Overview of hydrocarbon related research in Tjörnes

Bjarni Richter
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Prepared for National Energy Authority

ÍSOR-2010/007

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Abstract

Samantekt á rannsóknum sem stundaðar hafa verið á Gammsvæðinu undanfarinn áratug. Þær rannsóknir sem fjallað er um eru fjölgeisladýptarmælingar, side-scan sonar, grunnar hljóðendurvarpsmælingar (Chirp), kjarnataka á hafsbotni Skjálfanda, ljósmyndun hafsbotnsins í Skjálfanda, kjarnaborun í Tjörnessetlögin, gassýnasöfnum og kortlagning gasuppstreymis á söndum Öxarfjarðar ásamt greiningum á þyngri kolvetnissamböndum.

Einnig eru ráðleggingar um frekara framhald í tengslum við olíu- og gasrannsóknir á Gammsvæðinu. Skýrslan er á ensku með ítarlegum, íslenskum útdrætti.

Key words	ISBN-number
Gammsvæði, Gammur, Öxarfjörður, Skjálfandi, olía, oil, hydrocarbon, gas, gasanalysis, kolvetnisgas, fjölgeisladýptarmælingar, multibeam, side-scan sonar, hljóðendurvarpsmælingar, seimic syrvey (Chirp), seafloor photography, hafsbotnsmyndataka, kjarnataka, coring, kjarnaborun, Tjörnessetlög, Tjornesbeds.	
	Project manager's signature
	Reviewed by: BR, KG

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Gammur kallast olíuleitarsvæði fyrir Norðurlandi, sem tekur einkum til Tjörnesbrotabeltisins. Þetta er svæðið frá Öxarfirði vestur fyrir Eyjafjarðarál, um 150 km löng spilda og um 50 km breið. Jarðlagahöggun á þessu stóra svæði er afar flókin og mjög virk, eins og sést af sífelldum jarðskjálftum og nýlegri eldvirkni. Um svæðið kvíslast brotalamir jarðskorpuflekanna og tengja gliðnun í gosbeltinu á Norðausturlandi til norðvesturs í gliðnunarsprungu Kolbeinseyjarhryggjar. Suðurjaðar beltisins er markaður af miklu misgengi (sniðgengi), sem er framhald af Húsavíkurmisgenginu og gengur á milli Flateyjar og lands og vestur í suðurenda Eyjafjarðaráls. Þar norðan við hefur jarðskorpan hliðrast til austurs en einnig tognað og sigið. Jarðeðlisfræðilegar rannsóknir, endurkastsmælingar og þyngdarmælingar hafa sýnt að þar hafa safnast þykk setlög í sigdæld sem er mest á svæðinu frá Skjálfanda og vestur í suðurenda Eyjafjarðaráls. Setlögin eru þykkust næst misgenginu, ná allt að 4 km þykkt undir Eyjafjarðarál, en þynnast til norðurs. Setlögin hafa verið rakin norður undir Grímsey en norðurjaðarinn er óljós. Þessi jarðlög eru mjög ung í samhengi olíuleitar en hitinn í botni þeirra ætti að nægja til að mynda kolvetni ef uppsprettuefni er til staðar.

Núverandi jarðlagahöggun í beltinu einkennist af sigdældum með norðlæga stefnu, en nákvæm dýptarkort frá síðasta áratug hafa leitt í ljós brotamynstrið. Mikil sigdæld er út Eyjafjarðarál, þar sem misgengisstallar eru allt að 10 m háir, og nokkur höggun finnst í Skjálfandaflóa, sem magnast norðar í Skjálfandadjúpi. Austan Tjörness, sem er rishryggur, er þriðja sigdældin undir Öxarfirði, sem er í beinu framhaldi af gosbeltinu. Endurkastsmælingar á landi hafa sýnt þar allt að 1000 m setlagaþykkt.

Óvissa ríkir um hvort olíumyndandi jarðlög séu til staðar í verulegum mæli, og hvort þau hafi gefið frá sér kolvetni. Þetta eitt og sér nægir til að gera olíuleit á Gammsvæðinu mjög áhættusama. Þá skiptir einnig miklu máli hvort lífræna efnið sé af þeim toga sem myndar fremur olíu en gas, því olíulind væri mun arðbærari en gaslind. Í Breiðavík á Tjörnesi má sjá setlög sem hafa risið úr sæ og gætu verið dæmi um elstu og neðstu setlög í dældinni. Í þeim eru surtarbrandur, sem gæti myndað gas en síður olíu, þó að athuganir hafi sýnt að við réttar aðstæður geti það verið mögulegt. Gasleki hefur fundist við Skóga og Skógalón í Öxarfirði, bæði í yfirborði og í borholum, en gasið er líklega komið af allnokkru dýpi.

Nákvæm kortlagning á botni Skjálfanda hefur leitt í ljós holur, tuga metra í þvermál, sem liggja í þannig röðum að líklega fylgja þær undirliggjandi misgengjum. Þær gætu verið myndaðar af gas- eða vökvaútstreymi (svokölluð „pockmarks“), en gætu einnig verið jarðföll yfir gapandi sprungum. Slík svæði má finna beggja vegna í Skjálfandaflóa og meðfram Húsavíkurmisgenginu. Einnig hafa fundist merki um slíkt í Öxarfirði. Ef olíu- og gasmyndun á sér þar stað, mætti búast leka kolvetna um þessar sprungur og holur, og að smit af þeim efnum sitji í botnsetinu þar í kring. Hljóðendurvarpsmælingar í Skjálfanda hafa einnig gefið vísbendingar um að gas sé til staðar fremur grunnt í setlögum.Hér er lagt til að tekin verði sýni af botnseti í Skjálfanda og þau greind með tilliti til hugsanlegs gas í porum, og það sé nú hæfilegur áfangi til að styrkja mat á olíulíkum (sjá kafla 4). Tillögur um þau svæði sem leggja ætti áherslu á má sjá á mynd 5. Rétt er þó að leggja áherslu á það að jarðlagagerð og -aldur svæðisins er ólíkt öllum þeim olíusvæðum sem þekkjast annars staðar í okkar heimshluta. Vegna þessa er erfitt að koma á eiginlegri olíuleit eða freista olíufyrirtækja til að hefja hér viðamiklar olíurannsóknir, nema sýnt sé fram á að fyrir hendi sé mögulega ný tegund af olíumyndunarkerfi, svo sem óvenjulegt uppsprettuberg.

1 Introduction to the geology of the Tjörnes basin

The Tjörnes basin is located offshore on the northern shelf of Iceland. It includes a number of sedimentary sub-basins formed within the trans-tensional Tjörnes Fracture Zone (TFZ). This zone is a complex of active transform and extensional tectonic features which extends about 150 km from off Skagi in the west, to Öxarfjördur in the east and approximately 50 km from the north coast towards the Kolbeinsey ridge (Fig. 1) (Sæmundsson, 1974; McMaster et al., 1977). The Húsavík-Flatey Fault is the principal transform tectonic feature observed. It forms the southern boundary of the fracture zone, and the major sedimentary deposits. The trend of this right lateral fault is about 65°W, which is slightly oblique to the more westerly plate spreading direction. This leads to a tensional component and is the likely cause of extension and subsidence north of the fault line. The fault/basin extends for about 100 km and joins the western margin of the N-Iceland volcanic zone (Þeistareikir fissure swarm) to the extensional Eyjafjarðaráll Graben.

To the north of Húsavík fault another sub-parallel tectonic line, the Grímsey Tectonic Lineament, transforms the extension in the eastern part of the on-shore volcanic zone to the active graben in northern Skjálfandadjúp, which continues in further left stepping tectono-volcanic features towards the end of the Kolbeinsey Ridge. While earthquake data indicate transform movement on the HFF, the Grímsey Lineament (GL) consist of north trending en echelon features, possibly suggesting initial stages of transform formation (Rögnvaldsson et al., 1998). Recent submarine volcanism is observed along the GL but not along the Húsavík Fault system.

Three north-trending troughs or extensional grabens are superimposed on the transform features of the TFZ, from west to east: Eyjafjarðaráll, Skjálfandadjúp and Öxarfjörður, separated by the Grímseyjargrunn and Tjörnes highs. These troughs are prominent bathymetric features with water depths up to 600 m, and have also been the location of considerable sedimentary deposition.

The TFZ formed in association with an eastward shift of the spreading axis to its present location in north-eastern Iceland (Sæmundsson, 1974; Jancin et al., 1985) in Miocene times, probably about 7 Ma. The presently active rift axis in northern-Iceland extends north through Öxarfjördur graben, and is displaced westwards to the Kolbeinsey Ridge through 2–3 volcanic rift segments arranged in an en echelon fashion. The zone is associated with both high- and low-temperature geothermal systems (Fridleifsson et al., 1994).

The existence of thick sediments to the north of the Húsavík-Flatey fault was initially suggested by a gravity survey (Pálmason, 1974), and was subsequently confirmed by multichannel reflection data from a survey of the shelf north of Iceland by Western Geophysical Co. in 1979. Four seismic profiles were acquired over major part of the northern shelf, where the end of one profile extended over the thick sediments of Eyjafjarðaráll graben. In 1985 the National Energy Authority of Iceland followed up by shooting six more profiles over the deepest part of the Tjörnes Basin Fracture Zone, just north of the Húsavík-Flatey fault. These profiles are the main source data for the study of the sedimentary formations, and are reveal a complex tectonic pattern. The southern part of the deep Eyjafjarðaráll is shown to be an extensively faulted active graben, about 40 km wide. The faults are typically spaced at 1–2 km intervals and quite active, as up to 10 m high fault escarpments are observed in the bathymetry. This graben terminates at the western end of the Húsavík-Flatey Fault, where the fault is characterized by a steeply dipping upper part, changing into a listric geometry at depth, and a system of synthetic and antithetic faults are observed. Further west along the fault the extensional character gives way to strike-slip characteristics. Two separate branches are observed, each of which are displayed as positive flower structures.

The initiation of the major phase of the Tjörnes Basin sedimentation is assumed to be subsequent to the formation of the fracture zone, and thus a few million years old. The greatest sedimentary thickness is found adjacent to the Húsavík-Flatey Fault, up to 4 km in the Eyjafjarðaráll Graben, but thins out further north (Fig. 1). A 550 m deep drill hole on the island of Flatey penetrated Plio-Pleistocene sediments, 1–2 Ma old, and it is deduced that most of the sediments of the Tjörnes Basin were deposited during the glaciations of the last 3 Ma. (Flóvenz and Gunnarsson, 1991; Gunnarsson et al., 1984; Gunnarsson, 1998). This does not exclude possible source rocks, such as lignite, in the basal sequence or even within the basaltic basement. Due to the rapid Pleistocene sedimentation, maturation of hypothetical deeply buried source rocks could be still in progress.

The Tjörnes peninsula is a westwards tilted horst between the sub-basins of Skjálfandi and Öxarfjörður. There, a sedimentary section is exposed, which could be typical formations of the marginal units of the Tjörnes Basin. A basal unit of Tertiary lava flows, that are in the order of 10 Ma old (Sæmundsson, 1979), is overlain by about 500 m thick sediments (Tjörnes Beds) on the west coast of Tjörnes peninsula. These sediments are covered by a second lava unit of Pliocene age which in turn are succeeded by yet another alternating sequence of sediments and lava flows. Several lignite beds are present within this dominantly marine succession. The upper third of the sediments are mostly lava flows and Pliocene tills and other glacial-related sediments (Eiríksson, 1981). A correlation to a 600 m borehole in Flatey (Eiríksson et al., 1990) supports that at least 1/3 of the basin fill could be of Pliocene age.

The Tjörnes sediments probably extend eastwards into the Öxarfjörður rifting zone, where they are possibly buried at more than 1000–1500 meters depth (Ármannsson, et al., 1998). High- and low-temperature geothermal systems are presently active within this rift zone, as in Öxarfjörður. Such systems were probably active within the Tjörnes Basin in Miocene and Pliocene times. The geothermal gradient is very high around the Tjörnes Basin itself, reaching from about 40°C/1000 m to about 110°C/1000 m locally (Fridleifsson et al., 1994). In Öxarfjörður it reaches over 200°C/1000 m. This must have strongly influenced the thermal history of the basin and condition for hydrocarbon maturation. In areas close to active volcanism and geothermal activity, the maturation could be early and localized and at shallow depth. Positive evidence of hydrocarbon gas formation was observed at the Skógalón geothermal area on-shore in Öxarfjörður. Analysis of gas samples from a 450 m deep borehole confirms thermogenic origin at depth. In the western part of the deep basin, where volcanism is not observed, the temperature gradient is expected to be more moderate and maturation dependent on deep burial.

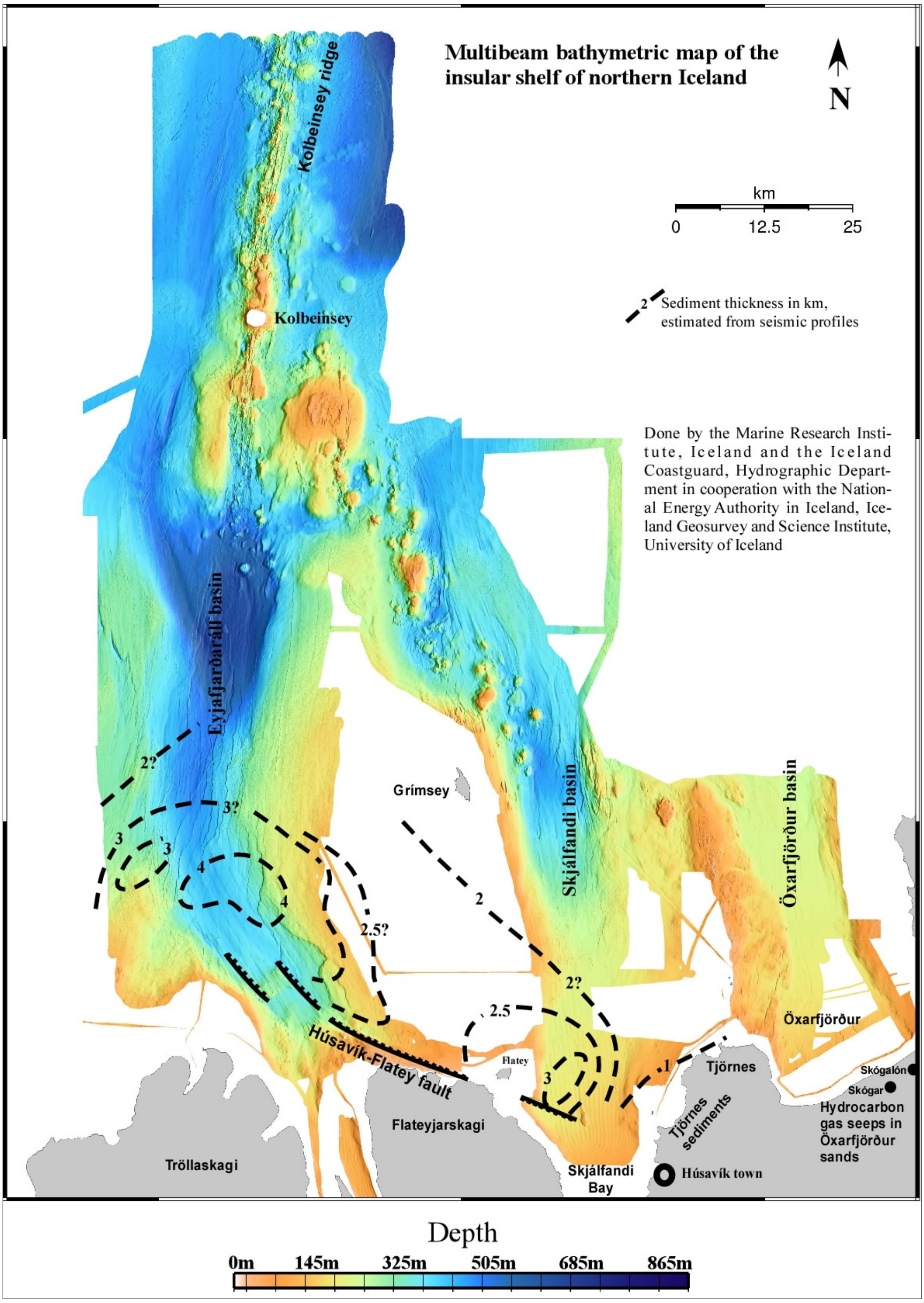

Figure 1. *Overview of the Tjörnes Basin on the northern insular shelf of Iceland.*

2 Recently acquired data from the Tjörnes fracture zone

2.1 Coredrilling the Tjörnes sediments

As mentioned in the introduction, thermogenic gasseeps have been discovered in Öxarfjörður (Ólafsson et al., 1993). But nothing was known regarding the source rock or depth to the source. Some ideas were put forward that the well known Tjörnes lignites or similar formations could be the source of the gas since gas analyses seemed to indicate that a significant portion of the gas was derived from terrigenous organic material.

Therefore, in 2001, The Tjörnes sediments were coredrilled to sample unweathered samples of the lignites to be able to analyse if they could yield similar gas as in Öxarfjörður and even oil (Richter, 2001, 2002).

Samples of lignites were sent to Science Institute, University of Iceland, which sent the samples to Aarhus University for isotope analyses. The results are as follows (Richter, 2003):

Table 1. *Results from isotopic analyses of the carbon from the Tjörnes lignites.*

Sample nr.	Depth (m)	d13C	RVK lab no.
HV-02 S-1	14	-28.95	CAAR-8681
HV-02 S-4	18	-27.31	CAAR-8650
HV-02 S-6	21	-28.11	CAAR-8673
HV-01 S-10	46.5	-27.59	CAAR-8645
HV-01 S-11	50.7	-27.06	CAAR-8643

2.2 Chemical analyses on lignites from Tjörnes

A total of 15 core samples collected from 3 different wells in the Tjörnes Fracture zone were analysed. Samples were collected from coaly or seemingly organic-rich sediments strata in the HV-01 (6 samples), HV-02 (7 samples) and TG-01 (2 samples) wells (Table 2). For description of methodology, see Richter and Bojesen-Koefoed (2002).

Vitrinite reflectance analyses was carried out on three samples. The results show values <0.40%, indicating very low level of thermal maturity (Table 2).

Total Organic Carbon (TOC) contents are very variable, ranging from 0 to 32%,

Total sulphur contents are variable, ranging from <0.20% to >10%. The variation observed does not appear well correlated to TOC (Table 2).

Rock-Eval screening pyrolysis data show Tmax in the range 418–425 °C, corresponding well to the maturity indication provided by vitrinite reflectance analysis. Values of S2 are highly variable, ranging from zero to 93 mg HC/g rock, leading to Hydrogen Indices (HI) from zero to 250. Based on Rock-Eval screening pyrolysis data, the kerogen is, at best, classified as gas-prone Type III, but the comparatively high values of both S2 and HI yielded by several samples may suggest the presence of at least minor potential for generation of waxy liquid hydrocarbons (Figures 2 and 3).

A total of six samples were subjected to solvent extraction and biomarker analysis. Sample selection was based on the results of screening analyses. All samples show high, yet variable, asphaltene contents, and maltene fraction compositions entirely dominated by hetero-components (NSO), and showing very low hydrocarbon to non-hydrocarbon ratios.

Table 2. *Results from the screening analyses of coresamples.*

Table 2										
Well	Lab#	Depth	TOC (wt-%)	H (wt-%)	N (wt-%)	S (wt-%)	Tmax (°C)	S1 (mg/g)	S2 (mg/g)	Hydrogen Index
HV-02	6563	14,00	24,15	5,75	0,30	5,25	420	1,78	37,20	154
HV-02	6564	14,40	37,48	4,84	0,55	4,95	423	5,88	92,87	248
HV-02	6565	15,20	25,06	3,52	0,49	1,82	424	2,53	55,27	221
HV-02	6566	18,00	41,80	5,24	0,68	5,27	418	4,39	87,54	209
HV-02	6567	20,00	0,79	1,05	0,06	5,40	-	0,01	0,15	19
HV-02	6568	21,00	28,20	4,66	0,50	1,71	429	2,43	59,69	212
HV-02	6569	23,50	0,05	1,27	0,03	0,17	-	0,00	0,00	-
HV-01	6570	22,50	0,15	2,03	0,03	0,69	-	0,00	0,01	-
HV-01	6571	37,50	0,25	1,77	0,03	0,23	-	0,00	0,01	-
HV-01	6572	46,50	8,72	2,20	0,17	10,26	423	0,09	7,16	82
HV-01	6573	50,70	18,89	3,05	0,39	1,85	424	0,45	31,55	167
HV-01	6574	51,60	9,80	2,75	0,19	0,47	425	0,40	14,69	150
HV-01	6575	53,50	0,15	2,15	0,02	1,58	-	0,01	0,02	13
TG-01	6576	20,60	0,32	2,13	0,04	1,54	-	0,01	0,07	22
TG-01	6577	22,80	0,22	1,97	0,04	0,26	-	0,01	0,06	27

The Tjörnes beds, as seen in the Tjörnes horst are thermally immature to early mature with respect to petroleum generation. Judged from the tectonic history, the Tjörnes bed samples probably provides a minimum-maturity indication. Hence, it is very likely that the same sediments, are considerably more mature in other areas, especially where the geothermal gradient is high, thus generating dry and wet gasses and even oil, given the right conditions. A maturation simulation has shown that these lignites can generate a waxy oil as well as gases.

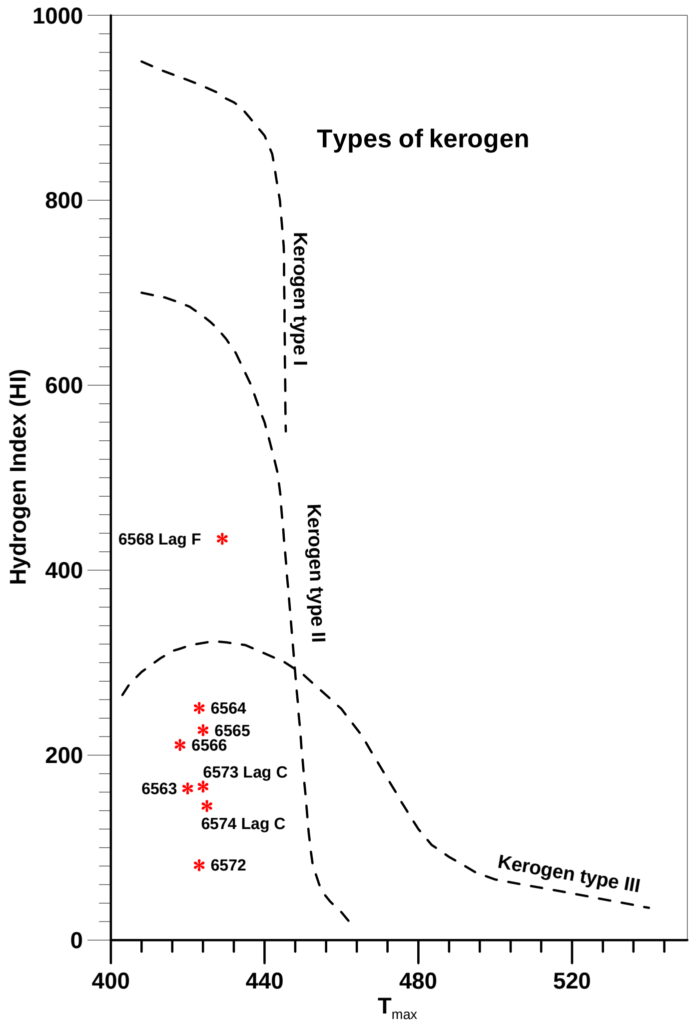

Figure 2. *A graph which indicates the type of kerogen found in lignites from the Tjörnes horst, extracted from Tmax and HI. The Tmax (420–430°C) indicates that the samples are thermally immature. Vit.ref. of 0.25–0.3 supports that. At least one sample consists possibly of more than terrestrial material, and even some of the other as well.*

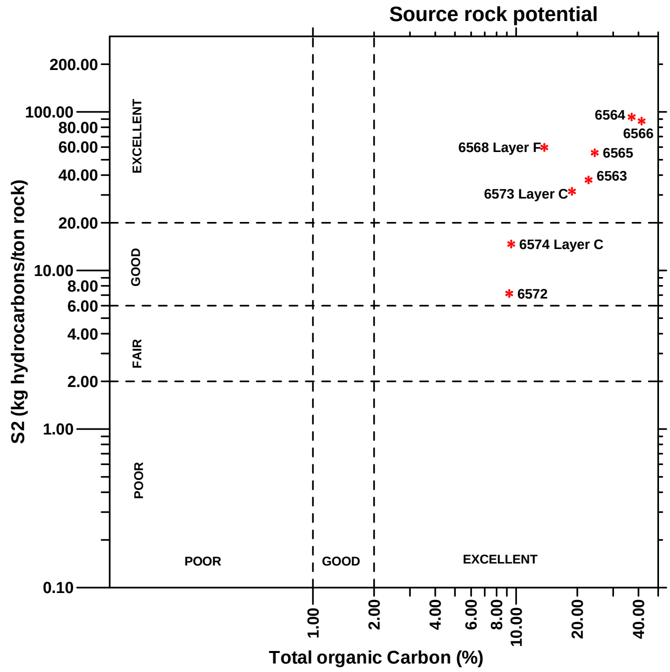

Figure 3. *Even though lignites in the Tjörnes beds are thermally immature, they show great potential for source rock, given the proper circumstances. This organic substance can very well be the source of the gases found in Öxarfjörður.*

2.3 Hydrocarbon gasses in Öxarfjörður

In 1989 geothermal holes were drilled near Skógarlón in Öxarfjörður. During and after the drilling, gases were emitted through the boreholes. Analysis of the gases suggests that they are thermogenic (both wet and dry) gases (methane through hexane), both of marine and terrestrial origin (Fig. 4). They are present in fairly high concentrations and possibly, at least to some extent, derived from lignite beds similar to the ones in Tjörnes beds (Ólafsson et al., 1993; Ármannsson et al., 1998).

In August 1999, the drilling of a deep geothermal well, BA-02, provided a good opportunity to study natural gas in Öxarfjörður. A gas-chromatograph (SRI 8610C) was used at the drill site to detect any gas leaking from the well.

In the Skógarlón area, where gasses seeping through boreholes have previously been detected (Ólafsson et al., 1993), it was apparent that gasses where also seeping directly out of the sands within the geothermal area.

The geochemical analysis documents that evolved hydrocarbons (methane, ethane, propane, butane, pentane and hexane) occur in fairly high concentrations in Öxarfjörður, e.g. methane ~ 6 %, ethane ~ 0.4 %.

Analysis of gas samples from the geothermal area at Skógar, produced similar results.

The total organic carbon (TOC) within the sediments is less than 0.05%, which makes it unlikely that these gasses are biogenic. Therefore it seems that they come from a deeper and older source. A ^{14}C age determination revealed that gasses in Skógarlón are more than 20,000 years old (Ólafsson et al., 1993).

Analyses of isotopic signals of gas samples from wells no. 1–4 in Skógarlón from Ólafsson, et al. (1993) are plotted in figure 4 along with results from gas samples from seep mounds from 2002 (table 3), when new samples were collected in Skógar and Skógalón and analyzed by Dr. Karlis Muelenbachs, University of Alberta, Canada (Richter, 2003). The general results from the analyses in 2002 is that this is most likely derived from thermal alteration of lignites and coal rather than a magmatic source.

Table 3. *Results from isotopic analyses on hydrocarbon gas collected from seep mounds and analysed in the University of Alberta.*

Feb. 3/2004 LSD	13C1	13C2	13C3	13iC4	13nC4	iC5	nC5
SK 2 (NaOH) Iceland	-24.55	-23.28	-20.46	-24.32	-25.14	-27.58	-29.85
AER-2 (NaOH)Iceland	-26.37	-27.6	-24.24	-23.85	-23.43	-21.16	-24.09

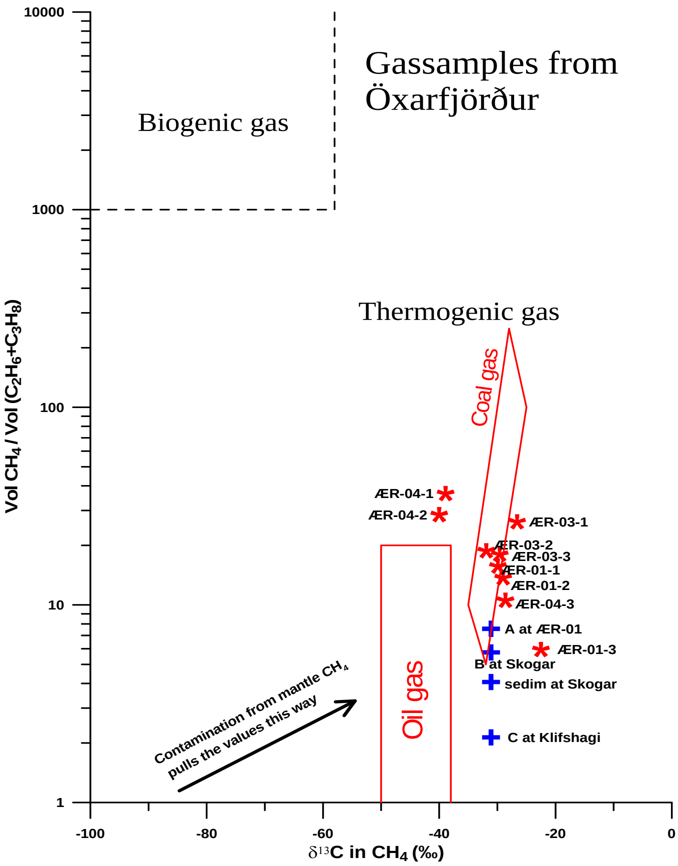

Figure 4. *Analyses made in 1999 (blue crosses) as well as analyses done 12 years ago (red stars). The gas is without doubt thermogenic and not biogenic. Since this is a volcanic region, it may be possible that methane from magma could contaminate the samples, shifting them towards the right and up. If that is so, many of the samples could actually have lower δ13C (mantle methane has δ13C > -10). Blue crosses have a δ13C mean value extracted from the older data. The value from the result of the analyses of Muelenbachs, indicates that the blue crosses should be shifted to approximately -25 δ13C.*

2.4 Bathymetric mapping and ocean floor photographs in the Tjörnes Fracture Zone

Recently collected EM300 (2001) and RESON8101 (2003 and 2004) multibeam bathymetric data, and CHIRP sub-bottom data combined with onshore mapping and data collection, have enhanced our understanding in the area of the Tjörnes Fracture Zone. Areas of large, elongated and circular depressions (pockmarks) within Skjálfandi Bay and Öxarfjörður were mapped during a multibeam bathymetric surveys in 2002, 2003 and 2004. These pockmarks reach 400–500 meters in length and 100–200 m in width and are commonly 2–5 meters deep.

The pockmarks in north-eastern Skjálfandi bay are all elongated NE-SW, with deeper NE ends. The pockmarks in the north-western part of the bay are elongated WNW-ESE, with deeper WNW ends. The north-eastern pockmarks seem to follow N-S lineaments and are possibly linked to sediment covered N-S aligned marginal faults of the Skjálfandi graben whereas the north-eastern pockmark field seems to be linked to two WNW-ESE trending transform faults with little or no vertical displacement.

Sidescan and RESON8101 data indicates the larger pockmarks to be made up of a cluster of smaller pocks, none which exceeds 25–30 meters in length. Pockmarks along the northern edge of the HFF seem to be of similar dimensions but are more rounded (Richter et al., 2003).

Ocean floor photography indicates that seeps occur in some of them, as well as documenting changes in sediment colour and hardness. Over 10000 photographs were collected in the summer of 2003, where some of them show indications of gas seeps/flux, i.e. possible gas bubbles in the water column and high density holes in the seafloor (Richter et al., 2003).

2.5 Indications of gas in Chirp (seismic) profiling from Skjálfandi

In 2001, a sidescan sonar imaging and CHIRP seismic sub-bottom profiling were conducted along the HFF, within Skjálfandi Bay. CHIRP data show amplitude anomalies and acoustic wipe-out zones, indicative of gas accumulation within the sediments.

A second Chirp seismic and sidescan-sonar survey was conducted 2003 along with gravity coring and digital bottom photography in order to assess the origin of these pockmarks and define the distribution of the gas charged sediments. Where present, acoustic wipe-out zones associated with the gas obscured all underlying reflectors as shallow as 5 meters below the ocean floor. The gas charged sediments are more widespread than previously observed within the bay. In northern Skjálfandi the gas seems connected to rather large, elongated pockmarks, which appear active, but in the southernmost Skjálfandi no pockmarks seem associated with the gas (Richter et al., 2003).

2.6 Backscatter as evidence for possible gas flux

Amplitude-versus-offset (AVO) analysis has been used successfully in the oil industry for the exploration and characterization of subsurface reservoirs. Multibeam sonars acquire acoustic backscatter over wide range of incidence angles, and the variation of the backscatter with the angle of incidence is an intrinsic property of the seafloor. With the necessary changes being made, a similar approach to seismic AVO analysis can apply to the acoustic backscatter. AVO analysis was applied to a Simrad EM300 (30kHz) multibeam sonar dataset from Skjálfandi Bay, Iceland. Based on known and new methods, acoustic backscatter model, the acoustic impedance, the roughness, and consequently the grain size, was estimated of the insonified area on the seafloor. In Skjálfandi Bay, the AVO attribute of fluid factor was calculated, which presented an estimate of the gas/fluid content in the sediment structure (Fonseca et al., 2004).

The areas with high fluid factor anomalies correlated to some extent to regions that showed evidence of gas in seismic profiles. It should be noted that this method is experimental, and some data inconsistencies could also contribute to some anomalies.

2.7 Core samples from Skjálfandi Bay and residual gas

In 2003, while mapping the seafloor with multibeam and CHIRP acoustic method, coring was attempted at several sites within Skjálfandi Bay using equipment provided by the Marine Research Institute, primarily to obtain sediment samples for hydrocarbon analysis. Core recovery was generally poor, primarily due to two factors – poor design of the core cutter and the fine grained, compacted volcanoclastic sediments in the bay. The cores were sent to Norway for analyses of possible residual gas in the cores.

The gaseous hydrocarbons for the northern part of Skjálfandi the occluded (interstitial) gas data indicate an anomaly in one sample (A-2 – Area A, see figure 5). In the southern part (samples C – Area C, see figure 5) the samples show two very high methane values. However the amounts of heavier n-alkanes are no different to the rest of the samples. The values of wetness suggest the more methane rich samples to be in total less thermogenic, i.e. the higher methane is due to bacterial activity in the sediments rather than seepage of thermogenic gas. The adsorbed gases show lower or similar yields and low wetness indicating a lack of historic thermogenic gas seepage.

The extraction data for the liquid hydrocarbons show only poor to fair yields of liquid HCs, and these will also include any liquid HCs from recent organic matter indigenous to the sediments. On the chromatograms of the extracts however, small amounts of possible seeped and biodegraded condensate/light oil hydrocarbons are seen in some samples. In these samples, apart from these peaks the heavy end of the chromatograms are dominated by n-alkanes with a distinct odd carbon-number dominance, representing immature recent organic matter (ROM) indigenous to the sediments. There are also some even heavier unidentified peaks which are probably related to the ROM. The chromatogram intensities also show that the samples are different in that they contain much greater amounts of ROM in absolute terms. In conclusion there are no recorded large (macro) seepages in any of the samples, however 2–3 where small amounts occur (Richter et al., 2005).

Since none of the cores were as long as recommended (1–3 m), it is expected that the results are not conclusive. Therefore thermogenic gas occupying pores deeper in the seafloor can not be ruled out. In the top level of the sediments it is highly likely that bioturbation and biodegradation has somewhat skewed the results.

2.8 Polycyclic aromatic hydrocarbons in Öxarfjörður and Skjálfandi

Polycyclic Aromatic Hydrocarbons (PAH) were collected both from Öxarfjörður sands as well as Skjálfandi bay (samples taken from the same cores as for the analyses of residual gas) (Geptner et al., 2006 a, b). The results from Öxarfjörður supports strongly the results found earlier that thermogenic gasses are emitted through the sediments.

Analyses from Skjálfandi bay indicate more strongly, than the residual gas in the dropcores (chapter 3.7), that some of the hydrocarbons in this area could be of thermogenic origin, the same way as in Öxarfjörður sands.

Polycyclic aromatic hydrocarbons have been analysed in 8 samples, which were collected in Skjálfandi at a depth of up to 200 metres.

Two samples from the southern part have a rather high total PAH content (123 and 200 ppb respectively) showing marked enrichment with hydrocarbons in comparison with all the other marine sediments.

In the centre of the Skjálfandi Bay, PAH composition shows an anomaly, which can be compared with a typical hydrocarbon association for high temperature oil fields. Correlation of this site with the transform fault zone (HFF) shows that zone of fissures might be a migration way for hydrocarbons.

The data from the southern part are characterised by the highest value of total PAH and perylene. It is possible that at this location there is a gaseous reservoir in depth, as indicated by shallow seismic profiles. Similar manifestations have been met in some other regions of the world (Geptner et al., 2006a).

2.9 Measurements on gas emissions through surface soil

Surface soil gas emissions were measured on shore in Öxarfjörður in 2004, with a gas flux meter from West Systems. The procedure involves a chamber which is pressed on to the ground surface and open to the soil. Air is continuously circulated by pumping from the chamber to a gas detector, and back to the chamber. Gas flux from the soil is seen as an increasing fraction of the emitted gasses with time. As the area of the chamber and volume is known, the gas flux can be calculated in grams or moles per time unit, commonly as grams per square meter per day.

The results from these measurements seem to be quite conclusive. Even though measurements were done in most areas of the Öxarfjörður sands, the only anomalous methane seep was reported in the geothermal areas of Skógar and Skógarlón. No indications were seen in other areas (unpublished data from Thráinn Fridriksson and Bjarni Richter).

3 Discussion and proposal for further investigation

While most aspects of hydrocarbon generation and accumulation are highly risky and uncertain in the Tjörnes Basin, we feel that the question of significant source rock and appropriate maturation history is critical. The lignite beds of Tjörnes are the only known exposed potential source rocks, and the chemistry of the gas seeps in the onshore Öxarfjörður graben suggest similar terrigeneous or gas-prone source. Oil-prone source rocks of marine origin are economically more important, but have so-far not been detected or indirectly inferred. The most likely location of such formations would be the deepest sedimentary basin north of the Húsavík-Flatey Fault lineament, stretching from western Skjálfandi to Eyjafjarðaráll. In this area the extensive sedimentation would also promote maturation of any source rocks. An ambitious program of 3D deep seismic surveying and drilling would be the direct way to assess this question, but is presently quite risky.

We suggest that the next logical step in the assessment of the Gammur area could be to ascertain whether thermogenic hydrocarbons can be found as gas traces in samples of seafloor sediments, close to possible seepage locations. This could better clarify the question of possible source rocks and maturation processes.

3.1 Sampling of bottom sediments and gas analysis

The demonstrated presence of near-bottom gas in sediments, and the various indications of possible gas expulsion, presents the possibility of sampling hypothetical thermogenic (hydrocarbons) gas in the bottom sediment. We propose a tentative program of 15–30 cores at least 5 locations.

Depth of penetration should be up to 3 meters or more in order to obtain samples below the biogenic zone. Experience suggests that a vibracorer or pistoncorer is required to reach these penetration depths, as previous attempts with a droppcorer to these depths have not been successful. This is not the preferred tool for this purpose as more disturbance of the material is risked, but probably unavoidable. The sediment cores will then be deep frozen (to approximately -20°C) and shipped for gas analysis.

The locations of sampling stations should be as close to gas indications as possible, but it is unlikely that a corer can be dropped to 100–200 meters depth with accuracy to hit individual pock marks. It will be assumed that traces of gas have intruded the shallow sediments of pock mark fields, both inside and outside the pocks. Of the following seven areas, the first four are here considered priority targets, while the rest is secondary (fig. 5):

1) Area A in north east past of Skjálfandi. A wide field of pock marks in en-echelon arrangement (NE) along a probable set of N-S trending deep faults. Small expulsion holes within some pock marks.
2) Area B along the main surface expression of the Flatey Fault in south-western Skjálfandi. Pock marks on the northern uplifted side.
3) Area C in south-eastern Skjálfandi offshore Húsavík. Patches of gas reflections in shallow seismic profiles. Top of gas reflection at 12–18 m depth. No pock marks but hard-ground character of bottom (photos).

4) Area D in North-West Skjálfandi. Pockmarks along a set of WNW-trending faults, parallel to the Húsavík-Flatey fault.
5) Area E in an apparent offset of the Húsavík-Flatey Fault in middle of Skjálfandi. Sub-bottom gas reflections.
6) Area F is close to shore south of Húsavík-Flatey Fault. Seismically detected shallow gas in sediments.
7) Area G: Within the Eyjafjarðaráll trough, where the seismic data has shown the deepest sedimentary basin with the thickest sedimentary pile. The area at the junction of the extensional NS fault system and the transform fault systems. Though no direct indications of gas seep have been observed, the thick sediments suggest the possibility of more mature hydrocarbon conditions.

3.2 Pre-study before coring cruise

Before the plan for the coring project is finalized, a revision of existing survey data is needed in order to fix suitable and exact locations for sampling stations. Included in this work is inspection of hydrographical and shallow seismic data in an attempt to detect seepage features:

1) Detailed mapping and positioning of pockmarks in multibeam hydrographic maps and side scan sonar. This could be restricted to likely sampling areas.
2) Inspection of tow-camera near bottom photographs to select likely seeps, such as fluid expulsion features (holes).
3) Inspection of shallow seismic data for the purpose of detecting a) shallow gas reflections and b) gas plumes above seafloor. Data from the 2002 cruise of Bjarni Sæmundsson, and 2003 seismic data with Chirp source.
4) Inspection of side-scan sonar data for pocks, seeps and gas plumes.
5) Inspection of raw hydrographic data (multibeam), in order to estimate if gas plumes in the water column have been recorded.

The items 1–3 are obligatory, as these studies will result in detailed maps where the final sampling locations will be determined. The items are 4–5 are less critical, and primarily an attempt to ensure that no important seep indications have been missed in the original raw data.

In addition to the above preparatory work, we suggest that a compilation and integration of the various datasets, hydrographical, geophysical and geological would be of great value. This could be organized in appropriate software such as a “Petrel-project”.

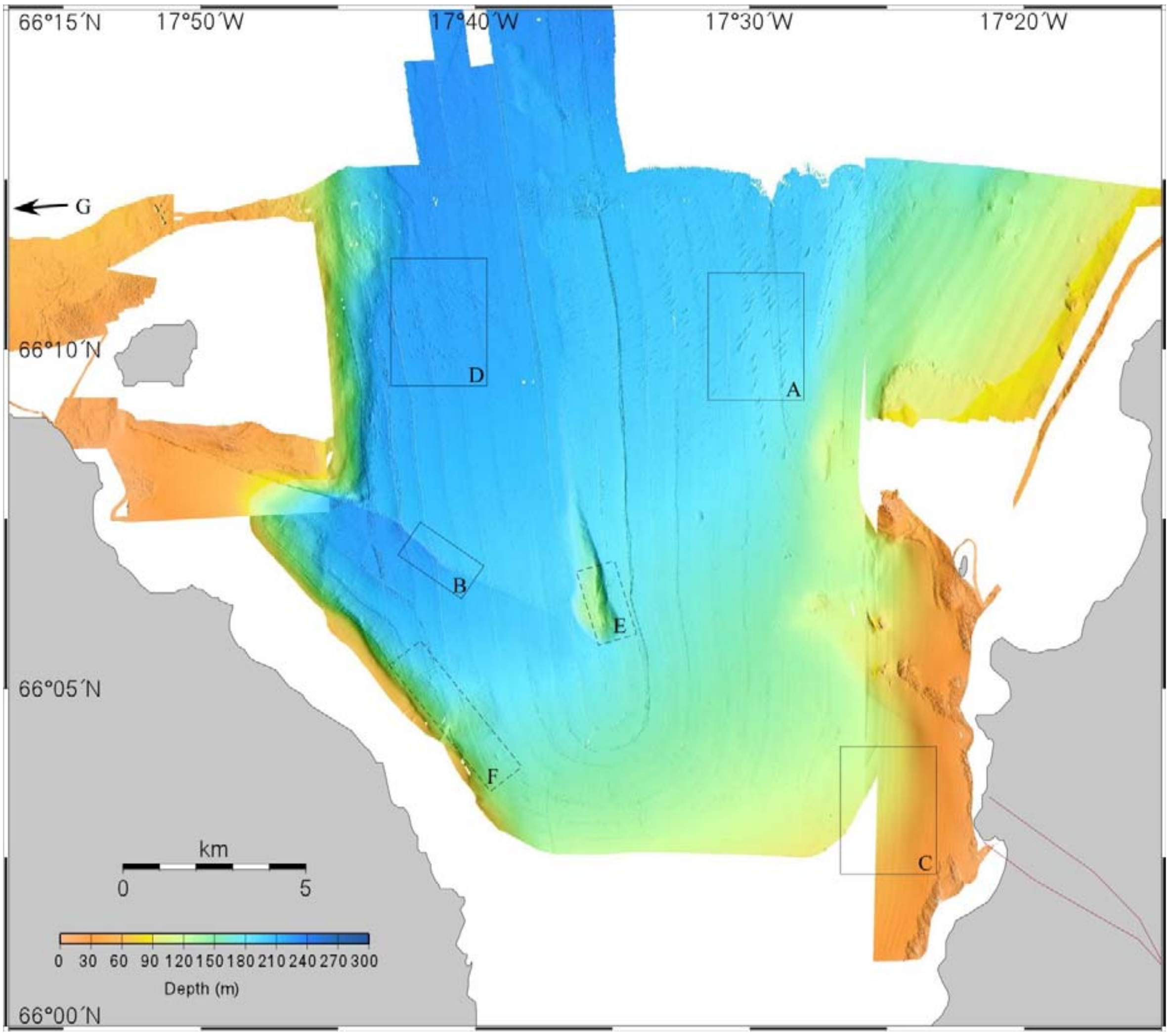

Figure 5. *Locations of suggested sampling sites with vibracorer or piston corer.*

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