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SEDIMENTARY BASINS OF THE N-ICELAND SHELF

Draft version for discussion (April-May 1998)

OS-98014

Reykjavík, April 1998

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1. INTRODUCTION

In this report we attempt to present available geological and geophysical data from the shelf and coast of N-Iceland, relevant to the problem of estimating the hydrocarbon potential of the area. The region offshore the central north coast is singled out because no comparable sediment accumulations have been detected on other parts of the insular shelf. The main emphasis of this report is on presenting sedimentary thickness and stratigraphy as deduced from multichannel seismic reflection data, and other geopysical data. This presentation is based on reinterpretation of best available data, and replaces the previously published information of this kind. A short review of relevant literature is also provided, but for additional and alternative review the report of Eiríksson and Friðleifsson (1994) is suggested.

Orkustofnun (National Energy Authority) is a governmental energy research institute with the role of a national geological survey in the field of energy related studies. Much of the exploration activity described below has been conducted or supervised by Orkustofnun. The present analysis of the N-Iceland shelf sedimentary basins is primarily based on the following data groups:

- Multichannel seismic reflection data in the posession of Orkustofnun. Two surveys from 1978 and 1985, 1100 km in total (see Figure 1.1).
- Single channel reflection seismics of various kinds. Generaly not useful for the study of thicker sediments. Reporting is often such that it is difficult to confirm the quality of data and interpretations.
- Two 500 m deep drillholes in the sediments, logged by Orkustofnun.
- Geological mapping onshore in Iceland, including the exposed Tjörnes sedimentary sequence.
- A gravity and aeromagnetic map of Iceland and surounding shelf (Eysteinsson and Gunnarsson, 1995).
- Earthquake seismicity mapping and fracture analysis.

2. GEOLOGICAL SETTING

Iceland has been formed by the sea-floor spreading process, and the spreading axis of the Mid-Atlantic Ridge runs through the country where it is referred to either as the "axial rifting zone" or the "volcanic zone". This segment of the axis is affected by an underlying hot-spot or mantle plume, which is the cause for the anomalous elevation of the country and the surrounding sea-floor.

Tectonism and volcanism is more diffuse in Iceland than on a normal ridge segment, and the geological history shows eastwards shifts of the spreading axis during the time of formation. Presently two main axial rifting zones exist. The Western Zone joins with the Reykjanes Ridge axis in south-west Iceland. Inland the activity is shifted eastwards to the Eastern Zone, and a tectonic zone with transform characteristics joins the two in southern Iceland. The Eastern Zone continues north into the N-Iceland Volcanic zone which terminates off the coast, where the spreading axis is shifted about 100 km westwards along the Tjörnes Fracture Zone to the Kolbeinsey Ridge spreading axis (Figure 2.1).

The crust consists mainly of volcanic rocks, mainly basaltic lavas and intrusions. In general, the age of the crust increases away from the axial rifting zones, and ages up to about 15 Ma are found on the east and west coasts. No indications of much older oceanic or continental rocks have been found. Sediments exist as thin interbedding in the Tertiary, while the Plio-Pleistocene glaciation produced somewhat greater amounts of clastics. No significant sedimentary basins are found exept those associated with the Tjörnes Fracture Zone area (see below). Some sediments, possibly of the early Plio-Pleistocene glaciation, are expected to be buried below younger volcanic formations in the region of the central south coast. A 600 m thick sequence has been drilled below Vestmannaeyjar island.

The Tjörnes Fracture Zone (TFZ) is a complex tectonic region on the insular shelf of N-Iceland, and is primarily defined by earthquake activity. Two major sub-parallel transform features or seismic lineaments are active, with trends in the range of 50°-65°W and spaced about 40 km apart. This is oblique to the regional sea-floor spreading direction, which is about 75°W, and leads to north trending extensional features within the zone. Diffuse and widespread seismicity is also seen between and about these major features (Figure 2.2). The geological structure and history of the entire area is not known in sufficient detail, but the current plate tectonics theories postulate that the TFZ was initiated about 6-7 Ma ago when there was a 140 km eastwards jump in the spreading axis in North-Iceland to the location it presently occupies. The location of the previous westerly, now extinct axis is at Skagi Peninsula, and plate reconstructions show that prior to the shift this volcanic zone lined up with the Kolbeinsey Ridge axis to the north (Sæmundsson, 1974; Sæmundsson, 1979; Jancin et al., 1985). Sea-floor spreading generated magnetic lineations along and parallel to the KR show that the axis has maintained a central location on the outer shelf area for at least 10 Ma. On the inner shelf the magnetic anomalies are too indistinct for mapping the spreading process.

There are however some unresolved complications which suggest tectonic deformations in the TFZ area prior to the 6 Ma event. An earlier "proto-volcanic zone" in NE-Iceland has been postulated to account for this, and a possible age of 9 Ma for the initiation of the TFZ (Jancin et al., 1985).

Exceptionally thick accumulations of sediments are found in an area comprising several sub-basins on the central N_Iceland shelf, roughly 150 km long and 100 wide. The formation of these deep basins is due to subsidence and extensional tectonics which have taken place within the TFZ. The abundant sediment supply from the Pleistocene glaciers of Iceland must have provided much of the infill, as the greatest rate of erosion is encountered during this period. In this report we will concentrate on the tectonic and sedimentary aspects of this region.

3. THE OUTER SHELF AND MARGINAL AREAS

3.1 Sedimentary thickness

The map in Figure 1.1 shows the sparse regional multichannel seismic lines available. The 1978 "ICE"-lines, shot as a speculative survey by Western Geophysical Co., extend over wide parts of the shelf area, while the OS-1985 survey (F-85-lines), shot by Geco for Orkustofnun, is concentrated in the region of the greatest sedimentary thickness. A sketch map of regional sedimentary thickness is shown in Figure 3.1. It is based on approximate depths calculated from interpretation of the migrated multichannel data. In areas where there are no such data, evidence from gravity and magnetic mapping, combined with geological trends have been used to evaluate likely sedimentary thickness, but this must be considered as partly guesswork. Figure 3.2 shows in greater detail the deep basin of Skjálfandi-Eyafjarðaráll area. In general, the data suggest that sediments are thin on the banks off the north-western and north-eastern coasts (Strandagrunn, Sléttugrunn), while the generally deeper central shelf area is underlain by sediments, sub-divided by the high of Kolbeinsey Ridge and complex graben and horst features.

Looking first on the more marginal areas, we can state that sediments are thin off the northwest coast, less than 100 m or so, as seen on line ICE-B and the western end of line ICE-A. Magnetic measurements (Vogt et al., 1980) also show that the magnetic basement is shallow on banks between line ICE-A and the north-west extremity of the country.

Going eastwards along line ICE-A into deeper water, we observe thickening of the sediments east of location SP-1100 to a maximum thickness of about 1 km (Figure 3.3c). This sedimentary basin is limited to the east by the steep-sided Kolbeinsey Ridge, which has a north-south orientation. The crest of the ridge is free of sediments and shows evidence of volcanism, as is to be expected for an active sea-floor spreading axis. Line ICE-C runs nearly perpendicular to the shelf edge in this basin, and shows clearly that the shelf edge in this region has been built up and out by sediments transported seawards along the shelf. This is especially clear for the outermost 40 km of the shelf, and the crossing line ICE-A shows that this sequence is quite young, as it formes a rather even drape on oceanic basement ranging from very young up to about 10 Ma.

The upper half of the sediments on section ICE-C is characterized by strong and smooth reflectors which are interpreted as marked unconformities. These are probably due to the frequent sea-level changes of the Pleistocene. The thickness increases landwards to a maximum of about 2 km at SP-570. South of this a basement high is observed and then the deep Eyjafjarðaráll basin, discussed below.

An approximately symmetrical picture is found east of the KR, where line ICE-D (not shown here in figure) shows prograded sediments underlying the outer shelf, 1-1.5 km thick. From a single cannel seismic line running east-west near the shelf edge ("Akademik Kurchatov", 1976 cruise; Þórarinsson, 1977) it can be concluded that a this outer basin is an analogous formation to the one to the west of the ridge, and thus quite young. On the basis of some single channel date and magnetic signature the sediments over the banks (Sléttugrunn) off the north-east corner of the country are expected to be thin.

3.2 Basement character and age

As mentioned above, we can assume that the basaltic basement of the outermost shelf is formed by symmetrical crustal formation on the Kolbeinsey Ridge axis. North of the shelf slopes we observe a clear sub-parallel linear magnetic pattern out to Anomaly 5, which is interpreted to be caused by regular sea-floor spreading for the last 10 Ma. (Vogt et al. 1980). The anomaly pattern becomes diffuse and disappears mostly below the slopes and shelf edge except for anomaly 5 on the western side. The central positive anomaly of the ridge is evident and probably the flanking negatives. The lack of datable linear anomalies is the norm in Iceland due to the large lateral spread and overlap of volcanic products, but Anomaly 5 is detectable in places because of its unusual width. By the location of this anomaly we can suggest that the spreading axis projected unbroken into the north coast of Iceland 10 Ma ago, and that the crust below the outermost shelf gets progressively younger towards the ridge axis. This spreading pattern could be characteristic for the shelf area all the way south to the line of the Húsavík-Flatey fault, but this can not be fully verified by the magnetic data.

The acoustic basement appears everywhere to consist of basaltic lavas, as far as can be ascertained by the seismic data. There are however ineresting variations in the character of the basement, which suggest variations in formation environment. A change of character is seen in the acoustic basement on line ICE-A as it gets deeper east of SP-1100. West of this location it is smooth and shows only indistinct sub-parallel internal layering, while a suggestion of increasing westward dip with depth is observed. To the east of this location the eastward dipping reflections become steeper and quite distinct and are clearly analogous to the the "seawards dipping reflectors" found on the volcanic continental margins. I this case they dip towards the axial zone of the KR and this suggest that this was where the lavas were erupted (Figure 3.3c).

East of this same transition we observe structures that are interpreted as prograding "lava deltas" or "forset breccias" built out into shallow seas, formed as lavas flow from land into water and brecciate. This region would therefore have been close to sea-level at the time of formation. The general rule of subsidence of oceanic crust, $d = c + 350*t^{1/2}$ (depth in meters, time in Ma), will give a subsidence of 1100 m for 10 Ma old crust, which is approximately what we observe if we correct basement depth for sedimentary load. Still further east, at about SP-700, the character of the basement surface changes again to a more chaotic type often typical of submarine eruptive formations.

Line ICE-C crosses ICE-A and runs in a south-esterly direction towards land. Basement at the crossing is about 10 Ma. The lava delta features are also seen on this line ICE-C, and traced landwards to a position at about SP-650. Further south a more complex basement character might suggest submarine formation, but later faulting and intrusions might also be the case.

The evidence suggests that the crustal generation and elevation of the Kolbeinsey axial zone on the shelf began to diminish about 10 Ma ago. Before this time, at the location of line ICE-A, the zone was elevated well above sea level but became submerged about 6 Ma ago. This transgression would then be likely to form the first opportunity for major sedimentation on the shelf. The appearance of better defined linear magnetic anomalies in this region can be explained by the narrower distribution of igneous rocks by oceanic type of crustal accretion.

The narrow and high shape of the present ridge axis cannot be represented by a steady state subsidence curve, and raises the question if there has been a resurgence in volcanism in the past 1 Ma, or so. It could be postulated that this increase is related to the emergence of the Grimsey Seismic Lineament 1-2 Ma ago, while the decrease in volcanism roughly 6 Ma (or perhaps as early as 10 Ma ago) was linked to the formation of the TFZ.

4. THE INNER SHELF BASINS

4.1 Tectonics and volcanism

The inner region of the central N-Iceland shelf is shaped by the tectonic complexities of the TFZ, and in this region the thickest sediments have been found, up to 4 km. The TFZ is tectonically very active and was originally defined on the basis of earthquake locations (Einarsson, 1976; Einarsson and Björnsson 1979). Several earthquakes of magnitudes 6 or 7 have occured during the last century, and smaller earthquakes are a daily occurance, although they typically occur in bursts or swarms. Figure 2.2 shows the distribution of earthquakes lager than magnitude 1 for a one year period (1994; data from the Icelandic Metrological Institute: www.vedur.is). Although the period is short, the distribution corresponds roughly with the pattern of faults as mapped by shallow reflection seismics.

The greatest activity is found on the two major transform lineaments. The Húsavík-Flatey Fault (HFF) is a clear transform fault trending about N65°W. Recently the activity is mostly at the western end, typically strike slip, while the eastern end is more quiet. Further north the Grímsey Seismic Lineament (GSL) has a more north-westerly overall trend and is traced by a chain of distinct earthquake clusters. A left stepping en echelon arrangement is suggested. These could be viewed as individual volcanic centers, and indication of active volcanism is found along this lineament, such as rough bottom and magnetic anomalies (Figure 2.2; McMaster et al., 1977; Sæmundsson 1979).

Recent advances in monitoring and processing have lead not only to more complete earthquake distribution mapping, but have also opened the possibility of determining relative location of earthquake swarms, with such accuracy that individual fault planes can be traced. (Rögnvaldsson et al., in press; also at www.vedur.is, home page of Sigurður Rögnvaldsson). Figure 4.1 shows the results of the first study of this kind in the TFZ, where red fault signs indicate the fractures. The fault planes on the HFF transform fault are partly subparallel to the fault trend, dip 72°-90° and show mainly right-lateral strike slip motion, but also north trending fault planes near the western end. East of Flatey, on the flank of the Grímsey platform, north trending fauls are found with left-lateral strike slip and also a dip-slip component. In contrast, the fault plane solutions on the Grímsey Lineament are all roughly north trending, mostly left-lateral and dip 70-90°.

The western limit of the earthquake zone is rather diffuse and extends some way west off the mouth of Skagafjörður. Scattered activity is also found south of the trace of the HFF, including large historical earthquakes in Eyjafjörður and at the mouth of Skagafjörður. A third transform lineament 30 km south of and subparallel to the HFF has been suggested to account for this, but surface features are not conclusive.

Between the two major transverse lineaments a complex tectonic pattern is observed, which can be broadly defined in terms of three N-S trending sdimentary grabens. They are named after the bathymetric depressions of Öxarfjörður, Skjálfandi and Eyjafjarðaráll, going from east to west. The Tjörnes peninsula and the Grímsey Platform form relative highs between these grabens. The deep structure of these features is mainly known from the seismic reflection data presented below. Although the seismic lines are relatively dense in this area, it is still imperfectly imaged.

Offshore active volcanism appears to be confined to the Grímsey Lineament, where historic volcanic eruptions have been noted, and mounds and volcanic ground on the sea-floor are observed at intervals along the lineament (Figure 2.2). These features culminate in the Kolbeinsey rock at the junction of the Lineament and Kolbeinsey Ridge.

Other active or recent volcanic sources in the TFZ have not been demonstrated, but lavas exposed on Tjörnes, Grímsey and Flatey, also at depth in the Flatey borehole, indicate that volcanic rocks can be found widely distributed in the area. It is generally not clear from the deep seismic data whether conformally emplaced thin lava flows might be present in the sedimentary pile of the Grímsey platform and the western graben. No buried volcanic mounds or prograded brecciated lava structures are seen (except possibly in the bay of Skjálfandi). A deep strong reflector below 2 km depth at the tectonic axis of the Eyjafarðaráll Graben is very likely volcanic. This could possibly be an intrusion (lines F-6-85 and ICE-C), but it is also possible that this is a buried lavaflow coming in from the west. A distinct lava horizon within the sediments is seen on line ICE-C on the western flank of the graben, possibly a part of the volcanic region that is exposed at the tip of the Skagi peninsula and active about 1-3 Ma ago.

In summary we can state that most of the area of the TFZ is seismically active, and this picture is supported by the available reflection profiling data, which indicates widespread tectonism in the surface layers and in may places distinct fault scarps in the sea-floor. The largest presently quiet bit is the north-western part of the Grímsey shoal. The Grímsey Fault of Lineament seems to be the presently volcanically active feature of the zone. The reflection data suggest extinct volcanism on the western flank of the Eyjafjarðaráll graben, which was probably linked to the near-by Skagi younger volcanics, about 0.7-3 Ma old.

4.2 Öxarfjörður Graben

4.2.1 Structure on land

The Öxarfjörður graben is a rift valley occupying the northern end of the eastern volcanic zone, partly onshore and partly offshore. It appears that this graben is a relatively late northward extension of the volcanic zone, since about 1-2 Ma ago, associated with the formation of the Grímsey Fault (Sæmundsson, 1974). Previous to that time the spreading motion was taken up by the more southerly Húsavík transform fault. While this is a likely scenario, it can not be ruled out that it is an over-simplified picture and some problems relating to spreading geometry have not been worked out.

In the coastal region the graben is filled by sediments which now form a wide delta plain (glacial fluvatile sediments, "sandur") at the southern end. Three fissure swarms extend northwards along the basin, originating in central volcanoes to the south. One of these, the Krafla volcano, was active in 1975-'81. The associated 5 km wide fissure swarm in the graben subsided by a couple of meters, and there were indication of deep dyke intrusions. It is likely the graben has been formed by repeated events of this kind.

Exploration for geothermal fluids has taken place in the area, and further work is planned. Temperatures above 200°C are expected in a suggested high temperature field in the Krafla fissure swarm. During this work traces of hydrocarbons were detected, and gave incentive for a special drilling effort to investigate this question. This has been described a report in English by Ólafsson et al. (1993), and this report provides also a more complete background material for this area.

Drilling (550 m) in the secondary geothermal area of Skógalón and reflection data show that post-glacial sediments (i.e. less than 10,000 years old) make up the uppermost section and are found to be up to 400 m thick in the Krafla sub-graben. These consist of marine silty sediments overlain by coarse grained deltaic deposits, reflecting transgression at the end of the last glaciation and subsequent regression due to infill/rebound. Below the the marine sediments variable sediments are found with evidence of more than one glaciations. This suggests a time interval of more than 100,000 years, and the long term deposition rate must therefore be much slower than found for the upper section. Extensive normal faulting is seen within the marine sediments in the reflection sections.

Drilling has not reached basement, and no clear basement reflectors are seen in the reflection data, but seismic velocities increase rapidly with depth within the lower section, and attain basaltic basement velocity at a about 1 km depth or less. It is thus likely that the sediments are no thicker than 1 km, and there are indications that the sediments thicken seawards towards north. However, it is not possible to exclude the presence of the equivalents of the so-called Tjörnes beds at depth, but they are about 5 Ma old and lignite bearing. The southern limit of the sediments has not been mapped but the indications are that the sediments thin to south and perhaps intercalate with lavas from the active volcanoes to the south.

A composite east-west section across the graben (on land) is shown in Figure 4.2, based on a seismic refraction section (Georgsson et al.,1993), a more limited multichannel reflection survey (Gunnarsson et al., 1996), geological mapping and drilling data. The basin is limited on the western side by the horst of Tjörnes, where Tertiary (about 7-10 Ma) basaltic basement is exposed and numerous normal faults are seen on the flank of the basin. The eastern flank is not so clear, where there is a wide belt of active volcanism and much younger rocks stretching to the east. Many features suggest a somewhat unsymmetrical tectonic pattern, with eastward dipping normal faults being dominant at depth, while associated west dipping antithetic fault systems appear prominent at shallow depth.

4.2.2 Offshore structure

Offshore the graben has not been investigated at depth, but shallow reflection profiling (Mcmaster et al., 1977) and earthquake data suggest that the tectonic pattern seen on land extends north into the transverse Grímsey Lineament within the fjord. A gravity high north of the lineament suggests a basement step and thinner sediments in the outer part of the fjord.

Further north we have the evidence of reflection line ICE-D, which runs to northwest from the eastern side of the mouth of the fjord. At the landward end the sediments are thin, underlain by a "opaque" volcanic rocks. As we proceed north the volcanic horizon is seen to peter out within the 1.5 km thick sediments of the outer shelf basin. The lowermost sediments disappear under the lavas towards land. A refraction experiment along this same line generally confirms this interpretation. It suggests roughly 2 km thick sediments over basaltic basement (4.5 km/s), and an increase in average velocity in the upper layer at the southern suggests greater lava content or a basement high (Sturkell et al., 1992). It is likely that these upper volcanic rocks originate in the northeasterly extension of he volcanic zone on the peninsula of Slétta (Melrakkaslétta). They could be emplaced by local offshore volcanism or possibly as "runoff" from the adjacent northeasterly extension of the volcanic zone on the peninsula of Melrakkaslétta.

4.3 The Skjálfandi Graben

This graben extends north from the bay of Skjálfandi, between the Tjörnes Peninsula high and the Grímsey shoal platform. Sediments have been observed on both flanks of this basin, in the borehole on Flatey (Gunnarsson et al., 1984; Eiríksson et al., 1990) and on the exposures on Tjörnes Peninsula. The multicannel seismic line F-1-85 provides a rather ambiguous cross section of the southern part of the graben, just north of the Húsavík-Flatey fault.

The Tjörnes Peninsula horst is west and north tilted and limited to the south by the major dextral strike slip Húsavík-Flatey Fault. On land at the base of the peninsula the northern side of the fault zone is uplifted, exposing about 7-10 Ma old Tertiary lava basement. Overlying these basement lavas on the western and outer part of the peninsula, a younger composite section of sediments and lavas are is exposed. The dip is NW and N, dimishing with time. The combined stratigraphic thickness is about 1 km. The lower half consists of the Tjörnes Beds sediments, at least up to 5 Ma old, followed by sediments and lavas extending up through the Plio-Pleistocene glaciation. The latter is characterised by at least 13 cycles of fluctuating sea-level due to the glaciation cycles (Eiríksson 1981; Eiríksson and Friðleifsson, 1994). Lignite seams are found in the Tjörnes beds, but no other possible source rocks have been reported.

South of the fault at Húsavík the younger rocks of the volcanic zone are in evidence. Drilling in the southern edge of the fault zone Húsvík revealed what seemed to be a Plio-Pleistocene sediment/basalt sequence, 1200 m thick (Tómasson, 1969). However, the nature of these rocks has been disputed (Sæmundsson 1974) and its relation to the sequence north of the fault is very uncertain.

The seismic line F-1-85 shows quite clearly westwards dipping sediments below the deep part of the Skjálfandi bay, that are at least 1.7 km and possibly 2.5 km thick (this section is not presented here). The top of this sequence is an unconformity, overlain by a thin drape (up to 100 m) of "transparent" sediments, which have been investigated by shallow seismic profiling and thought to be of post-glacial age (Thors, 1982).

Further west on line F-1-85, to the west of Flatey, the sediments appear to be 2.2-2.5 km thick. This is also evident on the crossing section for line F-4-85 in Figure 4.3a. Data quality in the shoal region near Flatey is very poor, but this sequence appears to continue under the island. There is however a suggestion of a flexure east of the island below the eastern flank of the Grímsey platform. The platform and Flatey island appear thus to be uplifted relative to the Skjálfandi region. The amplitude of this is however not large compared with the thickness of the sediments, and thus the Skjálfandi Basin can be seen as secondary feature within a much larger sedimentary basin that extends towards west. Tentative interpretation suggests that the sediments reach a thickness of 3 km east of the flexure (Figure 3.2).

The crossing section F-3-85 just east of Flatey is not conclusive, but suggests at least 2 km, thick intensely faulted sediments. A strong near-surface reflector masks deeper structure of the northern part of the line. The northern end of line F-2-85, just off the coast of Tjörnes, shows about 1 km thick sediments above a clear basement reflection. This sequence would be the continuation of the Tjörnes sedimentary sequence on land. It is likely that the the basement reflection corresponds to the Kaldakvísl basal lavas, but a correlation with the stratigraphically higher Höskuldarvík lavas seems also possible (See Chapter 5; Figure 5.1).

The western margin of the Skjálfandi graben is suggested by the zone of normal faulting seen on the eastern escarpment of the Grímey Platform, as revealed in the shallow seismic data of McMaster et al. (1977). This is more prominent in the northern region, and it is possible that the flexure east of Flatey is the southern continuation of this weakness. A great deal of earthquake activity has been observed lately below the entire flank. This activity includes northerly trending faults with left-lateral strike components east of Flatey (see Figure 4.1).

The lava flows that cap Flatey date from the late Matuyama epoch and show a period of non-deposition and possibly some erosion for the last 1 Ma, or so. This is in good agrement with the seismic evidence that the island sits atop an upraised fault block. These tectonics appear to be a part of the movements that raised and tilted the Tjörnes Peninsula, which are also thought to have begun about 1.5 Ma ago.

The trace of the Húsavík-Flatey fault shows very clearly up in the gravity field as a sharp edge anomaly, where the values over the offshore sediments are 30-40 mgals lower than south of the fault trace (Pálmason, 1974; map by Eysteinsson and Gunnarsson, 1995). This anomaly extends from the Skjálfandi Bay for about 80 km WNW, and coincides with the fault as suggested by earthquake seismicity. In high resolution shallow seismic profiles (Thors, 1982) the fault trace is clearly suggested as a basement escarpment with sediment infill on the north side. A 5-10 km wide zone north of the escarpment is characterised by a bathymetric depression and suggestions of subsidence and increasing tectonic disturbances with depth. This is likely to be the present active zone of deformation associated with the transform fault, and a definite extension component is suggested by the subsidence. The drape of the youngest (Holocene?) sediments is not conspicuously faulted and this suggests that the movement is presently not great. From the same data the trace of the fault zone across the bay of Skjálfandi is more complex, but a couple of faults are seen to extend up to the sea-floor through the thicker Holocene layer. Basement is seen to outcrop north of the offshore prolongation of the Húsavík faults near the Tjörnes coast. This basement, presumably the Tertiary Kaldakvísl lavas, is overlain further north by sediments with northerly dip, which should correspond to the onshore Tjörnes section.

4.4 The Eyjafjarðaráll Graben

This graben is named after the Eyjafjarðaráll deep that extends north towards the end of the Koleinsey Ridge, and where water depths up to 600 m are seen. Several multichannel seismic lines give a comparatively clear picture of this extensively faulted, presently active graben. Figures 4.4 and 4.5 show interpreted time sections, while Figures 4.6 and 4.7 show two depth converted cross sections. A semi-symmetrical pattern of normal faulting with a central axis is observed, but the axis is displaced to the west of the area of greatest subsidence where the sediments are thickest and the tectonics most active. In this area the faulting is seen in many places to extend up to the sea-floor, forming escarpements about 10 m high.

The eastern margin of the graben is defined by a band of major listric faults along the western flank of the Grímsey platform, which seems to trend southeast at the approach to the H-F Fault (Figure 4.4a). The closly spaced normal faults have an axis of symmetry located in the western part of the graben. The axis and the fault system this western region seem to have a southwesterly trend. It should be noted that the density of lines is not sufficient to map individual features of the complex tectonics. The overall pattern seems to indicate a widening of the graben system south towards the Húsavík-Flatey strike slip fault, where the normal faulting appears to terminate against the strike-slip fault. The width of the southern graben is about 50 km. However, judging from surface features and earthquake activity, it is likely that some of the westernmost active faults extend into the plate south of the trace of the transverse fault. The western margin is ill defined as the western fault system is seen to extend all the way to the western ends of the OS-1985 seismic lines, but Line ICE-C suggests that this is close to the western limit of the graben.

The faulting pattern is typically listric in the sediments, and reflections from within the basement seem to represent the continuations of these faults down to about 10 km depth. The dip of the deep faults is 45° and less, and appears even sub-horizontal below the eastern margin.

It is possible to trace a likely basement reflection, or at least to define a change in reflection character, over most of the mapped part of the graben. The sediments are up to 4 km thick, and seem to thicken south towards the Húsavík-Flatey Fault. The greatest thickness is found in about 20 km wide belt north of the fault. There are also suggestions of sub-parallel layering below the suggested basement in the southernmost part of the graben. If these are real reflections, they could represent additional sediments, or possibly lavas, of more than 1 km thickness. The basin exends some way beond the western end of line F-1A, but appears to be shallowing.

There are problems in tracing individual sedimentary horizons across the basin because of the frequent shifts and reflection character changes across faults. However, a likely solution for line ICE-C is presented in Figure 4.6, where a set of about 10 reflectors is traced across the basin. The deepest mapped intra-sedimentary reflector on the NW-flank is very strong, probably a lava horizon, and is seen to plunge from about 500 m depth (below sea-floor) to about 2500-3000 m in the central graben. This reflector extends for about 10 km to the west from the basin margin, and terminates in the middle of the sedimentary pile. It is suggested here that this reflector is likely to be not more than 2 Ma old for the following reasons:

1) It is possible to follow the approximate level of the reflector out to the intersection with line ICE-A, where it is still slightly above basement. As the layering of this line is sub-parallel with the basement, the suggestion is that the horizon can be traced onto 2 Ma old crust. This is however a rather long and uncertain correlation.

2) The lava horizon could be related to the rejuvenation of the Skagi volcanic zone to the southwest, which produced 1-3 Ma old volcanics on the tip of the Skagi peninsula. There are suggestions in the reflection data that the initiation of the faulting is older than the lava horizon. These tectonic events and the younger eruptive episode of the later Skagi volcanics could be related. The bathymetric features on new unpublished hydrographic maps for the sea-bottom off Skagi, suggest south-westerly tectonic trends that could be the continuation of the fault system in the western part of the deep graben.

3) The sedimentary sequence above the level of the volcanic horizon, both within and outside the graben, has the appearance of stronger sea-level fluctuation than below. This is possibly comparable to the Tjörnes sequence, where a marked change is seen at the 2 Ma level. The number of transgression cycles found there is also of the same order as the strong reflectors seen in the basin. However, the Tjörnes sequence could be too much affected by local tectonic movements to be regionally repesentative.

If this admittably uncertain analysis is correct, the subsidence and infill of the top 3000 m or so of the basin has taken place during the last 2 Ma. This has an importance in estimating maturation of possible source rocks.

5. LITHOLOGY AND PHYSICAL PROPERTIES OF SEDIMENTS

The uplifted Tjörnes peninsula provides the most complete access to the sediments of the offshore basins. A long series of exposures is seen on west and north coast of the peninsula (Figure 5.1b). The Tjörnes Beds make up the lower half and are formed roughly 5-2 Ma ago in near-shore environment with alternating marine and land sedimentation. The bulk is made up of marine fossiliferous sandstone. Lignite seams are found, and suggest intermittent terrestrial or transitional environment. The upper part of the beds reflect the cooling leading to the onset of he Pleistocene glaciation. Above the Tjörnes Beds abundant lavas are found in the the Breiðavík Group sediments, which alternate with diamictite (glacial deposits), volcanoclastic mudrocks and sandstones. Repeted cycles (12 or so) of marine transgression following deposition of many of the diamictite sheets are seen (Eiríksson, 1981).

A 554 m deep hole was drilled on the island of Flatey, about 30 km west of Tjörnes (Gunnarsson et.al., 1984; Eiríksson et al., 1987). As described in a previous chapter the island sits on top of a 2-2.5 km thick sedimentary basin, and this is the only offshore locality where the sediments have been sampled at depth. A nearly continuous core was retrieved of predominantly sedimentary rocks, but including two lava flows at the surface and the one at 400 m depth. The sediments are probably of early Pleistocene age, probably in the range of 0.7-1.5 Ma. The appearance of the sediments is comparable with the Breiðavík group on Tjörnes, consistent with formation in shallow marine or coastal environment, characterised be repeated regression/transgression glaciation cycles. The thickness of the cyclic deposits suggest that subsidence was much faster in the Flatey area.

Borehole logging was performed and physical properties of selected core samples were measured. Measurements on samples, ranging from silt to sandstone, indicate high porosity but relatively low permeability, probably due to easy cementation of the volcanoclastic material. Some conglomerates or beach deposits could be much more permeable. It could be noted that onshore geothermal utilization in Iceland usually depends on secondary fracture permeability in the basalts and tuffs, but little experience has been had for sediments. Total organic carbon tests gave only very low values, and no further investigations were done on the organic content.

The clay content of the the sediments sampled fo far, which are all nearshore formatins, is small and no shale beds are found, organic or otherwise. A few shallow gravity cores, up to 3 m long, have recently been obtained offshore N-Iceland, including fine grained sediments in Eyjafjarðaráll, showing total organic carbon values (TOC) of 4% at the surface and 2-3% at 3 m depth (Jón Eiríksson, pers. com.). These are relatively high values, as previous seafloor sampling has shown up to 1-2% TOC. It raises the question if environmental conditions in the interglacial period, as are presently in the Eyjafjarðaráll deep, have been beneficient for the formation of fine grained sediments rich in organic carbon. This, beside the coastal lignites in the lower Tjörnes beds, are the only known indications of possible source rocks.

A 550 m deep well has been drilled on the coast in the Öxarfjörður sub-basin, the sedimentary graben formed in the junction with the inland spreading-axis. This well was drilled with the purpose of investigating traces of thermogenic hydrocarbon gasses that were detected in a discharge from a previous well drilled for geothermal exploration. This gas is the only direct evidence of oil formation found sofar (Ólafsson et al., 1993).

The sediments drilled and cored are Recent to probably late Pleistocene in age, and show the effects of several glaciations. Seismic profiling in the vicinity of the borehole indicates extensive faulting, reflecting the effects of fissure swarms originating in the volcanic centers further inland. The post-glacial strata (less than 10.000 years old) are thought to be 400 m thick, indicating rapid subsidence in recent times, while seismic velocity structure indicates basement at about 1 km depth.

Some general indications can be had from the appearance of the seismic sections. The outer shelf sediments are regularly layered and relatively "transparent", suggesting more homogeneous fine-grained deposition. On the inner shelf the picture is much more irregular, but much of this is because of intense faulting which is not always possible to distinguish from possible depositional geometry. The considerably greater reflective variability reflects greater variability in the section, and a scattering of individual lava flows is expected.

It is difficult to determine how much lava could be included in the predominatly sedimentary sequence, as is suggested by the example of the Flatey borhole where one lava-flow is present but no outstanding reflection is seen in the nearby seismic section (which is, however, poor). Strong reflectors are seen at the western flank of the Eyjafjarðaráll graben which are interpreted as lava flows, One such horizon below the tectonic axis of the basin could possible be a intrusion. In general there are few suggestions of intrusives in the mapped sedimentary basins, and no clear instance.

Observed indications of hydrocarbons in the seismic data are few and uncertain. A part of section F-1A-85 (SP 3000-3200) shows reduced reflections and a strong surface multible, which could possibly be due to some gas content in the shallow leyers. A few instances of local structural instability and enhanced reflections and are seen on the northern half of line ICE-C, e.g. at SP770-7780. This could be a due to gas, but minor basement faulting could also be at work.

6. TEMPERATURE AND HEAT FLOW

Heat flow is quite high in Iceland, as can be expected in the vicinity of the mic-oceanic spreading axis. Observed regional temperature gradients range from 50-150°C/km, and generally increase towards the flanks of the volcanic zones (Flóvenz and Sæmundsson, 1993). The temperature in the rifted zones themselves is much disturbed by groundwater convection. Geothermal activity is widespread and typical for tectonically active areas. The observed gradients onshore, south of our area of investigation, range from 60°C/km in Eyjaförður to 90°C/km at the margin of the Eastern Volcanic Zone.

Direct measurements in the offshore basins are are available from the Flatey drillhole where a gradient of 50 °C/km was observed (Gunnarsson et al., 1984). A similar gradient of 50-60°C/km has also been observed further north on the island of Grímsey, but this measurement is in fact not very dependable and can hardly be taken as definite (ÓGF, pers.com.). These values are relatively low compared with the inland data, and as conductivity in the Flatey sediments is probably lower than in the basaltic crust (judging from higher porosity), the heat flow value would be lower still.

Practically the entire basin area is seismically active and this is bound to affect the thermal regime of the uppermost crust. Geothermal exploration in Iceland has demonstrated that earthquake fracturing causes vertical convection and alternative local cooling and heating. Flatey drillhole is close to the still active Húsavík transform fault zone and, and it is quite possibile that the local gradient is disturbed by convection.

In order to investigate the transient effect of the possibly very rapid sedimentary accumulation in the Flatey area, a thermal conductivity model was calculated (Karl Gunnarsson et al., 1984). In the calculations it is given that the uppermost 2 km were accumulated steadily during the period between 2 and 1 Ma ago and heat was only transferred by conductivity. These calculations are very uncertain, not the least because of the probable convection disturbances, but suggest that the temperature gradient would now be close to the original value.

A very high gradient of 170°C has recently been observed in a shallow borehole in the Tjörnes sediments. This could however possibly be due local hydrothermal effects. High temperature submarine fluid discharges have been discovered along the Grímsey Lineament, just east of Grímsey and near Kolbeinsey. Geothermal areas also exist at shallow depth in onshore Öxarfjörður basin where temperatures of up to 250°C are expected at less than 1 km depth. These locations are in very active volcanic and tectonic regimes where shallow magma could be at hand.

7. SUMMARY AND DISCUSSION

An area of complex tectonics and considerable sedimentary accumulation has been demonstrated on the central N-Iceland innsular shelf, exceptional for the mid-oceanic ride environment. This accumulation is on one hand due to abundant sediment transport from the adjacent land, epecially in Pleistocene times, and on the other because of subsidence of the oceanic crust within the Tjörnes Fracture Zone area due to thermal and extensional tectonic effects.

A pair of basins with 1-2 km thick sediments are found on each side of the active Kolbeinsey Ridge on the outer shelf, hedged in by basements highs on the NW and NE part of the shelf. Oceanic crust ranging in age between 1-10 Ma underlies these basins. Declining magma production since 6-10 Ma ago is suggested as the cause of these depressions, having caused transgression of the sea from a costal position close to the present shelf slope, far south into the present shelf. This event could have occurred about 6 Ma ago in conjunction with the postulated eastwards jump of the axial rifting zone. It is postulated that the transgression initiated the sedimentation on the present shelf area, and that the basal sediments are not more than 6 Ma old. The bulk of the sedimentary pile is probably less than 3 Ma old, as most of the supplying onland erosion is associated with the Plio-Pleistocene glaciation. The outermost 30-40 km belt is formed by young prograded sediments, most likely of late Pleistocene age.

The thickest sediments are found on the inner shelf where the N-S trending Eyjafjarðaráll and Skjálfandi Grabens terminate against the Húsavík-Flatey Fault. A sedimentary thickness of more than 4 km is found in the former. The sediments are thicker than 3 km in an area about 20 by 40 km, but are between 2 and 3 km in thickness over a much larger area. The northern parts of the two grabens have not been mapped with deep seismics. They could also contain thick sediements, but greater effects of the volcanism of the Kolbeinsey Ridge and the Grímsey Lineament are to be espected. The third N-S graben is in Öxarfjörður, where sediments of the order of 1 km have been detected. This tectonic feature is a prolongation of the onland volcanic zone, and is thought to have formed about 1.5 Ma ago.

It is suggested that the most of subsidence and infill in the Eyjafjarðaráll Graben has taken place during the last 2 Ma. The considerable active extensional tectonics of this 50 km wide feature suggest that some of the sea-floor spreading has been taken up by crustal extension, parallel to the rifting in the Öxarfjörður zone. A rough estimate based on observed fault block dips at depth in the basin (ca. 20-30°) and subsidence cross section (about 70 km^2) suggest that an extension of about 5 km (factor 1.1) has taken place. As sea-floor spreading amounts to 20 km/Ma, this part is not large but significant.

A number of features are seen within the TFZ that suggest a radical change of spreading activity roughly 1-2 Ma ago, and although some are not definite or well dated, the whole suggests a pattern:

- The N-Iceland axial rift zone propagated north accross the line of the Húsavík-Flatey Fault, and a new major transform feature, the Grímsey Lineament, was formed.
- The uplift and western tilt of the Tjörnes horst, with associated erosion and non-deposition appears to affect the area as far west as Flatey.
- Volcanism occurred along the new tranverse lineament and volcanic production increased on the Kolbeinsey Ridge.
- The segment of the Kolbeinsey Ridge between the Grímsey Lineament and H-F Fault must have suffered a decrease in activity and retreated. However, some formation of new crust is suggested in the northern half, while a 50 km wide extensional graben has formed in the southern part, the Eyjafjarðarall Graben.
- The rate of strike slip movement on the H-F Fault must have been reduced, but some movement has taken place during this time as is evident from the continuous extension of the graben.
- The rejuvenile volcanism of the extinct Skagi volcanic zone could be related to the formation of the fault system of the Eyjafjarðaráll Graben.

Relatively high temperature gradients are normal in Iceland, and gradients of the order of 100°C/km are found in the vicinity of the volcanic zones. The only reliable measurement from the offshore basins is the 50°C in the drillhole on the island of Flatey. This is rather lower than expected, but hydrothermal convection could cause variations in the thermal regime of the basins. The onland Öxarfjörður graben contains high temperature areas at shallow depth.

The only hydrocarbon finds consist of traces of "wet" gases in the hot water discharge from 500 m drillholes in Öxarfjörður Basin. Lignite seams that are found in Plio-Pleistocene sediments (and lava sequences) can possibly be the source for this.

7.1 Possible future investigations

The exposed Tjörnes sediments could be subjected to various investigations at minimum cost. Flatey forms a natural platform for relatively inexpensive deeper drilling. The seismic suggest that a zone of intense faulting underlies the island.

The island of Grímsey is also a potential site for investigative drilling. The near surface rocks are volcanics, lavas and tuff layers and coarse sediments, older than 0.7 Ma. The nature of the deeper strata is not known. The seismic lines do not come within 12 km of Grímsey, but the basement slope at the end of the lines and the gravity data suggest that the sedimentary section could easily extend beneath the island. The gentle westward stratigraphic dip of the island is as would be expected in this case. However, the island is close to the tectonic and volcanic features of the Grímsey Lineament, and dykes and faults are seen. It is posssible that a large part of the section is made of volcanics. Recent faulting and some intrusive activity could also be problematic. The islands of Mánáreyjar north of Tjörnes are young volcanic formations that could possibly overlie some sediments.

Seismic multichannel reflection has been seen to give good results in parts of the area, while the more volcanic areas are problematic. More seismic profiling would add detail and fill in blank areas. High resolution shallow seismics could define tectonic patterns and recent subsidense. Side-scan sonar and swath bathymetry mapping would also reveal the active tectonics and volcanism affecting the sea bottom. Possible fluid or gas discharges could be detected.

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FIGURE CAPTIONS.

Figure 1.1. A bathymetric map of the N-Iceland shelf. Multichannel seismic lines are shown. "ICE"-lines are the W.G.Co. 1978 cruise, while the simply numbered lines are the F- -85 lines of the OS85 cruise (by Geco for Orkustofnun in 19859.

Figure 2.1. A simplified geological map of the north coast of Iceland. (From Eiríksson and Fridleifsson, 1994).

Figure 2.2. A generalized map of faults and volcanic terrain on the sea floor from shallow seismic reflection data (McMaster et al. 1977; Orkustofnun reflection data). Earthquakes recorded for a limited period are shown with dots (Icelandic Meteorological Institute). Background is magnetic field: red is positive, blue negative.

Figure 3.1. A sketch of sediment thickness of the central N-Iceland shelf, superimposed on bathymetry. Seismic lines are shown. Estimates of thickness values away from seismic lines are hypothetical and based on considerations such as potential field data and regional structures.

Figure 3.2. Sediment thickness in the Skjálfandi-Eyjafjarðaráll region, based on multichannel seismic sections from OS-85 and W.G.Co. 1976 cruises.

Figure 3.3. a) Interpreted depth converted section for the entire line ICE-C (migrated). Calculated depth on the vertical axis; exaggeration is 8 fold. Broad line is basement, continuous where continuous reflection is seen but broken where less clear. More prominent reflections within the sediments are emphasised with dark lines.
b) Time section equivalent to the ICE-C section in a).
c) Interpreted time section of a part of line ICE-A.

Figure 4.1. Results of fault plane analysis for earthquake swarms (Rögnvaldsson et al., in press). Red line segments indicate location trend and dip of fault planes. All measured dips are steep (70-90°).

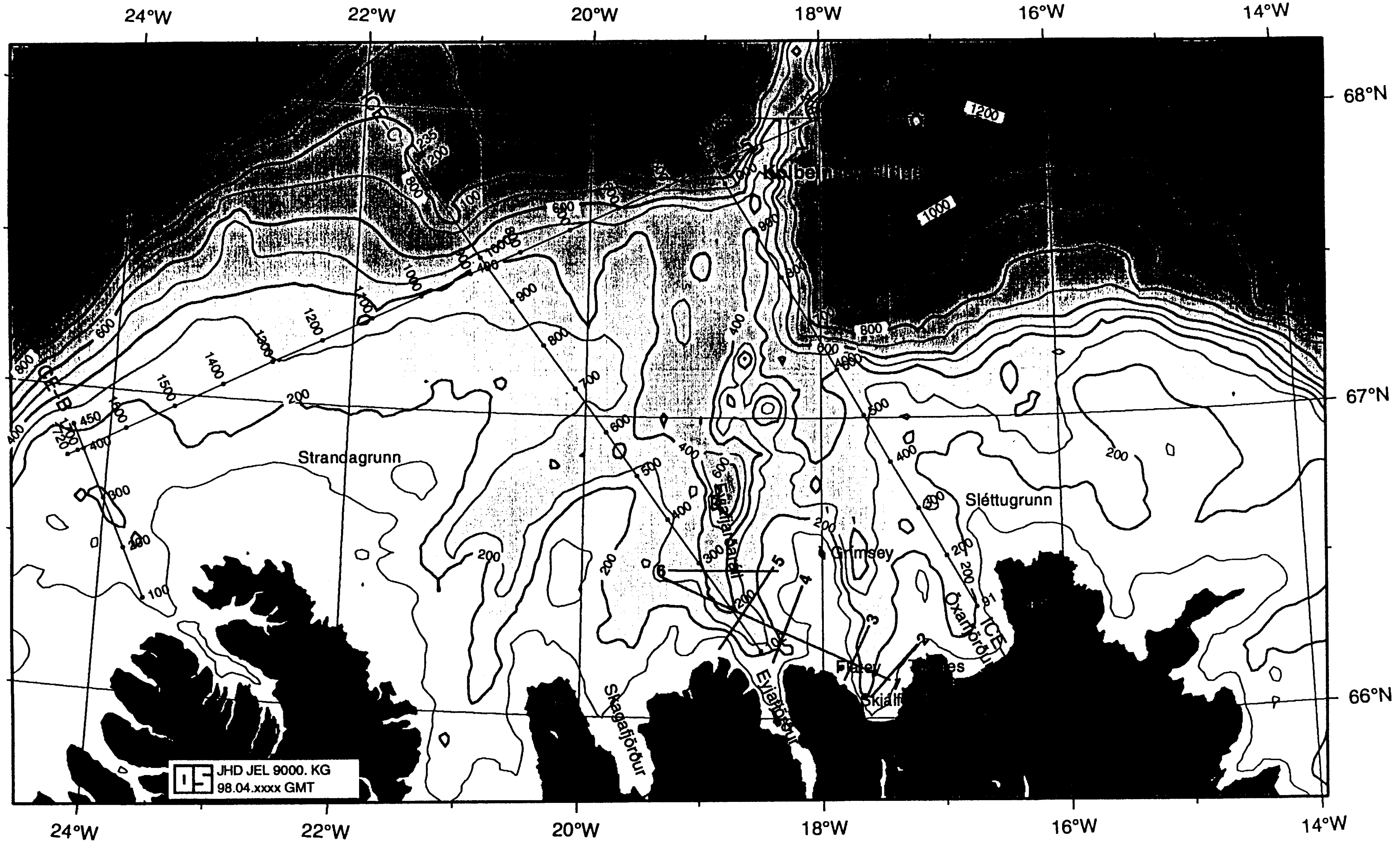
Figure 4.2. A section across the onshore Öxarfjörður Graben, based on a seismic refraction velocity model and geological mapping, with schematic tectonics and lithology as suggested by reflection and drilling data. (Adapted from Gunnarsson et. al., 1996).

Figure 4.3. Interpreted line drawings of the OS-85 cruise reflection data in the southern part of the TFZ. Time sections for lines F-4-85, F-3-85 and F-2-85. Vertical/horizontal ratio is conventional (1 s to 2.5 km).

Figure 4.4. Interpreted line drawings of the OS-85 cruise in the western part of the TFZ. a) Time sections for line F-1A-85, and b) for line F-5-85. Vertical/horizontal ratio is conventional for line F-5-85, but F-1A-85 is slightly horizontally contracted.

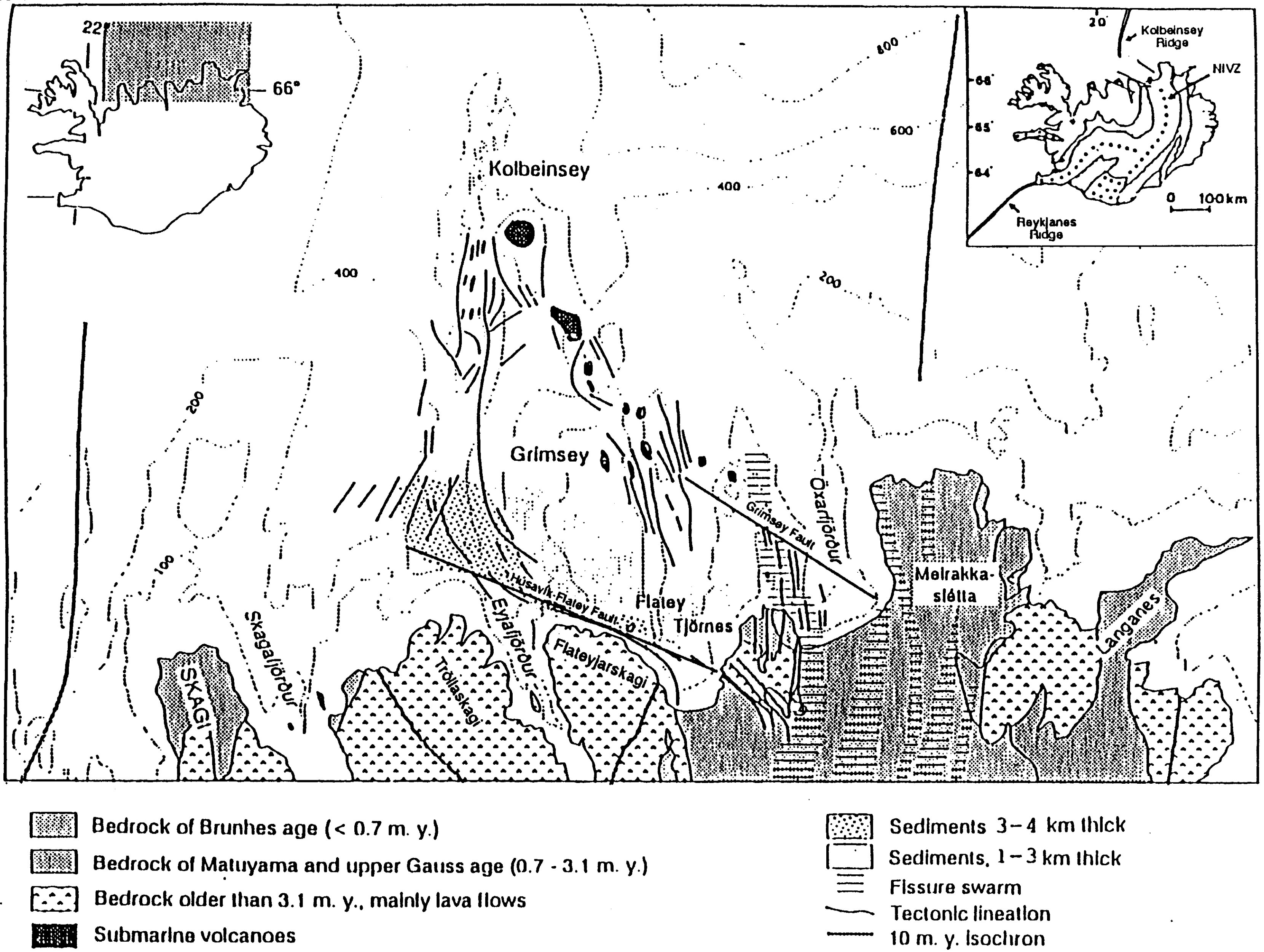
Figure 4.5. Interpreted line drawing for line F-6-85 of the OS-85 cruise (GECO, 1985) in the western part of the TFZ. This interpretation is not consistent with line F-1A-85 in figure 4.4, as the basement suggested here is a rather higher horizon.

Figure 4.6 a) Interpreted depth section of the south-eastern end of line ICE-C accross the Eyjafjaðaráll graben. Vertical exageration is 4 fold. Basement is marked "Basem.-B". The basement line is dashed where a definite basement reflections is not continuously traceable. A possible deeper basement at the south end is marked by question marks. More prominent reflections within the sediments are emphasised; the broken lines are for facilitating correlations. The "Lava-L" horizon is interpreted as volcanic. Deep



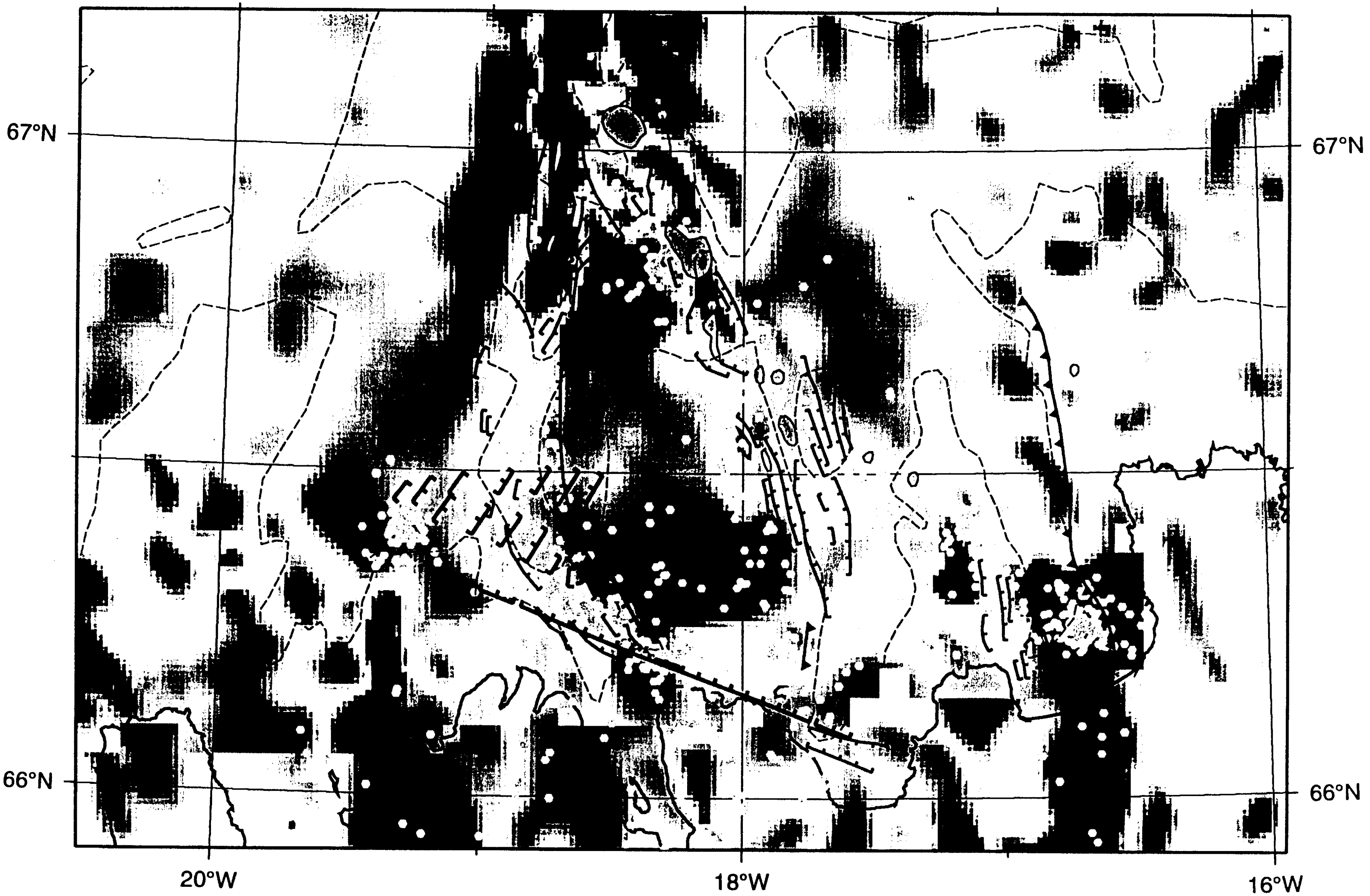
GMT Apr 27 11:47 _/seis/lg/lgnor/v98/milnur_1.g

Fig. 1.1



22
66°
20
Kolbeinsey Ridge
NIVZ
66
65
64
0 100km
Reykjanes Ridge
800
600
400
400
200
200
100
Kolbeinsey
Grimsey
Grimsey Fault
Öxarfjörður
Melrakka-sletta
Langanes
Húsavík-Flatey Fault
Flatey
Tjörnes
Eyjafjörður
Flateyjarskagi
Tröllaskagi
Skagafjörður
SKAGI
Bedrock of Brunhes age (< 0.7 m. y.)
Bedrock of Matuyama and upper Gauss age (0.7 - 3.1 m. y.)
Bedrock older than 3.1 m. y., mainly lava flows
Submarine volcanoes
Sediments 3 – 4 km thick
Sediments, 1 – 3 km thick
Fissure swarm
Tectonic lineation
10 m. y. isochron

Figure 2.1.



Liter

Fig. 2.2

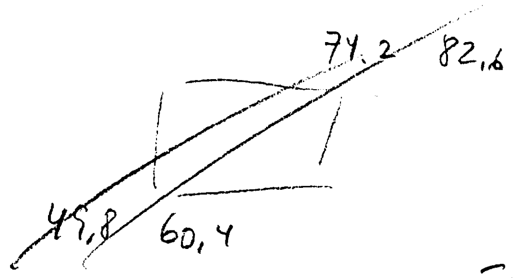
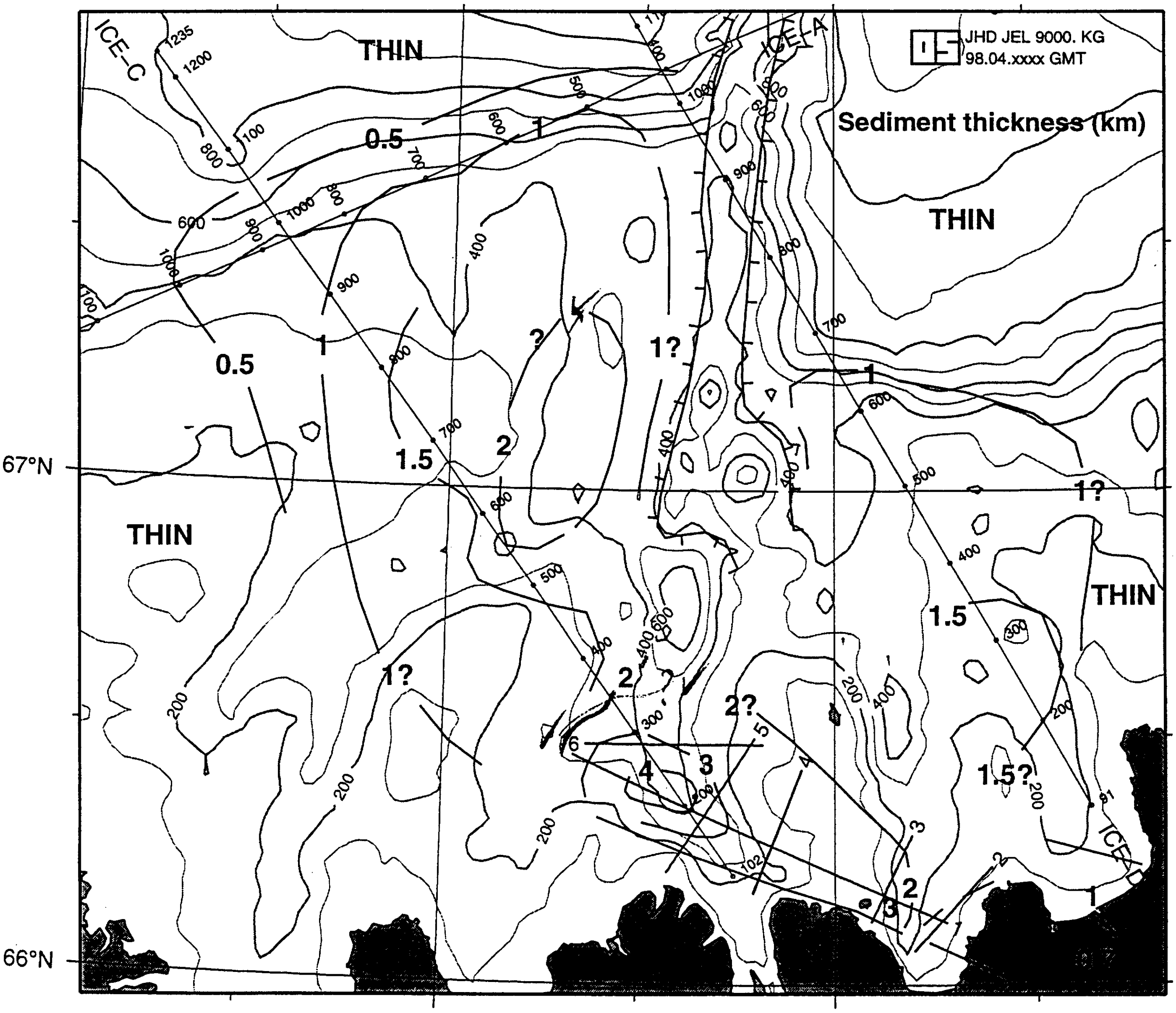
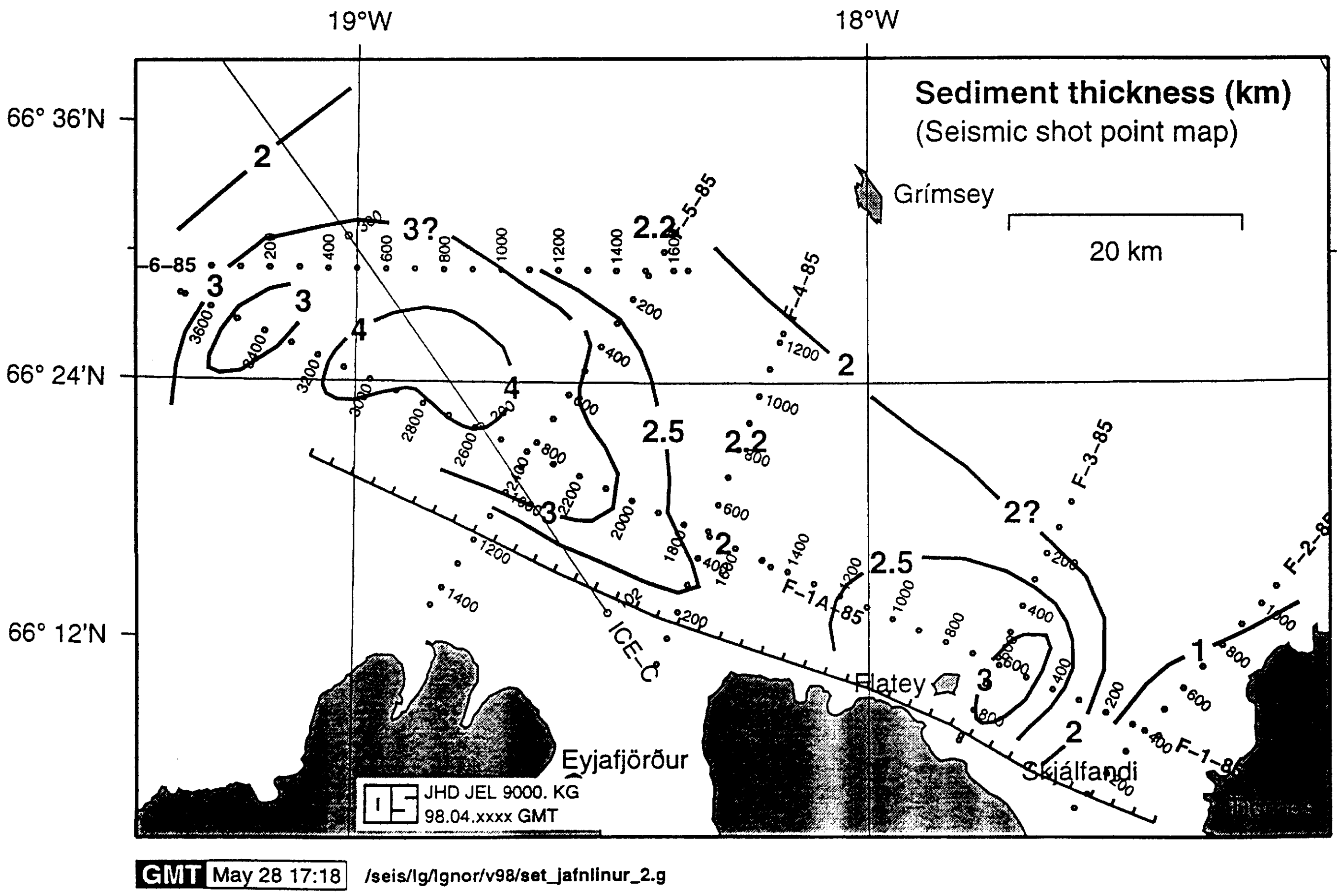


Fig. 3.1



GMT May 25 16:20 _/seis/lg/lgnor/v98/milnur_2.g

Fig. 3.2



Sediment thickness (km)
(Seismic shot point map)
19°W
18°W
66° 36'N
66° 24'N
66° 12'N
Grímsey
20 km
Flatey
Eyjafjörður
Skjálfandi
ICE-C
F-1A-85
F-3-85
F-4-85
6-85
JHD JEL 9000. KG
98.04.xxxx GMT
GMT May 28 17:18
/seis/lg/lgnor/v98/set_jafnlinur_2.g

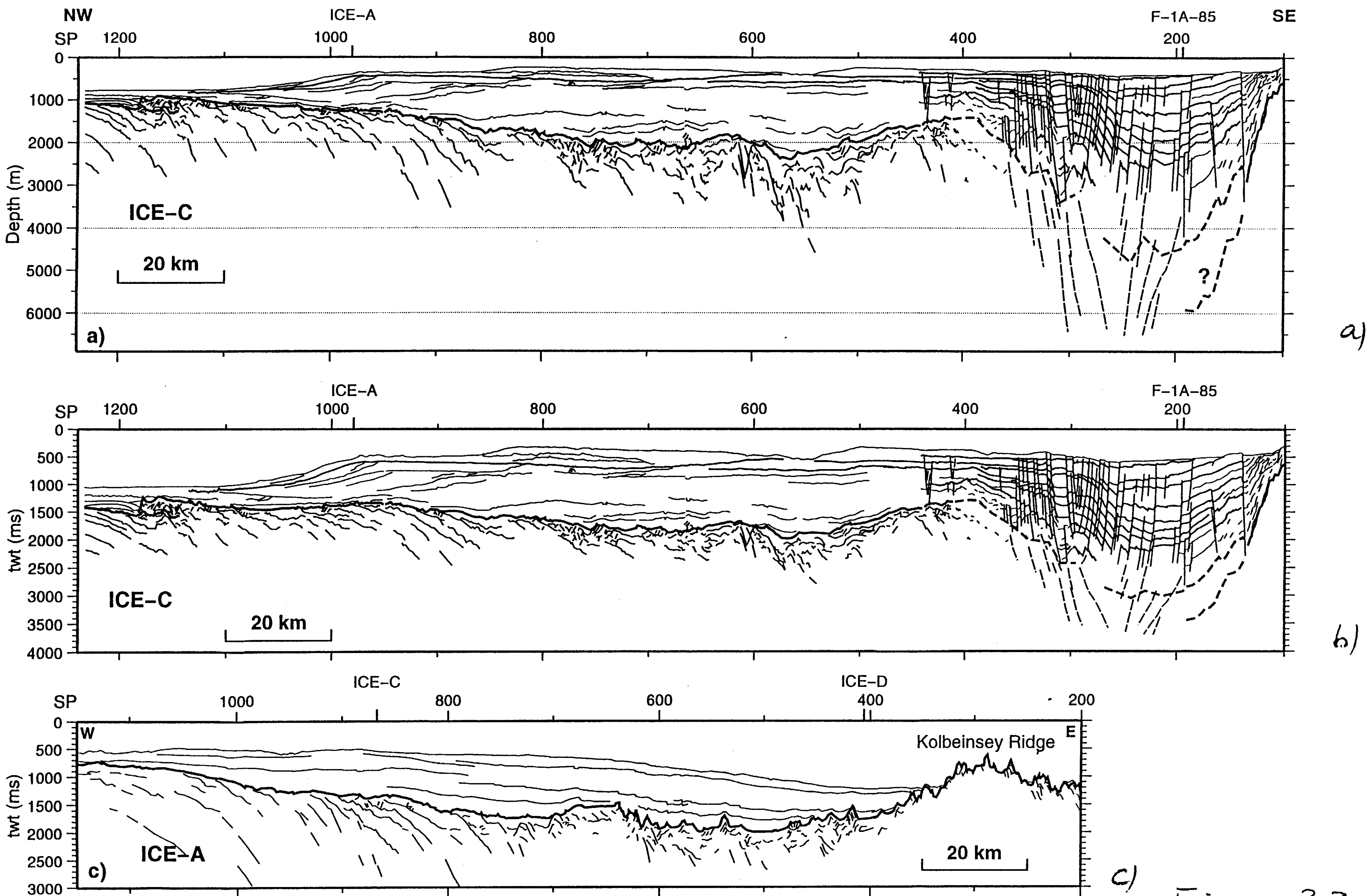
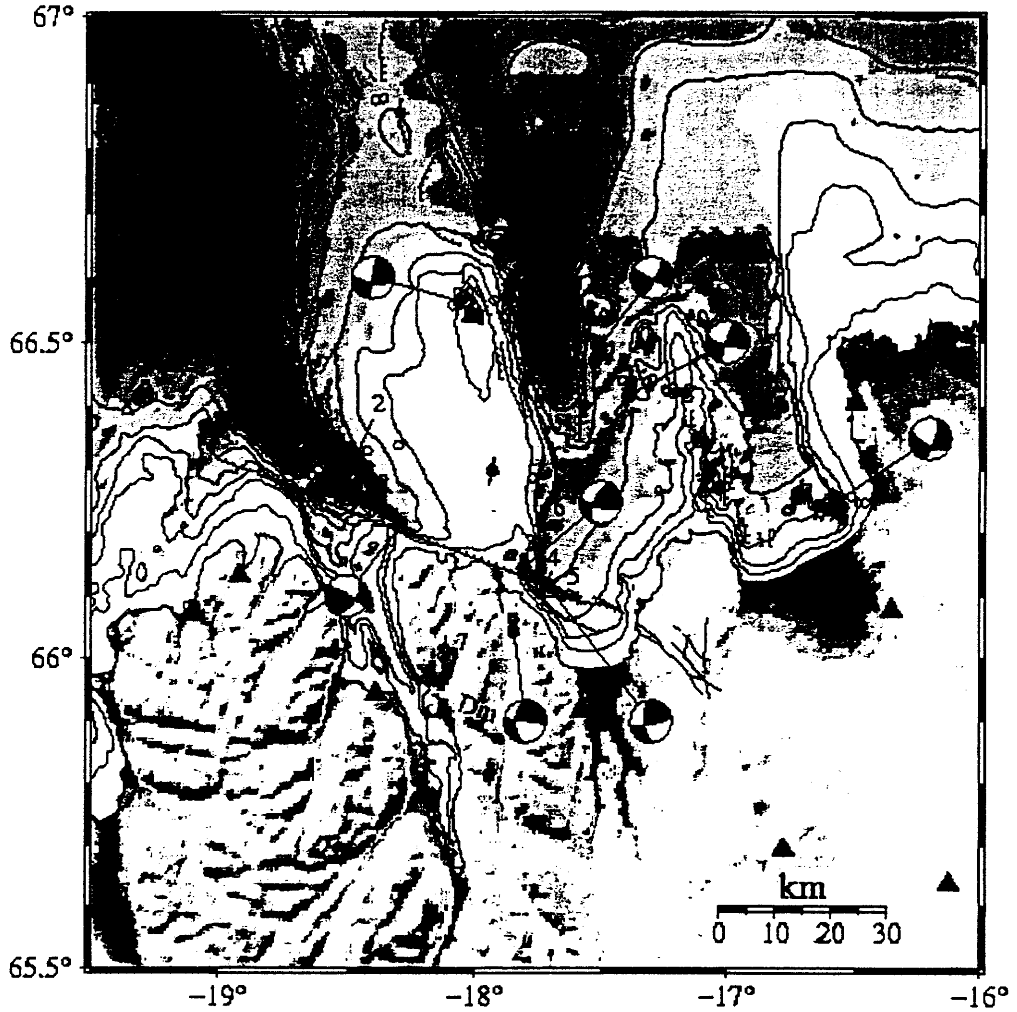

NW
SE
ICE-A
F-1A-85
SP
1200
1000
800
600
400
200
0
1000
2000
3000
4000
5000
6000
Depth (m)
ICE-C
20 km
?
a)
twt (ms)
500
1500
2500
3500
b)
ICE-C
ICE-D
W
E
Kolbeinsey Ridge
ICE-A
c)

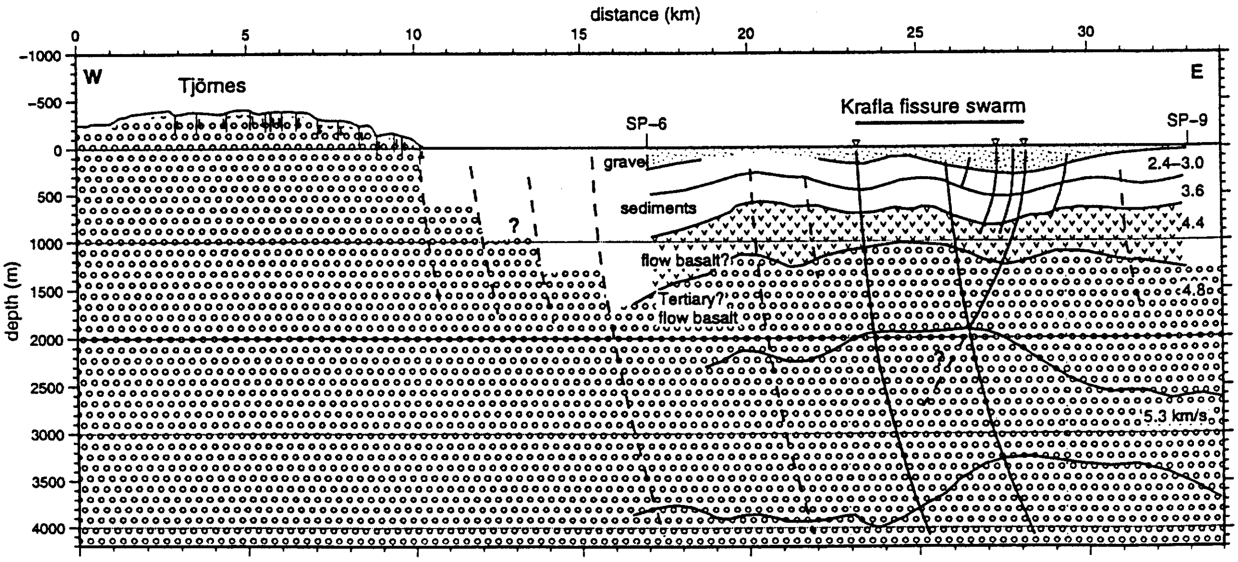
Figure 3.3



Litur.

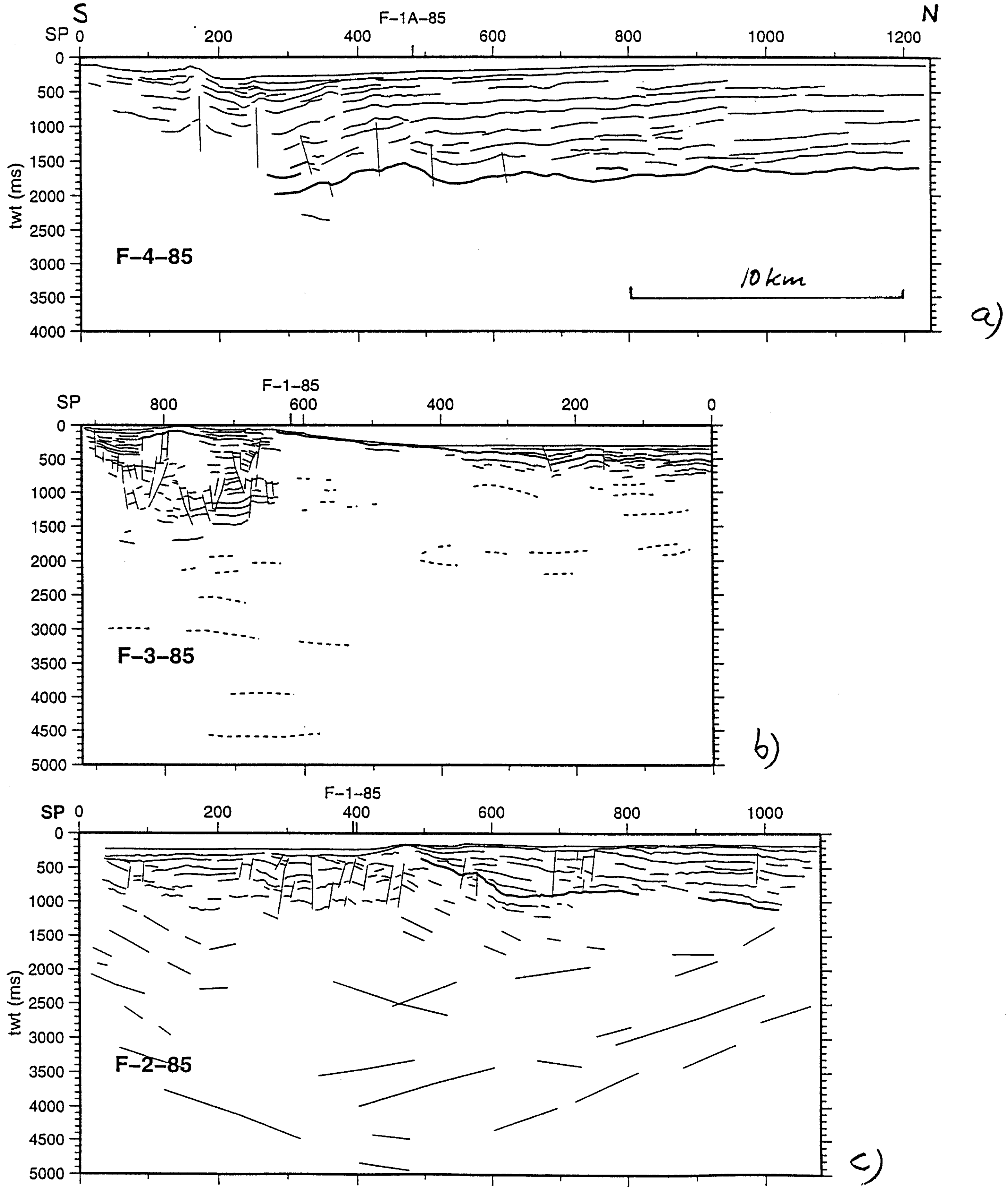
Fig. 4.1

Figure 4.2



distance (km)
0
5
10
15
20
25
30
-1000
-500
0
500
1000
1500
2000
2500
3000
3500
4000
depth (m)
W
E
Tjörnes
Krafla fissure swarm
SP-6
SP-9
gravel
sediments
?
flow basalt?
Tertiary?
flow basalt
2.4-3.0
3.6
4.4
4.8
5.3 km/s

Figure 4.3



S
N
F-1A-85
SP
0
200
400
600
800
1000
1200
twt (ms)
500
1000
1500
2000
2500
3000
3500
4000
F-4-85
10 km
a)
F-1-85
SP
800
600
400
200
0
4500
5000
F-3-85
b)
F-1-85
SP
0
200
400
600
800
1000
twt (ms)
F-2-85
c)

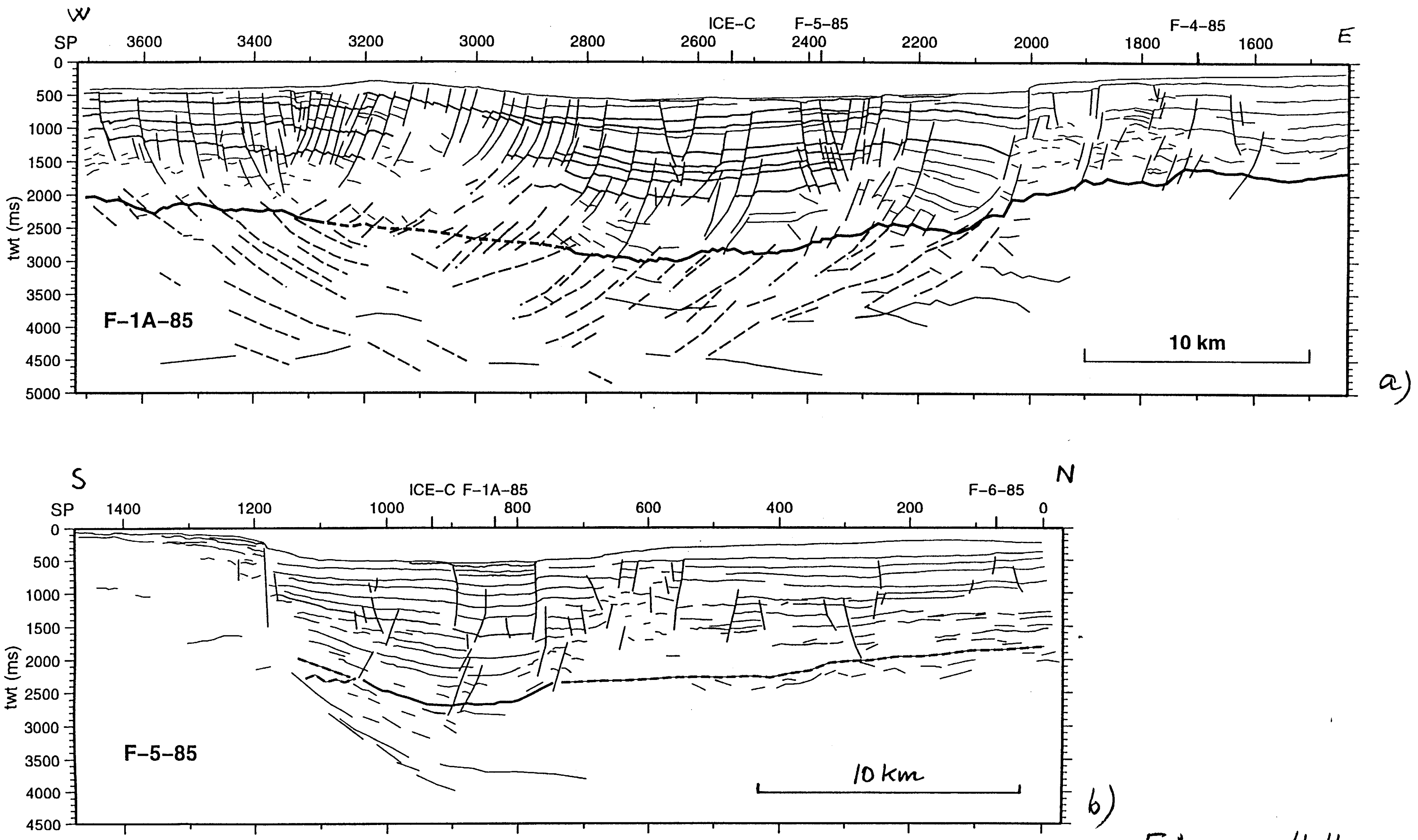
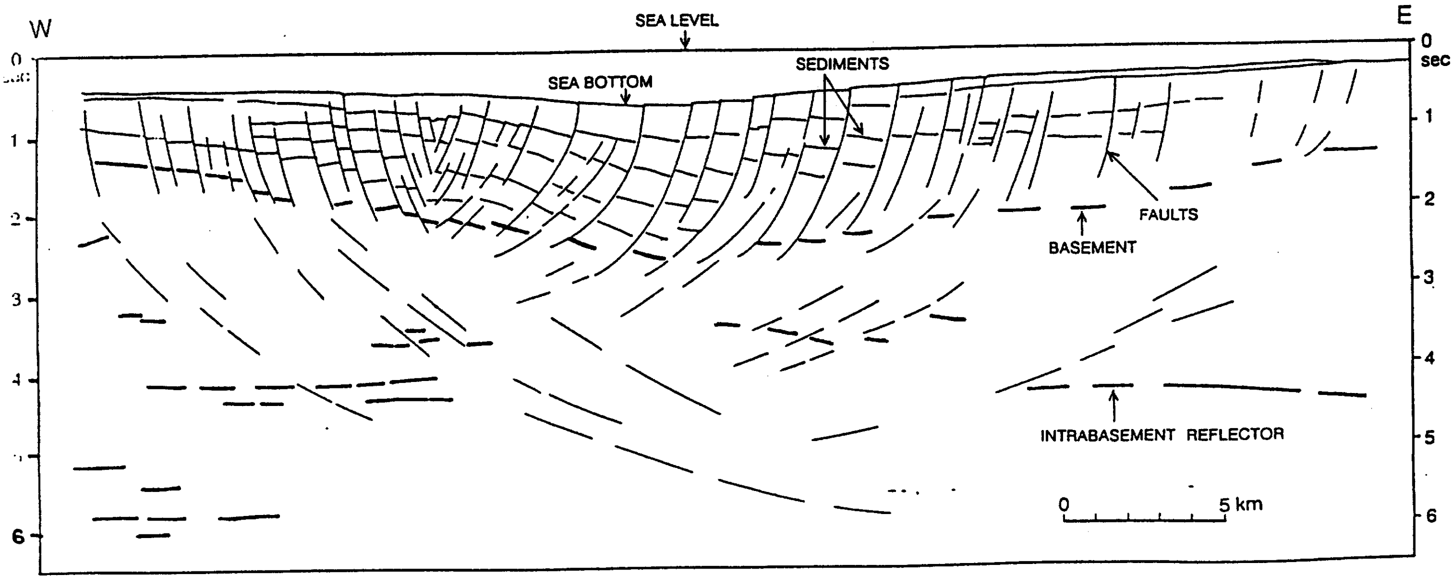

W
E
SP
ICE-C
F-5-85
F-4-85
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
twt (ms)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
F-1A-85
10 km
a)
S
N
ICE-C F-1A-85
F-6-85
1400
1200
1000
800
600
400
200
0
F-5-85
10 km
b)

Figure 4.4



W
E
SEA LEVEL
SEA BOTTOM
SEDIMENTS
FAULTS
BASEMENT
INTRABASEMENT REFLECTOR
0
1
2
3
4
5
6
sec
0 5 km

Figure 4.5

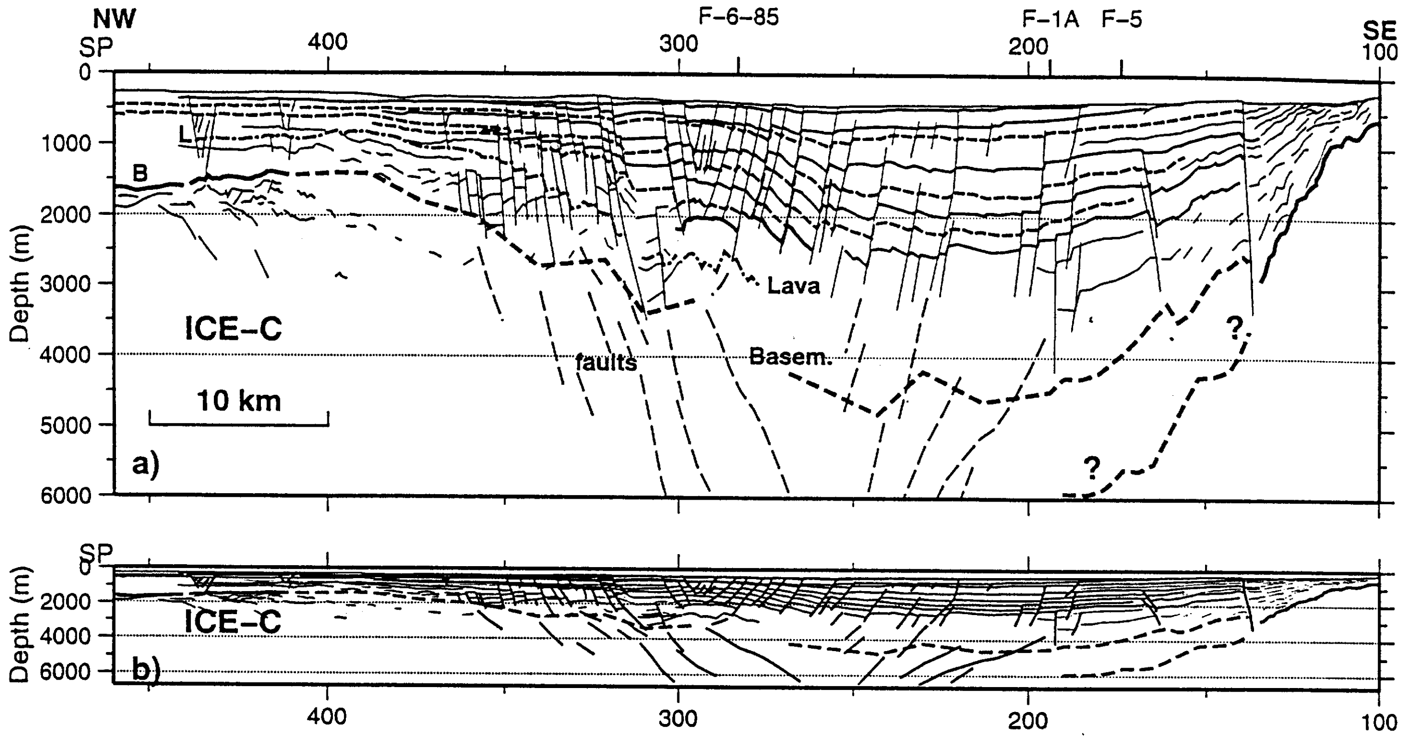


Figure 4.6

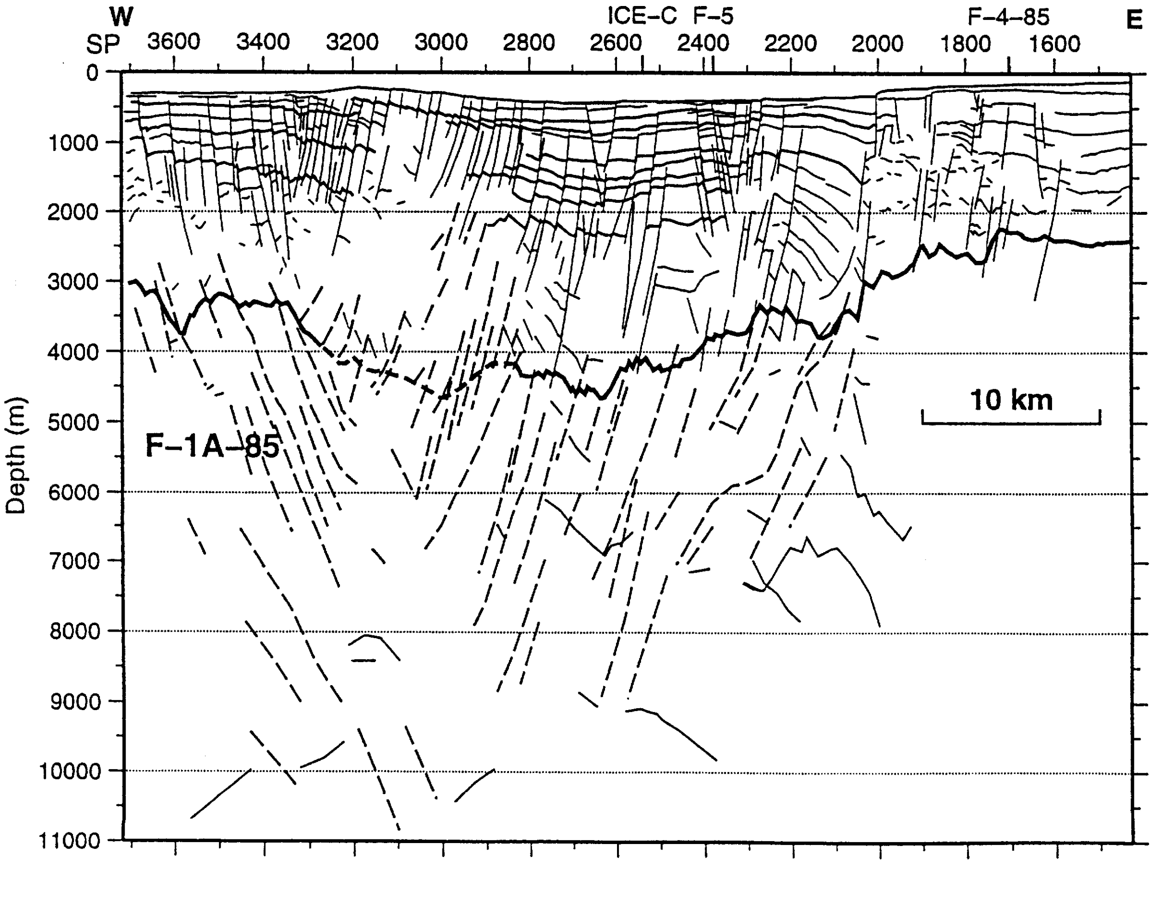


Figure 4.7

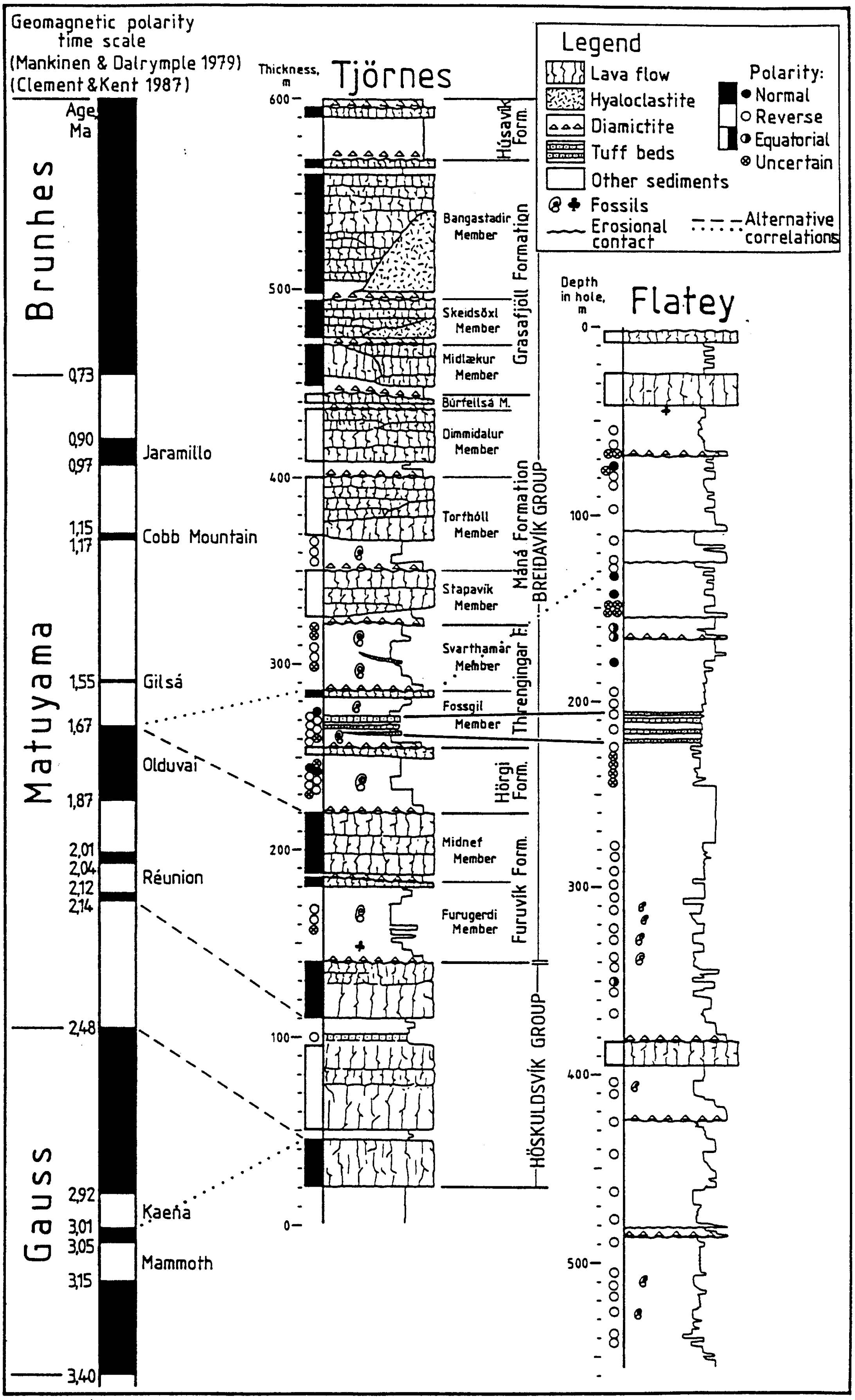
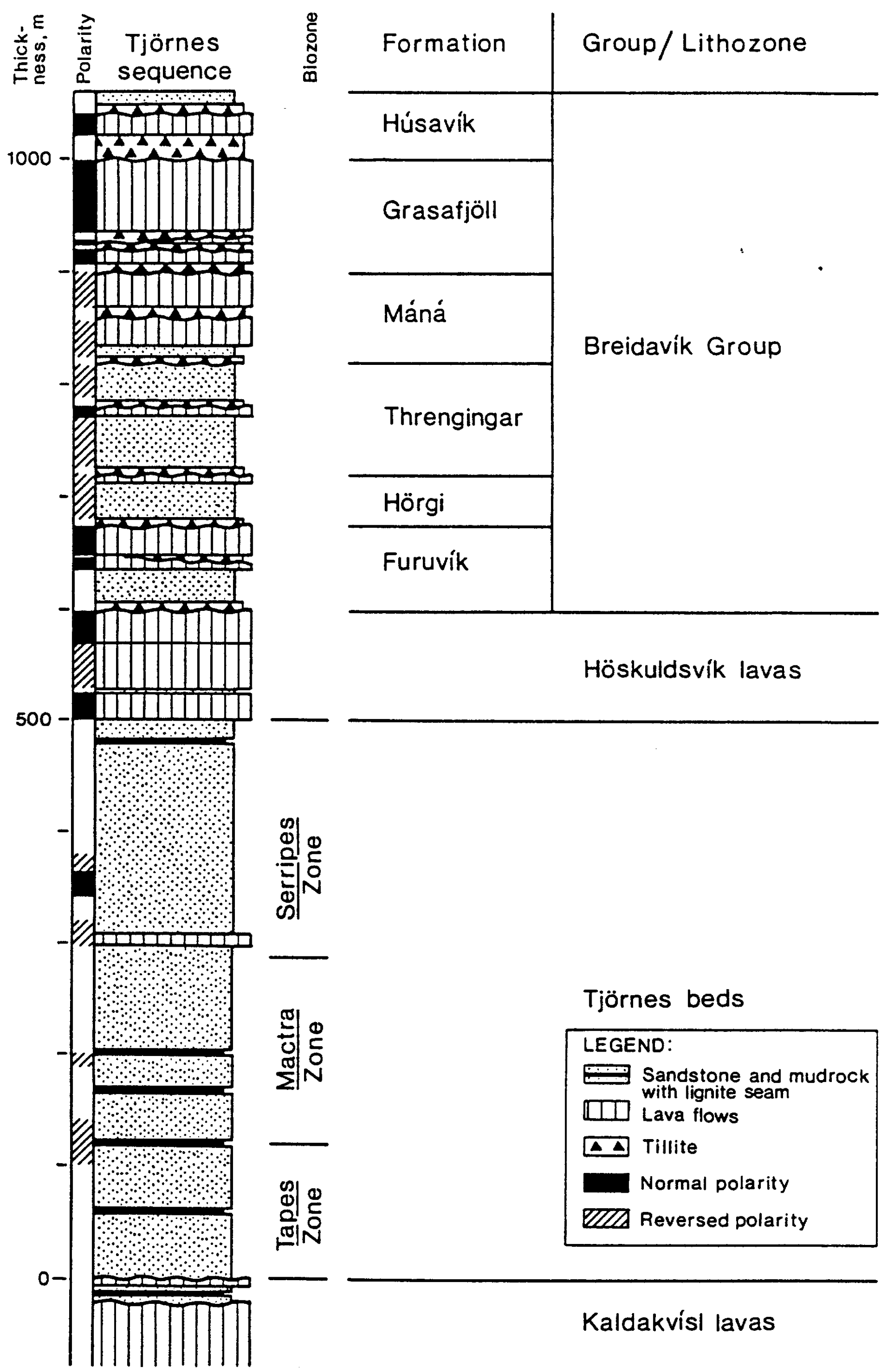

Geomagnetic polarity time scale
(Mankinen & Dalrymple 1979)
(Clement & Kent 1987)
Age, Ma
Brunhes
Matuyama
Gauss
0,73
0,90
0,97
1,15
1,17
1,55
1,67
1,87
2,01
2,04
2,12
2,14
2,48
2,92
3,01
3,05
3,15
3,40
Jaramillo
Cobb Mountain
Gilsá
Olduvai
Réunion
Kaeña
Mammoth
Thickness, m
Tjörnes
Húsavík Form.
Bangastadir Member
Skeidsöxl Member
Midlækur Member
Grasafjöll Formation
Búrfellsá M.
Dimmidalur Member
Torfhóll Member
Stapavík Member
Máná Formation
BREIDAVÍK GROUP
Svarthamar Member
Fossgil Member
Threnginger F.
Hörgi Form.
Midnef Member
Furugerdi Member
Furuvík Form.
HÖSKULDSVÍK GROUP
Legend
Lava flow
Hyaloclastite
Diamictite
Tuff beds
Other sediments
Fossils
Erosional contact
Alternative correlations
Polarity:
Normal
Reverse
Equatorial
Uncertain
Depth in hole, m
Flatey

Figure 5.1 a)



~~Fig. 4.~~ Composite columnar section of the Tjörnes sequence, based on coastal sections. Palaeomagnetic data from Hospers 1953, Gladenkov & Gurari 1976 and Th. Einarsson et al. 1967 (from Eiríksson 1981).

Figure 5.1 b)

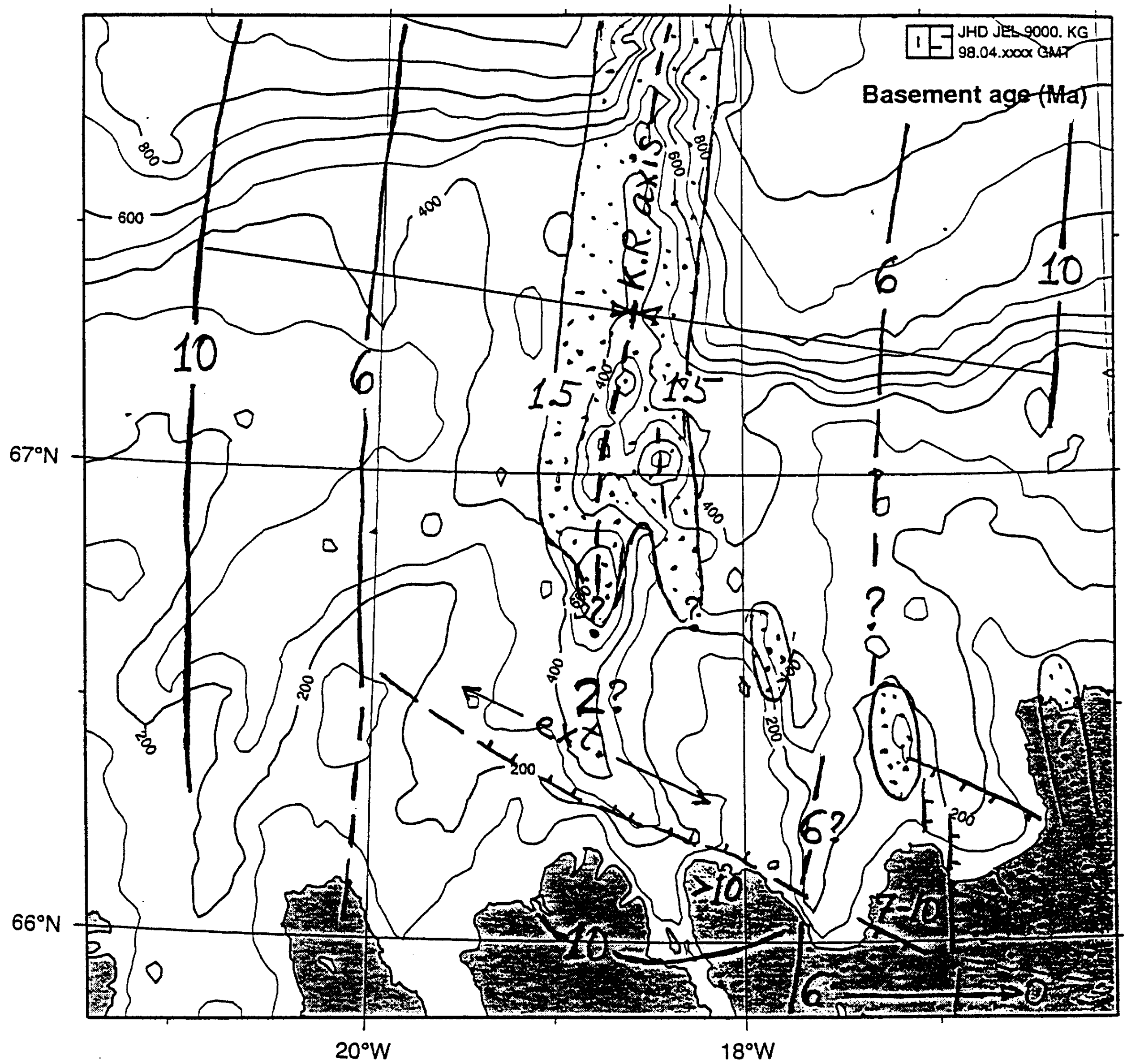

JHD JEL 9000. KG
98.04.xxxx GMT
Basement age (Ma)
67°N
66°N
20°W
18°W
800
600
400
200
10
6
15
K.R. axis
2?
ext.
6?
?

Figure 6.1