Master Thesis, Department of Geosciences

Volcanic Margins: A Quantitative Analysis of Magmatic Activity

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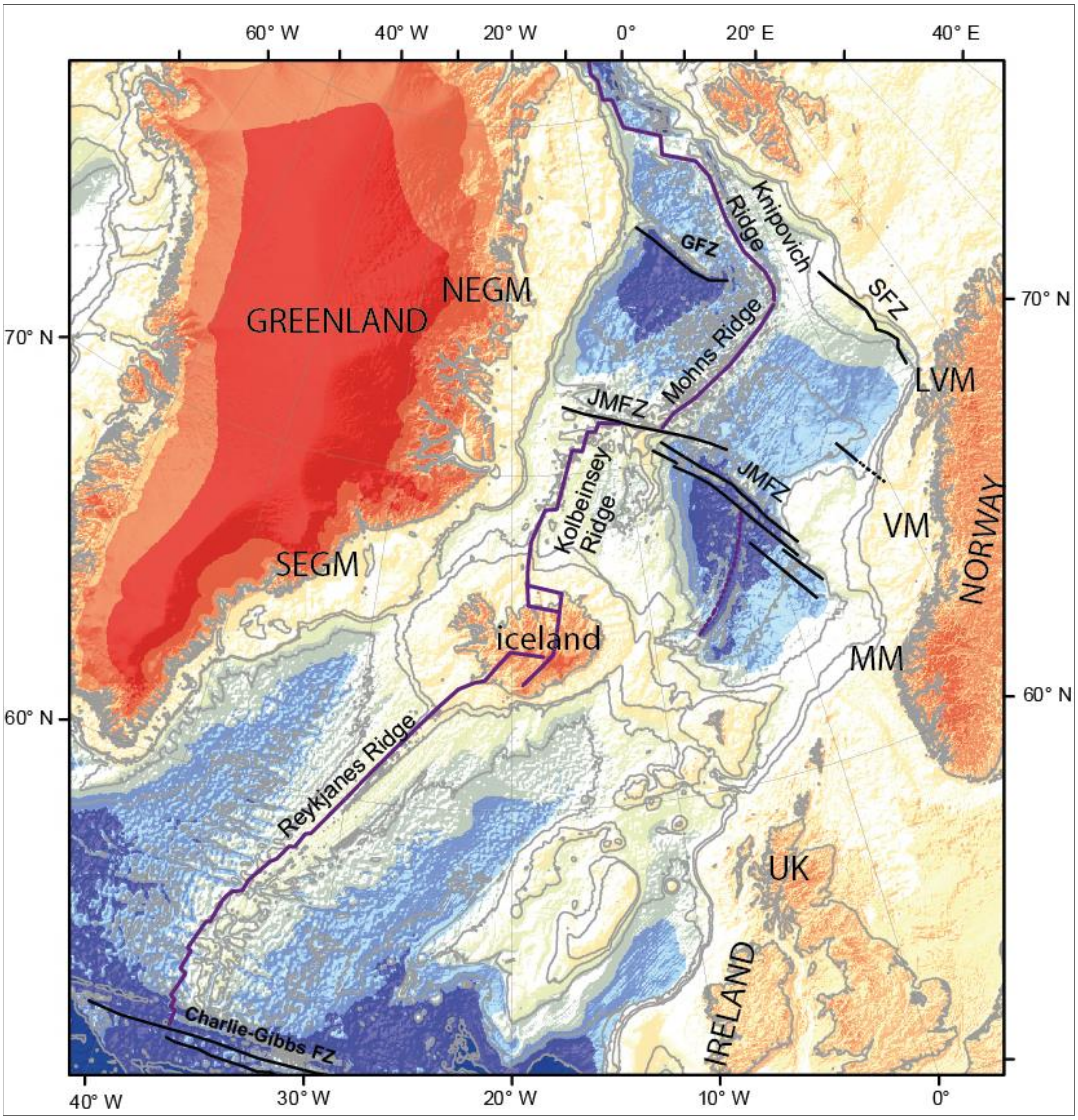
Sabbareh Kabiri



UNIVERSITY OF OSLO

FACULTY OF MATHEMATICS AND NATURAL SCIENCES

Volcanic Margins: A Quantitative Analysis of Magmatic Activity

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Master Thesis in Geosciences
Discipline: Geophysics
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Sabbareh Kabiri

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ABSTRACT

Continental breakup and initial seafloor spreading in the North Atlantic area was accompanied by widespread intrusive and extrusive magmatism and the formation of volcanic passive margins. The breakup related igneous rocks are divided into: (1) extrusive complexes erupted in different depositional environments, (2) shallow intrusive complexes (sills and dykes), and (3) deep intrusive complex (the Lower Crustal Body: LCB).

Volcanic conjugate margins along the North Atlantic Igneous Province are the most extensively studied continental margins, with significant data available along the whole length of the break-up axis. Theses margins have been investigated by seismic refraction data, multichannel seismic reflection data, exploration drilling and scientific drilling. High quality potential field data cover the whole area. The NE Atlantic is the key area to investigate the breakup related magmatism in this project. Relation between the extrusive and intrusive volumes could be calculated. Other large igneous province and volcanic margins around the world suffer from a lack of data and then uncertainties in volume estimation. By defining relation between the different components of the breakup igneous rocks we can improve melt estimation in volcanic margin where the data do not allow such calculation. Nevertheless, and despite a number of studies that attempted to estimate the volumes of magmatic material within volcanic rifted margins detailed quantitative estimations are still missing or they do not account for all processes involved like erosion, the complex pattern of intrusions and the real nature and composition of the LCB.

From the available seismic reflection and refraction data as we mapped the extent and we quantify the thickness of the extrusive and the deep intrusive (LCB) magma components. A total of 23 representative refraction profiles across the conjugate margins are used in this study. Generally the Seaward Dipping reflector (SDR) forms the thickest part of the extrusives.

Our result shows that the North Atlantic conjugated margins presents asymmetric distribution of magmatism. The thickness of the LCB vary significantly along-strike and across-strike the conjugate margins. The thicker part of the LCB is usually situated below the SDR. The average thickness ratio between the LCB and the extrusive volcanism is ranging between 1 and 4 in the West European margin while it is ranging between 2.5 and 4 in the Greenland margins. The average thickness ratio between the LCB and SDR in the west European margin

is mainly less than 3 whereas on the East Greenland margin it varies significantly, between 0.5 and 6.

Starting with the North Atlantic area, our results and workflow will provide the base for a new improved calculation of magma volumes in volcanic passive margins on a broader worldwide scale.

Contents

1 Introduction

1.1 General context

Continental breakup and initial seafloor spreading in Large Igneous Provinces (LIPs) are accompanied by widespread intrusive and extrusive magmatism and the formation of volcanic passive margins (Coffin and Eldholm, 1994; White and McKenzie, 1989). Volcanic passive margins represent more than 50% of the rifted passive margins around the world. Most of the present-day volcanic margins are submerged offshore and are therefore difficult to study by direct observation. These margins are therefore mostly studied by geophysical methods such as seismic reflection and refraction data and potential field data (gravity and magnetic data).

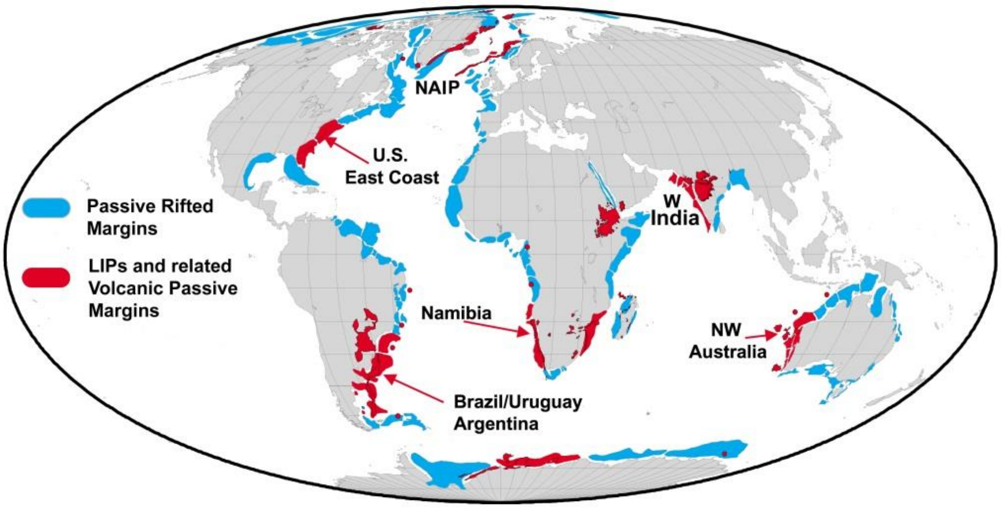


Figure 1.1: Global distribution of passive rifted margin and volcanic passive margins. Modified after (Skogseid, 2001).

1.2 Volcanic Passive Margin (VPM)

It is now well known that eextensive mantle melting at a volcanic passive margin occurred, before, during and after plate breakup (e.g. Abdelmalak, 2010; Abdelmalak et al., 2012; Geoffroy, 2005). Magmatic activity is typically expressed within the stretched continental crust by: (1) large wedges of seaward-dipping basaltic flows and tuffs extruded at the surface (SDRs) (Eldholm, 1991; Hinz, 1981; Menzie et al., 2002; Planke et al., 2000); (2) massive sill/dyke intrusions within the sedimentary basin (Planke et al., 2005b); (3) intense intrusions into the upper and mid continental crust by mafic to ultramafic intrusions (Geoffroy et al., 2007; Karson and Brooks, 1999; Klausen and Larsen, 2002; Lenoir et al., 2003; Meyer et al., 2009; Svensen et al., 2004); and (4) the presence of seismic lower crustal bodies (LCB) at the base of the crust recording high Vp velocity (Vp> 7.0 km/s) (Holbrook et al., 2001; Kelemen and Holbrook, 1995; Mjelde et al., 2009b; Mjelde et al., 2009d; White et al., 1987).

In volcanic passive margins we divide the breakup related igneous rocks into: (1) extrusive complexes erupted in different depositional environments, (2) shallow intrusive complexes (sills and dykes), and (3) deep intrusive complex (the Lower Crustal Body: LCB) (Figure1.2).

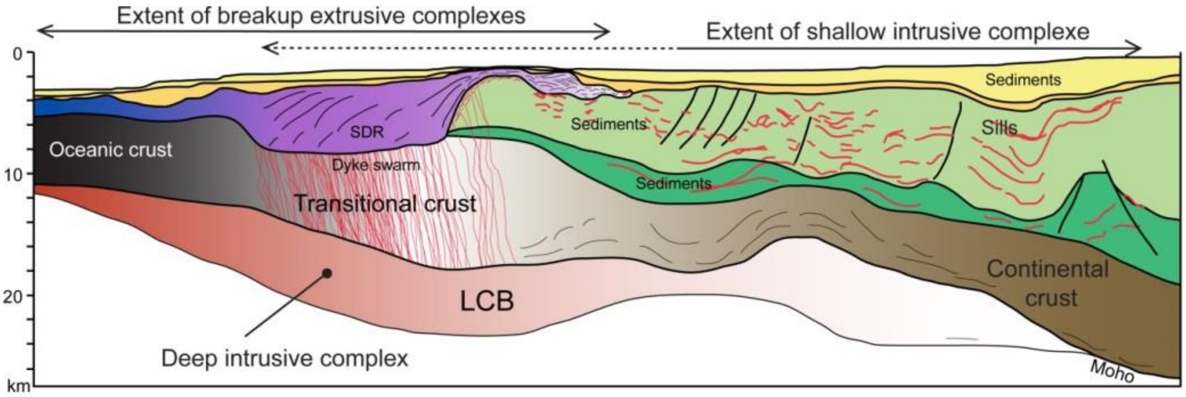


Figure 1.2: Crustal structure and magmatic activity in volcanic passive margin (Courtesy from Abdelmalak).

1.2.1 Extrusive complexes

In volcanic margin, major volumes of flood basalts erupted in submarine to subaerial settings during the onset of breakup (e.g. Berndt et al., 2001). These peculiar volcanic successions display a large variety of seismic facies that are indicative of the style of volcanic emplacement, depositional environment and subsequent mass transport (Abdelmalak et al., Submitted; Brendt et al., 2001; Jerram et al., 2009; Planke and Alvestad, 1999; Planke et al., 1999; Planke et al., 2000; Wright et al., 2012) (Figure 1.3).

Multichannel seismic data have allowed the definition and characterization of the seismic “volcanostratigraphy” concept based on their shape, reflection pattern, and boundary reflections [e.g., Planke et al., 2000; Berndt et al., 2001b]. Several volcanic seismic facies units have been identified: (1) Landward Flows, (2) Lava Delta, (3) Inner Flows, (4) Inner Seaward Dipping Reflectors (inner SDR), (5) Outer High, and (6) Outer Seaward Dipping Reflectors (outer SDR) (Figure 1.3). Such facies succession represents a typical volcanic rifted margin sequence and describes the evolution of the breakup extrusive complex landward of, and/or very close to, the first magnetic seafloor spreading anomalies. Further information and explanation based on interpretation of these seismic facies units are summarized in table 1-1.

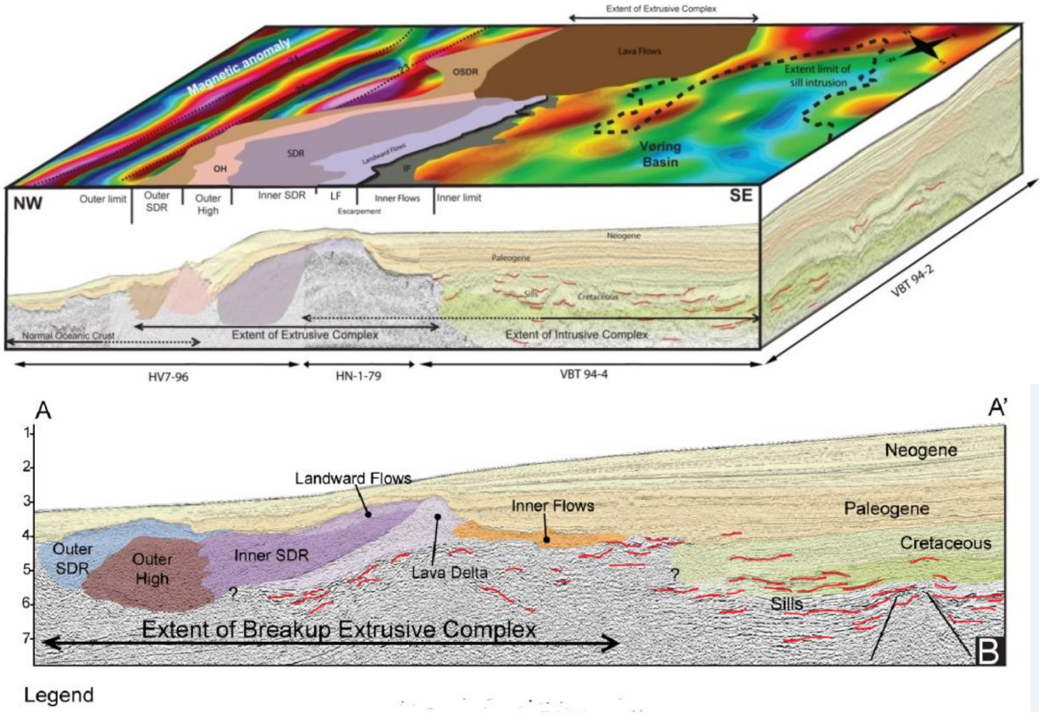


Figure 1.3: The volcanostratigraphy shows distribution of volcanic seismic facies (Courtesy from Abdelmalak).

1.2.2 Shallow intrusive complexes (sills and dykes)

The sills are easily identified by their characteristics: high-amplitude seismic response, saucer shaped, discordant reflection geometry and abrupt terminations (Planke et al., 2005a). They are also associated with hydrothermal vent complexes (Figure 1.4) which were formed mainly by explosive eruption of gases, liquids and sediments during sills emplacement (Svensen et al., 2004). Below the Seaward Dipping Reflectors (SDR) sequences, vertical and inclined reflections are interpreted as dyke feeder systems (Abdelmalak et al., 2015).

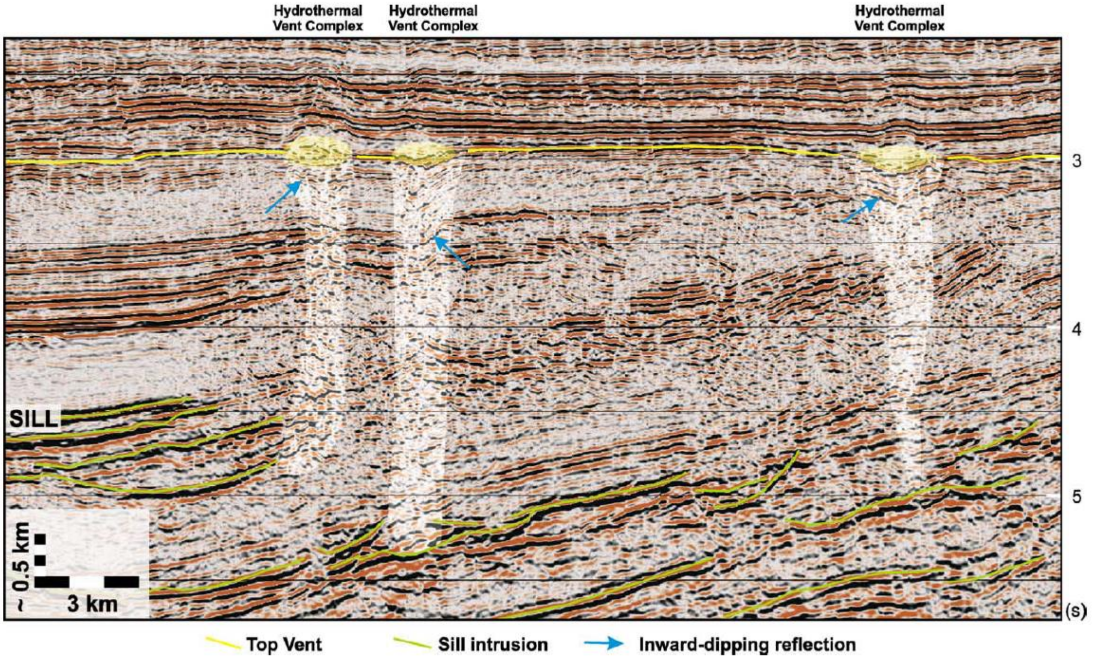


Figure 1.4: Seismic interpretation of hydrothermal vent complexes in the central Vøring Basin (Planke et al., 2005a)

Tabell 1.1 Description of the Volcanic seismic facies (Abdelmalak et al., 2016a).

Seismic facies unit	Reflections characteristics			volcanic facies	Depositional environment
	Shape	Boundaries	Internal		
Inner Flows	Sheet	Top: high amplitude, Disrupted, rough being onlapped or concordant. Base: negative polarity often obscured	Chaoitic sheet-like body of very disrupted or hummocky reflections	Massive and fragmented flows, volcanoclastics and hyaloclastics	Shallow marine deposited in broad basin
Lava Delta	Bank	Top: High amplitude or reflection truncation. Base Reflection truncation or termination	Progradational reflection configuration	Massive and fragmented basalts and volcanoclastics	Coastal
Landward Flows	Sheet	Top: high amplitude, smooth being onlapped or concordant. Base: law amplitude, disrupted	Parallel to subparallel. High-amplitude disrupted	Flood basalts	Subaerial or shallow marine flood basalts deposited on a plain or in broad basin
Inner SDR	Wedge	Top: Intermediate to high amplitude, smooth with pseudoescarpment. Base: seldom defined	Divergent arcuate or sometimes a divergent-planar pattern	Flood basalts	subaerial flood basalts deposited in subsiding structure
Outer High	Mound	Top: high amplitude, disrupted and rough. Base: not visible	Chaotic	Hyaloclastic flows and volcanoclastics	Shallow marine environment
Outer SDR	Wedge	Top: Intermediate to high amplitude, smooth with pseudoescarpment. Base: seldom defined	Divergent arcuate internal reflectors, lower amplitude than the Inner SDR	Flood basalts mixed with pillow basalts sediments and sills	deep marine depositional environment
Lava Flows	Sheet	Top: high amplitude with pseudoescarpment. Base: not visible	Chaotic	Flood basalts	Subaerial to shallow submarine depositional environment

1.2.3 Deep intrusive complexes (LCB)

In the volcanic passive margins, seismic multichannel and wide-angle surveying revealed a high-velocity, high-density layer at the base of the crust referred to as the lower crustal body (LCB) (Holbrook et al., 2001; Mjelde et al., 2009c; Mjelde et al., 2007; Mjelde et al., 2005b; Voss and Jokat, 2007b; Voss et al., 2009b) (Figure 1.2). In general these bodes characterized by high p-wave velocity between 7.1 - 7.7 km/s and a Vp/Vs ratio between 1.8 and 1.9 (Mjelde et al., 2003; O'Reilly et al., 1996).

The early works proposed that LCB represented mafic magmatic underplating emplaced during the final stage of rifting, continental breakup and the onset of sea floor spreading (e.g. White and McKenzie, 1989). The anomalously high velocities may reflect the concentration of MgO within magmatically underplated material, which in turn may signify differences in the magma composition, possibly reflecting asthenospheric temperatures or compositional inhomogeneities in the asthenospheric source (White and McKenzie, 1989). High-velocity lower crustal bodies are often located along the continent-ocean transition (COT) (Eldholm et al., 2000), but can extend beneath the continental part of the crust. In the continental domain, there are fewer constraints on their nature and chronology. In recent years, there has been a renewed discussion about the interpretation of the LCB (Ebbing et al., 2006; Gernigon et al., 2004; Mjelde et al., 2009a; Reynisson et al., 2010), and the distinction between igneous underplating below stretched continental crust where magmatism is triggered by a mantle plume (Eldholm and Grue, 1994; White and McKenzie, 1989), and the distinction between igneous underplating below stretched continental crust where magmatism is triggered by a mantle plume (White et al., 2010b; White et al., 2008b), and other non-magmatic models. Several non-magmatic alternatives have been proposed to explain the origin of the LCB, like a Tertiary core complex model (Dore et al., 1997; Ren et al., 1998), a serpentinised model (Osmundsen and Ebbing, 2008; Reynisson et al., 2010), and a retrograde, high-grade rock model (2006; Gernigon et al., 2004).

1.2.4 Continental Oceanic Transition zone (COT) and Continental Ocean Boundary (COB)

By definition, the 'COB' (Continent Ocean Boundary) is the spatial and temporal line where and when continental-derived basement (incl. crust and mantle) and oceanic crust are juxtaposed. The definition of the COB is often unclear as it is subjective, and strongly dependent on the dataset (Peron-Pinvidic and Osmundsen, 2016) the context of volcanic passive margin, it has been suggested that the COB is located at the seaward end of the base reflector near the inner wedges of the seaward dipping reflectors (SDRs) (Abdelmalak et al., 2016a; Eldholm and Grue, 1994; Planke, 1994; Planke and Eldholm, 1994).

By definition the COT (continent ocean transition) is the transition between continental crust and oceanic crust. The nature, width and thickness of the COT can be characterized by the processes, related to the continental rifting and development of Oceanic crust (Mjelde et al., 2005c). According to (Whitmarsh and Miles, 1995), the COT constructed as a part of the lithosphere which consists of intermediate velocity between the stretched continental crust and thickened oceanic crust characterized by fault blocks at the surface. furthermore the seaward termination of the COT can identified from the oldest magnetic anomaly of oceanic crust or as seaward termination of the wedges of the SDRs (Mjelde et al., 2005d; Mutter et al., 1982). The landward boundary can based on the clearly identifiable fault block of stretched continental crust (Breivik et al., 2006; Mjelde et al., 2005c). In general, the COT on volcanic margins is less well constructed, due to the strong reflectivity from the thick covered basalt layer and the lower intrusion of massive magma. The width of COT is estimated to be narrow with an average about 50 km on volcanic margins based on velocity model. The COT on the non-volcanic margins is wider and has an average value about 80 km.

1.3 Aim of study

In the volcanic passive margins, recent investigations on the breakup related magmatism have revealed variation in geometry and composition of magmatism along strike, across strike and between the conjugated margins. Also it has been suggested that the variable distribution of breakup magma is related to the extension rate, composition and mantle temperature.

Even though there are several studies have tried to estimate the volumes of magmatic material within the volcanic rifted margin however the detailed quantitative estimations are still not clear or didn't consider for all the process such as erosion, the complex pattern of intrusions and the real nature of LCBs.

The main objective of this study is to find a relationship between LCB and extrusive basalts (SDRs) using 2D reflection, refraction, gravity and magnetic data along and across the volcanic passive margin. Such relationships between extrusive and intrusive volumes are important because they could be used in other volcanic margins where the lack of data precludes the calculation of different magma volume from various breakup related igneous rocks.

2 Geological Setting

The NE Atlantic margin is situated between latitude ~50°N to ~75°N and longitude ~46°W to ~20° E. It is composed by six main from the East Greenland part and West European margins are as follows: NE and SE Greenland margin, Hatton margin, Faroe-Shetland margin, Møre margin, Vøring margin and Lofoten-Vesterålen margin (Figure 2.1). Geographically, the NE Atlantic margin contains a continental shelf and slope with variable width and depth. The water depth from the shelf edge to the foot of the slope increases intensely from ~100 m to ~4000 m (Tsikalas et al., 2012). The NE Atlantic margins are asymmetric with respect to their width and the large bathymetric events. Continental shelf along the southern part of the East Greenland margin is narrower and gradually become wider toward the north, whereas in the European margins it is wider in the south and become narrow with steep continental shelf in the north (Figure2.1). An extensive bathymetric feature along the Greenland Iceland Faroe Ridge (GIFR), divided the NE Atlantic in two main geographic domains. Thus the NE Greenland and the conjugate Mid-Norwegian margins are located in the northern domain and the SE Greenland and conjugated Hatton-Rockall and Faroe margins are in the southern domain.

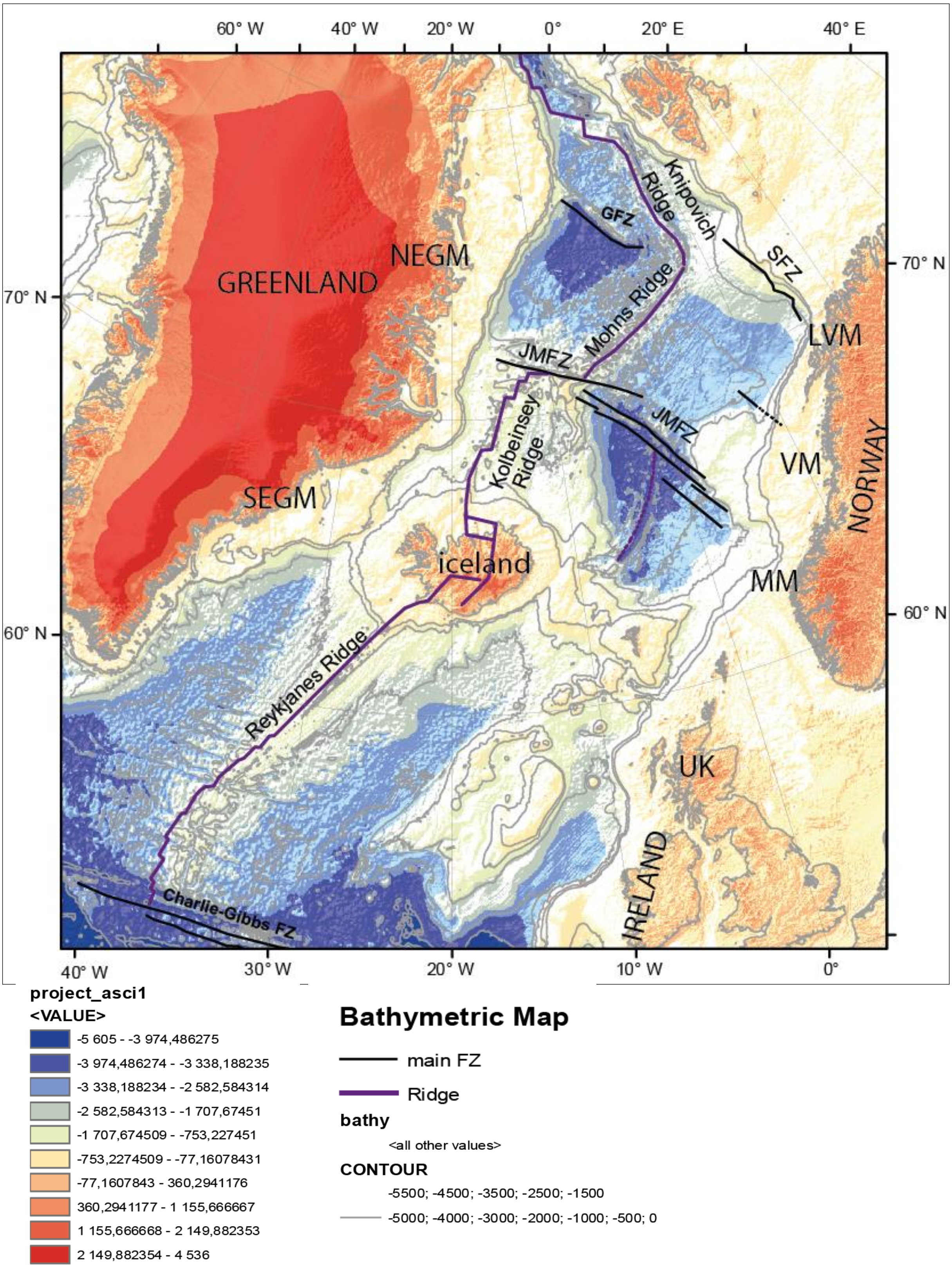


Figure 2.1: Bathymetric map of NE Atlantic Passive margin based on GEBCO bathymetry/topography grid (The GEBCO_08 Grid, version 20100927, http://www.gebco.net), LVM, VM, MM, NEGM, SEGM: Lofoten-Vesterålen, Vøring, Møre, North East and SE Greenland margin respectively, GFZ: Greenland Fracture Zone.

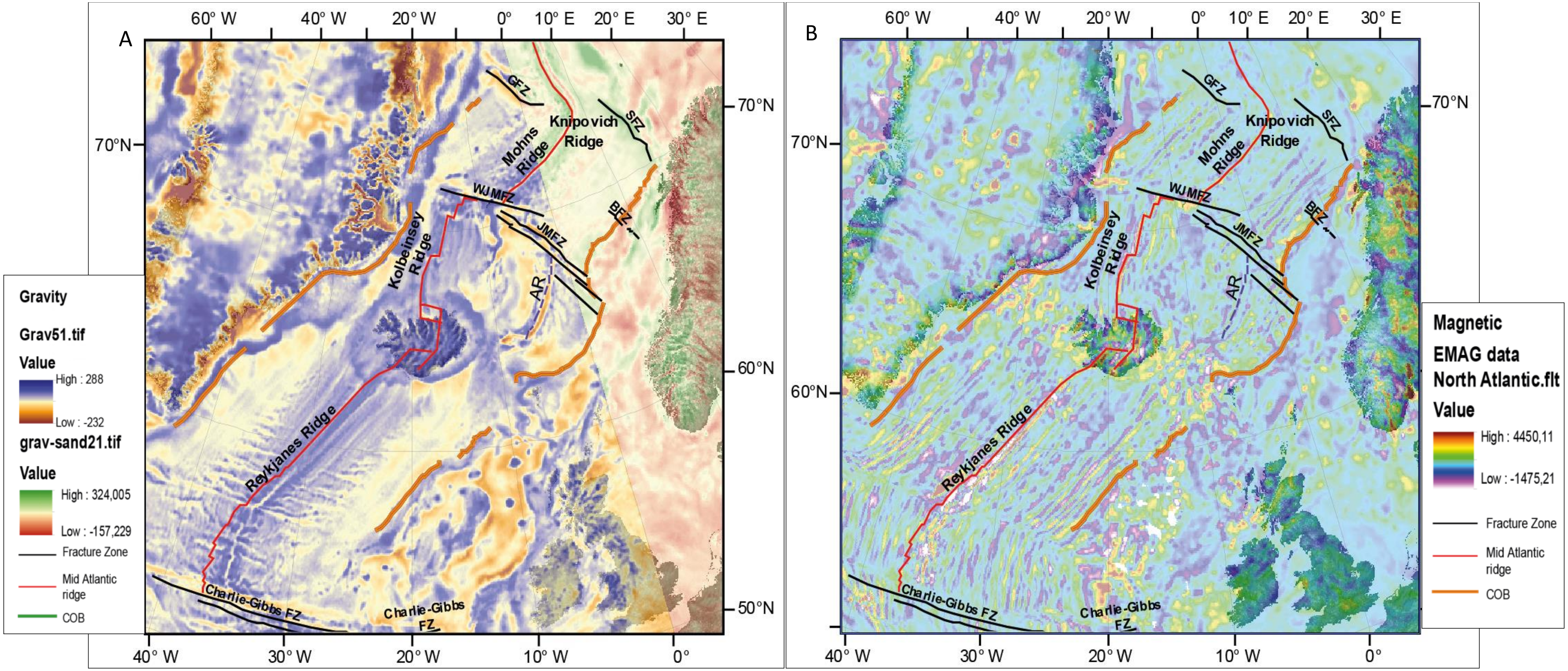


Figure 2.2: A: Satellite gravity map (Becker et al., 2009), B: Magnetic anomaly map (EMAG2) (Maus et al., 2009) in the NE Atlantic region.

The conjugate volcanic rifted margins along the NE Atlantic are the major magmatic component of the North Atlantic Large Igneous Province formed during the final continental breakup during the Paleogene (Abdelmalak, 2010; Abdelmalak et al., 2012; Eldholm et al., 2000; Ganerød et al., 2010; Hansen et al., 2009; Meyer et al., 2007; Saunders et al., 1997; Torsvik et al., 2001). The onset of continental breakup marked a culmination of a ~350 Ma period of predominantly extensional deformation and intermediate cooling events subsequent to the Caledonian orogeny (Doré et al., 1999; Faleide et al., 2010; Skogseid et al., 2000; Tsikalas et al., 2008; Ziegler, 1988).

During the Late Cretaceous–Paleocene the locus of maximum extension migrated to the NW toward the zone of the future continental separation (Skogseid et al., 2000). The final continental breakup occurred at early Eocene (~ 56-55 Ma according to Gradstein et al., 2012 timescale) and resulted in voluminous igneous activity generating both extrusives and intrusives into the adjacent sedimentary basin and pre-existing (continental) crust (Breivik et al., 2014; Eldholm and Grue, 1994; Hinz, 1981; Mjelde et al., 2007; Mutter et al., 1982; Planke et al., 2005a; White and McKenzie, 1989) constituting the breakup-related igneous rocks. The different fracture zone and lineaments are responsible for the segmentation of the North Atlantic area into several segments with different tectono-magmatic and post Caledonian sedimentary distribution. The different margin segments constituting the North Atlantic area are described below.

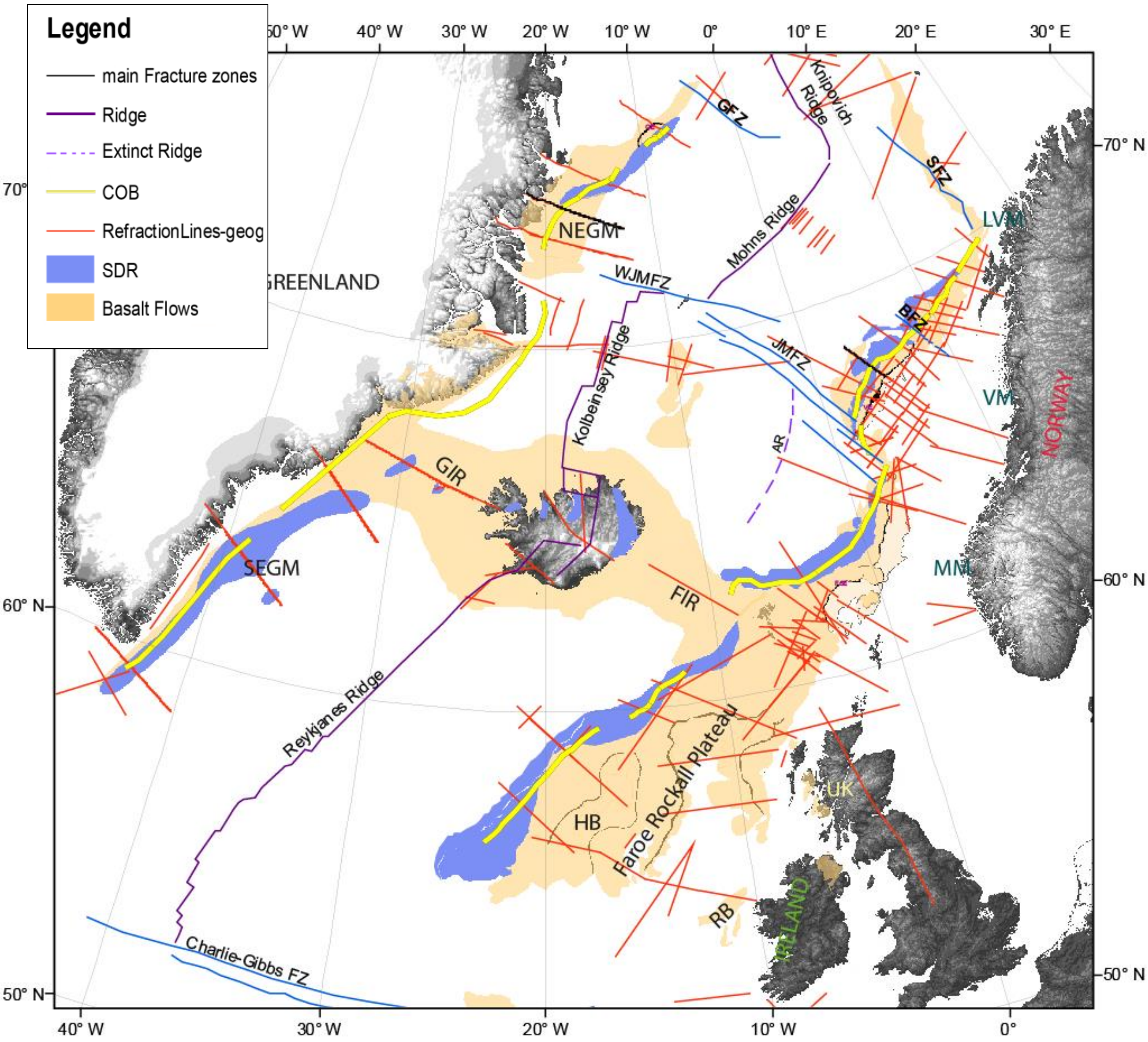


Figure 2.3: Map of NE Atlantic Volcanic passive margin with accessible OBS Profiles. Edited from (Abdelmalak et al., 2016b; Tsikalas et al., 2012). LVM, VM, MM, FM, and HRM indicate Lofoten-Vesterålen, Vøring, Møre, Faeroe and Hatton-Rockall margin respectively. SEGM and NEGM are the southeast and northeast Greenland margins, respectively. AR: Aegir Ridge (Extinct), BL: Bivrost Lineament/ transfer zone, FIR: Faeroe-Iceland Ridge, FSE: Faeroe-Shetland Escarpment, GE: Greenland Escarpment, GFZ: Greenland Fracture Zone, SFZ: Senja Fracture Zone, GIR: Greenland-Iceland Ridge, HB: Hatton Bank, JMFZ: Jan Mayen Fracture Zone, WJMFZ: West Jan Mayen Fracture Zone, RB: Rockall Bank, RP: Rockall Plateau.

2.1 Mid Norwegian margin

The mid Norwegian margin is constituted by three main segments, the Vøring, the Møre and the Lofoten-Vesterålen. The East Jan Mayen Fracture zone separates the Møre margin from Vøring margin. The Bivrost Lineament/transfer zone separates Lofoten-Vesterålen from Vøring margin (Figure 2.4).

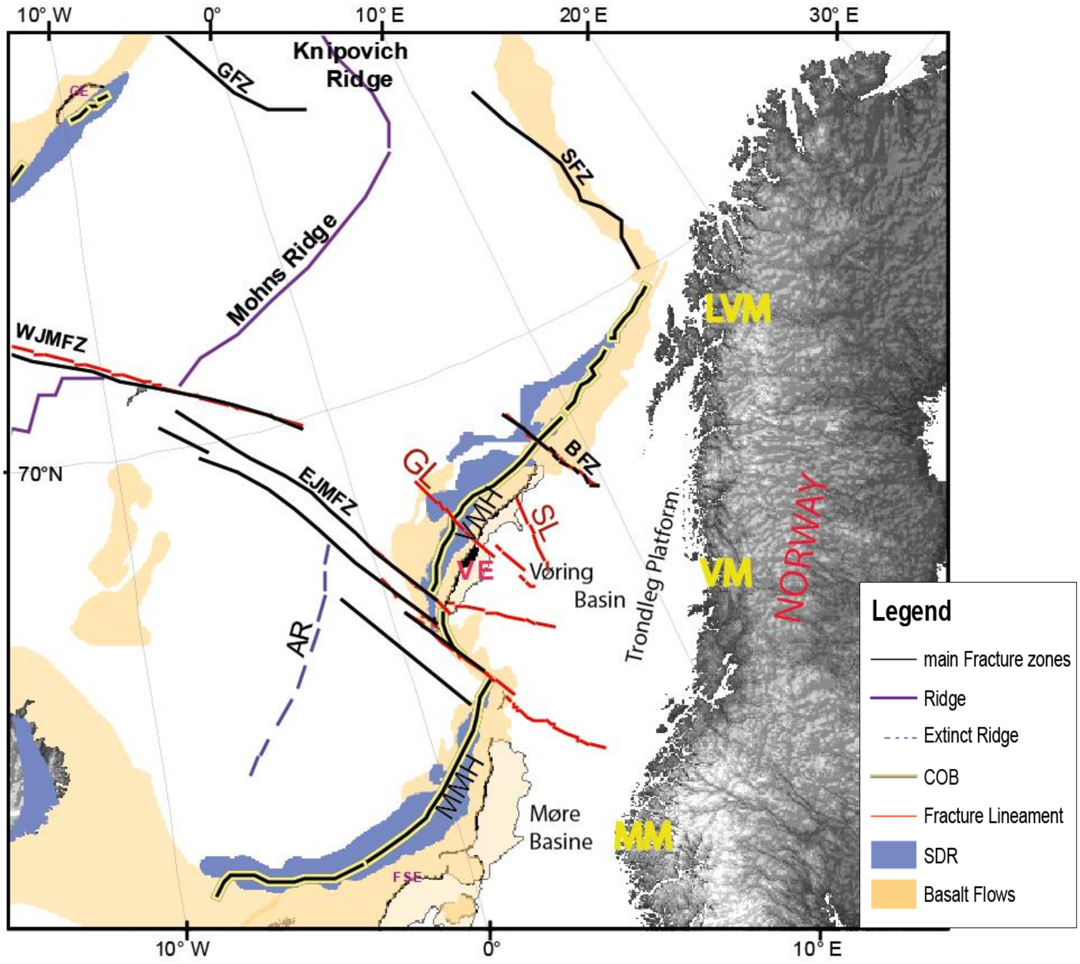


Figure 2.4: Mid Norwegian margin (Abdelmalak et al., 2016b); MM, VM, LVM: Møre, Vøring, Lofoten-Vesterålen. SL, GL, BFZ: Surt, Gleipine, Bivrost Fracture zone/ Lineament.

The mid-Norwegian Margin experienced a prolonged history of intermittent extension and basin formation events that occurred in late Paleozoic-Triassic, Late Jurassic- Early Cretaceous and Late Cretaceous-Paleocene times (Brekke, 2000; Eldholm and Grue, 1994; Faleide et al., 2010; Faleide et al., 2008; Gernigon et al., 2004; Lundin and Doré, 2005; Tsikalas et al., 2012). Through the Paleozoic and Mesozoic, lithospheric thinning resulted in large sedimentary basins controlled by normal faults. Subsidence was especially severe during the Cretaceous giving rise to the accumulation of up to 8 km of sediments in local depocentres in the Vøring and Møre basins (Scheck-Wenderoth et al., 2007). Final continental breakup occurred at the Paleocene-Eocene transition (~56 Ma according to Gradstein et al., 2012 timescale) after a 3–6 m.y. period of intense magmatic activity (Eldholm et al., 2002) , which generated both extrusives and intrusives into the adjacent sedimentary basin and pre-existing (continental) crust (Gernigon et al., 2004; Planke et al., 2005a).

2.1.1 The Lofoten-Vesterålen margin (LVM)

The Lofoten-Vesterålen margin is 400 km at the northern part of the Mid Norwegian margin and characterized by a narrow shelf and steep continental slope. The sedimentary strata on the continental part are thinner and shallower compared to the Møre and Vøring basin. Also the amount of breakup magmatism is considerably decreasing further north (Faleide et al., 2008). The Lofoten-Vesterålen margin is subdivided into three rifted margin segments Lofoten, Vesterålen and Andøya trending NW-NNW prior to opening. The emplacement of extrusive lava (~ 55 Ma) is occurred mostly at the continental slop within the continental ocean transitional zone (Tsikalas et al., 2005).

2.1.2 The Vøring margin (VM)

The Vøring margin is about ~ 500 km wide and consists of Trøndelag platform, Vøring basin and Vøring marginal high (Figure 2.4). The Trøndelag Platform mainly remained unchanged from Jurassic time and has a form of deep sedimentary fill from Triassic to upper Paleozoic (Faleide et al., 2008). Structurally, the Vøring margin could be has a distinct bathymetry and subdivided into three complex structural domains: 1) the proximal margin with the Trøndelag Platform with numerous minor basin and ridges 2) The necking domain consist of significance rift domain (the Vøring Basin) 3)and the distal domain with troughs and the ridges along the COB(Hopper et al., 2014).

2.1.3 The Møre Margin (MM)

The Møre Margin is about 300 km wide and lies in the southern side of the Jan Mayan Fracture Zone. This margin is characterized by narrow shelf and flat continental slope with deep sedimentary rocks in the Møre basin (Figure 2.4). The continental crust thins rapidly from >25 km to <10 km under the Møre basin where mainly consists of a thick mid-Cretaceous sedimentary basin (see the crustal transect in Figure 4.8). A large amount of sill intrusions are clearly observed within the craterous sediments in the central and western parts of Møre basin (Faleide et al., 2008).

2.2 The Faeroe –Hatton margin

The Faeroe –Hatton margins are located between two major fracture zones, Charlie Gibbs fracture zone and Greenland Iceland Faroe Ridge, there is also several other transfer zones present in this region (Figure 2.3).

Faroe – Rockall Plateau is a broad region trending NE-SW along offshore to the British Isles. It has a rough bathymetry with shallow bank and high elevated which is bounded between two sedimentary basin of European continental shelves, from the west to the oceanic Iceland Basin and the Rockall Trough in the eastern part (Smith et al., 2005).

2.3 The East Greenland Margin

The East Greenland Volcanic passive margins is about 3000 km long and is located between 60^{o} N – 77^{o} N along the western part of NE Atlantic (Figure 2.3). The East Greenland margin is subdivided in two parts. The south eastern part is located in the south of Greenland Iceland Ridge (GIR) and north east Greenland margin is in the north. In contrast to the European margins the continental shelf in the Greenland Volcanic passive margin is narrower in the SE Greenland and become wider northward. Also there is a clear difference in oceanic crustal thickness in the North and South Greenland margins. In the northern part between the JMFZ and Greenland Fracture Zone (GFZ), oceanic crust thins rapidly from 10-13 km to 7-5 km where the oceanic crust is thinner than average thickness. Whereas, the normal oceanic crust in the South Greenland margin is ~5 km thicker than North Greenland margin (Voss et al., 2009a).

2.3.1 The Southeast Greenland Margin

The SE Greenland is located between GFZ and SFZ and characterized by narrow shelf. The southern part of SE Greenland margin is tectonically less active and exhibits gradual seafloor spreading (REFF). While, the northern part of SE Greenland margin has complex geological structures close to the Greenland-Faroe Ridge. The SE Greenland continental shelf is wider about 500 km in the north whereas it becomes narrower (45-55 km) significantly in the southern part. Furthermore, the sedimentary and erosional processes have affected the continental shelf, slope and rise of SE Greenland margin (Heirman et al.).

2.3.2 The North East Greenland Margin:

The NE Greenland marine is located between JMFZ and GFZ, on the landward of the continental margin the Caledonian fold belt (formed in Silurian) and Devonian sedimentary basins (formed after the extensional collapse) are observed (Figure 2.5). Then after, long term sedimentary deposition took place during Mesozoic rifting event and terminated with breakup related magmatism in Tertiary (Figure 2.5) (Voss and Jokat, 2007a). Moreover, the break up related magmatism is mainly observed in the northern parts of JMFZ (Figure 2.3) (Voss and Jokat, 2007a; Voss et al., 2009a). The study of the crustal structure in NE Greenland margins between GFZ and JMFZ is mainly based on AWI refraction profiles acquired in 2003 (Voss and Jokat, 2007a; Voss et al., 2009a) and multi-channel seismic reflection profile (Hinz et al., 1987; Jokat et al., 2004).

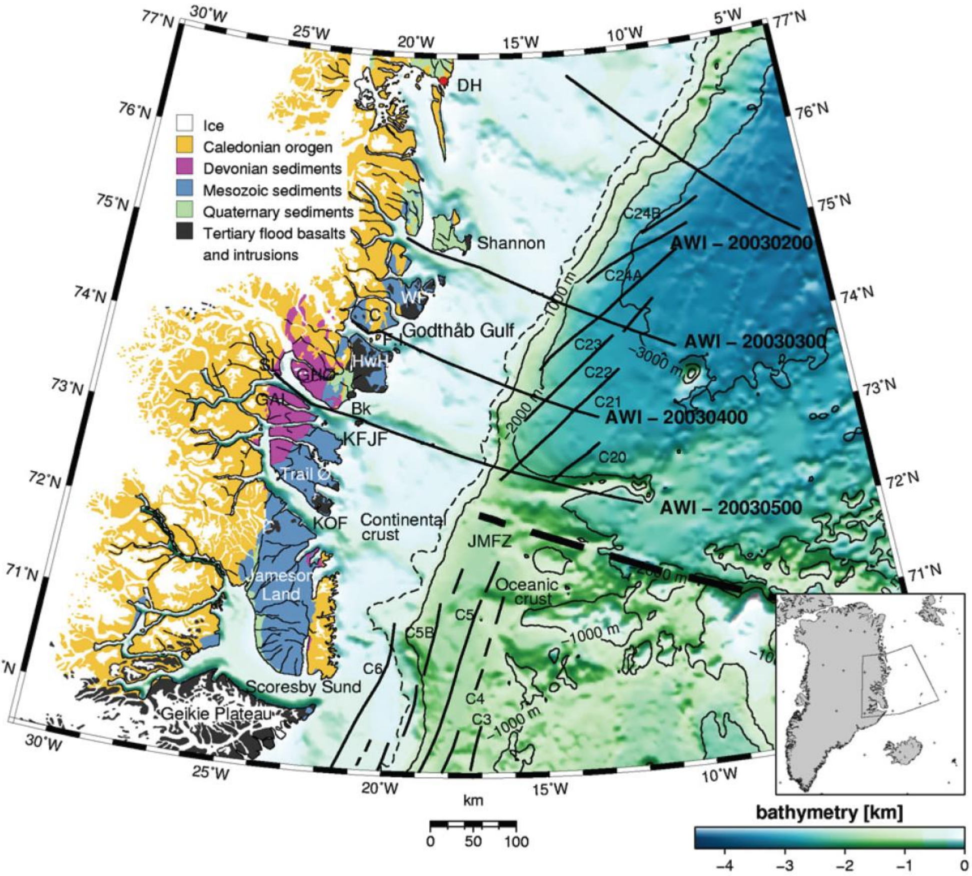


Figure 2.5: Simplified geological map of East Greenland Fjord Region after Escher and Pulvertaft (Escher and Pulvertaft 1995) (copyright Geological Survey of Denmark and Greenland) and Henriksen et al. (2000). IBCAO Bathymetry after Jakobsson et al. (2000). Bk: Bontekoe Ø. C: Clavering Ø. DH: Danmarkshavn (magnetic base station). F.I.: Finsch Island.GAL: Günnar Anderson Land. GHØ: Gauss Halvø. HwH: Hold with Hope. JMFZ: Jan Mayen Fracture Zone. KFJF: Kejser Franz Joseph Fjord. KOF: Kong Oscar Fjord. SL: Strindberg Land. WF: Wolaston Foreland. All seismic profiles acquired in 2003 shown as thick solid black lines. Thin solid black lines mark ocean spreading anomalies. Thick dashed line representsthe location of JMFZ as reference. Thin dashed line marks the smoothed shelf edge (330 m). Scale is valid for 73°N (Voss and Jokat, 2007a).

3 Data and Methods

The NE Atlantic is an ideal region to study the breakup related magmatism. The main part of this region has been investigated both commercial and scientific drilling as well as geophysical investigation. The NE Atlantic region is covered by several regional grids of deep wide-angle seismic Ocean bottom seismometers (OBSs) (se Figure 2.3 for OBSs data coverage) and Expanded Spread Profiles (ESPs), multichannel seismic reflection (MCS) data, potential gravity and magnetic field data (see Table 3.1 for the references).

One of the tasks in this study is to collect the seismic OBSs and MCS profiles across the margin in the area. For this purpose 23 OBS profiles (cross-section) have been selected, which appropriately constrained magmatic bodies in the NE Atlantic passive margins. The table 3.1 shows all collected profiles with length, profile name and references. Each profile has been digitized using Arc GIS and the area of the LCB and Extrusive basalt (SDRs) are calculated, then after the thickness variation along the margin also estimated. The thickness changes and the ratio between the LCB thickness and extrusive thickness are plotted in every 10 km using Matlab (Figure 3.1).

Magnetic and gravity anomalies have been generated along each profile using Arc GIS and Matlab. The magnetic anomaly on the profile can give information about seafloor spreading rate, the major tectonic events (like escarpments, fracture zone, seafloor spreading ridges) and the structural complexities (ridge jump, magma center, hot spots). The gravity anomaly can helps to get more understanding about the crustal thickness and density variations. The magnetic anomalies have been extracted from (EMAG2) (Maus et al., 2009) and NAGTEC-isochrones 2016 (Gaina et al., (in review)) and the gravity anomaly from Satellite gravity map (Becker et al., 2009). The anomaly A24o has been defined on the profiles which are based on the oldest anomaly of the seafloor spreading. Furthermore the Anomalies C23 to C20 are based on central peak anomalies. For the profile where the magnetic anomaly is chaotic and not indefinable, using the anomalies from previous publication. Figure 3.1 shows an example of the created profiles.

Table 3.1: The collect key parts of OBSs and MCSs data across the NE Atlantic margin.

Profile_no	**Line_name**	**length**	**margin**	**Reference**	**Type of data**	**Extrusive area(kn**	**LCB area (km2)**
P-1	CT-4	250	Lofoten	(Tsikalas et al., 2005)	non	130	0
P-2	CT-2	260	Lofoten	(Tsikalas et al.,2001, 2002, 2005)	Reflection/ Refraction	160	412
P-3	CT-1	220	Lofoten	(Tsikalas et al.,2001, 2002, 2005)	Reflection/ Refraction	236	559
P-4	P10-03, P5-96	300	Vøring	(Breivik et al., 2009), (Mjelde et al., 1998)	Reflection/ Refraction	302	1617
P-5	Lab99, L6-92,L4-03	360	Vøring	(Mjelde et al., 2005b),(Mjelde et al., 1997)	Reflection/ Refraction	329	1418
P-6	L11-03, L10-96	400	Vøring	(Breivik et al., 2014),(Raum et al., 2002), (Mjelde et al., 2005a)	Reflection/ Refraction	345	2200
P-7	P1-00, P8A-96	400	Møre	(Breivik et al., 2006; Mjelde et al., 2008) (Mjelde et al., 2002)	Reflection/ Refraction	244	1135
P-8	P1-99	220	Møre	(Mjelde et al., 2009b)	Reflection/ Refraction	233	586
P-9	iSIMM	250	Faroes	(White et al., 2002; White et al., 2010; White et al., 2008)	Reflection/ Refraction	576	637
P-10	**FIR**	**370**	**Faroe Iceland Ridge(FIR)**	**(Richardson et al., 1998)**	**Refraction**	**2861**	**1971**
P-11	AMP- Line E	520	Northern Rockall Trough	(Klingelhöfer et al., 2005)	Refraction	705	886
P-12	HB89	160	Hatton	(Morgan et al., 1989), (White and Smith, 2009)	Reflection/ Refraction	241	775
P-13	iSIMM	400	Hatton	[White et al., 2002].	Reflection/ Refraction	234	842
p14	L21, L13	330	Hatton	Vogt et al., 1998b	Refraction	0	1010
P-15	SIGMA 4	348	SE Greenland	(Holbrook et al. 2001)	Reflection/ Refraction	0	
P-16	SIGMA 3	390	SE Greenland	(Hopper et al., 2003)	Reflection/ Refraction	624	1326
P-17	SIGMA 2	350	SE Greenland	(Korenaga et al. 2000)(Holbrook et al., 2001)	Reflection/ Refraction	893	619
P-18	**SIGMA 1**	**500**	**Greenland Iceland Ridge(FIR)**	**(Holbrook et al., 2001)**	**Refraction**		
P-19	L1-88	420	CE Greenland	Weigel et al. (1995)	Refraction	0	644
P-20	AWI-20030500	460	NE Greenland	(Jokat et al. 2004),(Voss and Jokat, 2007),(Hinz et al., 1987)	Refraction	580	1790
P-21	AWI-20030400	320	NE Greenland	(Jokat et al. 2004),(Voss and Jokat, 2007),(Hinz et al., 1987)	Refraction	288	2048
P-22	AWI-20030300	360	NE Greenland	(Jokat et al. 2004),(Voss et al., 2009),(Schlindwein 1998)	Refraction	278	370
P-23	AWI-20030200	212	NE Greenland	(Jokat et al. 2004),(Voss et al., 2009),	Refraction	0	124

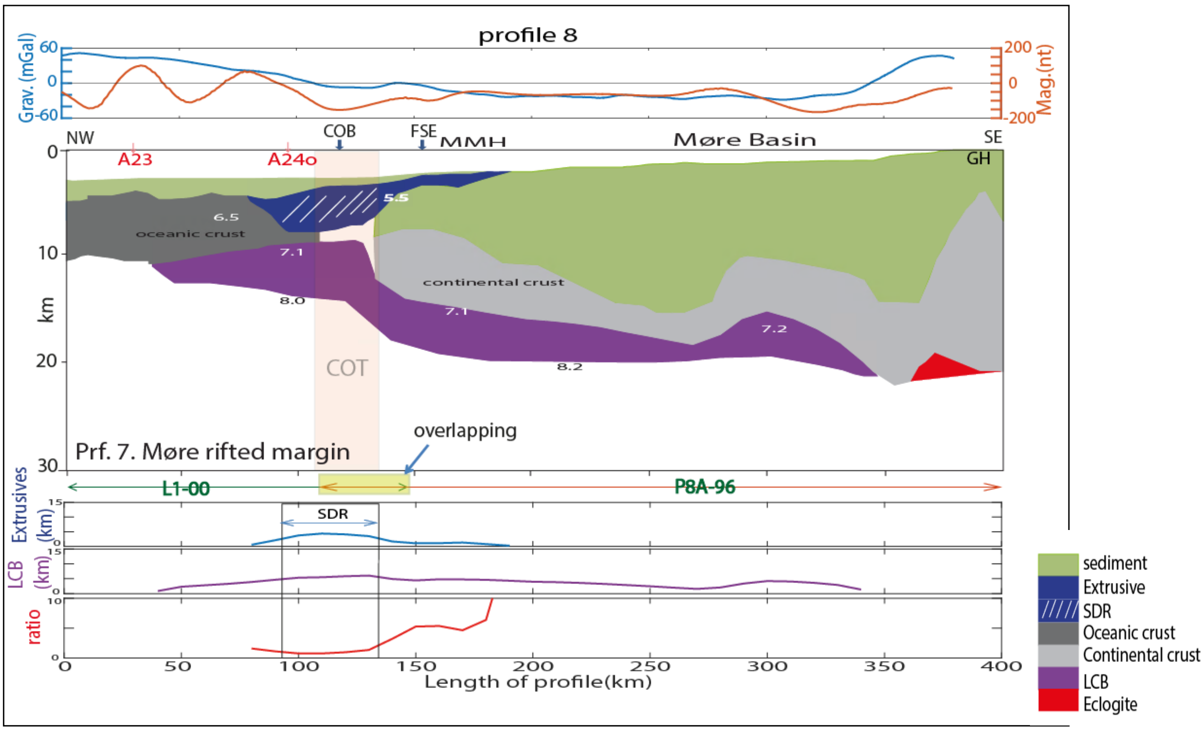


Figure 3.1 Crustal transect (Profile 7) across the Møre margin (see references in table 3.1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent-Ocean Transition Zone, COB: Continent-Ocean Boundary; VMH: Vøring Marginal High, VE: Vøring Escarpment, NH: Nyk High, HG: Hel Graben.

4 Results

Different profiles along the different margin segments are used in this study (Fig 4.1). The area of LCB and extrusive basalt (SDRs) have been quantitatively estimated and shown in table 4.2

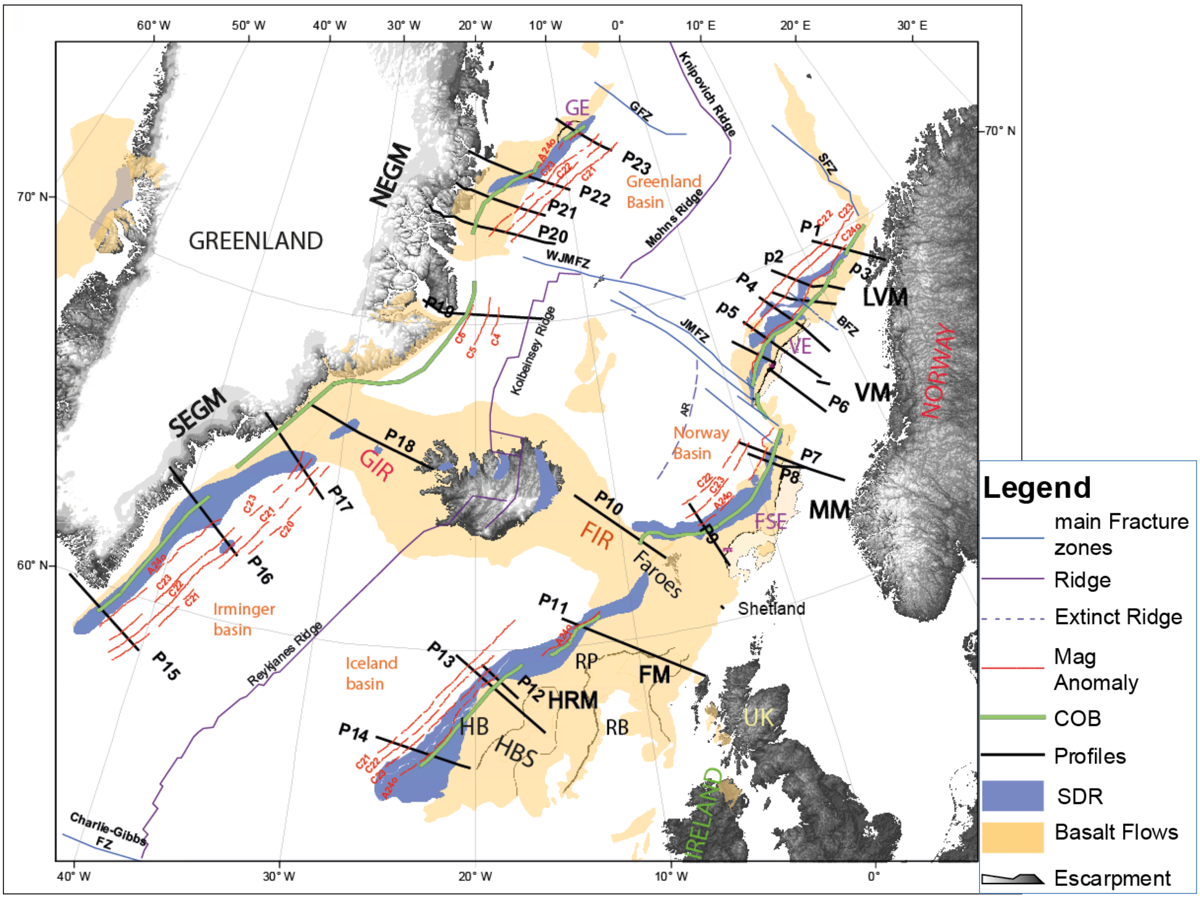


Figure 4.1: The map of NE Atlantic Volcanic passive margin with the selected OBS Profiles. Edited from (Abdelmalak et al., 2016b; Tsikalas et al., 2012) . LVM, VM, MM, FM, and HRM indicate Lofoten-Vesterålen, Vøring, Møre, Faeroe and Hatton-Rockall margin respectively. SEGM and NEGM are the southeast and northeast Greenland margins, respectively. AR: Aegir Ridge (Extinct), BL: Bivrost Lineament/ transfer zone, FIR: Faeroe-Iceland Ridge, FSE: Faeroe-Shetland Escarpment, GE: Greenland Escarpment, GFZ: Greenland Fracture Zone, SFZ: Senja Fracture Zone, GIR: Greenland-Iceland Ridge, HB: Hatton Bank, HBS: Hatton Bank, JMFZ: Jan Mayen Fracture Zone, WJMFZ: West Jan Mayen Fracture Zone, RB: Rockall Bank and RP: Rockall Plateau.

4.1 Profiles configurations West European Margins

A total of 14 profiles are constructed and described along the West European Margins (see Table 3.1 and Figures 4.2-4.15).

4.1.1 Lofoten-Vesterålen margin (LVM)

Three profiles have been selected across the Lofoten-Vesterålen margin (LVM) (Figures 4.1 and 4.2-4.4) and these are located between the Bivrost (BFZ) and Senja (SFZ) fracture zone (see Figure 2.3). The crustal structure and velocity models in profile 2 and 3 are constrained by the compilation and integration of wide-angle seismic profiles, multi-channel seismic (MCS) data set and crustal scale 2D gravity model (for references see table). The profile 1 has a simplified crustal model which is constructed from the neighboring transects with crustal velocity model, potential field data and crustal contour maps see (Tsikalas et al., 2005) for detailed information. The wide-angle seismic profiles have a good data coverage in the southern part of the margin (Figures 4.3-4.2), whereas the data coverage is very poor or absent in the northern part (Figure 4.2) (Tsikalas et al., 2005). The MCS profiles present a high density in the continental part of the margin and are very sparse toward the oceanic crust. The top of the crystalline basement (top of the oceanic layer 2, extrusive basalt, and the continental basement), top of the LCB and Moho boundary are well constrained on profile 2 and 3 (Figures 4.2 and 4.3).

The continental ocean boundary (COB) is defined by integrating MCS, magnetic data and plate reconstruction. The COB is located between the magnetic anomaly A24 and the foot of continental slop which represents as faulted blocks (Tsikalas et al., 2005). The continent ocean transitional (COT) zone is characterized by lateral increase in crustal velocity near the SDR wedges to the oldest oceanic crust near the magnetic anomaly A24o. The SDR wedges interpreted at shallower part of the profile 2 and 3, and the amount of extrusive basalt decreases toward the northeast on the margin. Hence, the extrusive basalt and SDR are absent on profile 1(Figures 4.2-4.4).

Profile 1 is located about 150 km south west of the SFZ in the north-eastern LVM (Figure 4.2). It extends 250 km in SE-NW direction from the continental crust with a maximum thickness of >30 km to ~7 km thick oceanic crust. The crustal velocity model on the profile is not resolved and the crustal structures are mainly defined by potential field data. The location of COB is defined by regional grid of gravity and magnetic anomaly and it placed landward of the A24o.

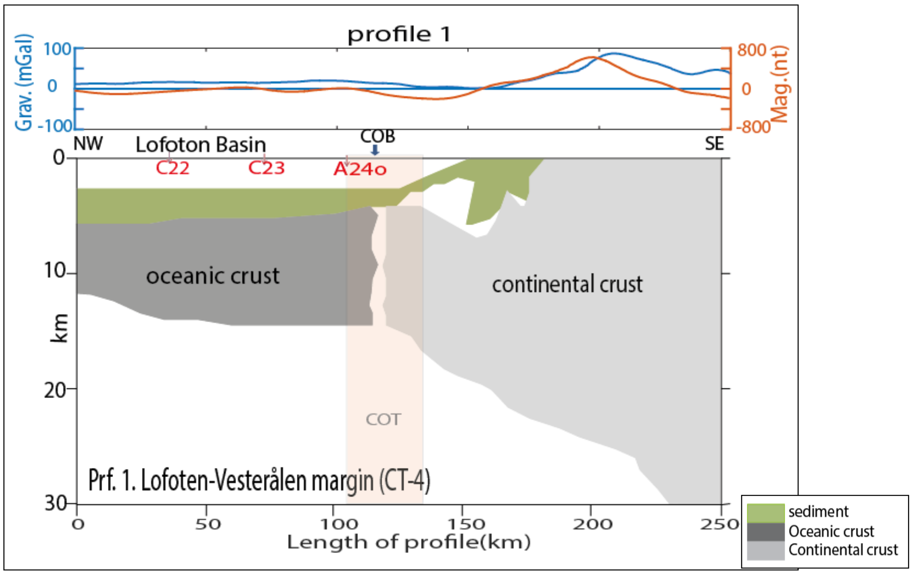


Figure 4.2: Crustal transect (Profile 1) across the north-eastern LVM (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile. COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary.

Profile 2 is situated about 60 km in the north east of BFZ with 260 km length extends from SE to NW across the steep continental crust to the oceanic crust (with 5 km thick) near the magnetic anomaly C21 (Figure 4.1 and 4.3). The maximum thickness of continental crust is 28 km and decreases towards the oceanic crust, where it became 13 km thick under the COB within 70 km distance.

The COT zone is ~40 km wide zone with landward limit near the SDR wedges and seaward terminating at magnetic anomaly A24o, and the COB is located at ~180 km on the profile. The extrusive basalt is interpreted under the anomaly 24 and has ~100 km landward extension with maximum thickness of ~3.1 km in the SDR wedges. The LCB has ~167 km length with maximum thickness of ~3.2 km observed along the lower crust in between anomaly C22 and landward termination of COT. The ratio between the LCB thickness and the extrusive thickness is ranging between 0.3 and 2.5. The average ratio is about 1.2 in the SDR extent.

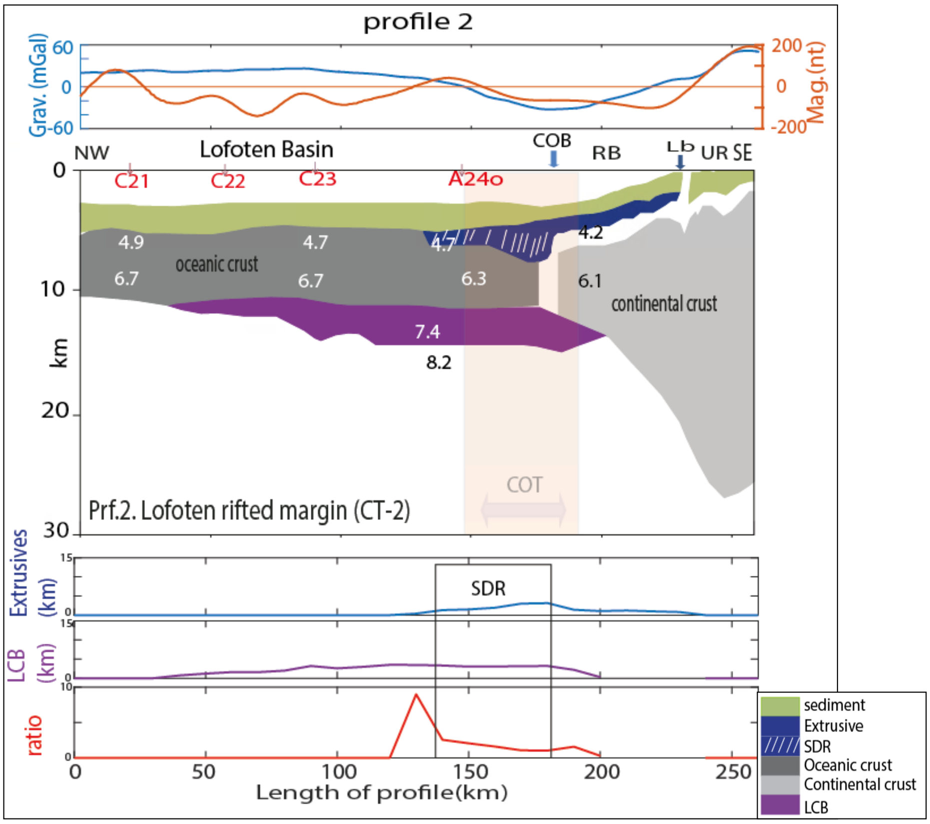


Figure 4.3: Crustal transect (Profile 2) across the LVM (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. RB: Røst Basin, UR: Utrøst Ridge, Lb: landward lava boundary, SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary.

Profile 3 is the southernmost profile in the LVM with 200 km length passing through Bivrost Fracture Zone (BFZ) in the Lofoten Basin (Figure 4.1 and 4.4). The maximum crustal thickness in the continental part is ~25 km and it decreases less rapidly as compared to profile 2 and it is about 10 km thick within 70 km distance. The COT zone is ~30 km wide with a landward limit near the SDR wedges and seaward termination at magnetic anomaly A24.The COB is located at ~140 km on the profile. The extrusive basalt is interpreted under the anomaly 24 and has ~100 km landward extension with maximum thickness of ~3.1 km in the SDR wedges. The LCB has ~167 km length with maximum thickness of ~3.2 km observed along the lower crust in between anomaly C22 and landward termination of COT. The average ration between the LCB thickness and the extrusive thickness is about 2.7 and is about 1.5 in the SDR.

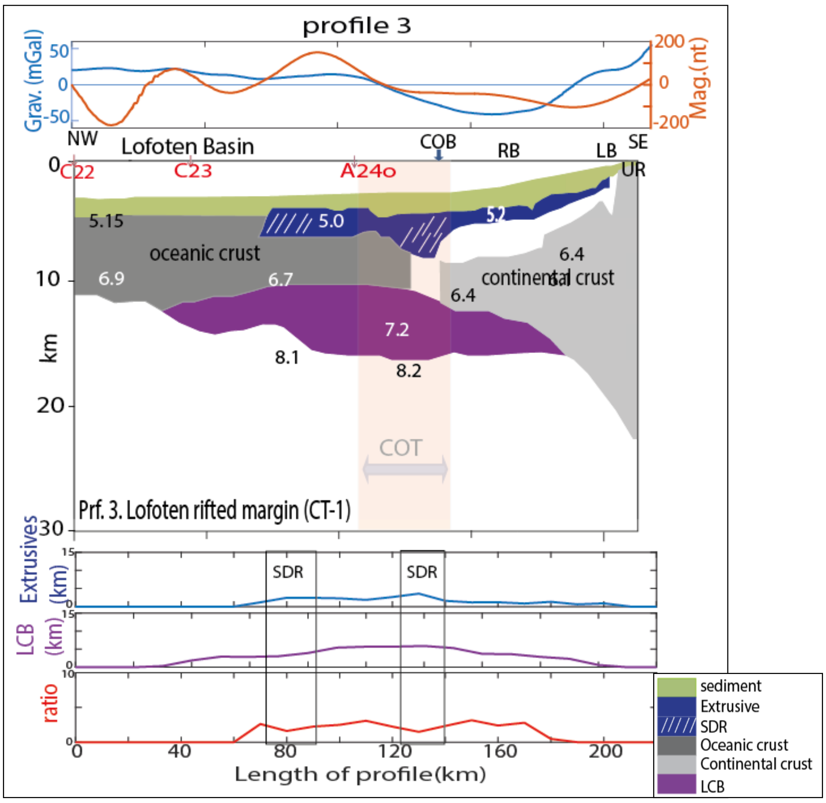


Figure 4.4: Crustal transect (Profile 2) across southern part of the LVM (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. RB: Røst Basin, UR: Utrøst Ridge, Lb: landward lava boundary, SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary.

4.1.2 Vøring margin

Profile 4 is located across the northern Vøring margin extends about 300 km from continental crust to normal oceanic crust close to the magnetic anomaly C22 (Figure 4.1 and 4.5). The profile is constructed from two deep seismic lines L10-03 (Breivik et al., 2009) and L5-96 (Mjelde et al., 1998) which are linked together around the Vøring Escarpment. The data quality of the profile westward of the Vøring Escarpment is very good but the data have low signal to noise ratio under the COT zone. There are no arrival observed at about 40 km horizontal distance in the middle and lower crustal part, along the eastern end of the line L10-03 (Breivik et al., 2009). Seismic line L5-96 (Mjelde et al., 1998) shows a good ray coverage in the middle part of the line to the offset of 50 km and models are unresolved at greater depths toward the end of the profile. The structure on the northwest corner of the L5-96 is constructed by the previous studies (Mjelde et al., 1998).

Seaward dipping reflectors (SDRs) are mapped from the previous regional study based on seismic volcanic stratigraphic facies distribution (Abdelmalak et al., 2016a; Berndt et al., 2001). The continent ocean transition zone (COT) is identified in the P-wave velocity model as a narrow zone with 30 km width and it is characterized by lateral increase in crustal velocity in the continental part near the wedges of inner SDR. The ~20 km thick oceanic crust in the COT zone contains a ~3 km thick SDR wedge in shallower part and is underlain by ~9 km thick LCB. Normal oceanic crust with a thickness of ~ 5 km is found near and seaward of magnetic anomaly C22.

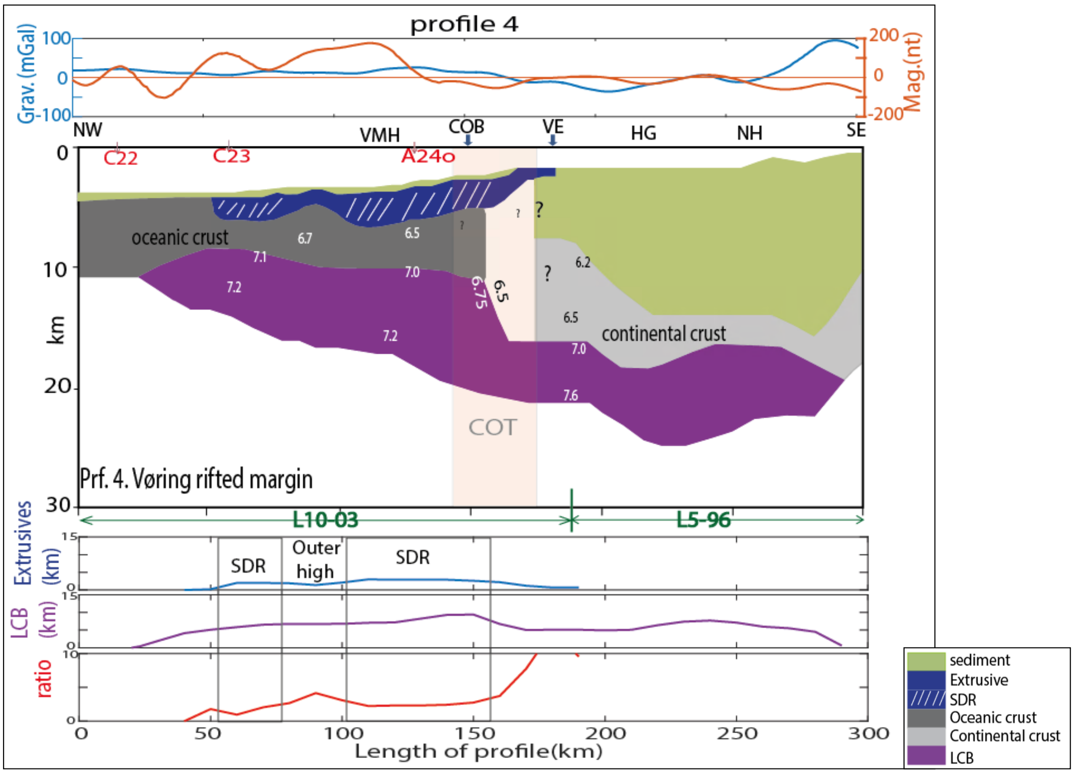


Figure 4.5: Crustal transect (Profile 4) across northern part of the Vøring margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the Thicknesses of the LCB and extrusives and the ratio between them for every 10 km. SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary; VMH: Vøring Marginal High, VE: Vøring Escarpment, NH: Nyk High, HG: Hel Graben.

The lower crustal body extends nearly throughout the entire lower crust along the profile and terminates seaward near the magnetic anomaly C22. The lower crustal velocity is between

7.0-7.6 km/s and the LCB has a maximum thickness of about 9 km. The ratio between the LCB thickness and the extrusive thickness is ranging between 7 and 2.5. The average ratio is about 3.5 in the SDR extent.

Profile 5 is located across the central Vøring margin with 360 km length and extends from SE to NW across the Vøring Plateau, Vøring Basin and normal oceanic crust at magnetic anomaly C22 (Figures 4.1 and 4.6). The profile is constrained from three seismic lines, lab99 with length of 180 km in northwestern part (Mjelde et al., 2005a) tied to L6-92 (150 km length) and southeastern part tied to the seismic line L4-03 (60 km length) (Mjelde et al., 2009a).

The seismic profile lab 99 consists of dense ocean bottom seismometer (OBS) and the data quality and ray coverage along most of the crust is very good. The crustal structure in the COT zone is documented by poor data coverage, and beneath/ landward of the inner SDR are obtained by moderate data quality. Gravity modelling was used toward the end of this profile where the ray coverage is absent (Mjelde et al., 2005c).

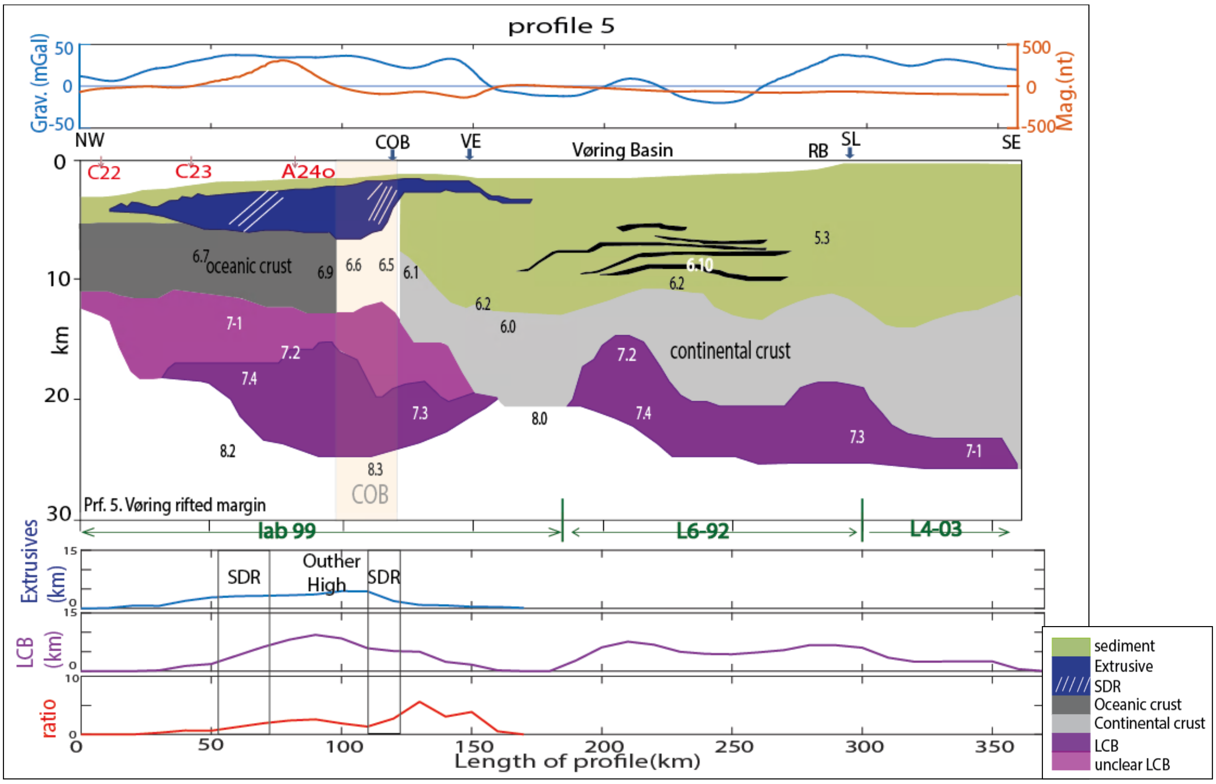


Figure 4.6: Crustal transect (Profile 5) across the Vøring margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary, VE: Vøring Escarpment, RB: Ribban Basin, SL: Surt Lineament.

The OBSs interval along profile L6-92 is relatively sparse, whereas the data quality is very good. The data quality is decreasing towards the south west. Clear first arrivals are observable along mean offset of ~ 55 km and misfit between observed and calculated travel time was less than 50 ms in most of the arrival, otherwise up to 200 ms. The interpretation of the deeper sedimentary interfaces, top of crystalline basements, sill intrusions, lower crustal layer and Moho boundary is based on the OBSs data (Mjelde et al., 1997).

The sedimentary layer in shallower part and the seaward dipping reflectors are identified by earlier study on multichannel seismic profile (MCS). The ~158 km long extrusive basalt extends seaward from the outer Vøring Basin to the oceanic crust at magnetic anomaly C22. The maximum thickness of extrusives defined along the inner SDR is about 4.4 km. The outer high and outer SDR are identified on the profile 5. The location of the COT is interpreted as a ~25 km wide zone seaward of the inner SDR wedges, characterized by lateral increase in crustal velocity from 6.0 km/s in the continental crust to 6.9 km/ s in the oceanic crust. The COB is defined from the MCS data, potential field and borehole data at the wedges of the inner SDR. The high velocity of continental crust in the COT is interpreted as intruded rocks (Mjelde et al., 2009c; White et al., 2008a). The shallow sill intrusions are found within the sedimentary layer and in the Vøring Basin. The intruded sill shows high velocity reflectors within the sedimentary layers on the OBS and multichannel reflection data (Figure 4.6).

The velocity in the lower crust is between 7.2-7.7 km/s which may relate to magmatic underplating/intrusion during the breakup in early Eocene. This magmatic body has a maximum thickness over 9 km at seaward end of the COT zone. The Lower crustal body extends nearly throughout the entire lower crust and terminated seaward near the magnetic anomaly C21. In the central part of the lower crust along the profile the typical LCB is missing in an about 30 km wide zone. The thickness ratio of LCB/extrusive is 0.6 and 5. The average ratio is about 1.4 in the SDR extent.

Profile 6 is located across the southern part of the Vøring margin with 400 km length, extends from SE to NW across the Ribban Basin, Vigrid Syncline, Gjallar Ridge and normal oceanic crust (Figure 4.1 and 4.7). The magnetic anomaly in this part of margin is very chaotic and only the anomaly A24 is identifiable. The magnetic anomaly A24o on the profile indicates the oldest anomaly of A24. The profile is constrained from two deep seismic lines L11-03 with 160 km length in northwestern part (Breivik et al., 2014) and L10-96 (250 km length) (Mjelde et al., 2005a). The seismic line L10-96 is located across the landward of the Vøring Escarpment and is located in the western end of L10-96 by a distance of ~30 km.

The seismic ray coverage in the lower crust of the outer Vøring plateau (L11-03) is well constrained and the OBSs located near the Vøring Escarpment (VE) contains of low signal to noise ratio. Interpretation of extruded basalt and SDRs thickness of the sedimentary layer are defined on the single-channel reflection profile along the Vøring plateau (Breivik et al., 2014).

The data quality and ray coverage along the deep seismic line L10-96 are very good, clear first arrivals from the continental basement and upper mantel are observed. The deep sedimentary layers, continental crust, sill intrusions and LCB are well constrained on the OBSs data. Interpretation of the sedimentary layers in the shallower part is based on the OBS data (Raum et al., 2002).

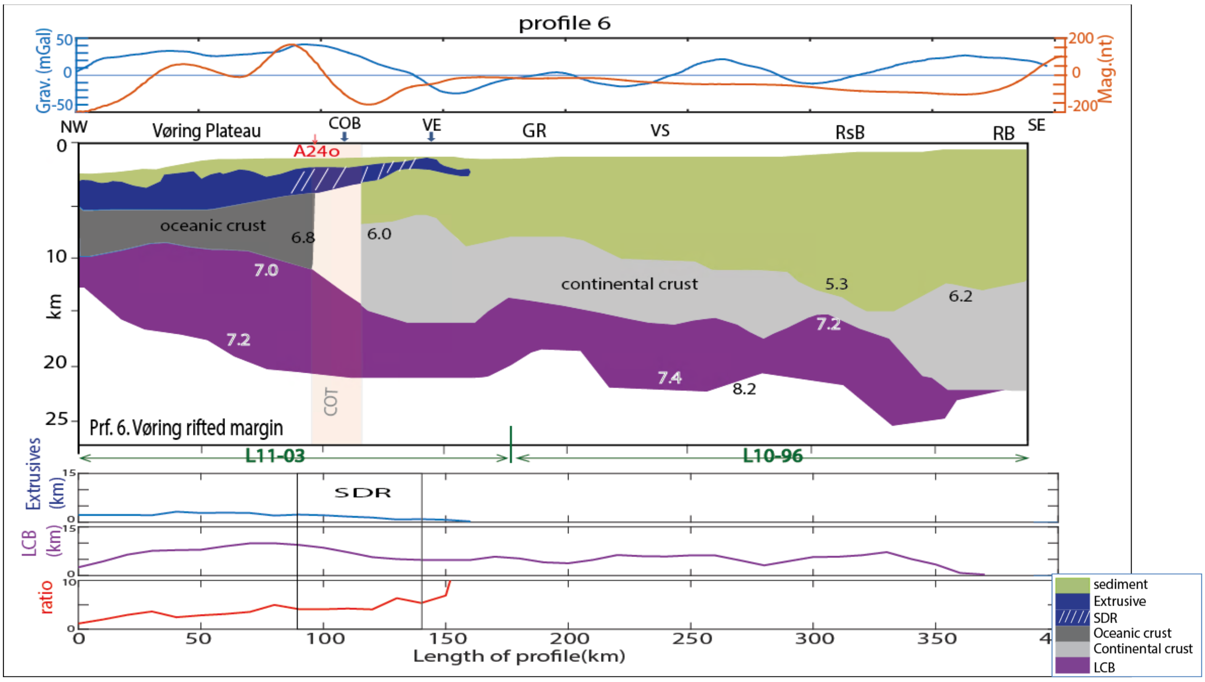


Figure 4.7: Crustal transect (Profile 6) across southern part of the Vøring margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives and the ratio between them for every 10 km. SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary, VE: Vøring Escarpment, RB: Ribban Basin, GR: Gjallar Ridge, VS: Vigrid Syncline, RsB: Rås Basin.

The COT zone found on OBS data is ~20 km wide zone below the SDR wedges, characterized by lateral increase in crustal velocity from 6.0 km in the continental crust to 6.8 km/s in the oceanic crust at magnetic anomaly A24o. The SDR extends ~40 km seaward of the Vøring Escarpment and the extrusive lava deposited westward over the oceanic crust.

The thick LCB throughout the entire lower crust and the velocity is between 7.0-7.4 km/s. The maximum thickness of the LCB is about 10 km blow the magnetic anomaly A24o and the LCB is thinner beneath the continental crust. The ratio between the LCB thickness and the extrusive thickness is ranging between 7 and 2.5. The average ratio is about 3.5 in the SDR extent. The thickness ratio of LCB/extrusive is 0.6 and 5. The average ratio is about 5 in the SDR extent.

4.1.3 Møre margin

Profile 7 is located across the Møre margin and extends about 400 km in SE-NW direction from Gossa High, Møre Basin, Møre Marginal High and normal oceanic crust with magnetic anomaly C23 (Figure 4.1 and 4.8). The profile is prepared from two deep seismic lines L1-00 with 145 km length in northwest (Breivik et al., 2006) tied to P8A-96 with 290 km in the continental side (Mjelde et al., 2008). These two seismic lines are partially overlapping near the COT zone and it helps to get a good mapping of the COT (Breivik et al., 2006).

The OBS spacing is relatively sparse along both of the seismic lines, whereas the data quality and reconstruction of the lower crust in line P8A-96 is comparatively lower. The lower crust and the Moho are characterized by opaque reflectors adjacent to the COT zone (Breivik et al., 2006). The crustal structure of the Møre Basin is based on the S-wave modelling extracted from the P-wave and gravity models (Mjelde et al., 2008).

The location of the COT is interpreted as a ~25 km wide zone and the shallower part is defined from P8a-96, whereas the deeper part is interpreted on L1-00. The extrusive basalt extends about 100 km from the Møre Marginal High to the oceanic crust with magnetic anomaly A24. The SDRs are defined in the main part of the extrusive basalt with a maximum thickness of 4.4 km.

A LCB with velocity between 7.1 -7.4 km/s is present beneath the entire basin and terminates seaward at magnetic anomaly C23. The LCB has a maximum thickness of about 6 km in the COT zone. The thickness of normal oceanic crust at magnetic anomaly C23 is about 5 km. The lower crustal body near the eastern end of the profile is interpreted as eclogite body with velocity > 8 km/s (shown in red color in the Figure 4.8) (Mjelde et al., 2013; Mjelde et al., 2008) . The thickness ratio of LCB/extrusive is 0.6 and 5. The average ratio is about 0.8 in the SDR extent.

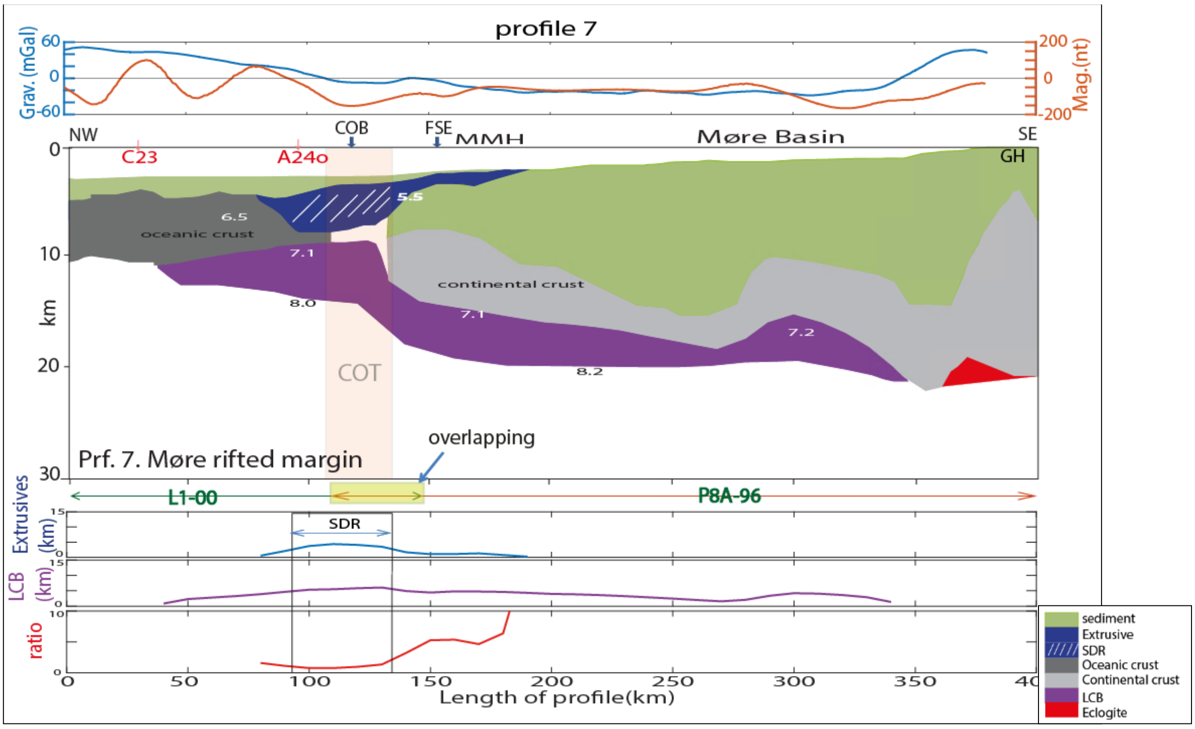


Figure 4.8: Crustal transect (Profile 7) across the Møre margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary, FSE: Faroe-Shetland Escarpment, MMH: Møre Marginal High, GH: Gossa High.

Profile 8 is located across the Møre margin with 213 km length and extends from the outer part of the Møre Basin, the Møre Marginal High to the oceanic crust (Mjelde et al., 2009c) (Figure 4.1 and 4.9). OBS data shows good ray coverage in the COT and LCB, but the uncertainty is higher toward the end of the profile. The profile is poorly constrained at about 30 km in horizontal distance toward the end points and gravity modelling was used for these unresolved parts (Mjelde et al., 2009c). The interpretation of extrusive basalt and shallowest layer are based on MCS data. The top of the basalt layer and the shape of the SDR are well constrained, but the base reflectors exhibit higher uncertainty (Abdelmalak et al., 2016b; Mjelde et al., 2009c). The extrusive basalt has a landward continuation about 100 km in the shallower part of the Møre Basin and with an average thickness of about 500 m. The extrusive basalt terminates seaward at magnetic anomaly A24o and shows maximum thickness of ~4 km in the SDR wedge. The COT is a ~ 40 km wide zone seaward of the inner SDR wedges, characterized by lateral increase in crustal velocity from continental to oceanic crust. The oceanic layers in the western end of the profile are defined as layer 2A and 2B which shows extrusive pillow lava and a portion of the intrusive dyke complex, respectively.

The lower crustal body (LCB) extends throughout the entire lower crust and beneath the oceanic crust present as the oceanic layer 3B. The LCB velocity is 7.1 km/s on the top and 7.3 km/s at the base and has a maximum thickness of ~5 km. The estimated thickness ratio of LCB/Extrusives is ranging between 0.7 and 7. In the SDR extent the average ratio is about ~2, which in the SDR it has an average ratio of about ratio of LCB/extrusive is 0.6 and 5, which in the SDR has an average of about 1.7.

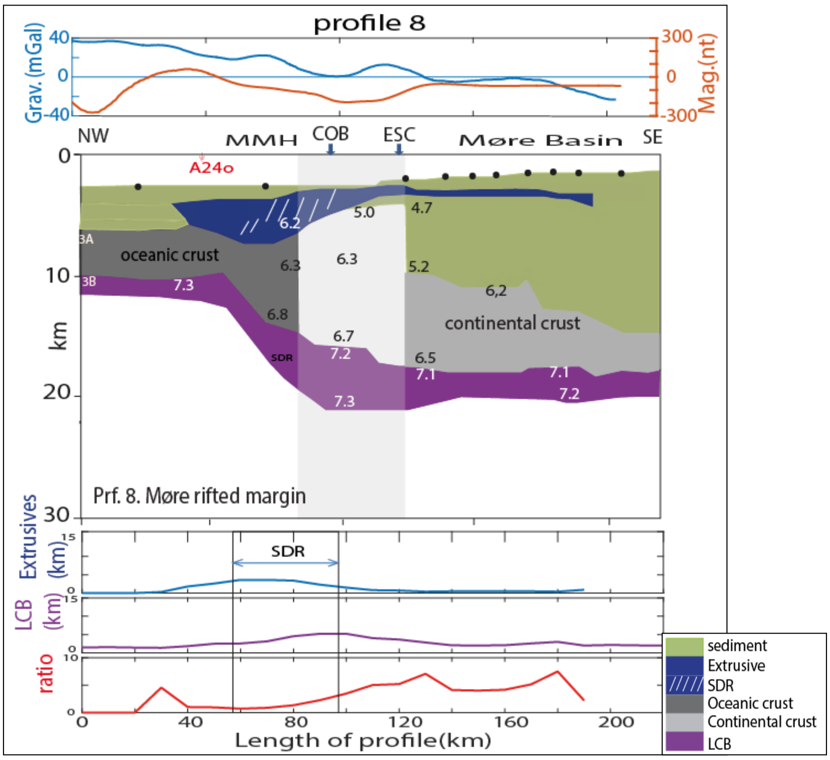


Figure 4.9: Crustal transect (Profile 8) across the Møre margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary, ESC: Escarpment, MMH: Møre Marginal High.

4.1.4 Faroe Hatton margin

Profile 9 is located across the Faroe Margin on the western side of the Faroe Iceland Ridge (FIR). The profile presents a ~400 km length. From the SE to NE the profile extends across the Faroe Shetland Basin (FSB), the Faroe Ridge (FR), the Norwegian Basin and terminates in oceanic crust with magnetic anomaly C22 respectively (Figure 4.1 and 4.10).

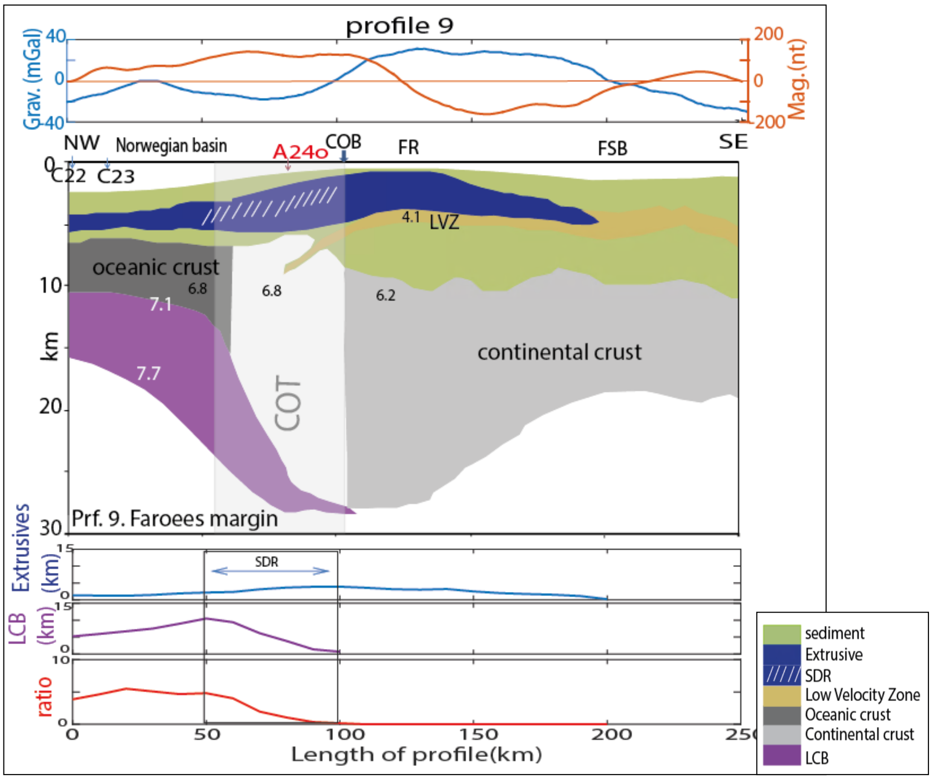


Figure 4.10: Crustal transect (Profile 9) across the Faroes margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary, FR: Fugloy Ridge, FSB: Faroe-Shetland basin.

Data quality is excellent and the OBS records clear arrival from the crustal diving wave and Moho reflection. Tomographic inversion of P-wave and S-wave gives better reflection image of the sub basalt lithology and the amount of extruded and intruded igneous melt. The tomographic inversion of the crustal velocity generates a good velocity variation along the entire crust.

The extrusive basalt is interpreted in the sedimentary layer of Faroe Shetland Basin (FSB) at km 200 on the profile and extends ocean-ward to the end of the profile. The base of the extrusive basalt is well defined due to presence of Low Velocity Zone (LVZ) (White et al., 2010a) . The velocity model P- and S-wave defined LVZ as a sill intruded into sedimentary rock (White et al., 2010a) (Figure 4.11).

The COT is a ~50 km wide zone under the SDR wedges and characterized by lateral increase in crustal velocity toward the ocean. The lower crust under the COT shows sub horizontal reflectors which have been interpreted as igneous intrusions. The SDR wedges extend along the COT zone and have a maximum thickness of ~4 km.

The LCB with velocity >7.0 km/s is present continuously along the COT and the oceanic crust. Maximum thickness of the LCB is ~9 km at the western end of COT zone. The average ratio of the thicknesses LCB/extrusive is about 5. The average ratio is about 2.5 in the SDR extent **Profile 10** is extends for about 360 km along the Faroe Iceland Ridge (FIR) (Figures 4.1 and 4.11). The crustal model is done by using seismic wide-angle, normal incidence and gravity data. The velocity model in upper and middle crust are well constrained. The LCB is mainly unresolved due to low seismic ray coverage and the refracted waves from the mantle are not recorded. A 30 km thick oceanic crust is interpreted for the Faroe Iceland Ridge.

According to (Richardson et al., 1998) the maximum thickness of extrusive lava is about 5 km and it continuously extends along the surface of the profile. The COT is estimated as a 60 km wide zone and it is characterized by lateral increase in velocity of the middle crust toward the oceanic crust at offsets of ~210 to ~280 km. The location of the COB is not identifiable, because the magnetic anomalies from the seafloor spreading on the Faroe Iceland Ridge are disrupted by lateral lava flow along the surface.

The velocity of the LCB ranges between 7.0 and 7.6 km/s under the Faroe Islands which is terminated under the oceanic crust approximately at km 150. The maximum Moho depth observed at base of the LCB is estimated between 40 and 46 km. The Moho depth is decreasing toward the oceanic crust. The ratio between the LCB thickness and the extrusive thickness is ranging between 1 and 3.

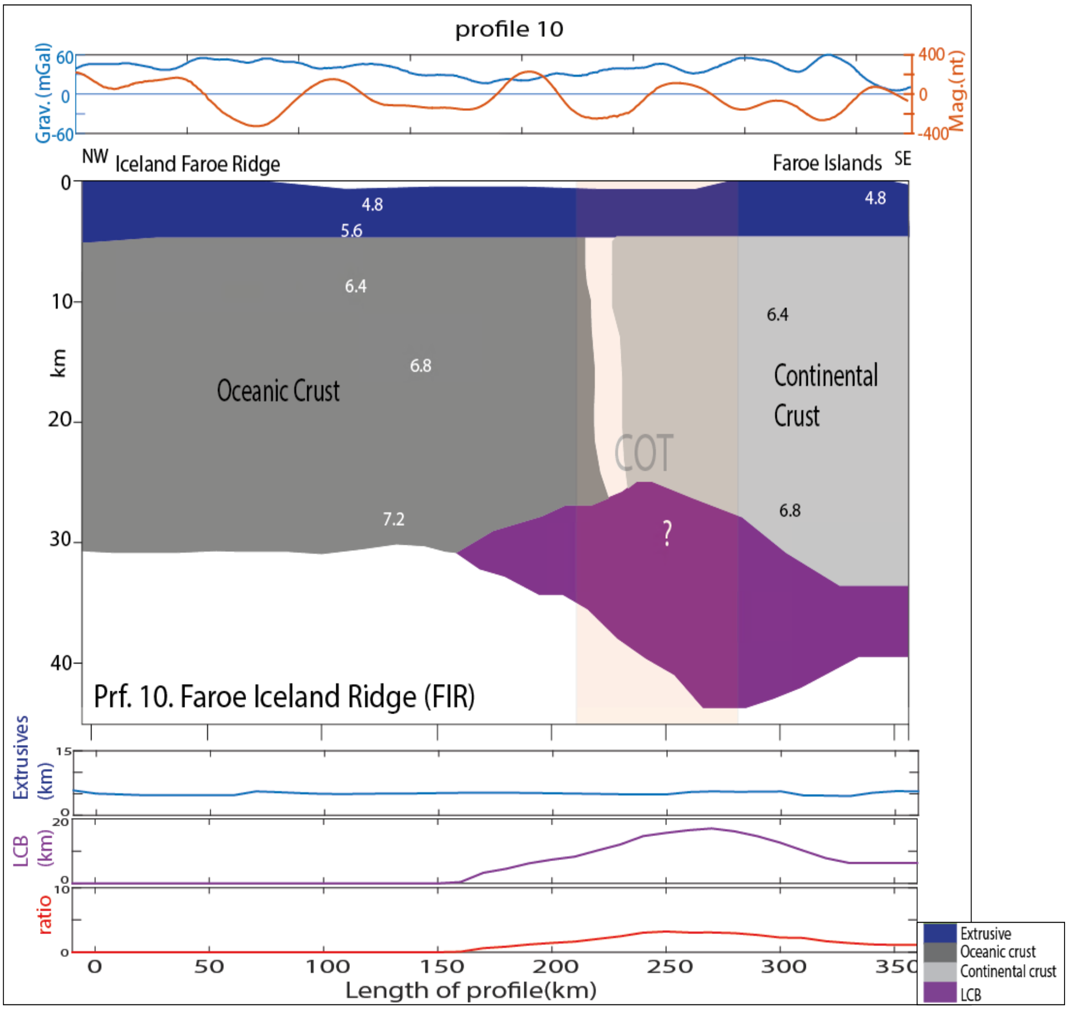


Figure 4.11: Crustal transect (Profile 10) along FIR (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary.

Profile 11 across the Northern Rockall Through extends about 520 km in SE-NW direction from NE Rockall Basin, Rockall Trough, the thickened oceanic crust with magnetic anomaly A24o and Lousy Bank (Figures 4.1 and 4.12). Thick extrusive basalt extends under and between sedimentary strata of Rockall Trough and it difficult to record the arrivals from the deeper crust due to strong non- homogeneity in the shallower part. The data quality is better in the eastern crustal layer, where the extruded basalt is thinner or absent. The extrusive basalt and shallow sedimentary layer are interpreted by high quality data (Klingelhöfer et al., 2005). The oceanic crust at the western end of the profile is well constrained, however the data quality decreases near the Lousy bank due to shallow water depth. The location of the COB is difficult to identifying due to the low quality data in the. Clear arrivals observed to the offset of 120 km with the arrivals reflected from the top of the LCB and Moho. The extrusive basalt with ~350 km length extends landward of the Lousy Bank and has a maximum thickness of ~4 km. The velocity model shows low velocity sedimentary layer between extrusive basalt under the Rockall Trough.

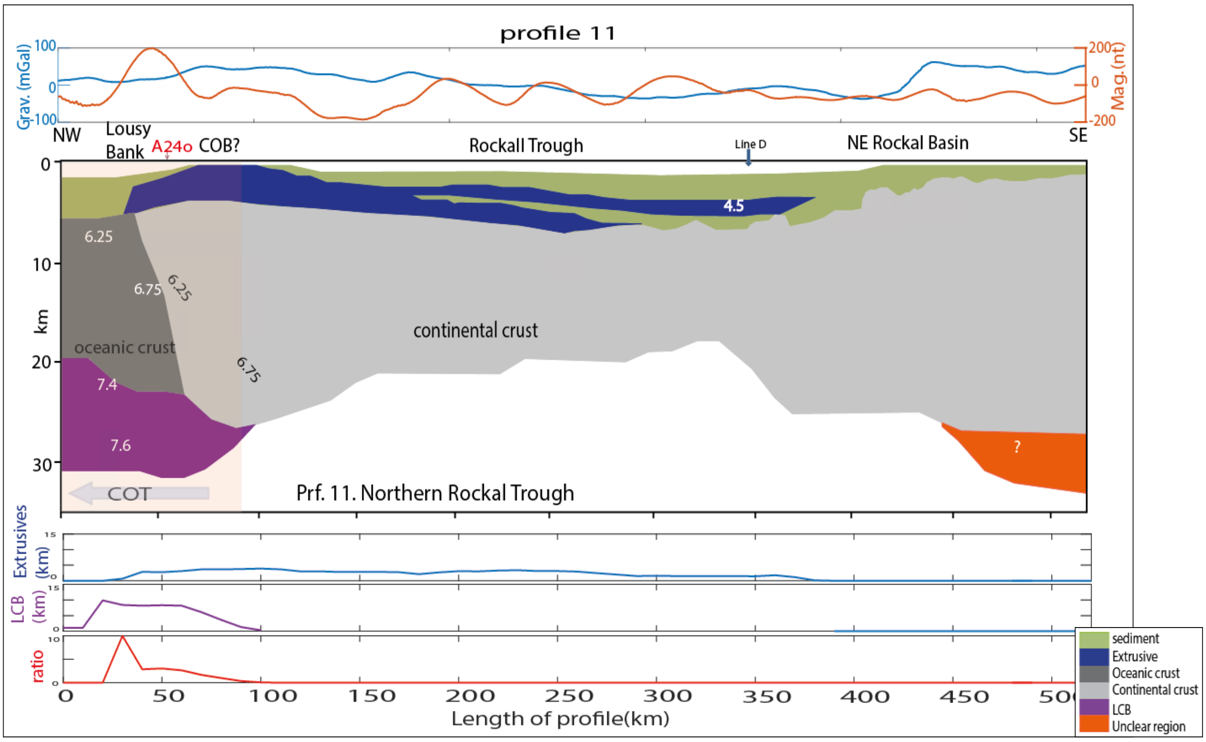


Figure 4.12: Crustal transect (Profile 11) Northern Rockall Trough (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary.

The location of the COT zone is placed at the western end of the profile and is characterized by lateral velocity variation from the continental to the unusual thick oceanic crust. The thickness of the oceanic crust is about 15 km, which is much higher than the average thickness of normal oceanic crust.

A LCB with a maximum thickness of ~10km and length of 100 km is identified at the western corner of the profile. A slightly increased velocity and density is interpreted in the lower crust at the eastern end of the profile. Due to low quality data in this region, the suggested lower crustal body is very uncertain (Klingelhöfer et al., 2005). The average ratio between the LCB thickness and the extrusive thickness is about 2.5.

Profile 12 is located across the Hatton margin with ~150 km length. The profile 12 extends from outer part of Hatton Bank to the normal oceanic crust and terminates at magnetic anomaly C22 (Figures 4.1 and 4.13). The wide angle profile has been studied earlier by (Fowler et al., 1989; Morgan et al., 1989) and modified by (White and Smith, 2009) with four 4 component OBS (2 OBS at each end) and a variable –offset tow-ship profile. The ray theory model of the travel time created 2-dimensional structure in the profile (White and Smith, 2009) and the starting velocity model based on expanding spread profiles (ESPs)(Fowler et al., 1989). In general, the path way of the one-dimensional velocity models is difficult for reconstruction of the crustal structure.

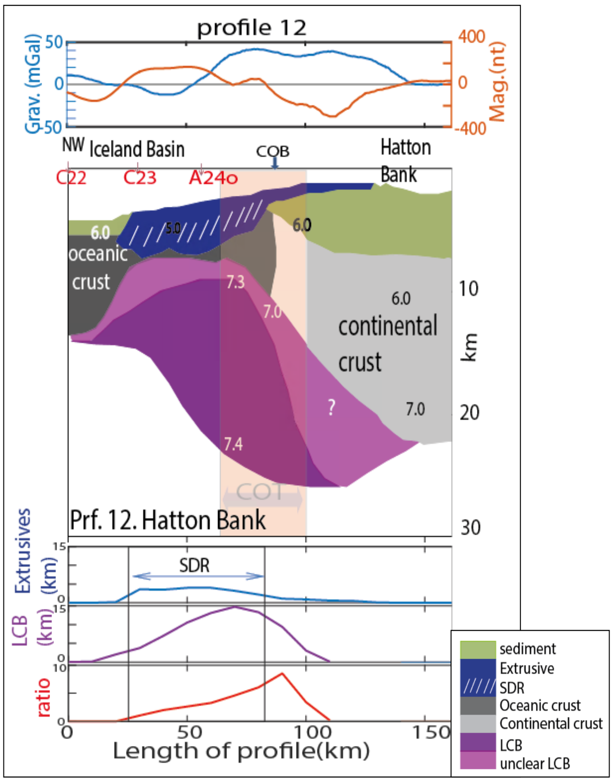


Figure 4.13: Crustal transect (Profile 12) Hatton margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary.

The COT is identified as a narrow zone with 40 km width. It is characterized by lateral increase in velocity of lower the crust. The SDR with a maximum thickness of ~ 3.6 km extends at distance between 25 km and 80 km on the profile and has seaward termination at anomaly C23. The LCB is interpreted with the velocity between 7.3 and 7.4 km/s and has a maximum thickness of about 15 km. Above the LCB, a thin layer with a velocity between 7.1-

7.3 km/s is present (light purple colure) and it proposed be a part of the underplated or intruded magma. In this example the SDR was formed the main part of the extrusive complex and has an average ratio of about 3.5 between the LCB and the SDR.

The **Profile 13** is situated at the Hatton margin with 400 km length and extends from SE to NW across Hatton Basin, Hatton Bank and oceanic crust (Iceland Basin) respectively (Figure 4.1 and 4.14).

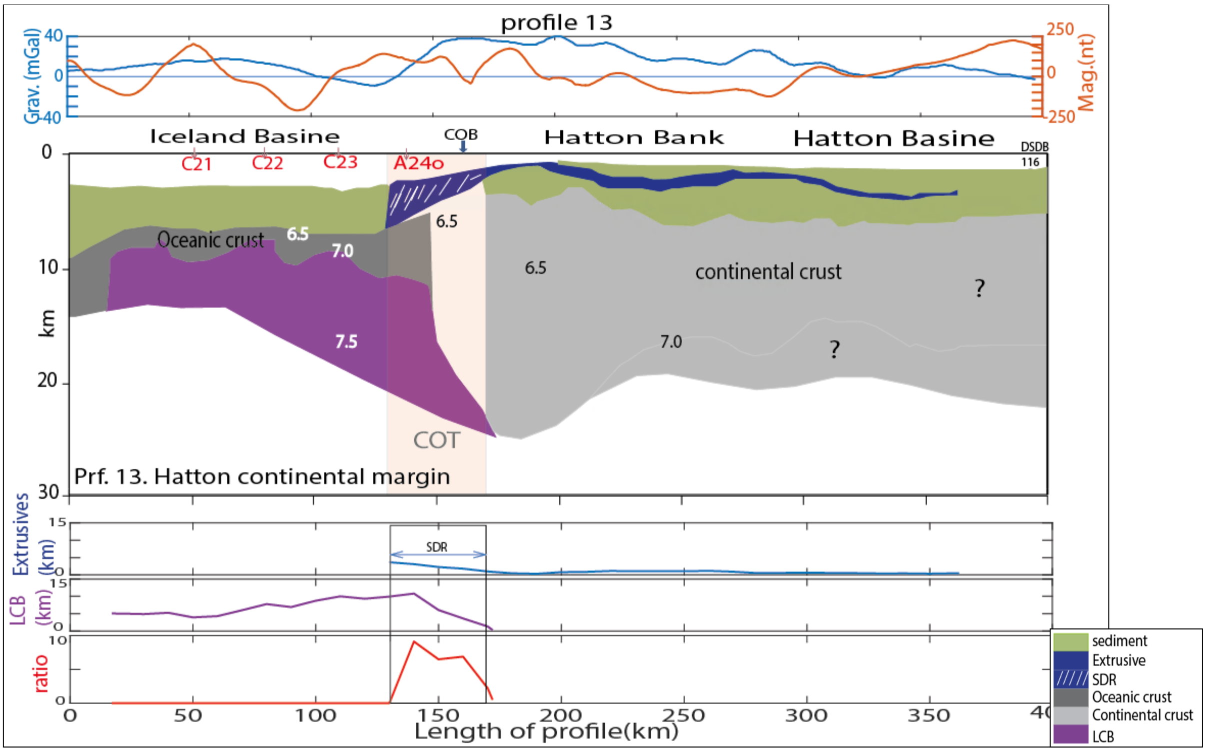


Figure 4.14: Crustal transect (Profile 13) Hatton margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary.

This profile has high quality and dense data coverage, except for Hatton Basin with spars OBS spacing. The study of the crustal structures and nature of the COT is based on travel time tomography of the wide-angle diving waves and reflections on the OBSs (White et al., 2002). The MCS profiles were used for interpretation of shallow sediments, top basalt horizon and the SDR morphology. The MCS profiles are also used for the starting model of wide-angle travel time tomographic inversion. The basalt layer is identified by low-frequency and high amplitude source, which makes it enable to propagate through the whole basalt.

The SDR wedges identified along 40 km narrow COT zone and have a maximum thickness of ~4 km. The extrusive basalt extends ~200 km landward of the COT zone with an average thickness of about 1 km. The maximum crustal thickness is ~23 km in the continental part of the Hatton Bank close to the COT zone. The crustal thickness beneath the COT zone decreases gradually from ~23 km to ~18 km and the lower crustal velocity is intermediate between the velocities along continental part of Hatton Bank and normal oceanic crust. The high velocity lower crust in COT zone ranges between 6.9-7.3 km/s and is defined as sill intrusion and extrusive basalt at the continental breakup time (White and Smith, 2009). The LCB with ~100 km length and maximum thickness of 10 km extends along COT zone to the normal oceanic crust (White and Smith, 2009). In this example only the SDR wedges overlaying the inner part of LCB and the average thickness ratio is about 7 between the LCB and the SDR.

Profile 14 is located in the southern part of the Hatton margin and extends about 320 km from SE to NW across outer part of Hatton basin, Hatton continental Margin and oceanic crust (Iceland Basin) where it terminates at magnetic anomaly C20 (Figures 4.1 and 4.15). The profile is prepared from two deep seismic lines (Line 21 and 13), and line 13 extends about 30 km along the southeastern end (Vogt et al., 1998) (Figure 4.15).

The Line 21 has dense OBS spacing (40 OBSs), whereas the Line 13 has very poor ray coverage and gravity model is used in the eastern part. The southwestern part of the LCB and the eastern part of the Moho boundary are unresolved (shown by question mark). In general, the reflected and refracted arrivals of the main crustal layer, LCB and Moho are recorded on the geophones and hydrophones along the Line 21.

The continental crust along Line 21 shows a 100 km broad region of crustal thinning and defined as COT zone on the profile. The COB is located near the oldest part of magnetic anomaly A24o at the breakup time. No evidence of extrusive lava and SDR are found in this profile. The shallower part of Hatton continental margin is a 2 km thick layer with a velocity of 4.2 km/s and has unclear origin(Vogt et al., 1998) .

The normal oceanic crust is defined at anomaly C23 towards the sea with an average thickness of about 8 km, but the crust is relatively thinner toward the west. The LCB has a maximum thickness of ~11 km and extends about 100 km under the COT zone.

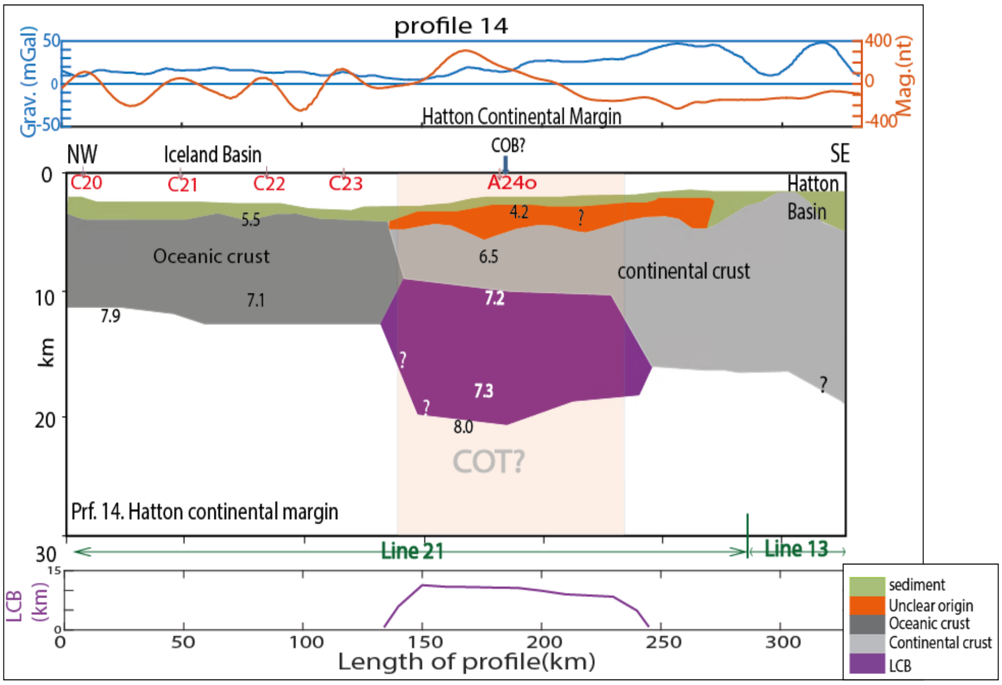


Figure 4.15: Crustal transect (Profile 14) Hatton margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary.

4.2 East Greenland Margin

A total of 9 profiles are constructed and described along the East Greenland margin (see Table 3.1 and Figures 4.15-4.23).

4.2.1 Southeast Greenland Margin

The **profiles 15 -18** cover the southern part of East Greenland margin (Holbrook et al., 2001a; Hopper et al., 2003; Korenaga et al., 2000). Profile 15 is located in the southernmost part of the margin and profile 18 extends along the Greenland-Iceland Ridge (GIR) (Figure 4.1).

The crustal velocities and thicknesses are well constrained by refracted and wide-angle reflection data recorded on OBSs. Data quality and ray coverage of the wide angle data are excellent on profiles 16 and 17, but the data quality of the profile 18 is moderate and the crustal structures constrained with higher uncertainty. Thickness of the shallow sedimentary layer is constructed by joint inversion of normal incidence from MCS reflection stacks with wide-angle travel time. The in situ sample control from ODP drilling wells were used into the upper crust. The crustal structures along the profile 16 derived from velocity contour lines based on seismic tomography (Hopper et al., 2003).

Profile 15 is the southernmost profile and extends about 350 km from continental to oceanic crust (Irminge Basin) (Figures 4.1 and 4.16). The maximum crustal thickness is about 28 km in the continental part and it decreases rapidly seaward to a thickness of about 10 km at magnetic anomaly C21.

COT is estimated about 100 km wide zone and is defined by the increase in the lateral velocity from continental to the oceanic crust at magnetic anomaly A24. The continental breakup related extrusive basalt has not found in this region (Tsikalas et al., 2012). The LCB has velocity >7.2 km/s and a maximum thickness of ~7 km (Holbrook et al., 2001) is located at the continental boundary of COT zone and terminates toward the oceanic crust near magnetic anomaly C22.

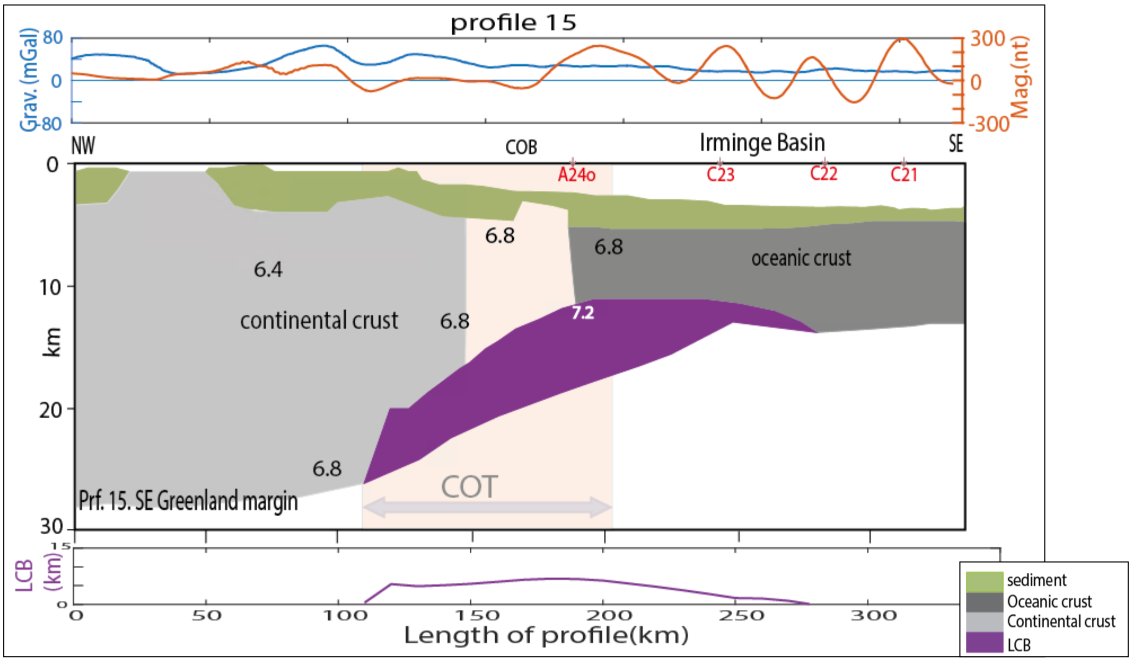


Figure 4.16: Crustal transect (Profile 15) across southernmost part of east Greenland margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary.

Profile 16 is positioned at 600 km to the south of GIR and extends 400 km from continental crust to oceanic crust (Figures 4.1 and 4.17). The maximum crustal thickness is about 30 km in the continental part and it decreases rapidly seaward to a thickness of about 10 km at magnetic anomaly C21. The COB is identified by ODP drilling and deep seismic reflection data and is located at 170 km where the crust is 20 km thick and shows the modest thinning before breakup. Similarly the COT zone is located at thinned and stretched continental crust which is underplated or intruded by igneous melt prior to breakup (Hopper et al., 2003).

The extrusive basalt and LCB have the same continuation, which shows the extension from 120 km on the continental crust and along the entire oceanic crust. The extruded basalt is defined as inner SDR (~80 km wide) landward of the anomaly A24 and outer SDR (~60 km wide) seaward of the outer High. The maximum thickness of LCB is ~7 km which interpreted with a velocity >7.1 km/s. The ratio between the LCB thickness and the extrusive thickness is ranging between 1.2 and 2.4.

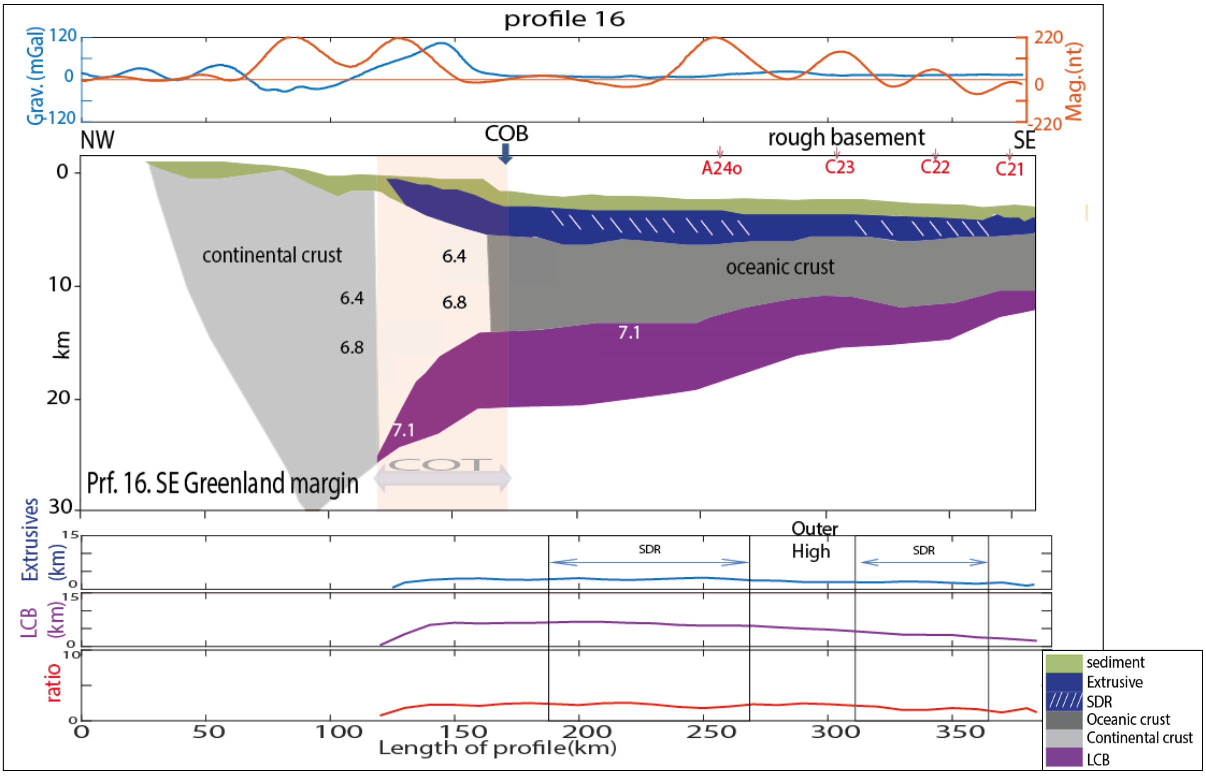


Figure 4.17: Crustal transect (Profile 16) across the south east Greenland margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary.

Profile 17 is situated about 200 km in the south of GIR and extends 350 km from continental to oceanic crust (Figures 4.1 and 4.18). The maximum crustal thickness is about 30 km in the continental part, whereas the crustal thickness decreases less rapidly compared to southern profiles. Also the crustal thickness is 14 km at magnetic anomaly C21 and is ~10 km thick at seaward end of the profile.

The COT is estimated about 70 km wide zone and is characterized by the increase in lateral velocity of continental crust toward the thick oceanic crust near the magnetic anomaly C23. Interpretation of SDR wedges is based on MCS reflection data, it has a maximum thickness of about 4 km and 60 km length (Korenaga et al., 2000). The extrusive lava extends from the continental boundary of the COT zone to the whole oceanic crust in the profile. The thin LCB (5 km thickness) with velocity >7.2 km/s and extends along the entire lower crust in the profile (Holbrook et al., 2001). The ratio between the LCB thickness and the extrusive thickness is ranging between 5 and 0.3. The ratio is about 0.5 in the SDR extent.

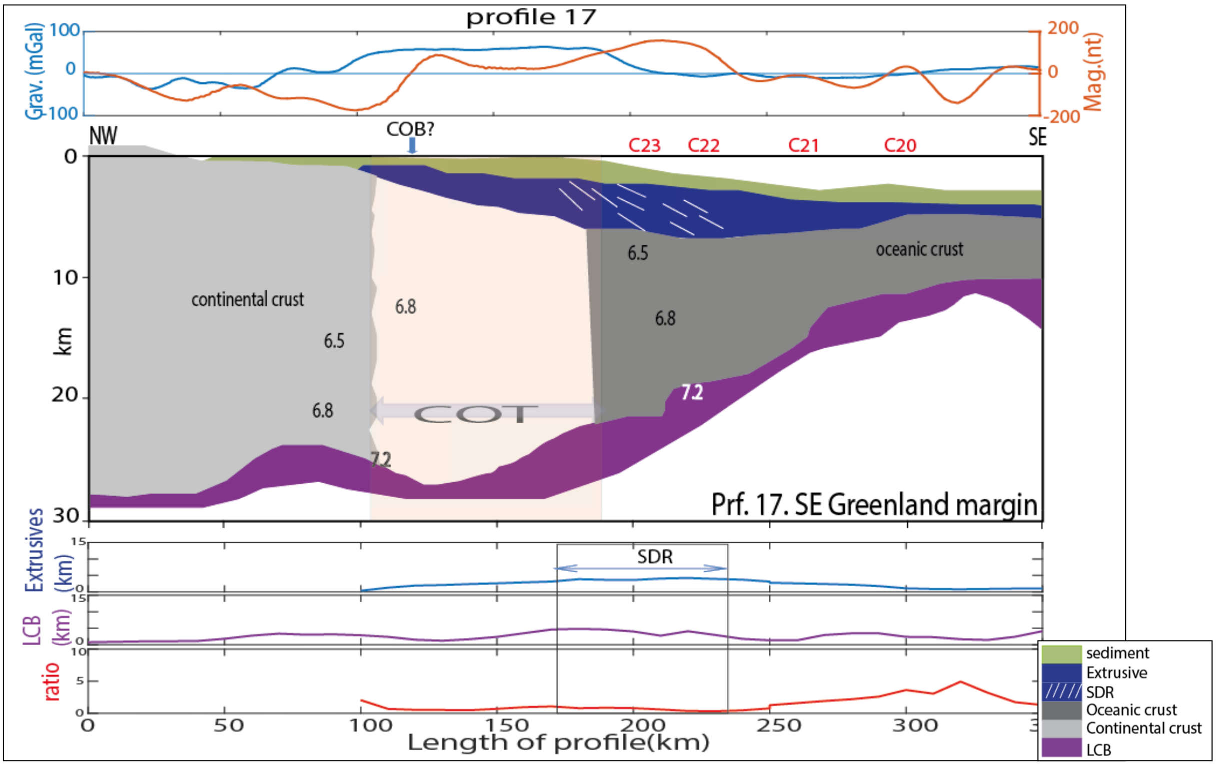


Figure 4.18: Crustal transect (Profile 17) across the south east Greenland margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary.

The **profile 18** located along the Greenland Iceland Ridge (GIR) with total length of 500 km and has maximum crustal thickness >30 km (Figures 4.1 and 4.19). The extrusive basalt with maximum thickness of ~5 km is interpreted in the shallower part of the whole crust. The location of the COB is very uncertain due to the lateral velocity variation in the upper crust remain unresolved, but it could be located on the western end of profile close to the coast. The LCB extends along the whole lower crust with a velocity ranging between 7.2-7.5 km/s and maximum thickness of about 15 km, the lower crust at the western end of profile may have higher thickness up to 40 km depth (Holbrook et al., 2001; Voss et al., 2009a). The average ratio between the LCB thickness and the extrusive thickness is about 6 km.

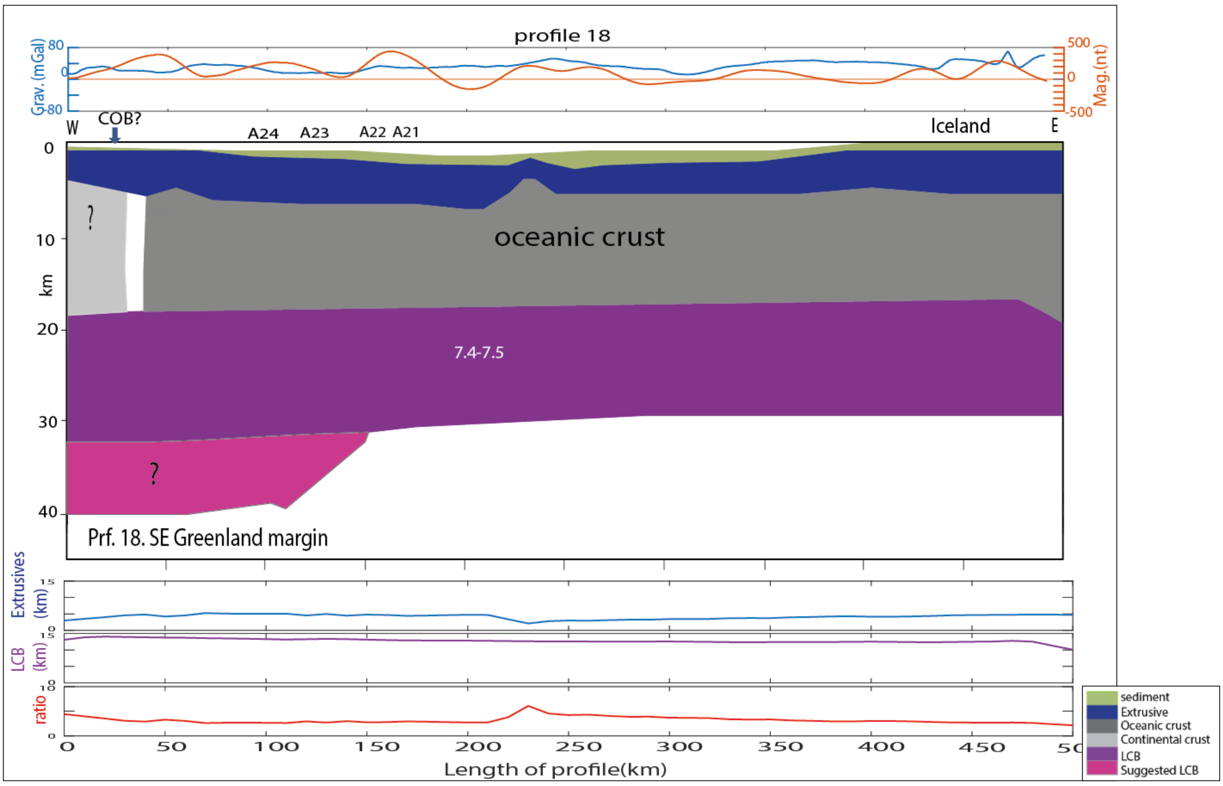


Figure 4.19: Crustal transect (Profile 18) along Greenland Iceland Ridge (GIR) (see references in table 1).

4.2.2 Northeast Greenland Margin

Profile 19 is located about 600 km in the north of Greenland Iceland Ridge and extends 400 km from West to East across the Jamson Land Basin, Liverpool Land Escarpment and Kolbeinsey Ridge respectively (Figures 4.1 and 4.20). The seafloor spreading of Kolbeinsey Ridge became active in ~15 million years ago and indicated by magnetic anomalies A4 to A6 on the profile (Figure 4.1).

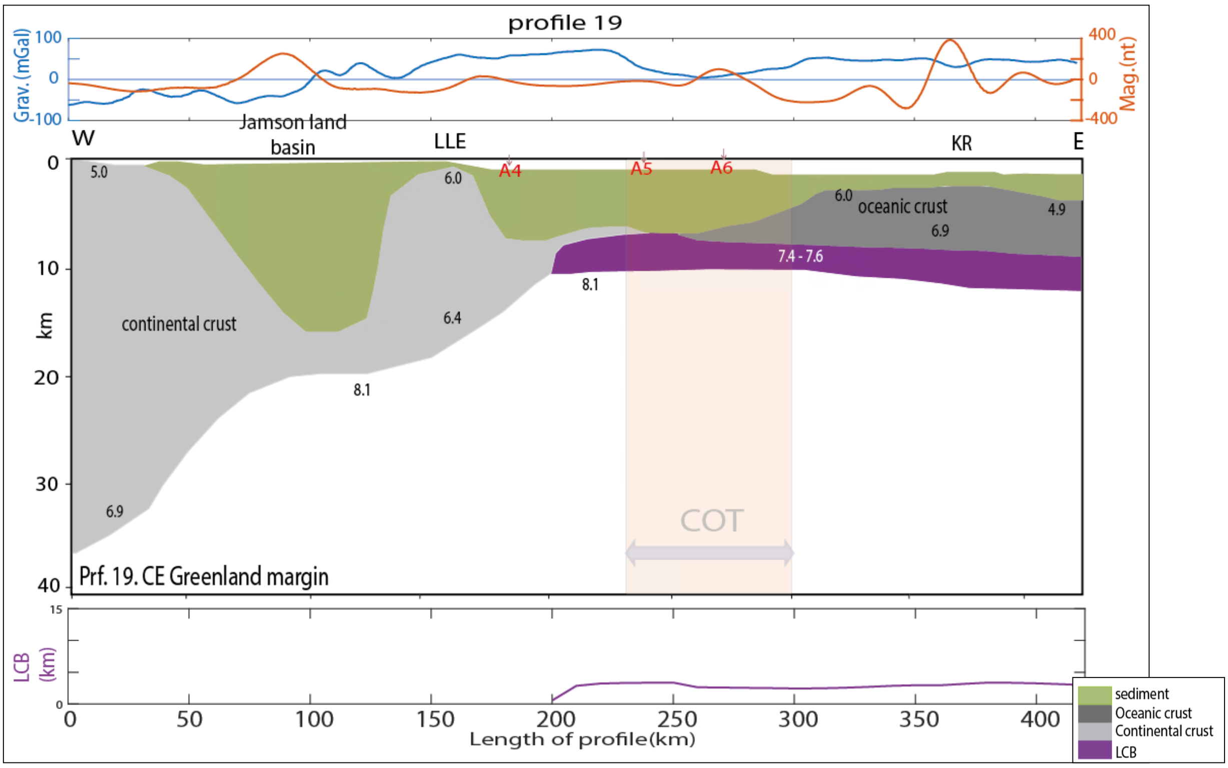


Figure 4.20: Crustal transect (Profile 19) across central part of the east Greenland margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary.

The offshore OBS spacing is sparse and the crustal resolution and ray coverage is low, the gravity modelling were used to constrain the crustal model (Weigel et al., 1995). The continental crustal thickness has strong variation. The maximum crustal thickness is about 37 km in the continental part and it decreases rapidly under the thick (~18 km) Jamson Land Basin. The COT zone is defined by high uncertainty between 130 km and 300 km and it shows a thinned crust underlain by a high velocity lower crustal body (LCB) (Mjelde et al., 2008). The LCB with velocity range between 7.4-7.8 km/s and an average thickness of ~3 km extends seaward of km 200 along the lower crust (Weigel et al., 1995).

The seismic **profiles 20 and 21** (Figure 4.21 and 4.22) consist of dense OBS spacing with an average interval of 10 km. The crustal structures have very good ray coverage of seismic refracted and wide-angle reflection data. But, the both end points of profiles exhibit poor or zero ray coverage. The crustal structures along upper sedimentary layer, intermediate layer, lower sediments, upper and lower crust and upper Mantle are well constrained by high quality OBSs and magnetic data (Voss and Jokat, 2007a).

Profile 20 is positioned across the Kejser Franz Joseph Fjord (KFJF) in the north Greenland margin and has a total length of 460 km (Figure 4.21). The profile is located close to Jan Mayen Fracture Zone (JMFZ) and extends from West to East across the continental crust with a maximum thickness of ~33 km to a ~6 km thin oceanic crust. The continental part of this profile overlaps about 120 km distance with seismic profile 94320, and it gives good match with crustal velocity and layer boundaries in the region (Voss and Jokat, 2007a).

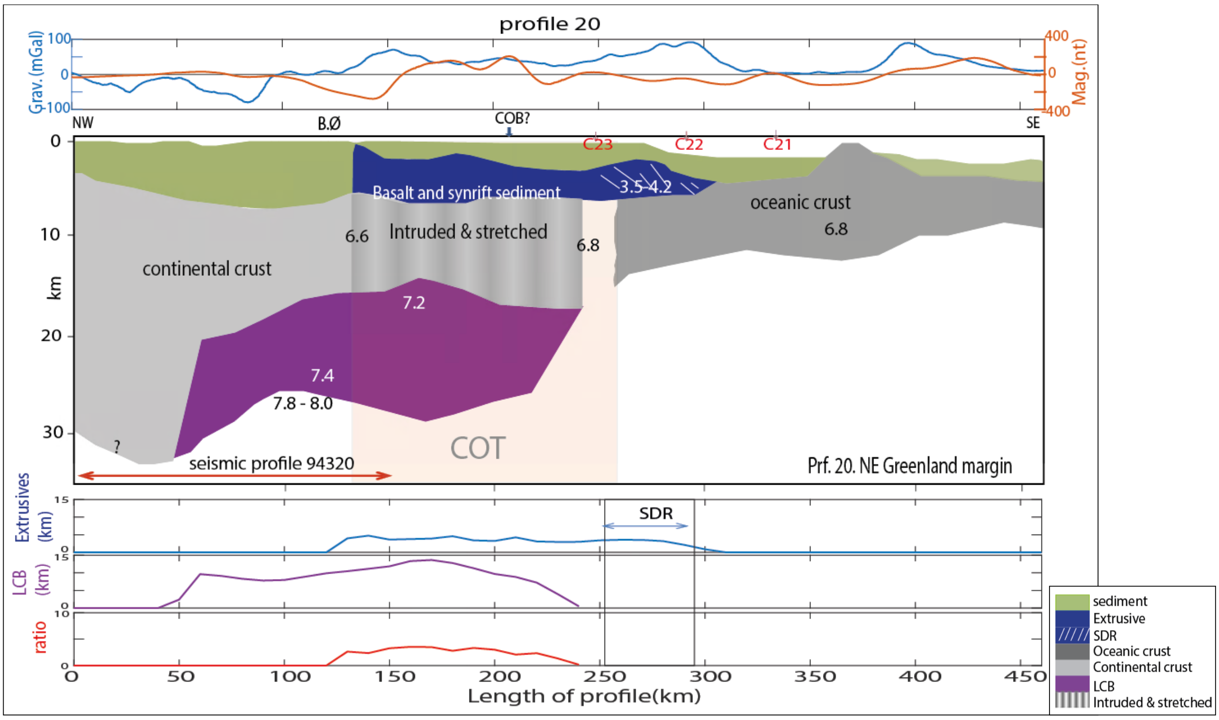


Figure 4.21: Crustal transect (Profile 20) across NE Greenland margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary, B.Ø: Bontekoe Ø.

The SDR is identified from earlier study of neighboring MCS profile after (Hinz et al., 1987), and is projected at about 40 km distance between the magnetic anomaly C23 and A24. It has been suggested that the SDRs erupted due to extensive continental extension before the seafloor spreading and therefore the seaward boundary of the COT zone is based on the SDR projection (Voss and Jokat, 2007a). The interpretation of the extrusive lava retrieved from (Tsikalas et al., 2012), and is present in between COT zone and terminates over oceanic crust at magnetic anomaly C22. The interpretation of the extrusive lava and SDR are very uncertain.

The COT (130 km width) is characterized by shallow extent of extrusives mixed with syn rift sediments. The velocity variation and lower crustal thickening are due to magmatic underplating. The landward boundary of COT is located at the seaward side of Bontekoe Ø where the continental velocity increasing due to highly magmatic intruded and stretched crust and the seaward boundary is at magnetic anomaly C23. The location of the COB is based on plate reconstruction from earlier publication and placed at a distance of 210 km on the profile, but this location does not correlate with the seismic velocity model (Voss and Jokat, 2007a).

The velocity in the LCB is between 7.2 km/s at the top and 7.4km/s at the base characterized as Tertiary magmatic underplating. This magmatic body has a maximum thickness of ~13.6 km in the COT zone. The LCB extends at km 50 in the continental lower crust and has a seaward termination in the COT at km 24. The estimated thickness ratio between extrusive and LCB is very uncertain, it has an average of about 3. In this example the SDR is not overlaying the LCB.

Profile 21 is situated across the Godthåb Gulf in the north Greenland margin and has a total length of 320 km (Figures 4.1 and 4.22). The profile is located about 100 km in the north of profile 20 and extends from West to East across the continental crust with a maximum thickness of ~30 km to the oceanic crust with a thickness of ~8 km.

The SDR is identified from earlier study of neighboring MCS profile after (Hinz et al., 1987), and has been interpreted at seaward of the volcanic basement high between 200 km and 225 km with a maximum thickness of ~1.5 km. The extrusive lava in this profile is very uncertain it defined as upper part of basalts and syn-rift sediments along the COT zone and terminates at the volcanic basement high.

The COT is identified as a wide zone with 120 km width characterized by shallow extent of extrusives mixed with syn-rift sediments, the velocity variation and lower crustal thickening due to magmatic underplating. The landward boundary of the COT is located at the distance of 100 km where the continental velocity increases due to highly magmatic intruded and stretched crust and the seaward boundary is located at the seaward termination of the SDR. The location of the COB is based on plate reconstruction and interpretation of magnetic lineation from earlier publication and is placed at a distance of 155 km on the profile, but this location does not match the seismic velocity model (Tsikalas et al., 2002).

The velocity in the LCB is between 7.2 km/s at the top and 7.4 km/s at the base characterized as Tertiary magmatic underplating. This magmatic body has a maximum thickness of ~15.8 km in the COT zone. The LCB extends at km 30 in the continental lower crust and terminates at km 270 beneath the oceanic crust (C22). The thickness ratio between the LCB and the extrusive is very uncertain and the estimated average is ranging between 6 and 1.

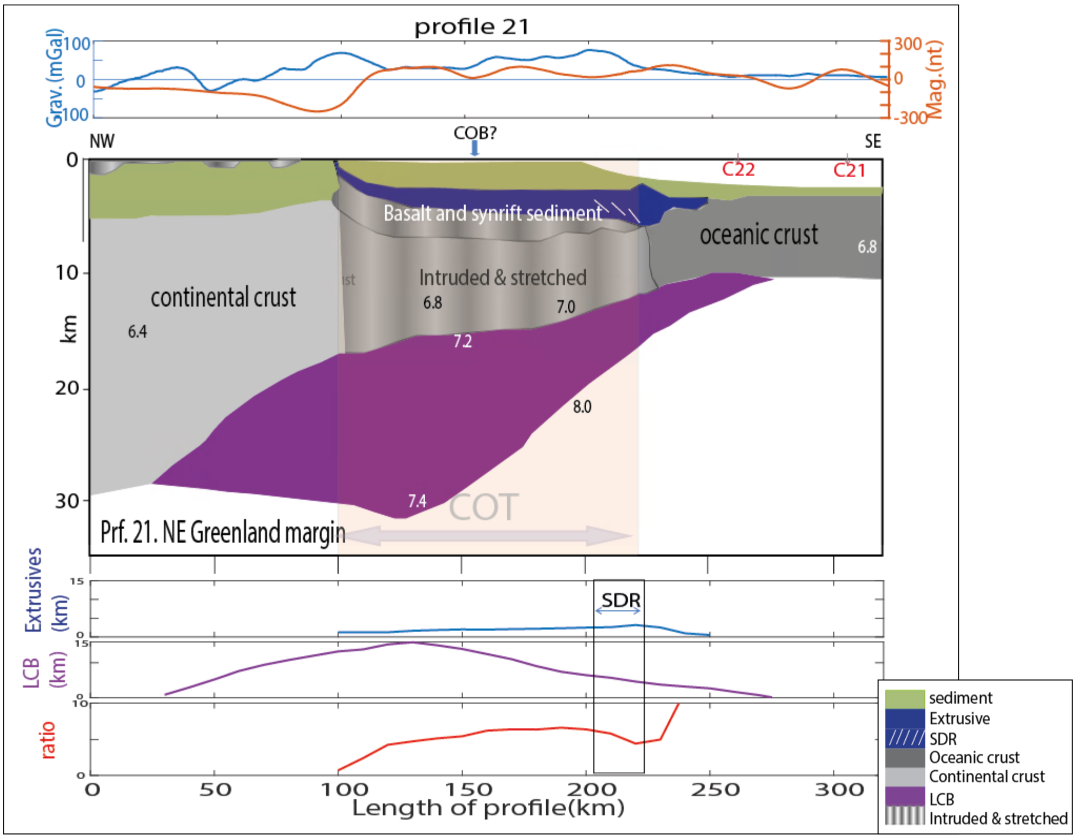


Figure 4.22: Crustal transect (Profile 21) across NE Greenland margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary.

The seismic **profile 22 and 23** (Figures 4.23 and 4.24) located in the north east Greenland margin between Shannon and Greenland Fracture Zune (GFZ) (Figure 4.1).

Profile 22 is located south of the Shannon Island and extends 360 km from continental to oceanic crust. The maximum crustal thickness is about 35 km in the continental part and decreases rapidly toward the oceanic crust which shows a thickness of about 7 km oceanic crust at magnetic anomaly C21 (Figures 4.1 and 4.23).

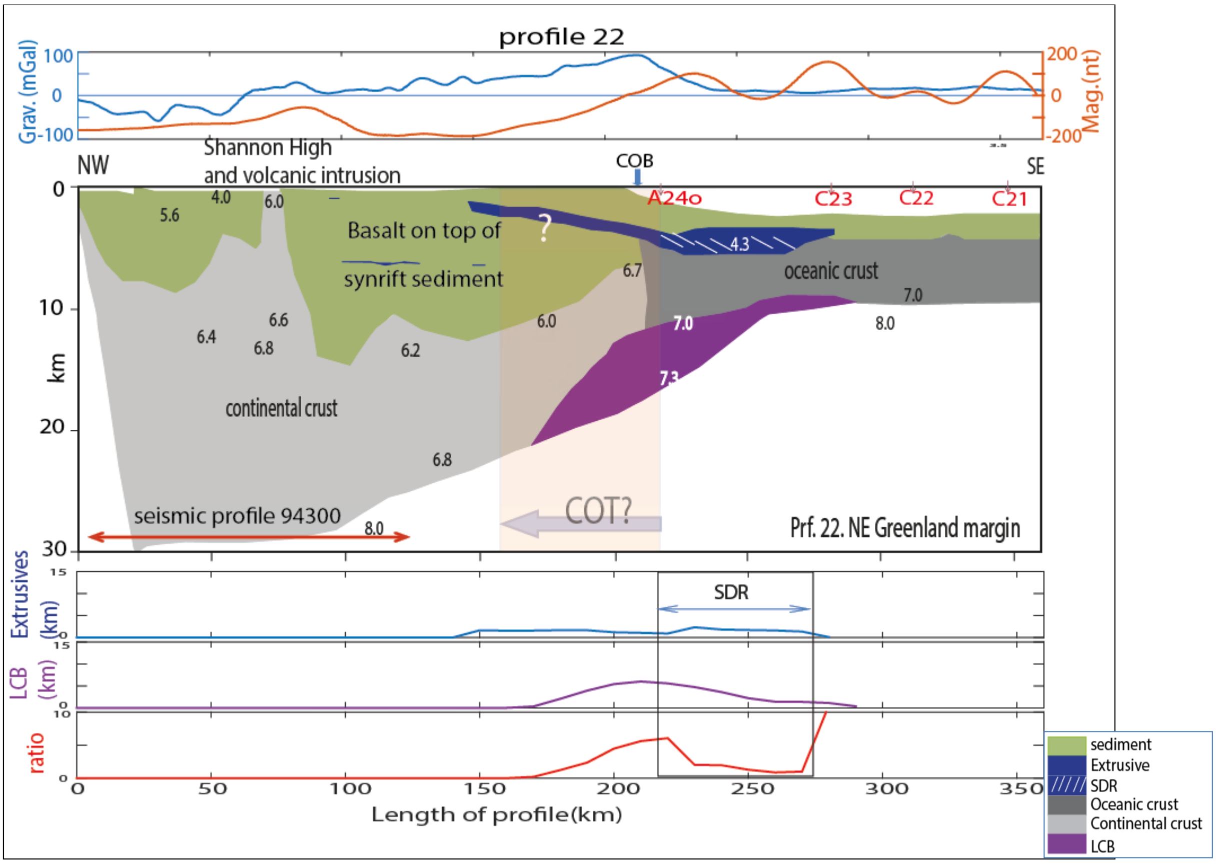


Figure 4.23: Crustal transect (Profile 22) across NE Greenland margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. SDR: Seaward Deeping Reflector, LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary.

The profile has very low data quality, the recorded arrivals are difficult to identify, and also recording from few stations cannot be used for modeling due to bad data quality. The lithology and final velocity model of the crust is constrained by 2D gravity modeling. The continental part is constrained by five layers within distance between 0-210 km and four layers were used for oceanic crust. The profile partially overlap about 100 km along the western end by seismic line 94300 from previous publication (Schlindwein, 1998) and it is used for reconstruction of the crust (Voss et al., 2009a). The thin sedimentary layer along the top of the oceanic crust is interpreted on MCS data. The Cretaceous syn-rift sediments and extrusive basalt are identified by P-wave velocity between 4.5-6.0 km/s, but the thickness of basalt layer is unresolved.

The seaward limit of the COT is located at km 210 near the magnetic anomaly A24o but the landward extend of the COT is not defined due to the weakly resolved structure of the basin between Shannon high and oceanic crust (Figure 4.23). The extrusive basalt is interpreted as strong reflectors between Cenozoic and older sediments with an uncertain thickness. SDR with ~60 km length is defined between COB and magnetic anomaly C23 and is characterized by slightly lower velocity layer between the oceanic layer and the sedimentary layer mixed with basalt (Figure 4.23).

The high gravity anomaly, increasing density and observed basalt layer on the Shannon Island could be the reasons for the existence of high velocity lower crustal magmatic intrusion. In general, the nature of the LCB between profile 22 and 23 is suggested as intruded magma (Voss et al., 2009a). The ratio between the LCB thickness and the extrusive thickness is ranging between 0.2 and 4. The ratio is about 0.9 in the SDR extent.

Profile 23 is located across at the northernmost part of the Greenland margin and situated at about 150 km in the south of Greenland Fracture Zone (Figure 4.1). The profile has a total length of 330 km (Figure 4.24), however the western part of the profile consists of very complex structures and remains unresolved, which is removed and the profile starts at km 210. It extends from West to East across the continental crust with a maximum thickness of ~20 km to the ~6 km thick oceanic crust with magnetic anomaly C21. At the western end of the profile about 40 km is unresolved due to very poor ray coverage along the middle and lower crust (Figure 4.24). The lithology and crustal model is constrained by 2D gravity modeling. The layer on top of the continental crust near the outer high is interpreted by MCS and reflection data (Voss et al., 2009a).

The width of COT zone is uncertain and the eastern part is defined along the Greenland Escarpment, outer high and western boundary is unresolved. The location of the COB is defined from the magnetic anomaly and it placed at a distance of 200 km on the profile (Figure 4.24). The extrusive basalt is absent and a small part of LCB is defined by high uncertainty due to low ray coverage in this area. The proposed LCB is located in a distance between 170 and 270 km and has a maximum thickness of ~2 km.

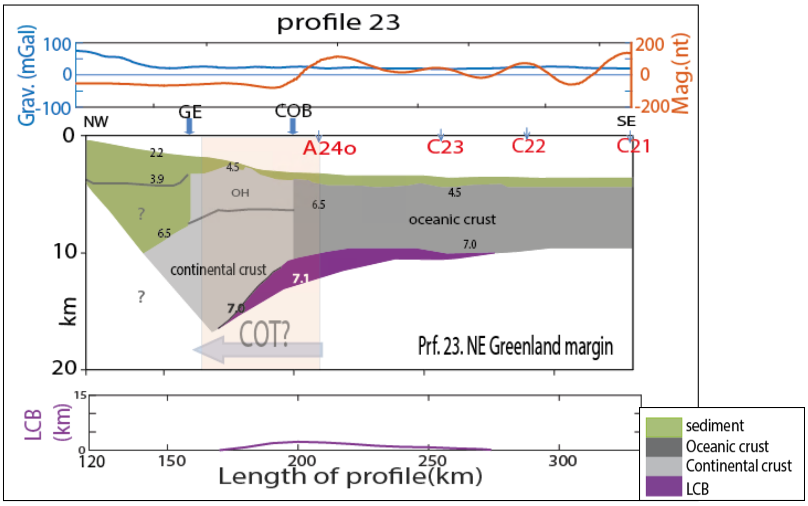


Figure 4.24: Crustal transect (Profile 22) is across the northernmost part of east Greenland margin (see references in table 1). Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km. LCB: Lower crustal body, COT: Continent Ocean Transition Zone, COB: Continent Ocean Boundary, OH: outer High, GE: Greenland Escarpment.

5 Discussion

5.1 Conjugated margins

The conjugated margins are selected according the flow line fin the isochron map (Gaina et al., (in review)) and according to the main fracture zones (Figure 5.1) . Also the chosen conjugated profiles in this study have been compiled on the basis of scientific papers for the NE Atlantic margins. The location of the conjugated margins is based on the margin segmentation to the south and north of the Greenland-Iceland-Faroe Ridge. The conjugated profiles are joined at anomaly 22 (49 Ma) which represents the transition to normal oceanic crust. The conjugated margins are clearly asymmetric both in terms of magmatic productivity and crustal structure. In this section, the main focus is to determine the relation of magmatic productivity along the conjugated margins.

5.1.1 Conjugated profiles in the northern domain of (FGIR)

The northern conjugated margins are located between the Greenland Fracture Zone (GFZ), Senja Fracture Zone (SFZ) and the Jan Mayen Fracture Zone (JMFZ). In general, the LCB is most extensive and has a landward prolongation close to the JMFZ and diminishes to the north a way form the JMFZ.

Profile 1 across the Lofoten-Vesterålen Margin (LVM) is approximately conjugated to **profile 23** on the NE Greenland margin which are located in the northernmost region (Figures 5.1 and 5.2). The normal oceanic crust at magnetic anomaly C22 in profile 1 is approximately 4 km thicker than on the East Greenland margin. The thickness of the crystalline crust (thickened crust) is almost the same around the COT zone and it shows more rapidly crustal tinning on the NE Greenland side. The extrusive basalt is not observed on both profiles. There is a thin layer of LCB beneath the Greenland profile whereas no LCB is observed on the conjugated LVM.

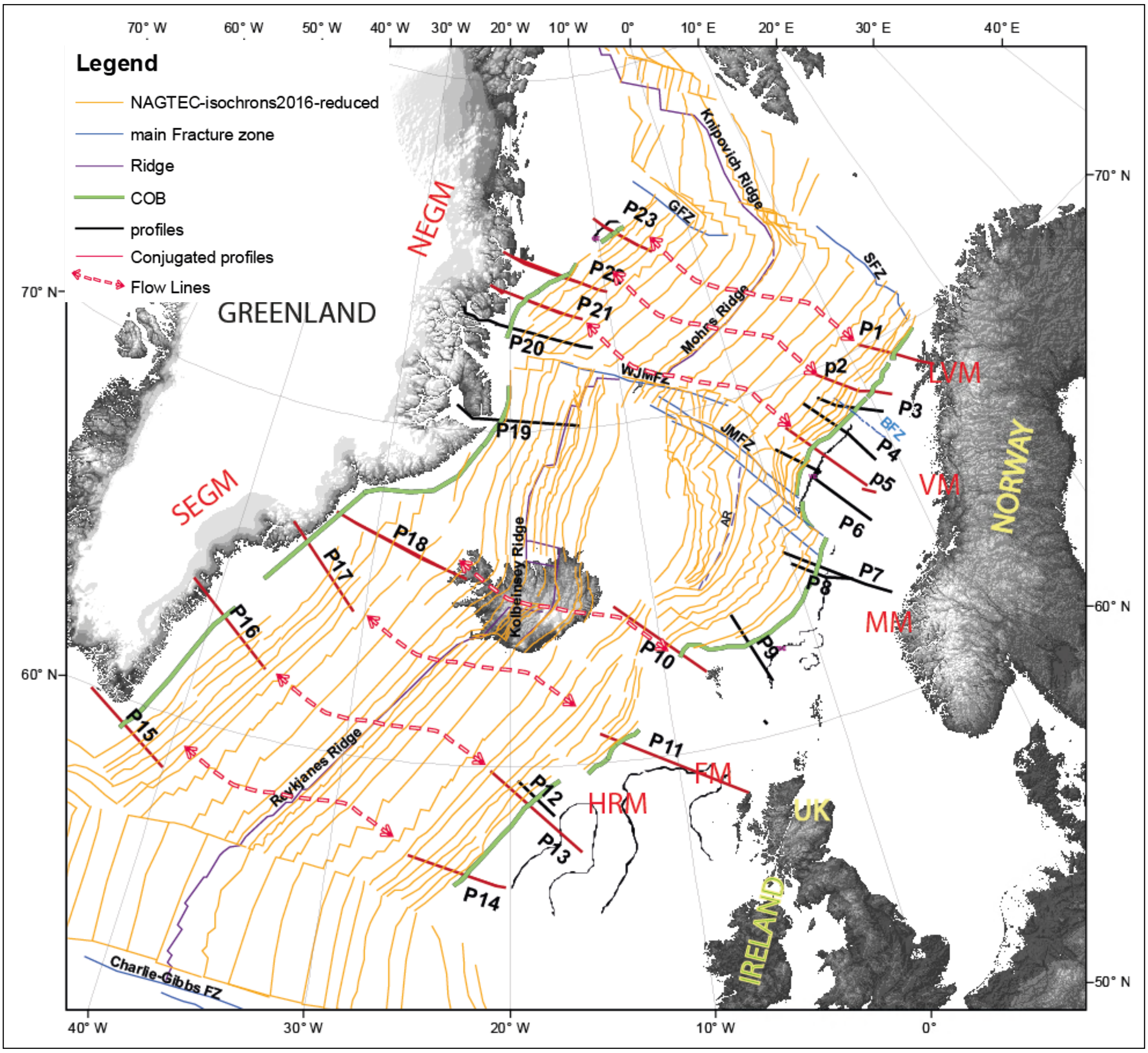


Figure 5.1: Isochron maps for the NE Atlantic Passive Margin (Gaina et al. (in review) showing Seafloor spreading pattern, flow lines and the approximated conjugated profiles.

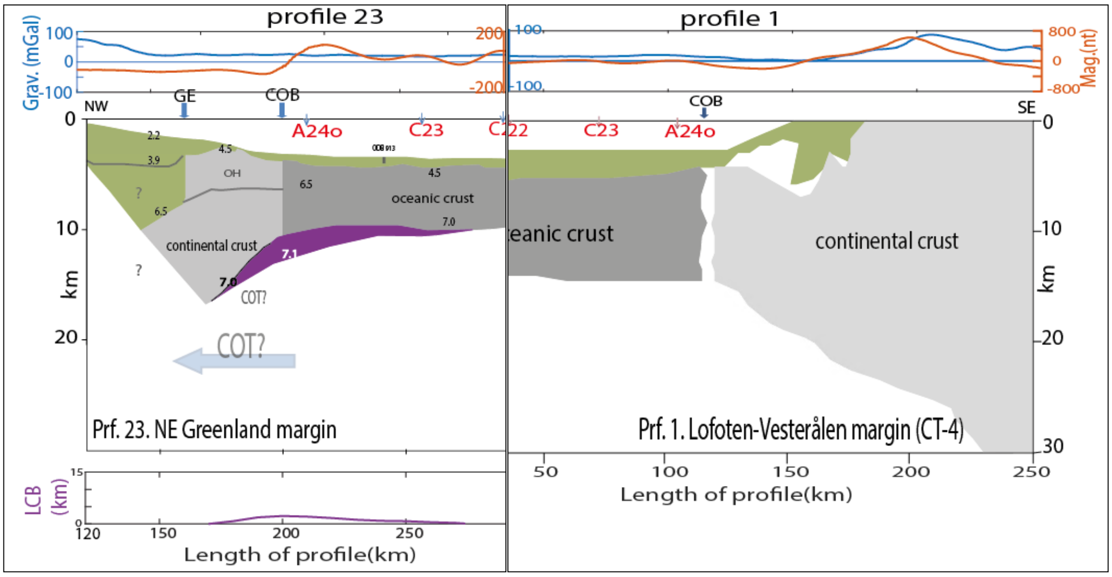


Figure 5.2: Conjugate Profiles 23 and 1, which are joined at anomaly C22. Describe the breakup magmatic evolution in the continental, oceanic crusts and COT zones across the Northern most part of NE Atlantic margins. Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km.

Profile 22, close to the Shannon Island in the NE Greenland is approximately conjugated to **profile 2** on the LVM (Figures 5.1 and 5.3). The oceanic crust at C22 is 2 km thicker (including a thin LCB) on the LVM side than on the Greenland side. The LCB is not extending to C22 on the Greenland side. However, the COB in the Greenland margin is ~20 km closer to C22 and the thickness of crystalline crust is ~3 km greater as compared to LVM (Figure 5.3). This shows that the crustal thinning and seafloor spreading are more rapidly in the northern part of Greenland relative to LVM. The amount of extrusive basalt and LCB are almost the same in both profiles, however the LCB in the LVM profile extends mainly beneath the oceanic crust whereas in the Greenland part it is observed with nearly equally extent beneath the continental and oceanic crust.

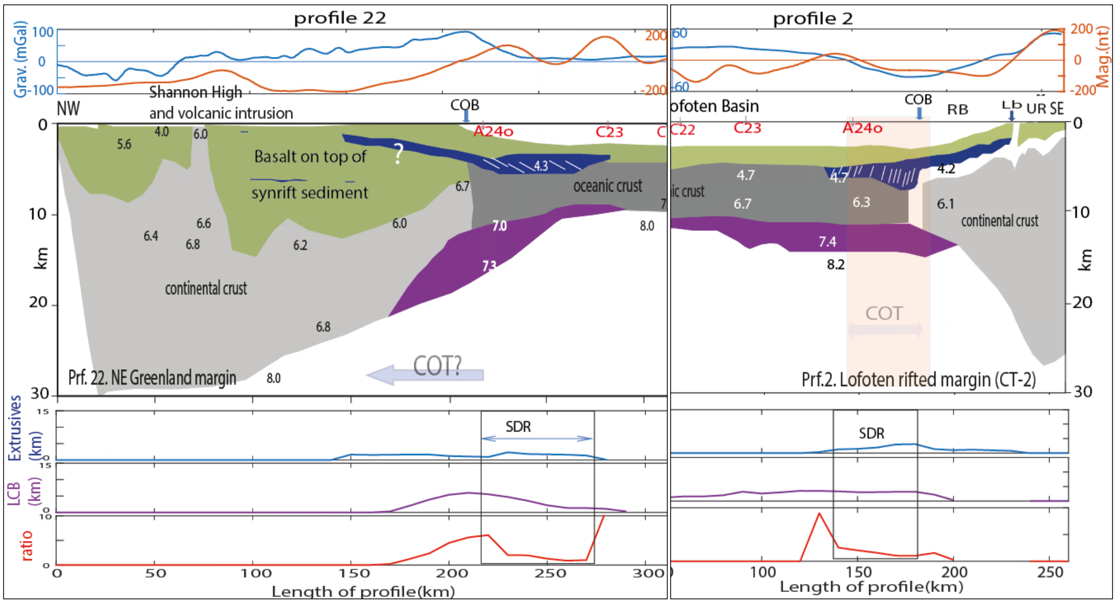


Figure 5.3: Conjugate Profiles 22 and 2 which are joined at anomaly C22. Describe the breakup magmatic evolution in the continental, oceanic crusts and COT zones across the NE Greenland and the conjugated Lofoten margin. Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km.

The conjugated **profile 21** (NE Greenland margin) and **profile 5** (Vøring margin) are located close to the north JMFZ (Figures 5.1 and 5.4). The thickened oceanic crust at C22 is nearly equal on both profiles but the LCB in the Greenland profile has higher velocity >7.2. The magnetic anomaly 24 along the Greenland profile is more complex compared to the northern profiles (see magnetic anomaly on the profile 21 in Figure 5.4). The location of the COB in the Greenland profile is uncertain, but the approximate distance from COB to C22 is nearly the same in both profiles that suggests the same seafloor spreading rate on both sides. The COT zone observed on the Greenland side is 100 km wider as compared to the narrow COT (25 km) in the Vøring margin. Also, the maximum thickness of the crust under the COT on the Greenland side is ~30 km, which is 8 km thicker than in the Vøring margin (Figure 5.4). The thickness of the LCB (> 7.2 km/s) on Greenland side is larger and it is distributed almost the same under the continental and oceanic crust whereas on the Vøring margin, it extends mostly under the continental crust (Figure 5.4).

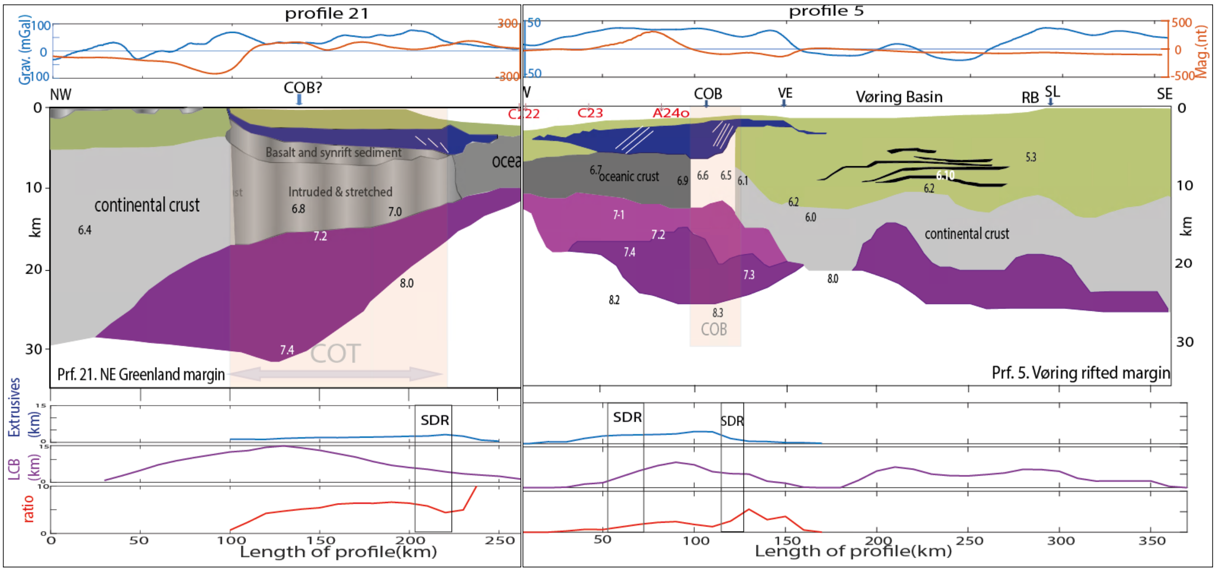


Figure 5.4: Conjugate Profiles 21 and 5 which are joined at anomaly C22. Describe the breakup magmatic evolution in the continental, oceanic crusts and COT zones across the NE Greenland and the conjugated Vøring continental margin. Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km.

5.1.2 Conjugated profile along the Greenland Iceland Faroe Ridge (GIFR)

Profile 18 located in the Greenland Iceland Ridge (GIR) is approximately conjugated to **profile 10** in the Faroe Iceland Ridge (FIR) (Figures 5.5 and 5.5). The oceanic crustal thickness is the same for both of the profiles and also the crustal thickening observed near the COT zone. The interpreted LCB on the FIR is located mainly within the COT zone and continuing towards the continental crust where a maximum Moho depth of about 40-46 km is identified. On the GIR, the LCB extends with a uniform thickness of ~15 km beneath the entire crust. The maximum Moho depth, with up to 40 km. is observed along the landward end of the profile (Figure 5.5).

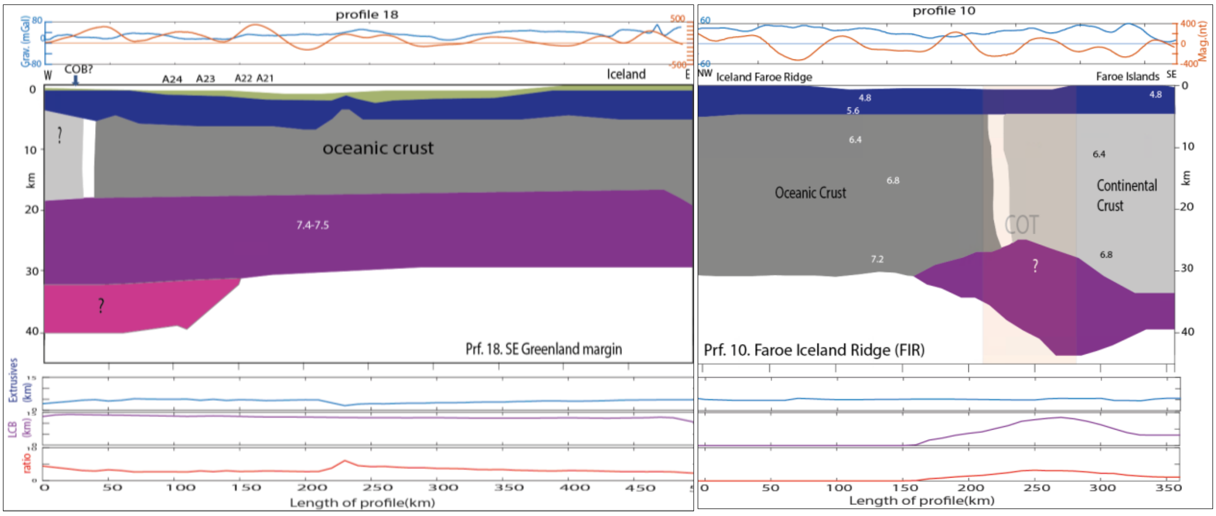


Figure 5.5: Conjugate Profiles along Greenland Iceland Faroe Ridge (GIFR). Describe the breakup magmatic evolution in the continental, oceanic crusts and COT zones in the GIFR. Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km

5.1.3 Conjugated profiles in the southern domain of (FGIR)

Conjugated **profiles 17 and 11** are located in the SE Greenland margin and Northern Rockall Trough respectively (Figures 5.1 and 5.6). According to the flow lines on magnetic isochron map, the profile 17 is approximately conjugate to the **profile 11**. The data quality is relatively poor in the northwestern part of profile 11 and observed COB and COT is very uncertain. The oceanic crust on profile 11 has a limit construction around the anomaly A24, due to the lack of data coverage in the northwest of Faroe Margin. Hence, the western end of the profile 11 in the COT zone joined to the magnetic anomaly C22 on the conjugated profile 17. The thickened crust at anomaly C22 on the Greenland side is about 20 km thick which comprises the extrusive lava (SDRs) and LCB. While, the COT in the western end profile 11 (Northern Rockall Trough) has a thickness of about 25 km and may underlies by ~20 km thick LCB and no extrusive basalt is observed in shallower part (Figure 5.6).

The observed extrusive basalt in the Northern Rockall Trough has a landward extent of about 350 km approximately from the middle part of the COT zone (under Lousy Bank), whereas in the SE Greenland margin it has a continuation from the land ward limit of the COT toward the whole oceanic crust. A thin LCB with a velocity >7.2 km/s extends throughout the entire lower crust of the Greenland profile, while in the Northern Rockall Trough it concentrates as a tick LCB beneath the COT and has a velocity higher than 7.4 km/s (Figure 5.6).

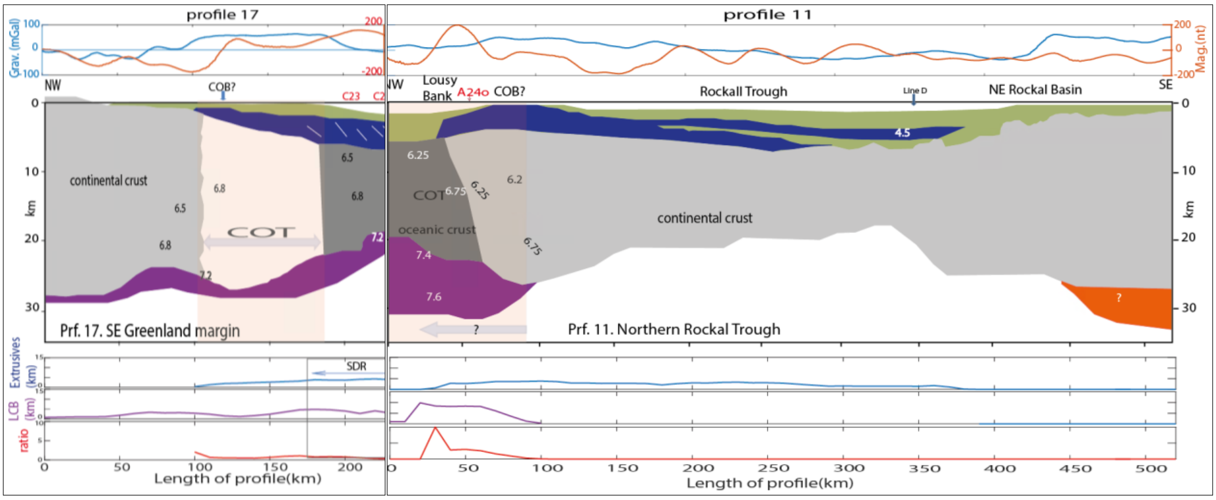


Figure 5.6: The Profiles 17 at anomaly C22 joined to the western end of the approximately conjugated profile. Describe the breakup magmatic evolution in the continental, oceanic crusts and COT zones across the SE Greenland and Northern Rockall Trough. Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km.

The Hatton margin (**profile 13**) and its approximate conjugated SE Greenland margin (**profile 16**) represent the extension through the continental crust, COT zone and the oceanic crust (Figures 5.1 and 5.7). The crustal structures in these two profiles are depicted by high-quality seismic data with broadly similar resolutions. Seismic velocities in the continental part of both profiles have similar pattern, which indicate that these two segments could have the same origin. The crustal thickness varies significantly along the Hatton and SE Greenland margins and therefore, the continental part of the SE Greenland margin is exposed subaerial while the Hatton side is under the sea level. This apparent dissimilarity is the result of Mesozoic seafloor spreading along the Hatton side where the Hatton and Rockall basins were formed (White and Smith, 2009).

Magnetic anomaly on the Hatton profile is very complex. The thickened oceanic crust at anomaly 22 on the Greenland side is composed of SDR wedges and LCB and is about 2 km thicker than on the Hatton margin, whereas no extrusive basalt or LCB are identified in this part (Figure 5.7). The distance from COB to C22 on the Greenland side is ~170 km and it is approximately 70 km longer compared to the Hatton margin. In the Greenland margin, the COT zone is ~70 km wide and the maximum crustal thickness is about 22 km at the landward boundary of the COT, while the Hatton margin has a narrow COT zone (40 km) and the maximum thickness of the thickened crust is almost equal at the landward limit of COT. It can be concluded that the Greenland side had a higher seafloor spreading rate and shows a moderate crustal thinning toward the C22 as compared to the Hatton margin.

The distribution of extrusive basalt is clearly asymmetric. In the Hatton margin it extends >200 km along the continental crust and the SDR wedges with ~40 km length interpreted in the COT zone, whereas the observed extrusive basalt with >100 km SDR wedges extends from the continental slope to the entire oceanic crust. The LCB has nearly the same continuation from landward limit of the COT to Anomaly C22, but on the Greenland side the LCB is about 130 km longer comparatively due to higher spreading rate (Figure 5.7).

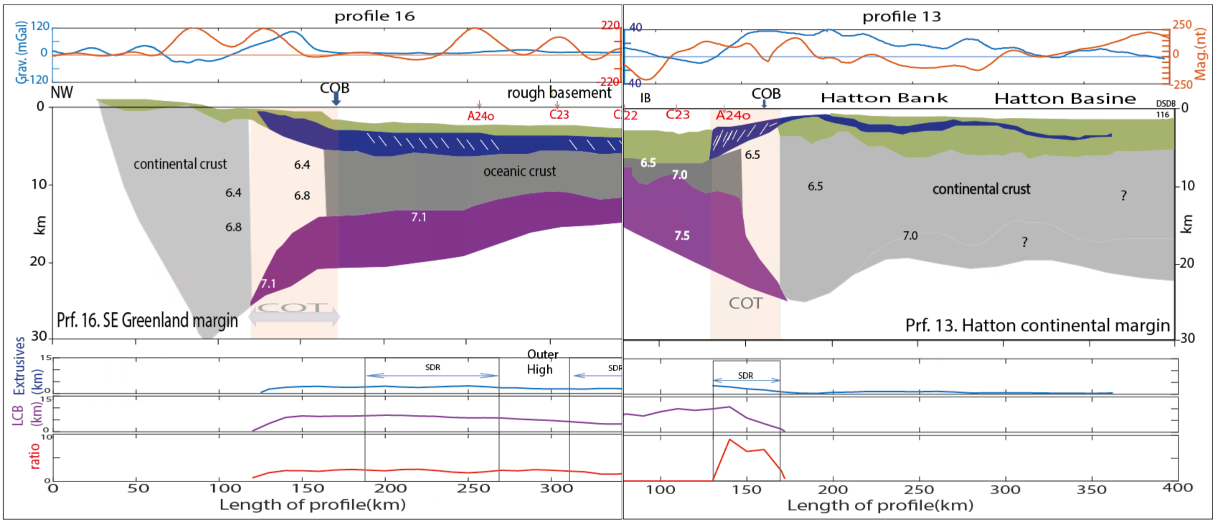


Figure 5.7: Conjugate Profiles 16 and 13 which are joined at anomaly C22. Describe the breakup magmatic evolution in the continental, oceanic crusts and COT zones across the SE Greenland and the conjugated Hatton continental margin Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km.

The conjugated **profiles 14 and 15** are located in southern most part of the NE Atlantic margins and passes through the Hatton continental margin and the SE Greenland margin respectively (Figures 5.1 and 5.8). Both profiles exhibit almost the same thickness (~9 km) of the oceanic crust at anomaly C22 and the distance from COB to C22 in the Greenland margin is only ~10 km longer than the Hatton margin. The continental crust on the Greenland margin has a thickness of ~28 km and shows a rapid crustal thinning (underlain by LCB) in about 100 km horizontal length within the COT zone. In the Hatton margin, the continental crust is ~20 km thick and along the COT zone (~100 wide) the crustal thickness increases due to developments of the LCB. The LCB in the Greenland margin has a velocity of >7.2 and an average thickness of ~5 km, and extends along the COT zone to the oceanic crust close to C22. However, the LCB on the Hatton side has a velocity between 7.2-7.4 km/s and has an average thickness of ~10 km with no continuation in the oceanic crust and mainly accumulated in the COT zone (100 km wide).

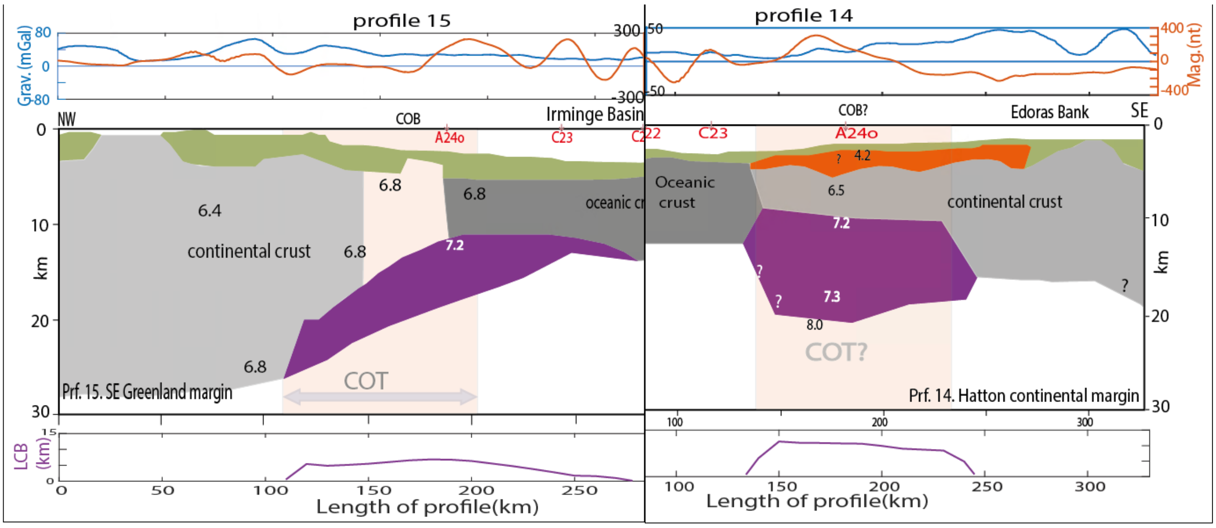


Figure 5.8: Conjugate Profiles 14 and 15, which are joined at anomaly C22. Describe the breakup magmatic evolution in the continental, oceanic crusts and COT zones across the southernmost part of NE Atlantic margins. Magnetic and gravity anomalies are shown on top of the profile and the graphs below the profile show the thicknesses of the LCB and extrusives, and the ratio between them for every 10 km

5.2 Lateral variations

A quantitative estimation of magma production in the conjugate NE Atlantic margin is established. The main purpose has been to describe the volumetric variation and extents of the magmatic bodies Table 5.1 shows calculated area, ratio and the maximum thickness of the LCB, extrusives and the SDR on the different profiles. The mapped area of the LCB and the extrusive basalt has been carried out along the conjugate margins (Figures 5.1).

South of the FIR the average area of the LCB is relatively constant about 800 km^2 and the extrusive ranges between ~700 km^2 and ~200 km^2 is only in P11, 12 and 13 extrusive are found. On the conjugate margin south of the GIR the area of the LCB is ranging between ~600 km^2 and ~1200km^2 the extrusive area ranges between 0 and ~800 km^2. South of the GIR-FIR the LCB area is comparable higher than the north. Between the EJMFZ and the North of the FIR the area of the LCB is ranging between ~600 km^2 and ~1200 km^2 the extrusive is between 200 km^2 and ~500km^2. On the conjugate margin between north of the GIR and the JMFZ the data coverage is very poor or absent and the only observed area of the LCB on P19 is about 300 km^2 (Figure 5.1).

North of the EJMFZ the area of the LCB is ranging between~2200 km^2 and~400 km^2 the extrusive is between ~200 km^2 and ~500 km^2 and in the northern most profile P1 the magmatic bodies are absence. On the conjugate margin north of WJMFZ the area of the LCB is ranging between ~2000 km^2 and ~100km^2 the extrusive area ranges between ~500 and ~200 km^2 in not found on the northernmost profile P23 (Figure 5.1).

The thicknesses of the LCB and extrusive basalts vary significantly along and across the margins. . In the SE Greenland margin the LCB has a wide extent from continental to oceanic crust while in the NE Greenland margin it is mainly observed below the continental part. Whereas the LCB in northern parts of the NW European margin has a vast distribution from the continental to oceanic crust, the southern parts of this margin have a LCB which mainly accumulated near the COT zone or beneath the continental crust.

The Figure 5.2 shows the thickness ration between the LCB, extrusive basalt and SDR on each profile along the margins located according to the oceanic crust at magnetic anomaly C22. In the West European margin all the ratios extend landward of the C22, whereas on the SE Greenland margin they have an extension seaward of C22. As a result, it shows that the extrusive basalt in the SE Greenland margin developed in longer periods. The SDR are the thickest part the extrusives and it is mainly defined around the COT and on the oceanic crust. The average thickness ratio between the LCB and SDR along the NW European margin is approximately less than 3 where as in the East Greenland margin the average ratio varies significantly between 0.5 and 6 (Figure 5.2).

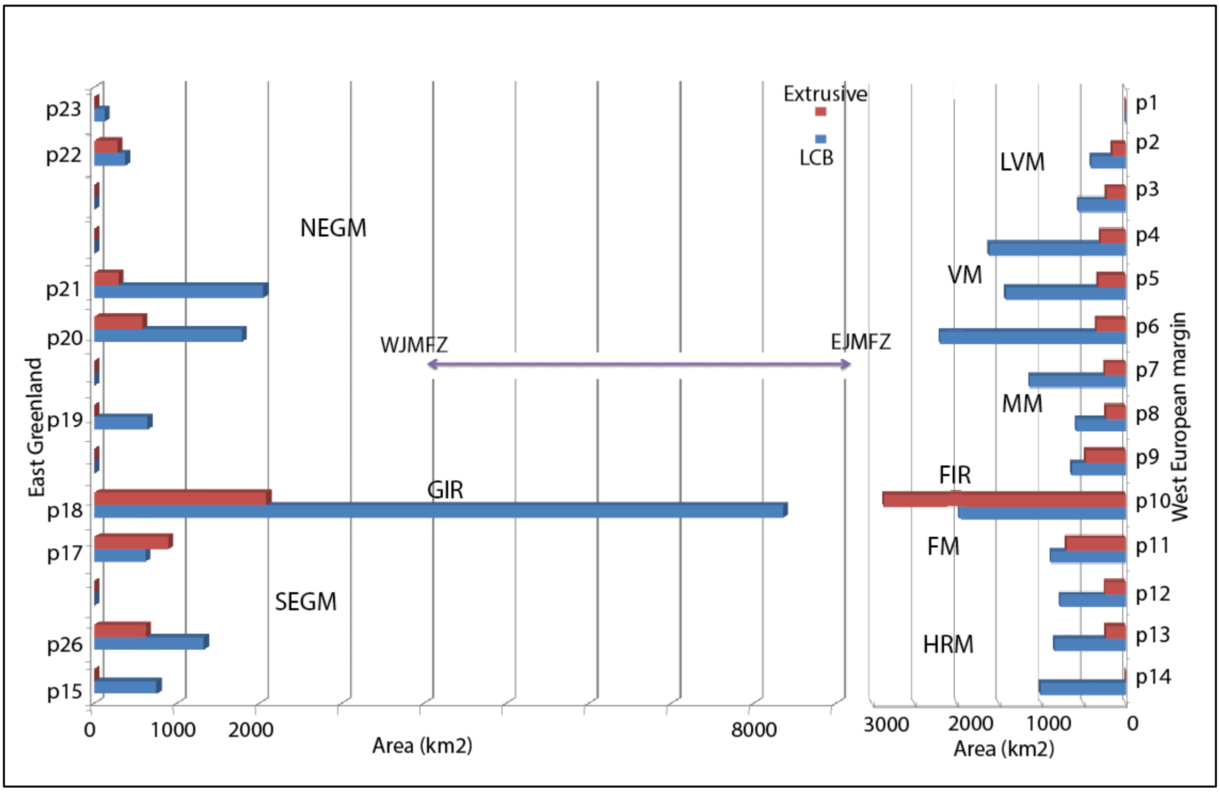


Figure 5.1: calculated area of the LCB (blue) and the extrusive basalts (red) along the NW West European and the East Greenland margins. EJMFZ: Jan Mayen Fracture Zone, WJMFZ: West Jan Mayen Fracture Zone, LVM, VM, MM, FM, and HRM indicate Lofoten-Vesterålen, Vøring, Møre, Faeroe and Hatton-Rockall margin respectively. SEGM and NEGM are the southeast and northeast Greenland margins respectively.

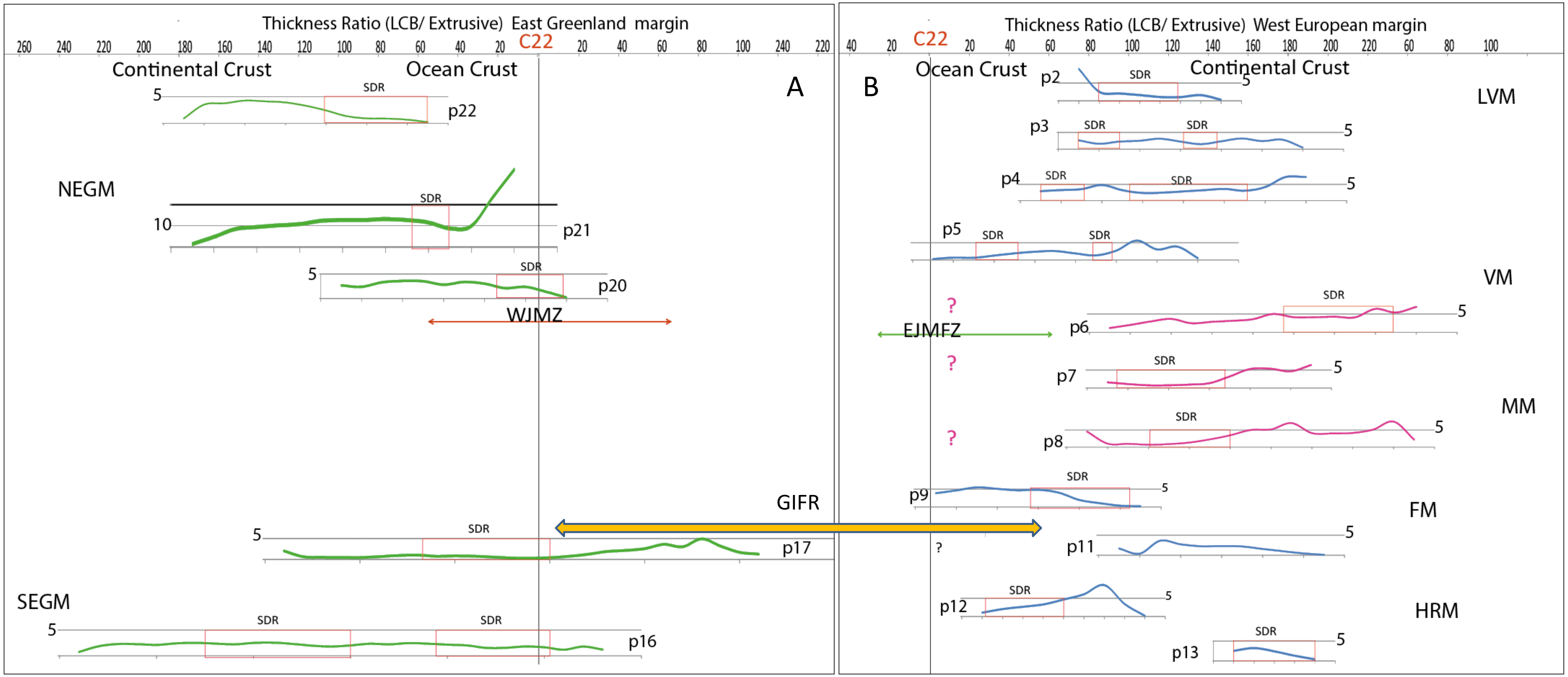
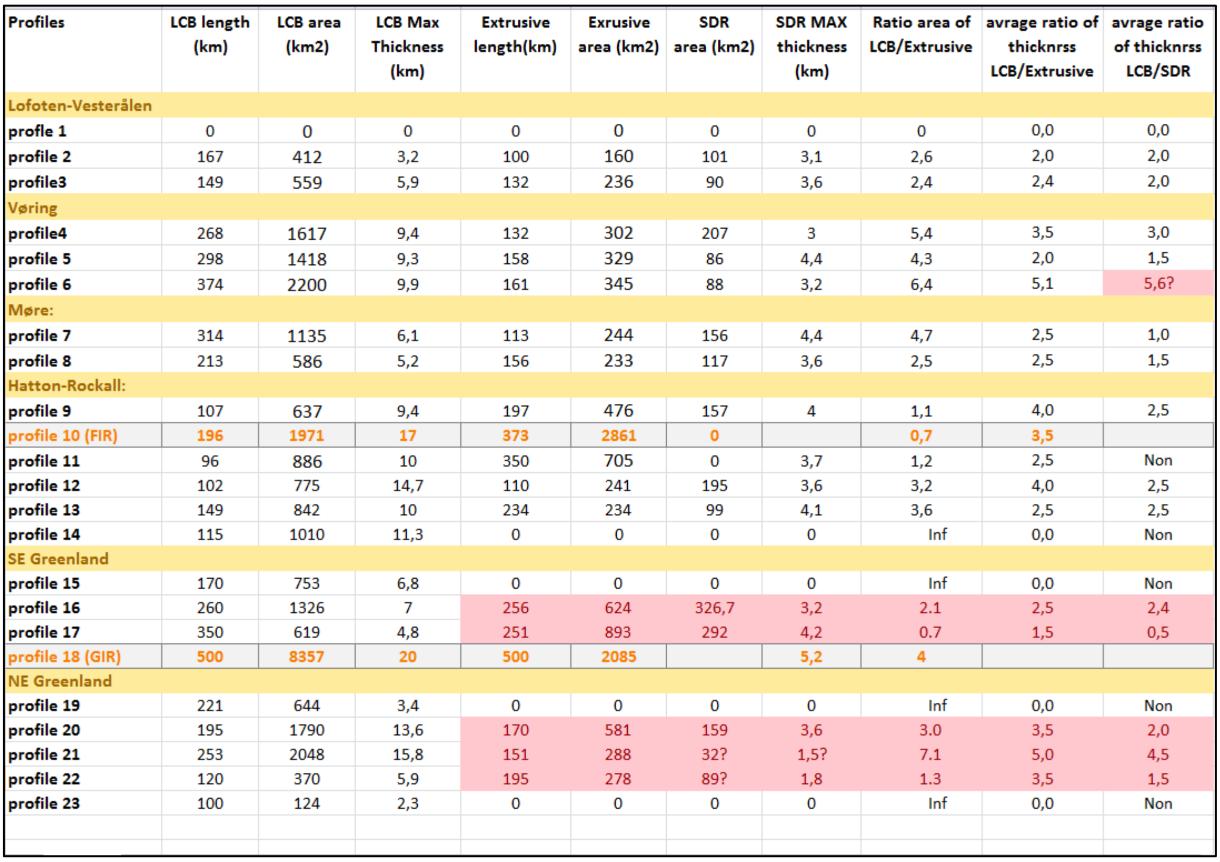


Figure 5.2: The estimated thickness ratio (LCB/Extrusive) together along the East Greenland margin (A) and the West European margin (B). The ratio graphs are placed with respect to the distance from magnetic anomaly C22. The graphs whit red color indicates the profiles where the anomaly C22 is not defined. EJMFZ: Jan Mayen Fracture Zone, WJMFZ: West Jan Mayen Fracture Zone, LVM, VM, MM, FM, and HRM indicate Lofoten-Vesterålen, Vøring, Møre, Faeroe and Hatton-Rockall margin respectively. SEGM and NEGM are the southeast and northeast Greenland margins, respectively.

Table 5.1: Quantitative analysis of LCB, Extrusive and SDR along each profile in NE Atlantic Margins (The red numbers have higher uncertainty).



Profiles	**LCB length (km)**	**LCB area (km2)**	**LCB Max Thickness (km)**	**Extrusive length(km)**	**Exrusive area (km2)**	**SDR area (km2)**	**SDR MAX thickness (km)**	**Ratio area of LCB/Extrusive**	**avrage ratio of thicknrss LCB/Extrusive**	**avrage ratio of thicknrss LCB/SDR**
Lofoten-Vesterålen										
profle 1	0	0	0	0	0	0	0	0	0,0	0,0
profile 2	167	412	3,2	100	160	101	3,1	2,6	2,0	2,0
profile3	149	559	5,9	132	236	90	3,6	2,4	2,4	2,0
Vøring										
profile4	268	1617	9,4	132	302	207	3	5,4	3,5	3,0
profile 5	298	1418	9,3	158	329	86	4,4	4,3	2,0	1,5
profile 6	374	2200	9,9	161	345	88	3,2	6,4	5,1	5,6?
Møre:										
profile 7	314	1135	6,1	113	244	156	4,4	4,7	2,5	1,0
profile 8	213	586	5,2	156	233	117	3,6	2,5	2,5	1,5
Hatton-Rockall:										
profile 9	107	637	9,4	197	476	157	4	1,1	4,0	2,5
profile 10 (FIR)	**196**	**1971**	**17**	**373**	**2861**	**0**		**0,7**	**3,5**	
profile 11	96	886	10	350	705	0	3,7	1,2	2,5	Non
profile 12	102	775	14,7	110	241	195	3,6	3,2	4,0	2,5
profile 13	149	842	10	234	234	99	4,1	3,6	2,5	2,5
profile 14	115	1010	11,3	0	0	0	0	Inf	0,0	Non
SE Greenland										
profile 15	170	753	6,8	0	0	0	0	Inf	0,0	Non
profile 16	260	1326	7	256	624	326,7	3,2	2.1	2,5	2,4
profile 17	350	619	4,8	251	893	292	4,2	0.7	1,5	0,5
profile 18 (GIR)	**500**	**8357**	**20**	**500**	**2085**		**5,2**	**4**		
NE Greenland										
profile 19	221	644	3,4	0	0	0	0	Inf	0,0	Non
profile 20	195	1790	13,6	170	581	159	3,6	3.0	3,5	2,0
profile 21	253	2048	15,8	151	288	32?	1,5?	7.1	5,0	4,5
profile 22	120	370	5,9	195	278	89?	1,8	1.3	3,5	1,5
profile 23	100	124	2,3	0	0	0	0	Inf	0,0	Non

6 Conclusions

A quantitative comparison of LCB and extrusives has been done on 23 profiles along NE Atlantic passive margins. The NE Atlantic margin is subdivided into several margin segments according to the fracture zones and lineaments. The amounts of magmatic material have significant variations along and across the conjugate margins. The area between the Greenland-Iceland ridge and Jan Mayen Fracture Zone has a complex tectono-magmatic model on both sides of the margins.

The ratio between the LCB thickness and the extrusive thickness has been estimated over each margin. Our result shows that the SDR in the west European margin developed mainly before C22 time, whereas in the SE Greenland margin it extends farther seaward of C22. The average thickness ratio between the LCB and SDR in the west European margin is mainly less than 3 whereas on the East Greenland margin it varies significantly, between 0.5 and 6.

We showed that the along the North Atlantic conjugated margin the distribution of magmatism is asymmetric. The thickness of the LCB varies significantly along-strike and across-strike. The thicker part of the LCB is usually situated below the SDR. The average ratio between the LCB and the extrusive volcanism is ranging between 2 and 4 in the West European margin while it is ranging between 2.5 and 4.5 in the Greenland margins. The average thickness ratio between the LCB and SDR in the west European margin is mainly less than 3 whereas on the East Greenland margin it varies significantly, between 0.5 and 6.

Finally we should mention that the extrusive basalts along the NE Greenland margin are poorly constrained and the area between the West Jan Mayen Fracture Zone and the Greenland-Iceland Ridge has very poor data coverage. Furthermore, some of the profiles have a limited construction of the magmatic body which is affecting the precision of the estimated value. Another limitation is the calculation of the shallow intrusive complex (sills and dyke), which has a clear relation between LCB and extrusive basalt. The nature of the LCB is ambiguous, which is an important aspect for interpretation of the LCB.

Starting with the North Atlantic area, our results and workflow will provide the base for a new improved calculation of magma volumes in volcanic passive margins on a broader world wide scale.

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