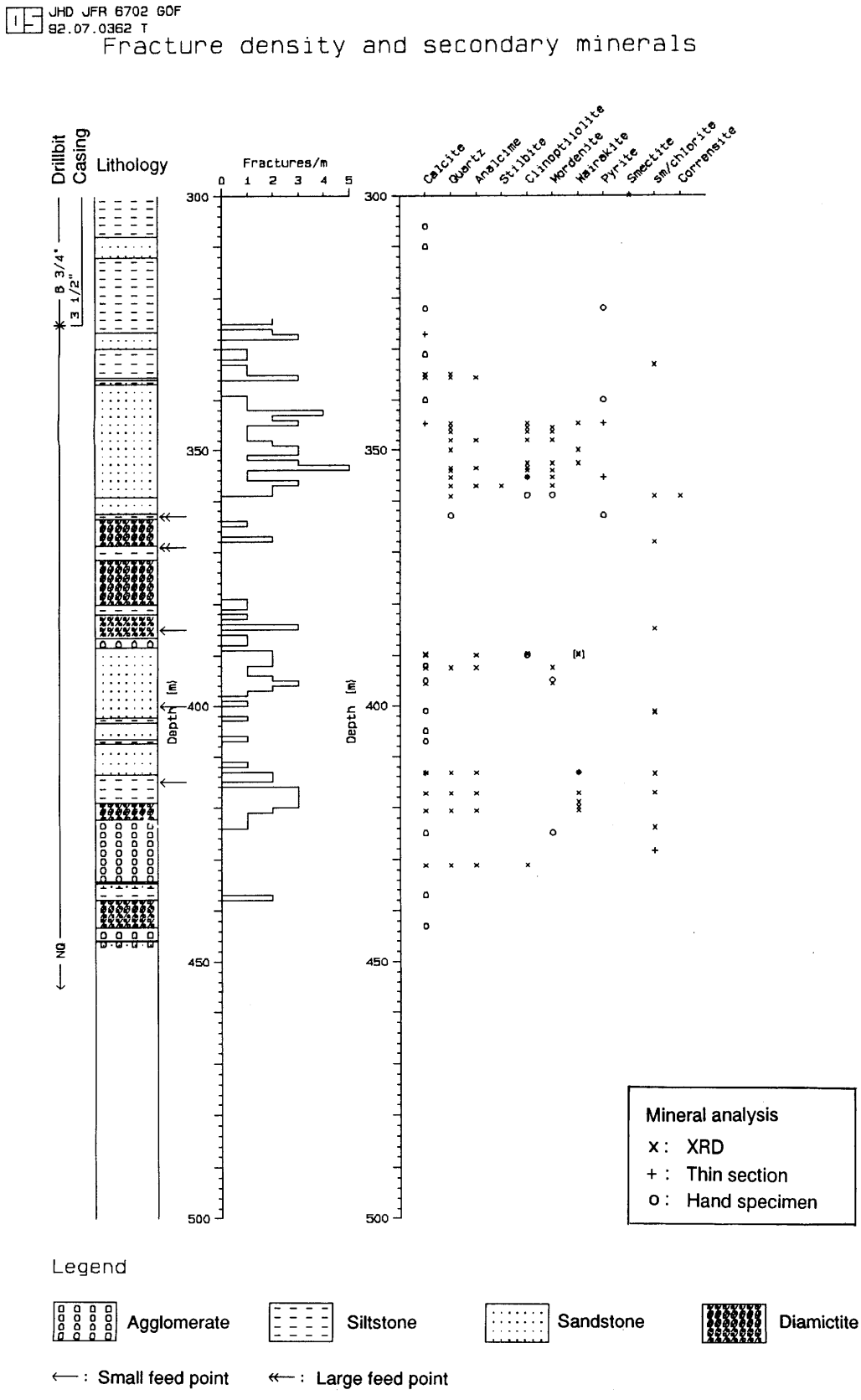

Figure 17. Fracture density and secondary minerals.

6. GEOPHYSICAL WELL-LOGGING

All the geophysical well-logs carried out in wells-1, 3 and 4 are listed in Table 5. Altogether some 50 logs were carried out, of which 33 were temperature logs (T-logs). Other logs include caliper log, inclination, and a number of lithological logs (resistivity, neutroun-neutron porosity, natural gamma rays and gamma-gamma density). The data is all conserved in an Oracle data base at Orkustofnun. In the database each log is labelled with a menu number, shown in Table 5 (and often referred to in the text). Most of the well logs were performed shortly after or during drilling, while 3 T-logs carried out four months after drilling are available from well-3.

6.1 Temperature logs

Several T-logs, mostly thermistor logs, are available from wells-1, 3 and 4. One T-log is available from well-2 but it is not of interest here since the well is on the sea shore outside or on the flank of the Skógalón field. Below the T-logs are discussed, feed-zones located, and formation temperature (T_F) estimated. In Table 6 the feed-points/zones are listed, and in Table 7 the T points used for the T_F esitmate. All T-logs from the wells are shown in Figs 18-23.

Six T-logs were performed in well-1, shortly after drilling, during repairing, cleaning and testing of the well, and after recovery. The highest T was 107.6°C at 70 m depth (6075, table 5).

Well-3 has been T-logged seventeen times, i.e. 13 times during drilling and 4 times later (Table 5). A number of feed zones are present in well 3. For analysis a reference is made to a T-profile from August 21, 1988. The well had been shut overnight (2035, table 5). A remarkably cold interval between 150-200 m depth is clearly seen in the T-profile. Circulation loss was insignificant at this depth during drilling and therefore the cold interval could not be explained as due to circulation disturbance (Georgsson et al., 1989; and drilling logs). The cold interval in the well is heated up during artesian flow, but cooles down again in a shut well (2042, 2043, 2034 and 2035, table 5). Feed-points/zones are located at 120 m, 130 m, 200 m, 210 m and 220 m, while the largest feed zone is at 120-130 m depth using the result of all T-logs.

Nine T-logs have been performed in well-4 long after the well had been cased off at 325 m depth (i.e. long after recovery). Eight logs were carried out during drilling, and only 2 of them by thermistor. The T-profiles during flow show most of the water to derive from 370 m depth (10825, table 5). During injection testing feed points are observed at 370 m, 385 m, 400 m and 415 m depths. No undisturbed T-profiles are available from the well after drilling. A similar cold interval is also observed in well-4 but at approximately 190 m depth. During drilling circulation increases at 130 m, 150 m, and 208 m depths were observed. A change in circulation is also recorded at 368-371 m depth.

Table 5. Summary of well-logging in all wells at Ærlækjarsel

Location no	Location code	Location name	Menu	Log	Date	initial depth	final depth	instrument probe	logging personnel
62551	ÆR-01	Ærlækjarsel	11173	Temperature (°C)	10-AUG-87	.0	70.0		GÓF
			11174	Temperature (°C)	11-AUG-87	.0	70.0		GÓF
			11175	Temperature (°C)	11-AUG-87	.0	70.0		GÓF
			11176	Temperature (°C)	13-AUG-87	.0	70.0		GÓF
			6075	Temperature (°C)	19-AUG-87	.0	70.0	RH	GÓF
			6076	Temperature (°C)	20-AUG-87	.0	70.0	RH	GÓF
62552	ÆR-02	Ærlækjarsel	6078	Temperature (°C)	01-SEP-87	5.0	90.0	RH	GÓF
			6079	Salinity (ppm)	01-SEP-87	5.0	90.0	RH	GÓF
62553	ÆR-03	Ærlækjarsel	7473	Temperature (°C)	14-AUG-88	.0	50.0	R47454	GjG/BS
			2030	Temperature (°C)	20-AUG-88	.0	200.0	RH	Rig crew
			2031	Temperature (°C)	20-AUG-88	.0	320.0	RH	Rig crew
			2032	Temperature (°C)	20-AUG-88	.0	216.0	RH	Rig crew
			2033	Temperature (°C)	20-AUG-88	.0	318.0	RH	GÓF
			2034	Temperature (°C)	20-AUG-88	.0	318.0	RH	GÓF
			2035	Temperature (°C)	21-AUG-88	.0	317.0	RH	GÓF
			2036	Temperature (°C)	21-AUG-88	.0	317.0	RH	GÓF
			2037	Temperature (°C)	21-AUG-88	.0	317.0	RH	GÓF
			2038	Temperature (°C)	21-AUG-88	.0	317.0	RH	
			7467	Temperature (°C)	21-AUG-88	.0	320.0	R47454	JH/BS
			7468	R16" (Ohmm)	21-AUG-88	.0	320.0	R47454	JH/BS
			7469	CBL (%)	21-AUG-88	.0	113.0	R47454	JH/BS
			7470	Neutron (API nu)	21-AUG-88	.0	320.0	R47454	JH/BS
			7471	Width (mm)	21-AUG-88	.0	320.0	R47454	JH/BS
			7472	Temperature (°C)	21-AUG-88	.0	320.0	R47454	JH/BS
			11017	R64" (Ohmm)	21-AUG-88	.0	320.0	R47454	JH/BS
			11018	Gamma (API gu)	21-AUG-88	.0	320.0	R47454	JH/BS
			2039	Temperature (°C)	23-AUG-88	10.0	320.0	RH	GÓF
			2040	Temperature (°C)	05-SEP-88	.0	322.0	R24585	BS/GrB
			6039	Inclination	05-SEP-88	30.0	300.0	R24585	BS/GrB
			2041	Temperature (°C)	19-DEC-88	5.0	300.0	RH	Locals
			2042	Temperature (°C)	30-DEC-88	180.0	299.0	RH	Locals
			2043	Temperature (°C)	30-DEC-88	120.0	200.0	RH	Locals
62554	ÆR-04	Ærlækjarsel	10731	Temperature (°C)	01-OCT-91	10.0	318.0		Rig crew
			10741	Temperature (°C)	08-OCT-91	.0	353.0	RH	Rig crew
			10784	Temperature (°C)	16-OCT-91	.0	420.0	R47454	JH/GuH
			10785	Neutron (API nu)	16-OCT-91	.0	420.0	R47454	JH/GuH
			10786	Gamma (API gu)	16-OCT-91	.0	420.0	R47454	JH/GuH
			10787	Gamma-Gamma (cps)	16-OCT-91	.0	420.0	R47454	JH/GuH
			10788	Inclination	16-OCT-91	200.0	400.0	R47454	JH/GuH
			10797	Temperature (°C)	16-OCT-91	.0	420.0	R47454	JH/GuH
			10789	Temperature (°C)	17-OCT-91	.0	419.5	R47454	JH/GuH
			10790	Neutron (API nu)	17-OCT-91	.0	419.5	R47454	JH/GuH
			10791	Gamma (API gu)	17-OCT-91	.0	419.5	R47454	JH/GuH
			10792	Gamma-Gamma (cps)	17-OCT-91	.0	419.5	R47454	JH/GuH
			10793	Width (mm)	18-OCT-91	.0	419.5	R47454	JH/GuH
			10794	Temperature (°C)	18-OCT-91	.0	419.5	R47454	JH/GuH
			10795	Temperature (°C)	18-OCT-91	360.0	360.0	R47454	JH/GuH
			10796	Temperature (°C)	18-OCT-91	.0	420.0	R47454	JH/GuH
			10825	Temperature (°C)	25-OCT-91	.0	410.0	R24585	GrB/GuH
			10834	Pressure (Bar)	25-OCT-91	.0	400.0	R24585	GrB/GuH

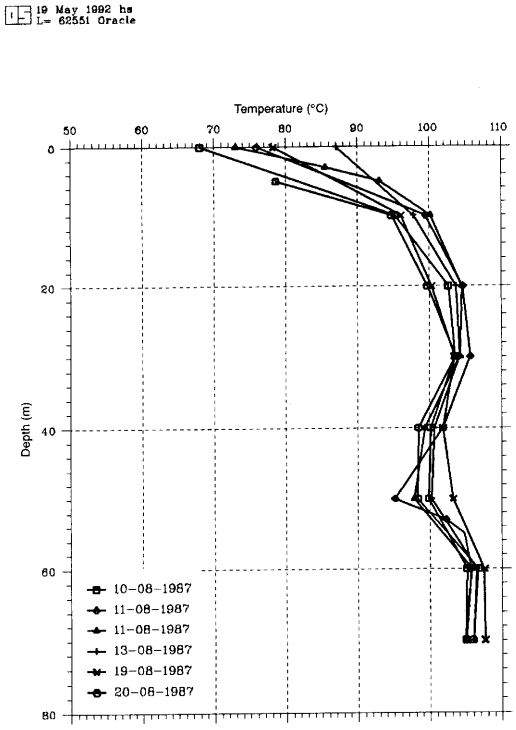

Figure 18. Temperature logs in ÆR-01.

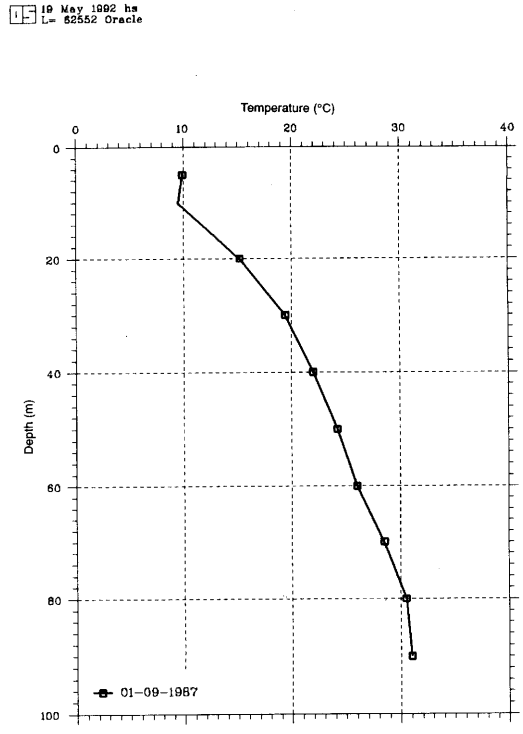

Figure 19. Temperature logs in ÆR-02.

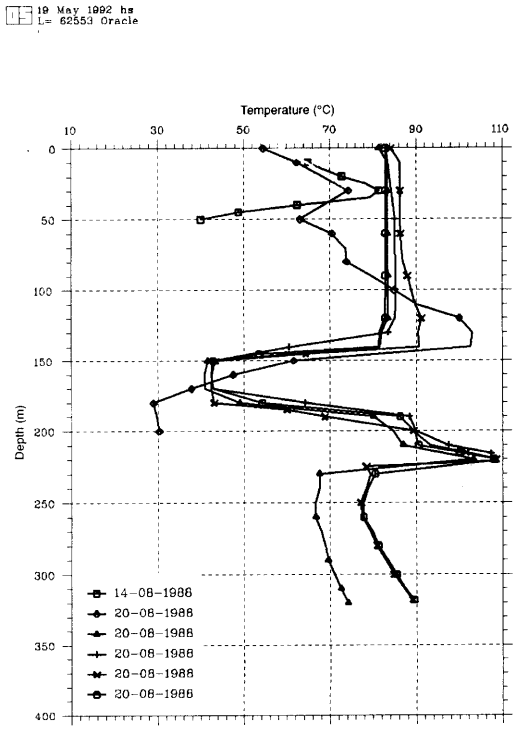

Figure 20. Temperature logs in ÆR-03.

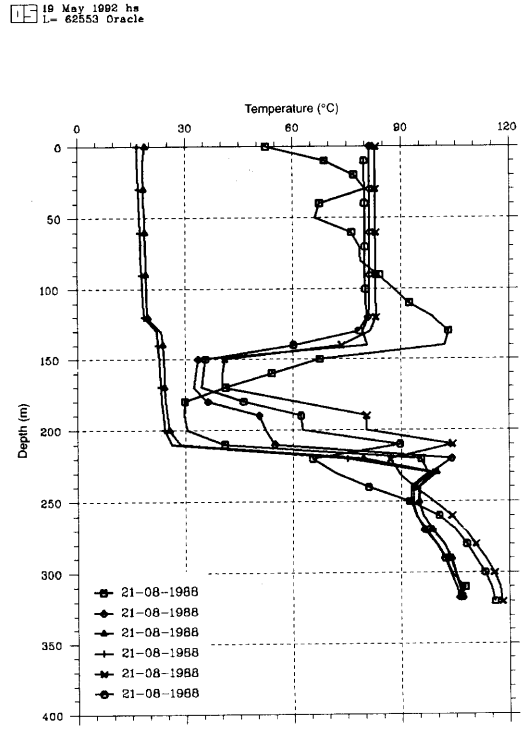

Figure 21. Temperature logs in ÆR-03.

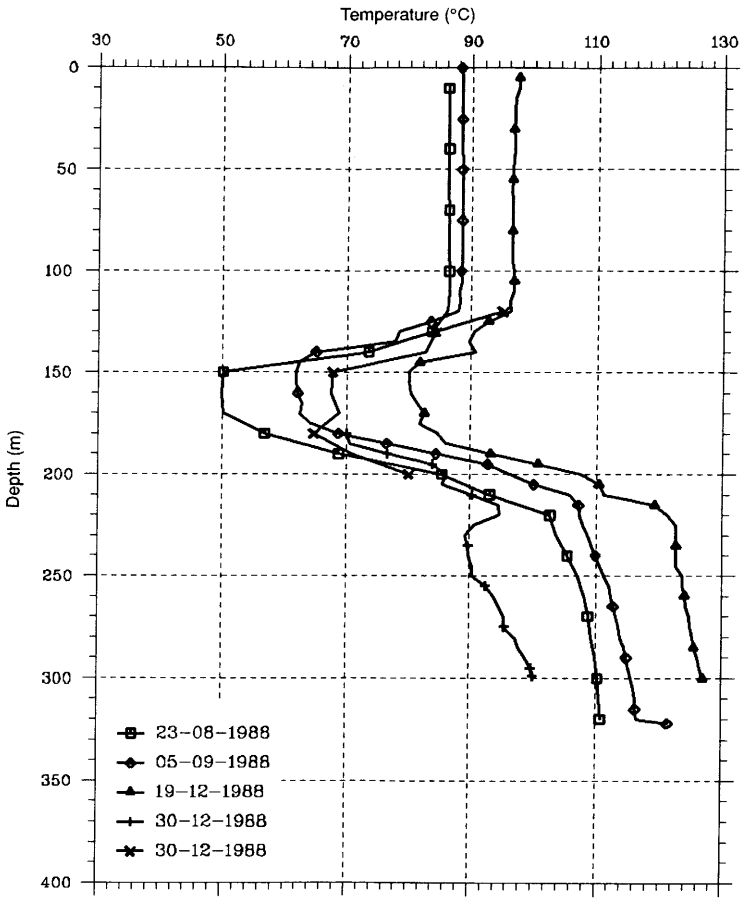

Figure 22. Temperature logs in ÆR-03.

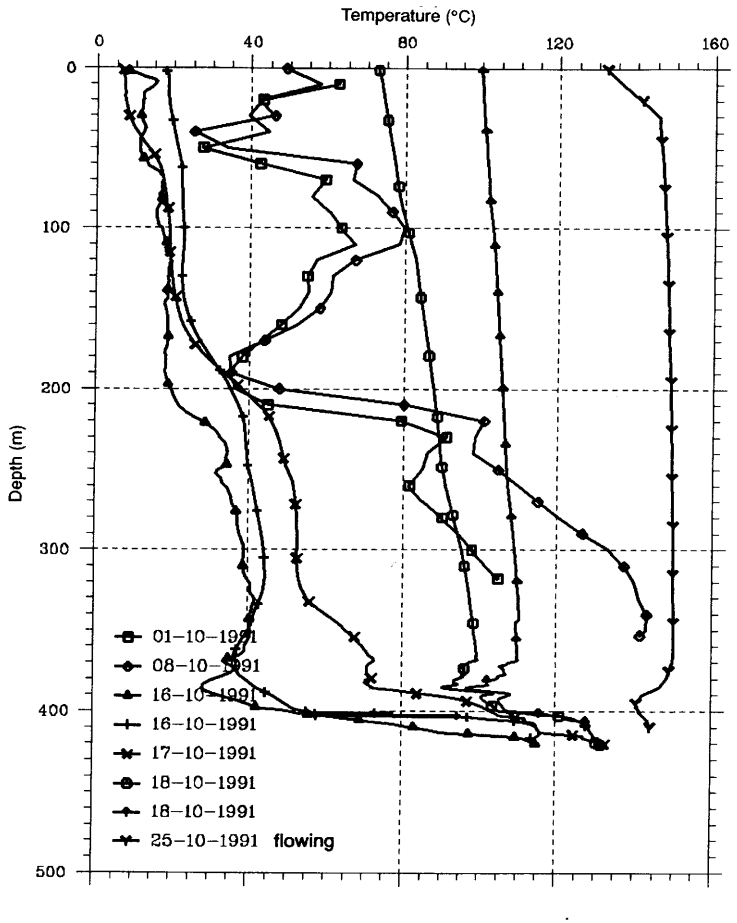

Figure 23. Temperature logs in ÆR-04.

Table 6. Feed points/zones in wells 3 and 4.

Well	Depth m	Remarks
ÆR-03	120 - 130	Largest feed zone
ÆR-03	200 - 220	Observed during injection
ÆR-03	230	Small. Observed during injection
ÆR-04	370	Largest feed zone
ÆR-04	385	Observed during injection
ÆR-04	400	Observed during injection
ÆR-04	415	Small. Observed during injection

6.2 Formation temperature

In order to estimate the undisturbed formation temperature T_F within the hydrothermal system, all temperature logs from wells-1, 3 and 4 were screened for temperature data - undisturbed from artesian flows or injection during drilling. As most of the T-logs are disturbed, however, the T_F estimate is somewhat inaccurate. In both wells-3 and 4 there are intervals at intermediate depths were the T_F is clearly lower than elsewhere in the wells. In well 3 the temperature is just about 30°C at 150-180 m, while in well-4 the temperature is about 35°C at approx. 190 m depth. This indicates a flow of 30-40°C hot water in a horizontal aquifer. The T-points used for T_F are shown in Table 7, where a note is made of the well condition during T-logging. A soft T_F profile is drawn between the T-points in Fig 24 with the aid of a computer programme.

Table 7. Temperatures used for T_F estimate

Well	Depth m	Temperature °C	Remarks T-log
ÆR-01	0	90	Well shut a few days, 25 days after drilling (11174)
ÆR-01	20	105	Well shut a few days, 25 days after drilling (11174)
ÆR-01	70	108	Well shut a few days, 1 month after drilling (6075)
ÆR-03	130	103	Well closed for 1 night (2035, table 5)
ÆR-03	150	33.5	Well opened after 1 night's rest (2036)
ÆR-03	170	32.3	Well opened after 1 night's rest (2036)
ÆR-03	180	29.8	Well closed for 1 night (2035)
ÆR-03	210	104.1	Logged with a thermistor (7467)
ÆR-03	260	124	Logged after 2 months artesian flow (2041)
ÆR-04	340	145	Logged during drilling (fishing)(10741)
ÆR-04	370	150	Logged after 6 days discharge (10825)

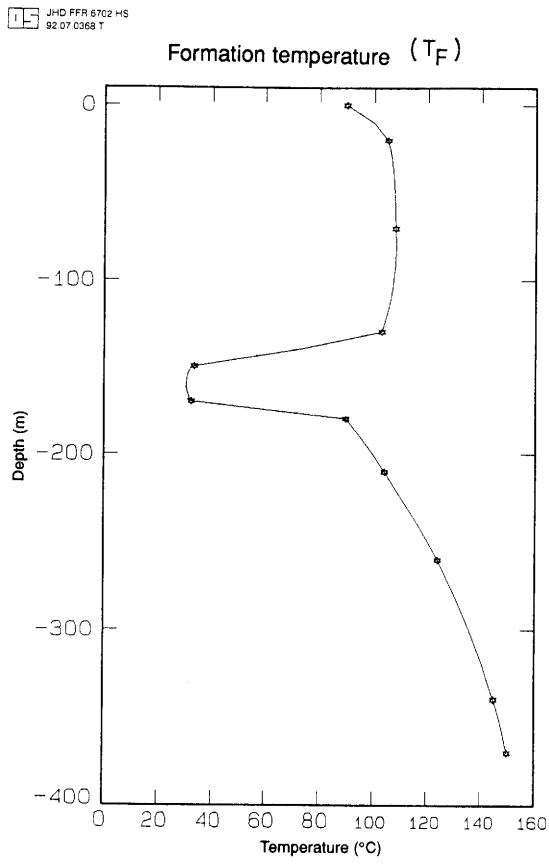

Figure 24. Formation temperature (T_F) in the Skógalón hydrothermal system.

6.3 Lithological logs

Geophysical lithology logs were carried out in well-3 and 4. The results of the geophysical logs in well 3 have been discussed elsewhere (Georgsson et al. 1989). These are compared with the logs from well-4 (Table 5) and all shown along with the lithology profiles in Figs 25 and 26.

The geophysical logs were carried out after the drilling of well-4. The upper part, down to 325 m depth, had already been cased off, and the logging instruments could only reach 419,5 m depth due to wall blockage. Thus only about 100 m of open section is logged. A resistivity log could not be obtained due to a malfunction in the probe, and the well width could only be measured from 405 m upwards because below that depth the caliper instrument didn't function properly due to mud.

The caliper log shows the well wall to be smooth from the casing down to 365 m, below which it is rough down to 388 m. This compares neatly with the lithology which is composed of diamictite in the lower interval. Two caves are seen one at 367 m and the other at 385 m. The open section of the well is all wider than 6" in diameter, even though the well was drilled with a 3" corebit. In the deepest part of the well the wall is again smooth but approaching 8" in diameter.

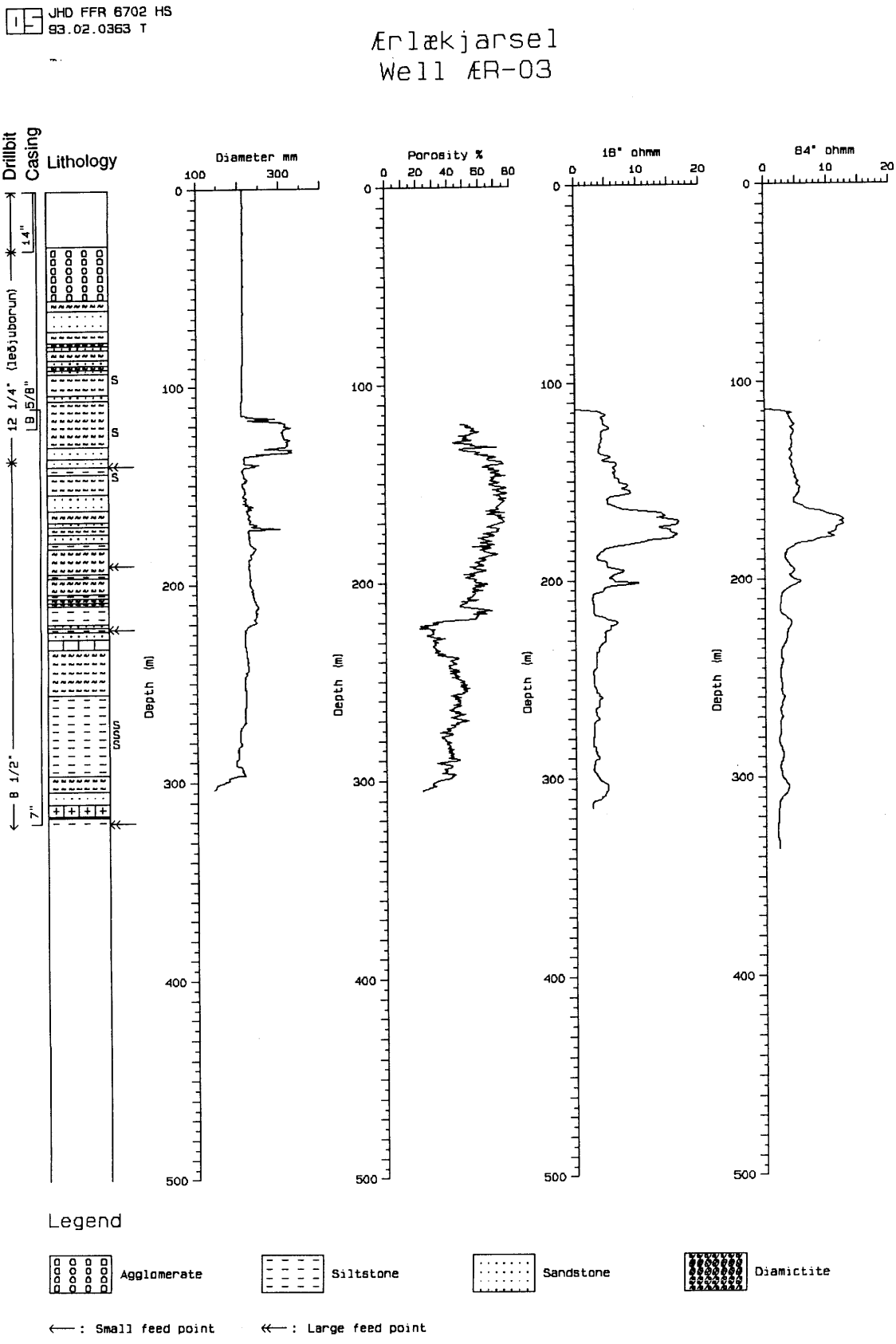

Figure 25. Lithological logs from well 3.

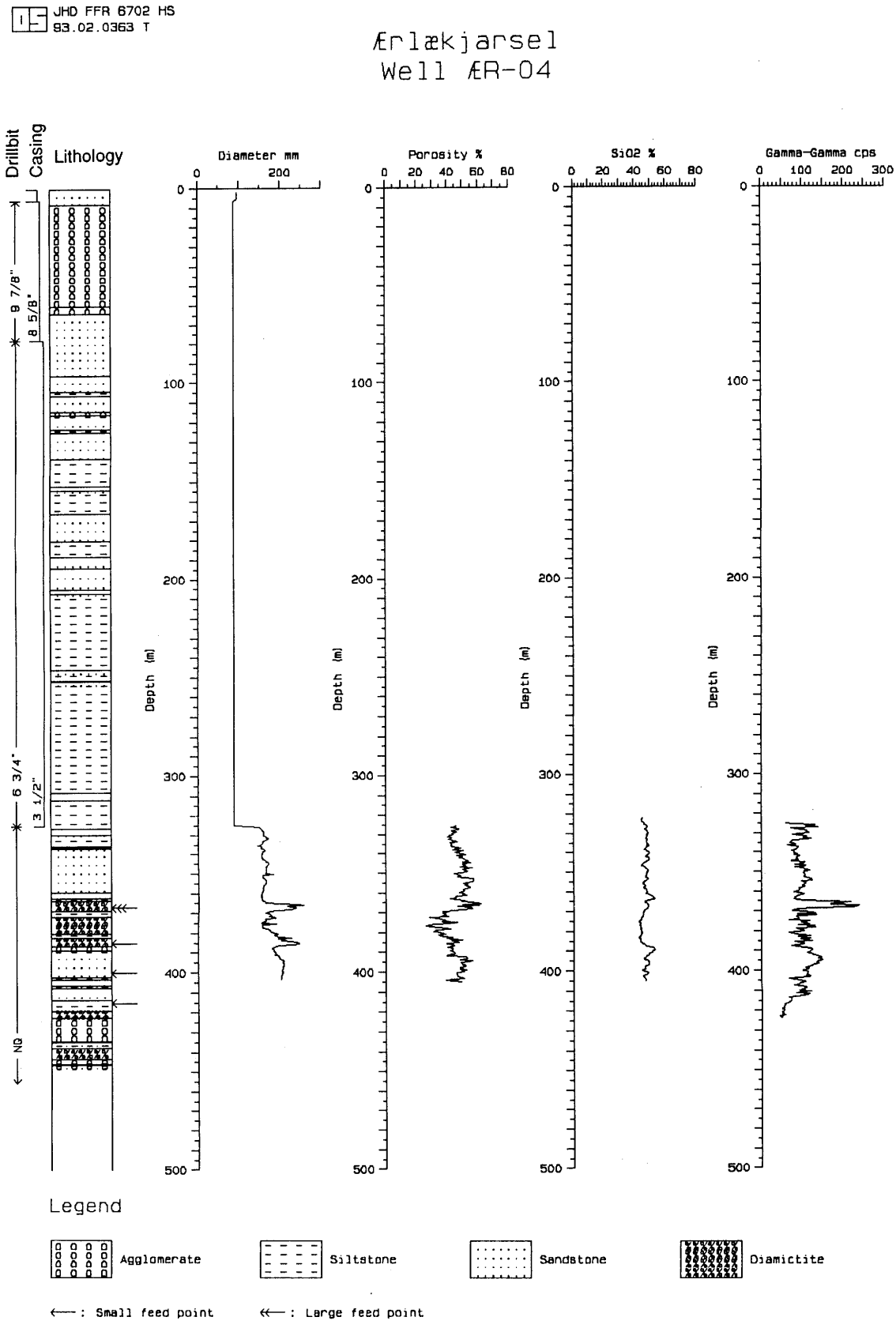

Figure 26. Lithological logs from well 4.

It is possible to calculate the water content in the rocks from a width-corrected neutron-neutron log, i.e. the ratio of all water in the rock versus the total volume of the rock. For unaltered rocks this quantity approaches the total porosity (in pores, fractures, etc), whereas in hydrothermally altered rocks the water bound in hydrous minerals is included. For the present discussion the terms "total porosity" and n-n porosity will be used as synonyms. The n-n porosity ranges from 26-62 % in the open part of the well (mean 45,8 +/- 6.5 %). The highest porosity value is found in the diamictite at 363-368 m, but much lower ones in identical rock type at 371-380 m depth. The porosity range in the diamictite appears to be considerable. The main reason for this variability is that the largest feed-zone of the well is at 367 m depth where the fractures are more numerous and wider than elsewhere, i.e. in an open fault-zone.

It is normally possible to estimate the rock's *bulk density* from a gamma-gamma log. As the probe is most sensitive next to the probe wall the probe has to be as close to the wall as possible, and as the sensitivity decreases drastically 5-10 cm away from the probe, monitoring within the casing is useless. Here the well casing is only 3 1/2" OD, but a 6 3/4" drillbit was used. The distance from the probe to the wall also differs depending on the casing orientation within the well, and the probe orientation within the casing. No corrections can be made.

In the open part of the well the erosion of the well-wall is too severe for an accurate calculation of the bulk density, which is therefore not attempted.

An estimate of the silica concentration of the rock may be made from natural gamma rays corrected for well-width. The silica content ranges from 42-58 % the mean being 46,7 +/- 2 % in the open part of the well. This calculation is based on an empirical formula valid only for crystalline Icelandic rock.

6.4 Inclination

The inclination of wells 3 and 4 was measured. Well-3 dips as much as 8°. The horizontal deviation has been calculated and shows the bottom of well 3 to be 27 m off vertical at 320 m depth. Well 4 dips less than 1° deviating by only 5 m at 455 m depth. Table 8 shows the measured values while Fig 27 shows the deviation from vertical.

Table 8. Inclination of wells-3 and 4.

Well	Depth m	Inclination °
ÆR-03	30	1.8
ÆR-03	60	1
ÆR-03	100	2.8
ÆR-03	150	5
ÆR-03	200	6.5
ÆR-03	250	8
ÆR-04	200	0.9
ÆR-04	300	0.8
ÆR-04	400	0.7

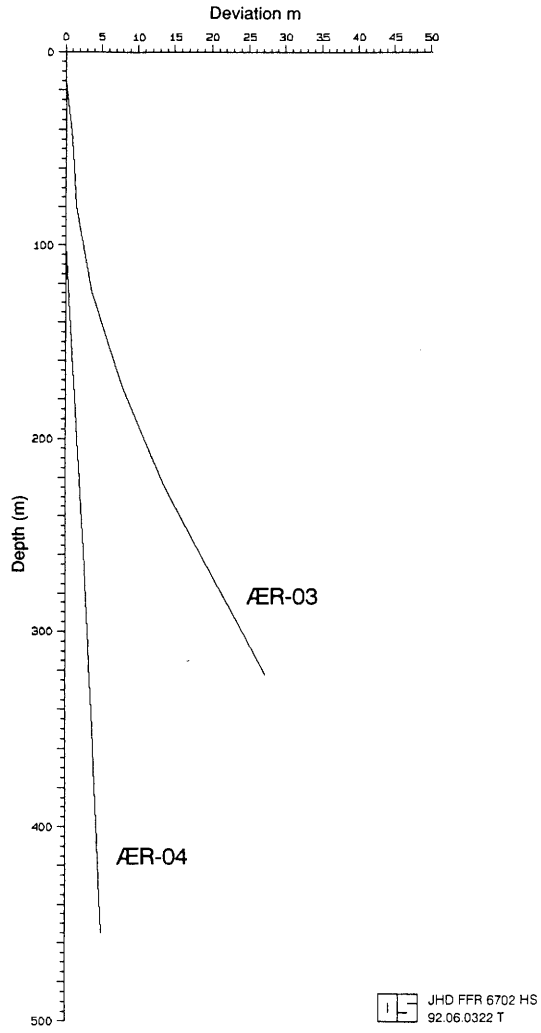

Figure 27. Deviation of wells-3 and 4 from the vertical.

6.5 Core analysis

A core was recovered from well-4 from the depth interval 329.5 to 444.4 m. Plug samples were selected at the drill-site and sent to DGU for further tests. The plugs were 1,9 cm (0,75") in diameter, and trimmed to 2.8 cm length. They were analysed for gas permeability, porosity and grain density (Table 9).

The gas permeability is measured by flowing nitrogen gas through the plug at differential pressures from 0-1 bar, and a mean is obtained from two or more measurements. The effective porosity is determined in a cleaned and dry plug by subtracting the measured grain volume from the measured bulk volume. The Helium technique, employing Boyle's Law, is used for grain volume determination, whereas the bulk volume was measured by submersion of the plug in a mercury bath using Archimedes' law. Using this method the ratio between open and interconnected pores versus total volume is measured, but no account taken of the sealed pores. Below a distinction is made between this "effective porosity" and the total porosity.

A mention is made of the difference between bulk density (rock + water) and grain density (rock only). The bulk density is determined from total volume, weight and porosity.

The core analyses were performed in accordance with API recommended practice for core analysis (API RP 40, 1960), a description of such measurements can, for instance, be found in an Orkustofnun report (Sigurðsson et al., 1988).

The results from the plug analyses is shown in Table 9, showing gas permeability with Klinkenberg correction, effective porosity and grain density.

Table 9. Result of the core analysis.

Core no	Depth m	Permeability mD	Effective porosity %	Grain density g/cm^3
P1	329.45	0.054	42.11	2.873
P2	339.80	0.053	38.46	2.726
P3	347.77	0.036	37.86	2.649
P4	350.98	0.034	40.31	2.656
P5	368.58		40.11	2.730
P6	395.50	0.037	41.34	2.729
P7	404.10	0.072	36.03	2.757
P8	411.00	0.268	40.75	2.807
P9	415.60	0.310	38.51	2.809
P10	437.70	0.061	36.00	2.840
P11	438.90	0.027	24.26	3.000

6.6 Comparison between the core and well logs

In comparing the results from the plug analysis at DGU and the neutron-neutron well logs, the volume difference is worth noting. The total porosity determined by the n-n log ranges between 26-62 % in the 325-405 m depth interval, with a mean of 45,8 +/- 7 %. Effective porosity

Table 10. Comparison of effective porosity and n-n log porosity.

Sample nr.	Depth m	Effective porosity Core %	Porosity n-n log %	Difference	%
P1	329.5	42.11	42.7	0.7	1.5
P2	340	38.46	46.2	7.7	20.1
P3	348	37.86	51.1	13.2	34.9
P4	351	40.31	46.0	5.7	14.1
P5	368.5	40.11	48.17	8.1	20.1
P6	395.5	41.34	48.52	7.2	17.4
P7	404.1	36.03	38.8	2.8	7.8

determined in the plugs ranges from 24 to 44 % with a mean of 37,8 %, in the depth interval 329,5-438,9 m. These are compared in Table 10, and in Fig 28 over a comparable depth interval. Also shown is a histogram for the open well n-n porosity in both wells-3 and 4. A comparison between the effective porosity and the total porosity is shown in Fig 29 along with a lithological profile.

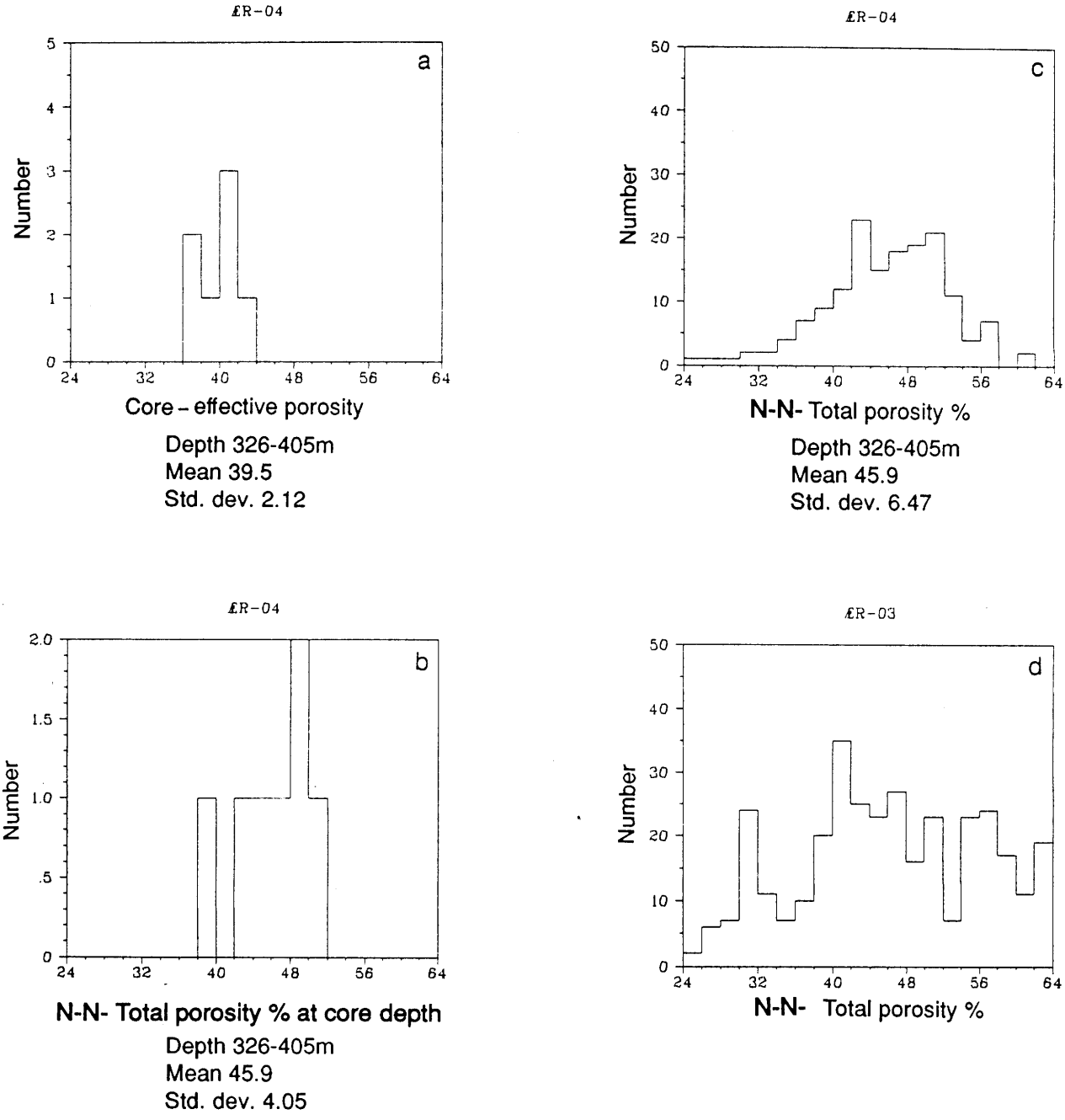

Figure 28. Effective porosity and total porosity in the core.
a) Distribution of effective porosity in the core
b) Distribution of total porosity at same depth as a)
c) Distribution of total porosity in ÆR-04
d) Distribution of total porosity in ÆR-03

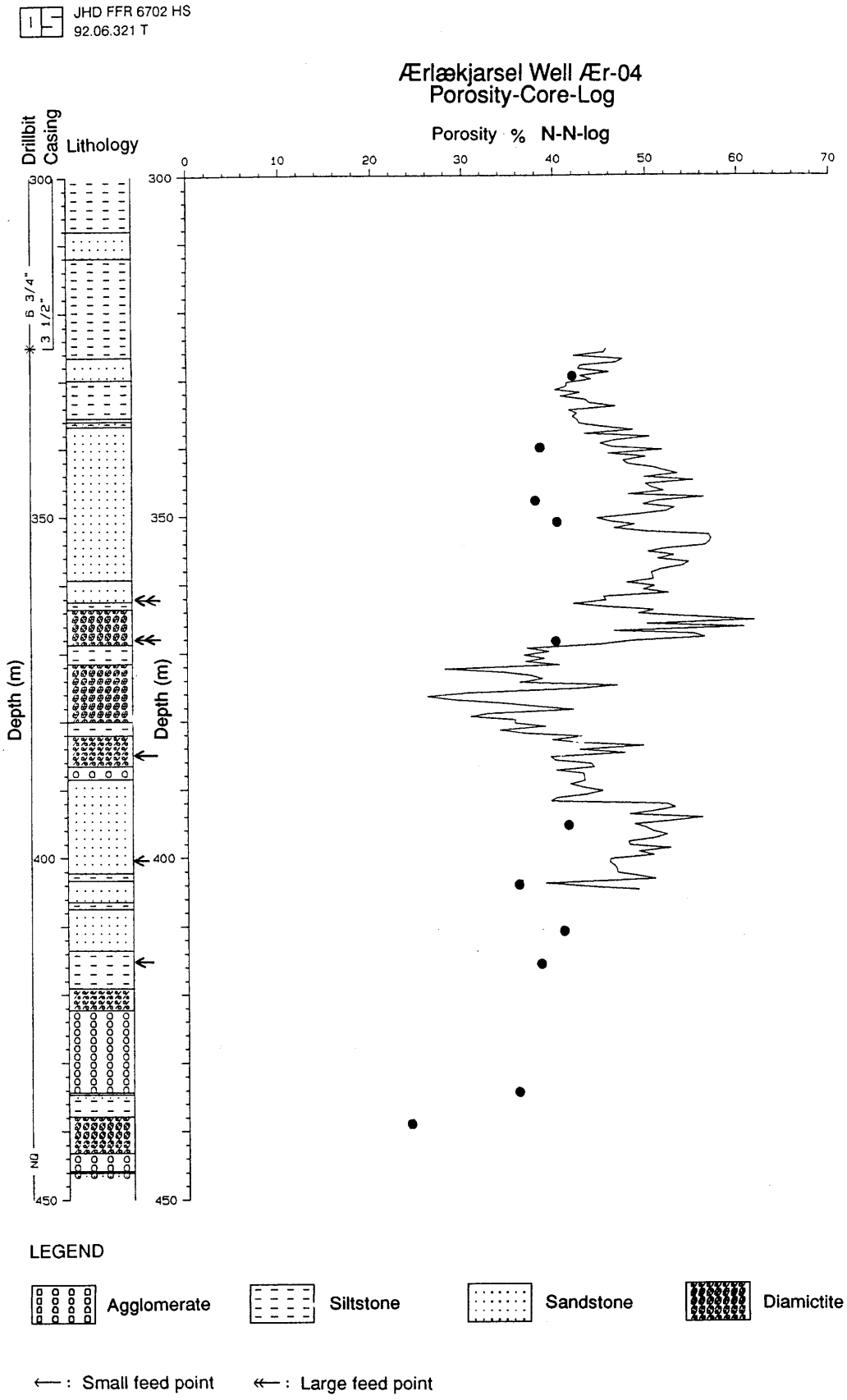

Figure 29. Lithology and porosity in well 4.

The data clearly shows that the n-n porosity values are higher than the effective porosity values, which is easily explained with reference to the different methods used.

6.7 The density of the core

The density of the core was determined by selecting an adequate piece of core from each corebox. The mass and volumes of the selected samples were determined and the density calculated. The results are shown in Table 11.

Table 11. The results of the determination of density

Depth m	Length cm	Diameter cm	Mass g	Density g/cm^3	Lithology
329.5	24.8	4.76	825	1.87	Siltstone
334.3	21.2	4.76	750	1.99	Sandstone
342.2	21.5	4.70	750	2.01	Fine siltstone
347.9	16.0	4.80	550	1.90	- " -
350.6	26.5	4.75	870	1.85	- " -
368.4	13.0	4.65	425	1.92	Siltstone
384.0	21.0	4.76	1025	2.69	Basalt boulder
387.0	10.0	4.70	350	1.93	Agglomerate
397.3	11.6	4.40	325	1.54	Layered siltstone
411.1	9.0	4.60	250	1.53	- " -
411.2	14.5	4.50	410	1.56	- " -
416.4	20.5	4.50	785	2.11	Siltstone
422.5	11.0	4.50	420	2.11	Agglomerate
423.8	11.5	4.70	550	2.64	Vesicular basalt
438.8	7.0	4.40	250	1.97	Agglomerate
441.6	7.5	4.50	250	1.84	- " -
443.0	7.5	4.60	300	2.21	- " -
444.4	8.5	4.70	340	2.21	- " -

The values in Table 11 show the density of the core pieces from the well, including porewater, thus approaching the bulk density, ranging from 1,5-2,7 g/cm^3.

Uniaxial point load tests were carried out at the well-site on several corepieces. The results are described in a short report (Jónsson 1992). In an upper well section, depth interval 332,5-351 m, the uniaxial fracture load was 16-20 MPa, but in a lower section it showed a mean of 34 MPa. For comparison a standard concrete (S-200) for houses has a value of 20 MPa after 28 days.

The caliper-log of the well shows the cored section to be wider than 6" despite the fact the well was drilled with a 3" corebit. For safety an excessive amout of circulation water was used to prevent a blow-out during drilling, because the drillrig's safety valve never functioned. As the well became wider, more and more cold water was needed for proper cleaning of the well. If circulation was temporarily decreased or halted the cuttings settled around the drillstring. This may be the cause of the broken drillpipes.

7. Sampling and chemical analysis

The core drilling rig left well-4 on October 18, 1991. Geophysical logs were completed the following day (Ch 6). Sampling and logging equipment was placed on the wellhead and the heating of the well observed. A small trickle of water started flowing from the well at 13:45, Oct. 18. At first the outflow consisted of cold circulation water. Four hours later the temperature had risen to 100°C and the flow increased to 5 l/s. These changes during the first few hours after pumping ceased are shown in Fig 30. It was not expected that reliable water samples could be obtained until two days later due to the presence of circulation water.

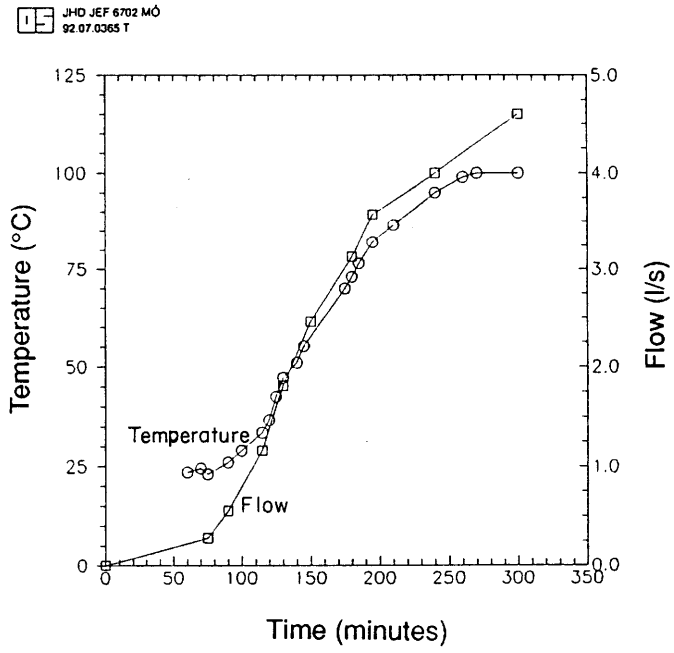

Figure 30. Well-4. Temperature and flow during the first hours of well discharge.

Two samples of water and gas were collected from well-4 for total analysis, the first one two days after the start of well discharge. By that time there was a powerful two phase discharge from the well. The closing pressure was 2.5 bar-g and the wellhead temperature 128.5°C. No flow measurements could be made. The second sample was collected after seven days had passed through a small steam-water separator of the type used for high-temperature geothermal wells. The wellhead pressure was then 2.6 bar-g and the wellhead temperature 132°C. Realistic results proved difficult to obtain for the flow from the well although all kinds of attempts were made to measure it. Combining the results of pressure logging at different flow rates and those of imperfect direct wellhead flow measurements suggested that the total flow from the wellhead was at least 10 kg/s of water at 100°C. After sampling the well was closed and all wellhead equipment removed to prevent damage from water and ice. In addition a road supporting canvas was stretched over the drill site to protect it from water erosion.

7.1 The chemical composition of the water

The results of chemical analysis of water samples from the Skógalón well-4, and from wells-1 and 3 for comparison, are presented in Table 12.

Table 12. The chemical composition of water from Skógalón wells

Well No.	ÆR-04	ÆR-04	ÆR-03	ÆR-01
Date	91-10-20	91-10-25	89-10-02	87-09-13
No.	91-0189	91-0209	89-0087	87-0119
Wellhead temp.(°C)	128.5	132	96	98
Mode	Wellhead	Separator	Wellhead	Wellhead
Sampling pressure(bar-g)	0,8	1,3	-	-
(pH/°C)	6.9/22	8.6/22	7.9/24	9.5/15
Silica (SiO_2)	199	214	129	139
Sodium (Na)	1151	1222	833	1250
Potassium (K)	70	67	43	77
Calcium (Ca)	187	185	154	259
Magnesium (Mg)	2.93	0.63	0.42	0.18
Iron (Fe)	-	0.009	0	<0.025
Manganese (Mn)	-	0.014	0	<0.05
Aluminium (Al)	-	0.045	0.023	-
Carbonate (CO_2(total))	21.6	5.1	24.3	12.4
Sulphate (SO_4)	151	150	97	138
Hydrogen sulphide (H_2S)	<0.03	<0.03	0.07	<0.05
Chloride (Cl)	2070	2110	1534	2460
Fluoride (F)	0.11	0.12	0.28	0.65
Total dissolved solids	4007	4085	2709	4630
δD (‰ SMOW)	-	-	-100,4	-
δ^{18}O (‰ SMOW)	-11.1	-11.1	-10.9	-10.0

The water from well-4 is relatively saline and high in dissolved solids as is the water from all other Skógalón wells. Inspection of the analytical results for water from the three wells shows that there are layers of different water masses in the geothermal reservoir. This result is in agreement with the results of the lithology and temperature logs which are reported in previous chapters. The water in the shallowest well, well-1 (70 m deep), is the most saline. The largest feed in well-3 is at 140 m depth and the water from there is less saline than that of the shallower feeds and a temperature drop is observed just below it. The main feed zone in the deepest well, well 4, is at 370 m depth where again the salinity is greater than in the main feed of well-3.

The results of calculations presented in Fig 31 show that the ionic product for calcium carbonate in the water from well-3 lies close to the theoretical saturation curve at the wellhead temperature and upon cooling The water from well-1 is on the other hand substantially supersaturated at comparable temperatures. For the well 4 water there is a considerable difference observed in the behaviour of the two samples in this respect. Water

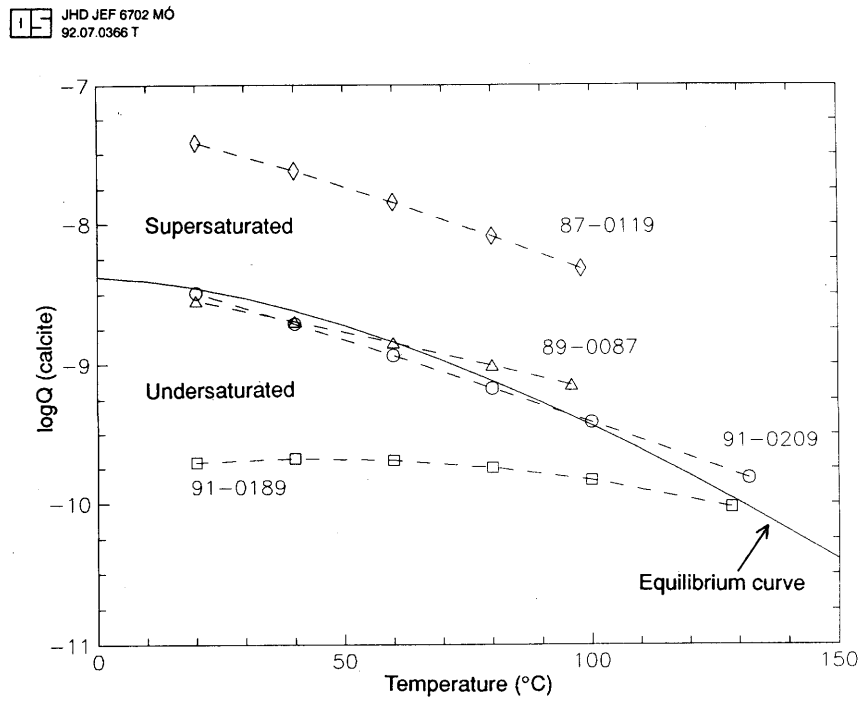

Figure 31. Calcite saturation state of water from the Skógalón boreholes.

sample No. 91-0189, collected directly from the wellhead two days after the start of artesian flow is seen to become severely undersaturated with respect to calcite upon cooling but the ionic product for sample No. 91-0209, collected through a small separator five days later follows the saturation curve pretty closely. This discrepancy is due to differences in pH and carbonate concentration which in turn are the result of different sampling techniques. The result for sample 91-0209, which was collected as a two phase sample through the separator without any loss of steam to the atmosphere and its total composition calculated from the results for the steam and water fractions, must be regarded as the more reliable. It reflects more closely on the actual situation than the first one which was collected directly from the wellhead without attempts to contain the steam fraction.

Several chemical geothermometers have been applied to the Skógalón analytical results, mostly those from well-4. Experience has shown that the most reliable geothermometer for Icelandic low-temperature geothermal water is based on equilibrium with respect to chalcedony dissolution (Fournier, 1977). This geothermometer yields temperatures ranging from 115 to 160°C for the water from the Skógalón boreholes (Table 13). The quartz (Fournier and Potter, 1982) and Na/K (Arnórsson et al., 1983) geothermometers are usually employed for high-temperature geothermal waters. These geothermometers have been applied too because results of alteration studies suggest that well-4 may extend into a high-temperature geothermal system.

The Na/K temperatures calculated for water from wells-3 and 4 are similar to the chalcedony temperatures obtained for the same water, whereas the Na/K temperature for water from well-1 is considerably higher than the corresponding chalcedony temperature. This difference is probably due to the fact that the Na/K temperature is unreliable at low temperatures, especially below 100°C, as well as the Na/K ratio being possibly disturbed by the relatively high salinity. The quartz geothermometer yields significantly higher temperatures than the

Table 13. Chemical geothermometer temperatures for water from Skógalón wells

Well No.	ÆR-01	ÆR-03	ÆR-04
Sampe No.	87-0119	89-0087	91-0209
Calsedony temperature (°C)	115	125	160
Quartz temperature (°C)	140	150	180
Na/K temperature (°C)	150	135	150

other two, suggesting an equilibrium temperature of 180°C for water from well-4.

The determination of a geothermometer temperature in a geothermal system entails in fact finding at which temperature the ionic product, Q, for a certain equilibrium reaction is equal to the solubility product, K, i.e. log (Q/K) = 0. The ratio (Q/K) can be calculated for a host of equilibrium reactions using speciation programmes such as SOLVEQ and WATCH. A few curves obtained this way are presented in Fig 32 It has been shown that the most probable equilibrium temperature for a geothermal fluid is the one obtained from the intersection of the maximum number of such curves, representing plausible reactions, with the line (Q/K) = 0 (Reed, 1982, Reed and Spycher, 1984, Tole et al., 1993). Fig 32 shows that the curves for most plausible reactions intersect this line at temperatures in the range 160 to 190°C.

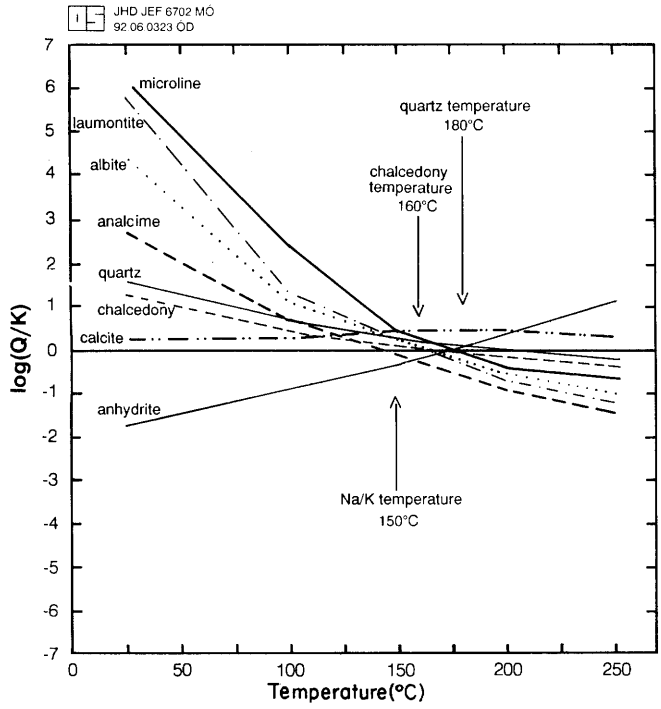

Figure 32. Some mineral-water equilibria in well 4 fluid.

These reflections on the temperature in the Skógalón geothermal system lead to the conclusion that the equilibrium temperature of the water in well-4, which is mostly drawn from a single feed at 370 m depth, is in the range 160 to 190°C which is thus the present water-rock equilibrium temperature in the system, but it is not known whether it is rising or falling at the present time.

7.2 The chemical composition of the gases

As the Orkustofnun gas chromatograph is not fitted with columns for the analysis of organic gases, gas samples from the three Skógalón boreholes have been sent for analysis to the British Geological Survey (BGS). The results of eight analyses are presented in Table 14, two from well-4, three from well-3 and three from well-1. Gas from Skógalón has also been analyzed in the Orkustofnun laboratory and an excellent agreement obtained with the results from the BGS laboratory for the constituents analyzed for. Looking at Table 14 it is clear that the main constituent gas at Skógalón is nitrogen (N_2), its volume percentage being 85-95%. Other constituents include oxygen and argon (O_2 + Ar) which may at least partially derive from atmospheric contamination, hydrogen (H_2) and carbon dioxide (CO_2) apart from methane (CH_4) and other hydrocarbons which will be dealt with in more detail in chapter 7.3.

As is the case with geothermal areas, geothermal gas can be divided into two groups, high-T and low-T gas. Low-T gas consists mainly of nitrogen but high-T gas of carbon dioxide, which is usually the main constituent gas, hydrogen and hydrogen sulphide. Methane may occur as a constituent of both types of gas. Natural gas that has been found in Iceland but is unrelated to geothermal heat, such as that found in Lake Lagarfljót, which is almost pure methane, but the gas emerging from soda springs is carbon dioxide. A closer look at the Skógalón results reveals that the volume percentage of nitrogen is 93-95% in most samples. Two samples, however, are distinctly different. One of them was collected from 200 m depth in well-3 in difficult conditions. A relatively high volume percentage of oxygen and argon suggests atmospheric contamination of this sample The other different sample is the second sample from well-4. This was collected through a small steam-water separator of the type used for high-temperature geothermal wells. A substantial amount of carbon dioxide was found in that sample suggesting a high-temperature geothermal influence. It was noted above that the temperature of the main water feed in this well is somewhat in excess of 150°C. The results of studies on alteration minerals in this well suggest furthermore, that the temperature in the Skógalón system has at some time exceeded 200°C and that the geothermal area shows more high-temperature than low-temperature characteristics. In summary there are many signs that this is a high-temperature geothermal area in the process of cooling.

The volume percentage of methane (CH_4) is 2 - 6%, except in the air contaminated sample from 200 m depth in well-3. The volume percentage of the higher hydrocarbons is 0.2 - 0.5%. Thus the organic gases are minor constituents, but what really matters is that this is the first time that higher hydrocarbons have been detected in natural gas in Iceland.

Gas geothermometry has been used to a considerable extent on fumarole gas to estimate the reservoir temperature of high-T geothermal systems (Arnórsson and Gunnlaugsson, 1985). Questionable as it may be to apply this method to the Skógalón system several gas geothermometer temperatures have been calculated with results ranging from 190 - 260°C, suggesting that that the system is more akin to a high-T than a low-T geothermal one, in agreement with conclusions drawn from studies on alteration minerals and the results from other geothermometers.

A new gas geothermometer based on the ratio of methane to ethane in geothermal gas has recently been proposed. The method was developed during studies on the East African Rift Zone and yielded convincing results in that environment (Darling and Talbot, 1991, 1992). Values calculated for the gas from well-4 are in the range 200 - 220°C (Darling, personal communication, 1992) and thus lend further support to the postulation of a high-temperature geothermal area at Skógalón provided that this new gas geothermometer is reliable. Values of 175 - 180°C for well-3 and 150 - 170°C for well-1 were obtained in the same way.

Table 14. The chemical composition of gas from the Skógarlón boreholes (volume %)

Well	ÆR-04	ÆR-04	ÆR-03	ÆR-03	ÆR-03	ÆR-01	ÆR-01	ÆR-01
Sample No.	91-0209	91-0189	90-0237	89-0087	88-0149	89-0088	88-0211	87-0119
Mode	separ-ator	well-head	200 m in situ	well-head	well-head	well-head	well-head	well-head
N_2	86.20	92.80	81.00	93.50	95.90	92.80	93.80	94.60
O_2 + Ar	0.1	0.10	18.40	1.10	1.80	1.20	1.70	2.70
H_2	0.07	0.25	0.06	0.02	0.02	0.07	0.23	0.00
He	-	0.00	0.00	0.00	0.01	0.00	0.03	0.00
CO_2	7.88	0.91	0.05	0.02	0.05	0.00	0.05	0.04
CH_4	5.70	5.80	0.45	5.20	3.60	5.60	4.00	2.22
C_2H_6	0.082	0.120	0.015	0.230	0.150	0.300	0.200	0.218
C_3H_8	0.074	0.083	0.002	0.047	0.050	0.057	0.092	0.156
i-C_4H_{10}	0.0088	0.0110	-	0.0066	0.0088	0.0076	0.0164	0.0251
n-C_4H_{10}	0.0240	0.0310	0.0034	0.0093	0.0110	0.0100	0.0208	0.0280
neo-C_5H_{12}	-	-	-	0.0002	-	0.0030	-	-
i-C_5H_{12}	0.0019	0.0052	0.0001	0.0016	0.0035	0.0027	0.0123	0.0147
n-C_5H_{12}	0.0042	0.0170	-	0.0018	0.0058	0.0036	0.0152	0.0132
i-C_6H_{14}	0.00010	0.00067	0.0001	trace	-	trace	-	-
n-C_6H_{14}	0.00100	0.00600	-	-	-	-	-	-
C_6H_6	0.01950	0.00440	-	-	-	-	-	-
ΣC_{2+}	0.216	0.278	0.021	0.297	0.229	0.384	0.357	0.455
$\delta^{13}C_{CH4}$ ‰ (PDB)	-	-	-25.6	-31.9	-29.6	-29.9	29.0	-22.5
δD_{CH4} ‰ (SMOW)	-	-	-	-138	-	-154	-	-

7.3 Organic gas at Skógalón

The general chemical composition of water and gas from the Skógalón boreholes has been discussed above. In this chapter the main emphasis is on the chemical and isotopic composition of the organic gas fraction. The following hydrocarbon gases have been detected in addition to methane: ethane, propane, iso-butane, n-butane, neo-pentane, iso-pentane, n-pentane, iso-hexane, n-hexane and benzene. A summary of the names of and formulae for these hydrocarbons is presented in Table 15.

The composition of the organic gas fraction has been established by subtracting all other gases and setting the total concentration of the remaining gases as 100% to make it comparable to other natural hydrocarbon gases. This reconstituted composition is shown in Table 16. An attempt was made to estimate the amount of gas discharged from well 4 by combining the chemical composition of a sample collected on October 25 (No. 91-029) with the results of a well flow estimate. The steam fraction is assumed to be 5%, the gas flow was measured and found to be 0.055 l gas/kg flow and the total flow from the well is assumed to be 10 kg/s. Using this information the total gas flow from the well is 0.5 l/s or 47.500 l/day of which 2140 l/day are hydrocarbons and hydrocarbons excluding methane (ΣC_{2+}) 240 l/day.

Schoell (1980) has classified natural gas of different origins basing his classification on the chemical and isotopic composition of the relevant gas. His classification was described in

Table 15. The names of some hydrocarbons and their formulae

Chemical formula	Name
CH_4	methane
C_2H_6	ethane
C_3H_8	propanr
i-C_4H_{10}	iso-butane
n-C_4H_{10}	normal-butane
neo-C_5H_{12}	neo-pentane
i-C_5H_{12}	iso-pentane
n-C_5H_{12}	normal-pentane
i-C_6H_{14}	iso-hexane
n-C_6H_{14}	normal-hexane
C_6H_6	benzene

Table 16. The chemical composition of the organic gas fraction (volume %)

Well	ÆR-04	ÆR-04	ÆR-03	ÆR-03	ÆR-03	ÆR-01	ÆR-01	ÆR-01
No.	91-0209	91-0189	90-0237	89-0087	88-0149	89-0088	88-0211	87-0119
Mode	separ-	well-	200 m	well-	well-	well-	well-	well-
	ator	head	in situ	head	head	head	head	head
CH_4	96.513	95.554	95.584	94.640	95.530	93.635	91.826	83.003
C_2H_6	1.388	1.977	3.207	4.186	3.980	5.016	4.591	8.151
C_3H_8	1.253	1.367	0.425	0.855	1.327	0.953	2.112	5.833
i-C_4H_{10}	0.149	0.181	-	0.120	0.234	0.127	0.377	0.939
n-C_4H_{10}	0.406	0.511	0.722	0.169	0.292	0.167	0.478	1.047
neo-C_5H_{12}	-	-	-	0.004	-	0.050	-	-
i-C_5H_{12}	0.032	0.086	0.021	0.029	0.093	0.045	0.282	0.550
n-C_5H_{12}	0.071	0.280	-	0.033	0.154	0.060	0.349	0.494
i-C_6H_{14}	0.002	0.011	0.021	trace	-	trace	-	-
n-C_6H_{14}	0.017	0.099	-	-	-	-	-	-
C_6H_6	0.330	0.073	-	-	-	-	-	-
ΣC_{2+}	3.649	4.584	4.400	5.396	6.079	6.419	8.189	17.012
$\delta^{13}C_{CH4}$ ‰(PDB)	-38.9	-40.0	-26.6	-31.9	-29.6	-29.9	-29.0	-22.5
δD_{CH4} ‰(SMOW)	(-92)	(-97)	-	-138	-	-154	-	-

Chapter 2 and Fig. 2. Methane is virtually the only hydrocarbon gas in young, immature organic gas formed by the decomposition of organisms (ΣC_{2+} < 0.05%). Gas found in Lake Lagarrfljót is of this type. Longer carbon chains are formed as the organic matter matures further and the concentration of other hydrocarbons increases (ΣC_{2+} > 5%). The first drops of petroleum are formed at this stage. Upon further maturation the carbon chains become even longer and solids are formed. Eventually gas formation decreases and the gas becomes nearly exclusively methane again (ΣC_{2+} <5%, usually < 1%). In these conditions higher hydrocarbons "crack" to methane and eventually graphite.

The stable carbon isotope ratio ($^{12}C/^{13}C$) in methane is related to the origin of the methane and has been used to distinguish between methanes of different origins. The proportion of

^{13}C in methane from the mantle is high, $\delta^{13}C$ being close to -70 o/oo on average, but low in methane of organic origin, with $\delta^{13}C$ usually in the range -60 to -100 o/oo. In thermogenic methane it is intermediate, usually -25 to -50 o/oo. These ranges are shown in Fig 33 along with results of $\delta^{13}C$ determinations on the Skógalón gas which shows all signs of being thermogenic.

Schoell (1980) also presents a host of results of isotope determinations on natural gases, classifies them on the basis of isotope composition and compares the results with his classification based on carbon chain length discussed above.

The distinction between different groups of natural gas based on carbon ($\delta^{13}C$) and hydrogen (δD) isotope ratios in methane is shown in Fig 34. The groups B, M, T and TT are clearly defined. Schoell's classification is described in Chapter 2 and Fig 2. It entails dividing hydrocarbons into two main groups; biogenic gas ("B") and thermogenic gas ("T") the latter being further divided into "wet" ("oil") gas ("T") and "dry" ("coal") gas ("TT"). A few gases fall into neither main group and have been classified as of mixed origin ("M"). The gases can furthermore be divided into those of marine ("m") and terrestrial (humic) ("h") origin. The results for two samples from Öxarfjörður are added to Fig 33 and one of them fits the TT(h) group (thermogenic dry gas of terrestrial origin) but the other the TT(m) group (thermogenic dry gas of marine origin).

Figs 35 and 36 show the relationships of higher hydrocarbons (ΣC_{2+}) with δ13C and δD respectively. The fields T, TT(h) and TT(m) are specifically marked. Results from Öxarfjörður fit the TT group, in some instances TT(m) but in others TT(h).

Nakai et al. (1974) have investigated the relationship of hydrogen isotope ratios (δD) in methane and its associated waters in Japanese oil and gas fields and Schoell (1980) did the same on natural gases of various origins. The results are nearly identical, i.e. that in the case of biogenic gas there is a distinct relationship of the hydrogen isotope ratio in methane with the same ratio in its associated water. This relationship is shown in Fig. 37 and for comparison the results for these ratios in samples from Öxarfjörður and Lake Lagarfljót added. The Öxarfjörður gas is way off the line suggesting that it is not biogenic, but the Lagarfljót results plot fairly close to it as is to be expected for a young, immature biogenic gas.

Thus according to Schoell's classification the Skógalón borehole gas is thermogenic but it is not clear whether its origin is marine or terrestrial. Some results suggest a wet gas but many that it is a dry gas and still others plot on the border between the two. The results of the determination of total organic carbon (TOC) in the sediments that were intersected during drilling revealed that the gas is unlikely to be formed within them. Furthermore the TOC concentration was too low for distinguishing between marine and terrestrial origin by measurement.

An attempt was made to date the gas from well 4 and preliminary results suggest that its ^{14}C-age is > 20.000 years and probably much higher (Sveinbjörnsdóttir, Á.E., personal communication, 1992). This observation, if correct, suggests that the gas is formed below 350 m depth because the sediments down to that depth are formed during the last 10.000 years.

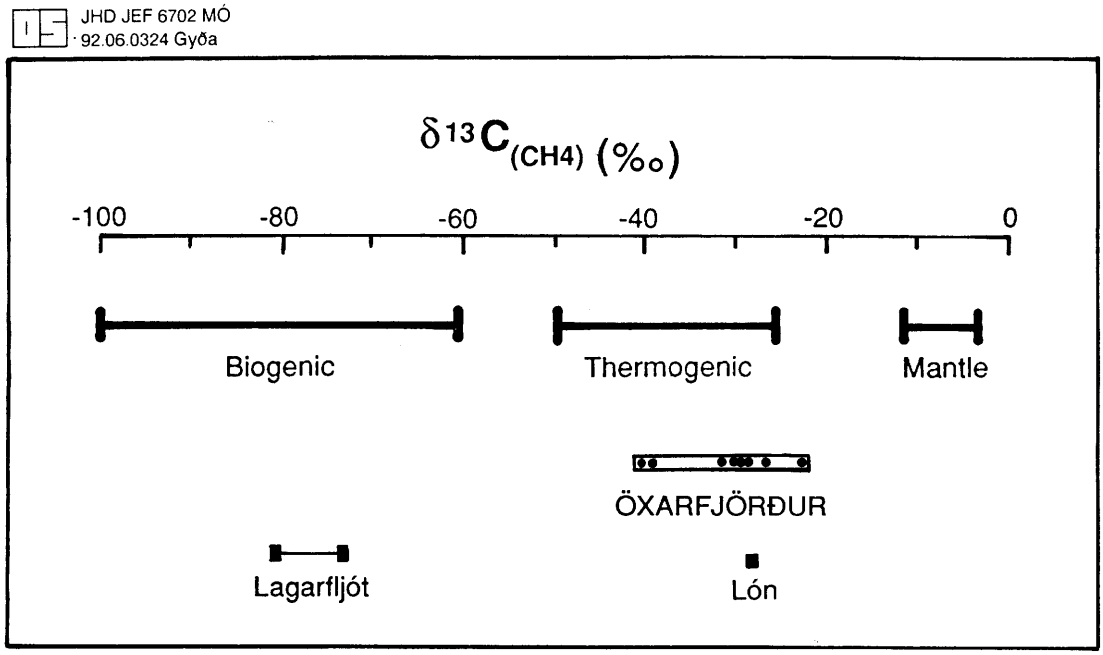

Figure 33. $\delta^{13}C$ in methanes of different origins.

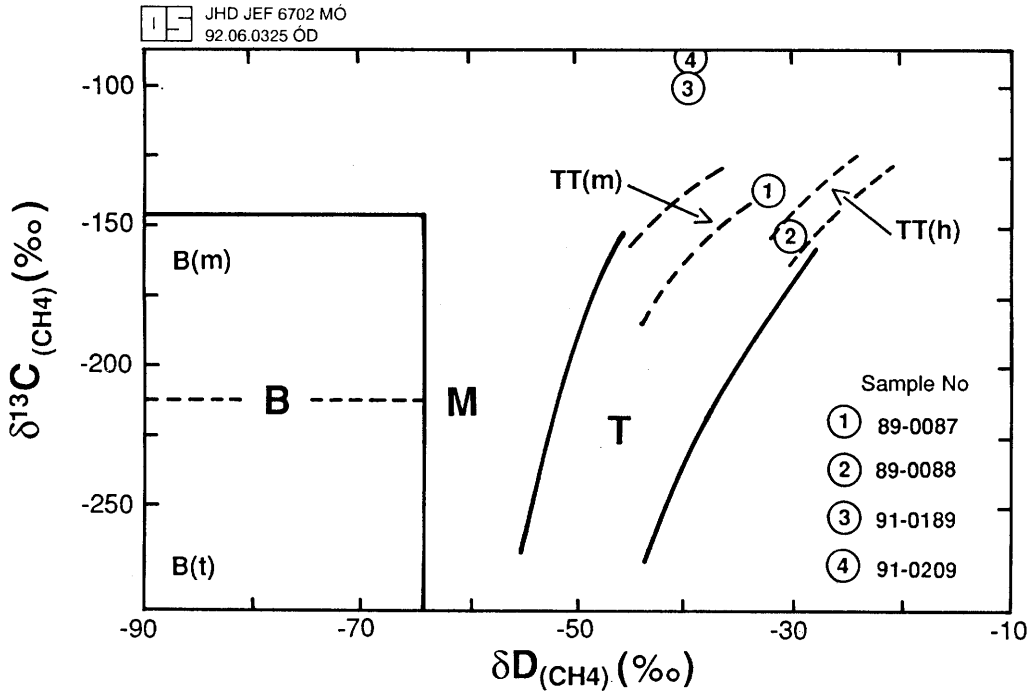

Figure 34. The relationship of $\delta^{13}C$ with δD in methanes of different origins.

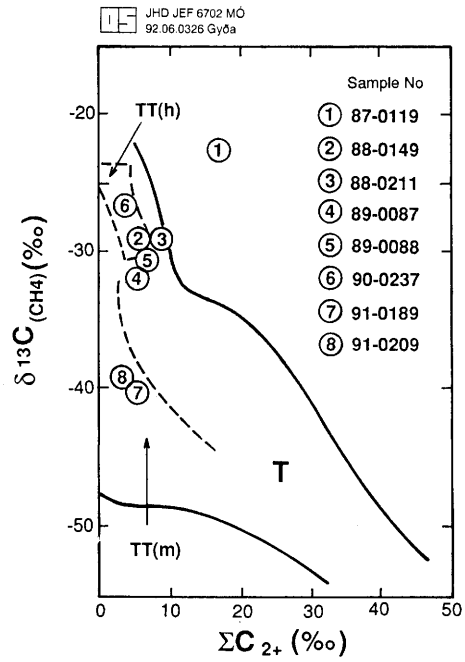

Figure 35. The relationship of $\delta^{13}C$ in methane with total concentration of higher hydrocarbons.

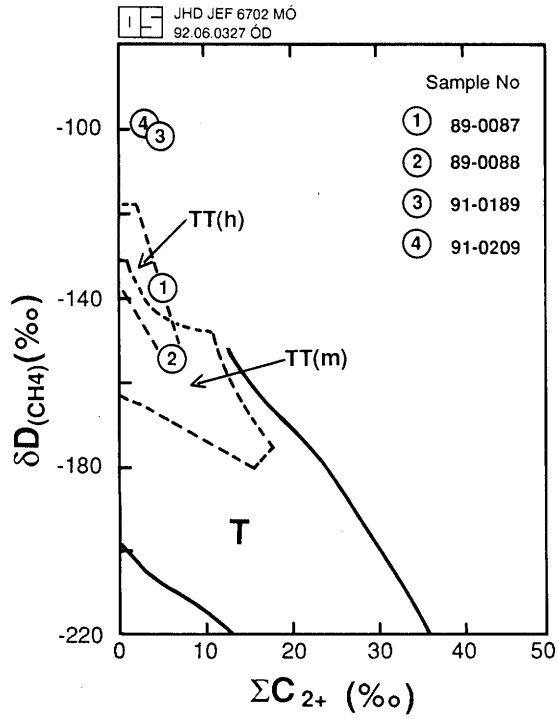

Figure 36. The relationship of δD with total concentration of higher hydrocarbons.

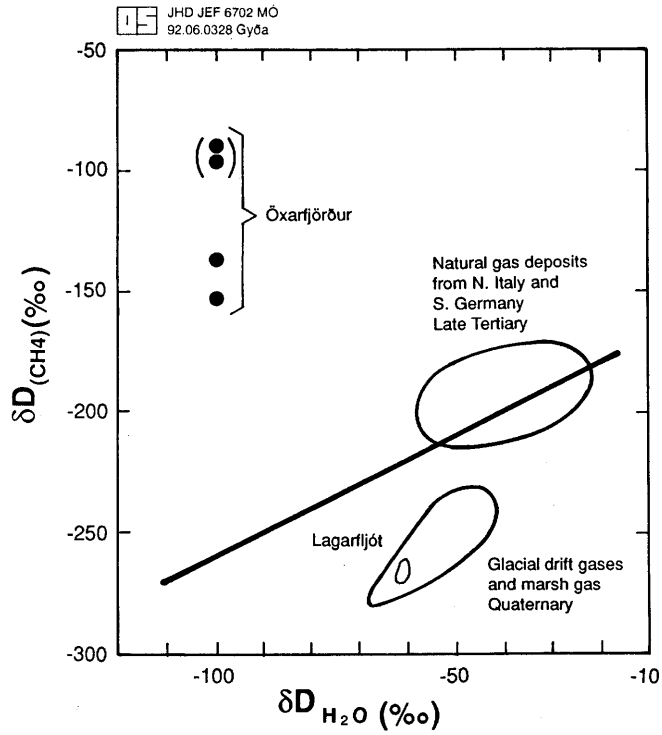

Figure 37. The relationship of δD in methane with that of its associated water

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