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Tectonic Variation and Structural Evolution of the West Greenland Continental Margin

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Abstract

Due to its geographic extent of over 2500 km, the West Greenland margin provides a much understudied example of a divergent continental margin, both with respect to hydrocarbon exploration and academic studies. A seismic interpretation study of representative 2D reflection profiles from the Labrador Sea, Davis Strait and Baffin Bay was undertaken to identify sedimentary and structural components to elucidate the tectonic development of the margin. Nine horizons were interpreted from six representative seismic lines in the area. Margin-scale tectono-stratigraphy was derived from isochron maps, the geometry of mappable faults and their associated stratal architecture.

Rifting began in Early to Late Cretaceous at c.145 -130 Ma, which was followed by two pulses of volcanism in Eocene and Palaeocene ages. The transition to the drift stage includes a typical subsidence phase but also erosion, uplift and deposition of Neogene postrift packages. The shift in the position of depocentres in the Davis Strait and the Labrador Sea during Palaeocene and Miocene times is evidence for structural modification of the basin bounding faults. Drift stage deformation suggests a possible anticlockwise rotation in the orientation of the spreading axis in Baffin Bay culminating in an ultraslow seafloor spreading.

Seafloor spreading on the West Greenland margin started in the south at 70 Ma in the Labrador Sea and propagated northward into the Baffin Bay by 60 Ma. Prospective petroleum systems include thick Cretaceous age strata, with structural traps provided by grabens and inversion structures. Our structural model provides insight into margin that is highly variable in its structural configuration, further modified by other processes such as magma-assisted rifting which may result in elevated regional heat flow which has considerable impact on hydrocarbon maturation. Further constraining the implications of heat flow associated with volcanic activities in comparison to that associated with lithospheric stretching will be critical in future exploration.

Keywords: Seismic Interpretation, Tectonic, Basin Architectures, West Greenland, rifting, magmatism

1.0 Introduction

Although there has been considerable interest, over a number of decades, in the evolution of sedimentary basins associated with lithospheric stretching (e.g. McKenzie, 1978; Wernicke, 1985; Lister, 1986), recent studies have made significant advances in our understanding of the processes involved. These studies have greatly expanded our understanding on the variability of margins, in particular: the differences between volcanic and non-volcanic margins (e.g. Reston and Perez-Gussinye, 2007; Franke, 2013); the role of depth dependent stretching and multiple rift stages (e.g. Huismans & Beaumont, 2011; Soares et al., 2012); and the influence of mantle plumes (White and McKenzie, 1989; Clift and Turner, 1995; Corti, 2009; Lundin and Doré, 2011). These studies commonly focus on portions of margins, or their equivalents on the conjugate margins. The aim of this study is to consider the lateral variability of a single margin. We chose the West Greenland Margin because of the interplay amongst a number of the key factors including: the presence of a mantle plume; the existence of volcanic and non-volcanic areas on the margin; and changes in extension orientations. Furthermore, the absence of salt enables us to understand margin architecture without the limitations of either sub-salt imaging or salt tectonics.

The West Greenland Margin includes the Labrador Sea, Davis Strait and Baffin Bay (Figure 1). The margin is considered to have formed by the northward propagation of continental rifting and seafloor spreading associated with the breakup of North America from Europe during the Late Cretaceous and Early Paleocene periods (Balkwill et al., 1990; Chalmers, 1991, 2000, 2012; Chalmers and Pulvertaft, 2001; Chalmers et al., 1993; Nielsen et al., 2002; Roest and Srivastava, 1989; Rowley and Lottes, 1988; Schenk, 2011).

The aim of this study is to consider the interplay amongst processes involved along an entire margin during lithospheric rifting and drifting. We describe the basin development along the West Greenland continental margin and consider the implication of this on hydrocarbon exploration. By doing so, we quantify the overall basin fill and architecture during the different phases of basin growth. We demonstrate that the timing of initiation and cessation of rifting together with the duration of sea floor spreading are critical to improving the evolutionary models for the West Greenland margin.

1.1 Tectonic and Geological settings of the West Greenland basin

The earliest rifting event probably occurred in the Early Cretaceous (c.145 -130 Ma) or Late Jurassic periods (Schenk, 2011; Harrison et al., 1999). A second rifting event of Late

Cretaceous and Early Palaeogene age culminated in thermal subsidence and subsequent passive margin sedimentation at ~ 60 Ma (Dam et al., 2000).

The Early Cretaceous rifting event is evidenced by deposition of clastics rocks in half grabens and graben basins, such as the Kitsissut and Appat sequences (Chalmers and Pulvertaft, 2001). Sedimentary facies within this area includes alluvial fan, fluvial, fan-delta, deltaic and shallow lacustrine sandstones and mudstones of the Kome and Atane Formations from Nuussuaq basin (Balkwill et al., 1990; Chalmers and Pulvertaft, 2001; Dam et al., 2000; Figure 2).

A Late Cretaceous unconformity separates deltaic deposits of the upper Albian Atane Formation from fully marine deposits of the lower Campanian Itilli formation (Dam et al., 2000). This Campanian Formation is equivalent to the marine deposits at Fylla Structure Complex Area (FSCA), which is overlain by Kangeq Formation offshore West Greenland. The Kangeq seismic sequences in West Greenland basins were probably deposited into thermally subsiding basins (Chalmers et al., 1993; Chalmers and Pulvertaft 2001). The oldest Mesozoic clastics rocks in the Baffin Bay region are Aptian to lower Albian sandstones of the Quqaluit Formation, described by (Burden and Langille, 1990; Figure 2).

The Aptian-Albian mudstones of the upper Bjarni Formation on the Canadian Labrador shelf are equivalent to the Appat Formation of Greenland. Similarly, the lower Bjarni Formation is equivalent to the Kitsissut Formation of West Greenland (Chalmers et al. 1993, 2012). An unconformity is present between the Cretaceous and Early Paleocene mudstones (Nøhr-Hansen and Dam, 1997). Early Palaeocene mudstones were deposited above the Kangeq Formation (Chalmers and Pulvertaft 2001).The onset of the second rifting event took place in the middle of Paleocene (61 Ma) and was probably associated with seafloor spreading along the West Greenland margin (Oakey and Chalmers, 2012). Extrusion of plateau basalts in both offshore and onshore West Greenland took place in the Late Paleocene and Eocene and is overlain by the fluvio-deltaic and marine deposits of Early Palaeogene age (Chalmers, 2012). Offshore basalts drilled in the Hellefisk-1 and Nukik-2 wells have been interpreted in the Hecla and Maniitsoq Highs (Chalmers et al., 1993, Rolle, 1985). Basalt layers in the southern part of Baffin Bay represent the northernmost extension of the volcanic rocks found in the Davis Strait and were possibly expanded equivalents of sea-floor spreading in Baffin Bay (Whittaker, 1997; Rolle, 1985).

The Labrador Sea and Baffin Bay regions are connected by the Ungava Transform Fault Zone (UTFZ) in the Davis Strait area (Figure 1). The (UTFZ) is characterized by complex structures that were initially extensional. These structures were subsequently affected by both transtension and transpression processes as the (UTFZ) evolved into a transform zone (Skaarup et al., 2006; Sørensen, 2006). A Mid-Eocene unconformity was then developed (Nøhr-Hansen and Dam, 1997) as a result of strike slip movement across the margin as well as the Ikermiut flower structure (Chalmers et al., 1999).

From Mid-Miocene time, the West Greenland basins subsided without further obvious evidence of tectonism, until Late Neogene times (Chalmers and Pulvertaft 2001; Green et al., 2011). Strata of largely fine-medium grained sandstones of slope and fan were deposited as as a result of the second postrift subsidence phase (Dalhoff et al., 2003; Schenk, 2011)

Neogene uplift in the central part of the West Greenland margin is recorded by 2-3 km uplift in the Nuussuaq basin (Chalmers, 2000, Chalmers and Pulvertaft, 2001). Offshore evidence on seismic can be seen in the uplift of the eastern Sisimiut basin (Dalhoff et al., 2003). In the northwest end of Baffin Bay channel erosion is observed which is probably related to Neogene uplift in the Jones Sound, southern Nares Strait and Lancaster Sound (Harrison et al., 2011). The cause of Neogene uplift is still unknown. Although, subsidence analysis of the margin reveals that Neogene uplift is unrelated to subsidence in offshore areas (McGregor et al., 2012).

2.0 Materials and methods

Hydrocarbon exploration started in the Arctic region in the Late sixties with the collection of gravity, magnetic, seismic and drilled borehole data. During the last 50 years existing information has been substantially enriched by a series of completed 3D seismic surveys and a significant amount of 2D seismic data. No major hydrocarbon discoveries, however, have yet been made. Access to ~ 65,000 km of 2D processed and stacked seismic reflection data was provided by the Geological Survey of Denmark and Greenland (GEUS) and the TGS-NOPEC Geophysical Company (TGS) for this study. In addition, information from seven published wells (Dalhoff et al., 2003) was used to create synthetic seismograms to tie well data with intersecting seismic sections. The well ties were used to constrain both the age and the lithology of the interpreted horizons. Since the wells are located farther from the seismic lines, extrapolation of the stratigraphic interpretation away from the wells was carried out by following key stratigraphic horizons where possible (Sørensen, 2006).

A seismic-stratigraphic approach was used (Figure 3) to interpret the seismic data (Badley, 1985). Reflection terminations (e.g. onlap, down lap, erosional truncation) were used to identify major sequence boundaries /unconformities on seismic sections. Reflection packages were categorised as prerift, synrift, and postrift (Figure 3). Furthermore, seismic facies used to discriminate megasequences include high amplitude reflections, continuity, frequency variation and lap geometries (e.g. Mitchum Jr et al., 1977).

Faults were manually mapped from seismic reflection then displayed as lines in map-view (Figure 1). Even with relatively large spacing between 2D seismic lines (8 km in Nuuk West Province, 50 km in Cape Farewell, and 20 to 25 km in Disko West and Baffin Bay respectively), it was possible to recognize and link major faults based on their geometries, dip direction and the amount of displacement. Multiple lines were used to connect the faults in order to create fault array maps and constrain the geological sense of regional faults trends along the margin.

Having correlated the key seismic reflections across the basins, surfaces were generated that accounted for picked faults and areas of erosion or non-deposition. Two way travel time (TWTT) thickness maps were used to establish 1) relative stratigraphic thickness trends, 2) zones affected by faulting, and 3) the overall basin architecture.

3.0 Tectonostratigraphy

The nine horizons interpreted include Sea Bed (SB); base Quaternary (BQ); Mid-Miocene Unconformity (MMU); Mid-Eocene Unconformity (MEU); Top Palaeocene (TP); Palaeocene Basalt (PB); Top Cretaceous (TC): Mid-Lower Cretaceous (MLC); and Acoustic Basement (Bs). The high amplitude (peak) and continuous nature of the SB, MMU, MEU, TP, and MEC reflections provided a high confidence interpretation whereas the moderate to discontinuous (trough) reflector character of TC, PB, BQ and Bs reflections resulted in some uncertainty in the interpretation. The Acoustic Basement (Bs), Mid-Lower Cretaceous (MLC) and Top Cretaceous (TC) reflectors were not mapped in Disko West as they have been masked by the overlying Palaeocene basalt (PB) (Figure 1).

The main structural domains of the margin are Baffin Bay, Davis Strait and the Labrador Sea. These major regions define the West Greenland margin and are characterized by a large variety of complex structures including grabens, half-grabens, horsts, flower structures, and thrust faults. These structures, and the associated sedimentary packages within the basin fill, represent a multi-phase evolution of the margin. At the margin scale, this complex evolution can be simplified into four phases of deformation rifting, transition, seafloor spreading and Neogene uplift. The pre-rift strata are characterized by parallel reflectors that can extend down to the acoustic basement.

Synrift sediments have wedge shaped seismic reflector packages and thickness increased towards the fault plane. The earliest rift phase is of Lower Cretaceous to Late Cretaceous in age and defines the main graben structures. The transition period from rifting to drift stage is interpreted to be of Early Palaeocene to Mid-Eocene age. Postrift phase, in which no fault controlled thickening is observed occur above the Mid-Miocene unconformity. There is significant erosional truncation and uplift in a number of areas of the West Greenland margin in particular at Mid-Eocene and Mid-Miocene level. Neogene uplift also affected the margin.

3.1 Structure and history of the individual basins in West Greenland

Recent studies have sub-divided the margin into four structural provinces namely, Cape Farewell, Nuuk West, Disko West and Baffin Bay basins (e.g. Knutsen et al., 2012; Figure 1).

We describe the main structures and basin fill within these provinces using interpreted 2D seismic lines to compare and contrast the variation in stratigraphic and structural configurations along the margin (Figure 2). We focus on the main basins in each province, which include Kivioq and Melville Bays and the Upemavik basin in Baffin Bay Province, the Aaisaa basin in the Disko West Province; the Lady Franklin, Kangamuit, Sisimuit and Fylla Structures Complex basins in Nuuk West Province; the South Fylla Structures Complex basin and the Cape Farewell basin in Cape Farewell Province (Figure 1).

3.2 Baffin Bay Province (BBP)

The structure of Baffin Bay Province is characterized by two NW-SE trending grabens (Kivioq and Melville Bays) that are separated by the intervening Melville Ridge (Figure 1). The two grabens, which are broadly asymmetric, comprise features that are approximately 50 km wide and over 310 km long with sedimentary rocks thickness of up to 5.0 second TWTT in the Melville Bay area (Figure 4). The Kivioq basin is 200 km long and 25 km wide; whereas the Umberk basin is 80 km long by 50 km wide (Table 1). The Melville Ridge has minor sedimentary rockson top of it (~0.1 second or less) suggesting that it remained a structural high throughout most of the evolution of the margin (Figure 4).

The graben-controlling faults are commonly planar structures with displacements of up to 4.5 second TWTT, and are correlatable along trend as a single fault (Figure 4) in excess of 310 km in length in the interior of the Baffin Bay basin (Figure 1). In addition to the graben forming structures, a number of intra-basin faults with the same orientation as the basin bounding faults are observed with displacements of up to 1.0 second TWTT (Figure 4). As would be expected, these latter faults have shorter lengths compared to the boundary faults.

Despite the distance from Baffin Bay to the closest well tie-point of 800 km away from the representative seismic line, the continuous nature of the principal megasequence reflections allows the correlation of the packages into the province with some degree of confidence. The rift phase in Baffin Bay Province is Lower Cretaceous and was controlled by many of the main basin bounding faults, e.g. the Melville Platform fault (Figure 4). However, not all the faults were active during the earliest stages of rifting, with much of the regional vertical displacement being accommodated on a master fault that is now in the middle of the Kivioq basin. These dominant faults became inactive before the cessation of rifting (Figure 4). Instead, the majority of thickening (often sedimentary rocks thickness up to 0.5 second TWTT) during the late stage of rifting is localised onto the graben bounding faults (Figure 4) such as the northern Kivioq Ridge Fault, the northern and southern Melville Ridge Fault and the southern Melville Platform fault (Figures 1 and 4).

During the transition phase from Early Palaeocene to Mid-Miocene sedimentary rocks are characterized by wedging and thickening towards the faults plane, are truncated against Kivioq Ridge fault and are thinner than Cretaceous synrift deposits. The postrift package from mid Miocene to present thins towards the south which is likely to be a reflection of a reduction in sediment supply from the margin towards the north and differential compaction (See Figures 1 and 4).

As noted, the Baffin Bay Province is dominated by a series of grabens demarcated to the south by the Kivioq Ridge (Figure 4). Across the ridge there is a rapid transition over 20 km from continental crust across the gravity high and into a transition zone (Figure 4). The continental region as a whole is characterized by large rotated basement blocks composed of seaward dipping faults and deep synrift basins. The central area of Baffin Bay is bounded by a collapsed structure created by an inclined West limb and a sub-horizontal to gently dipping eastern limb (Figure 4). The transition zone is characterized by thinner synrift sedimentary rocks, basalts and seaward dipping reflectors (SDRs) that separates rotated continental basement faulted blocks from the oceanic crust. The oceanic crust is interpreted in the southwest part of Baffin Bay and evident as a chaotic reflection occurring at depth of ~4800 ms TWTT.

The most common fault geometry observed includes horst and graben structures resulting from NW-SE normal faults that divide the Baffin Bay basin into NW-SE structural domains. A NE-SW fault also divides the Kiviog basin from the Upemavik basin (Figure 1). These NE-SW faults, ridges and basins were initiated during the earliest phases of rifting (Figure 4). Deposition of Cretaceous sedimentary rocks in Baffin Bay was into extensive basins in Kivioq and Melville Bay basin (Figure 4) which is at least 5.0 second TWTT thick. The Melville Ridge is a subsurface high on the NE part of the bay (Figure 4). The total thicknesses in Melville and Kivioq basins are approximately 5.0 second to 4 seconds TWTT respectively (Figure 4).

3.3 Disko West Province (DWP)

The deepest reflection that is imaged in the Disko West Province is the Paleocene Basalt (PB), which is identified as a high-amplitude reflection and is mappable both across the margin and along the Aasiaa basin. The Aasiaa basin is 350 km long and 30 to 110 km wide and the Disko High is 280 km long and 40 to 60 km wide (Figure 1). The Nussuaq basin is 130 km long and 60 km wide (Table 1). This indicates that the volcanic rocks cover an area of ~150,000 km^2 (Figure 1). Evidence from boreholes, seismic reflection and refraction data located both west and east of Disko Island indicate the presence of thick clastics rocks of

Cretaceous age (Chalmers et al., 1999; Dam et al., 2009, Funck et al., 2012; Suckro et al., 2013 and 2012). This is supported by the presence of similarly aged stratigraphy that is found in the east of the Disko West Province that has not been covered by basalt (Figure 1). Although the basalt geometry is not imaged, the basalt reflection package is remarkably continuous.

In Disko West Province, the faults are dominated by steeply dipping normal faults with a series of half grabens with lengths of up to 350 km and widths of 110 km (Figures 1 and 5). The faults show clear thickening of up to 0.6 second TWTT during the Top Cretaceous-Top Paleocene package (Figure 5). In contrast to the basin bounding faults in Baffin Bay, these faults (N-S and NW-SE) are present in sigmoidal plan view geometry and most likely resembles fault within a pull-apart basin (Figures 1 and 5). This is supported by the presence of strike-slip faults within the area. Towards the southwest, postbasalt faulting is very limited. The exception is a few relatively small normal faults on the eastern flank and a normal fault on the northern edge of the Davis Strait High (Figure 1). However, mapping of gravity and magnetic anomalies suggest that oceanic crust is present with a probably age of 60 Ma (Oakey and Chalmers, 2012). Reflections above the oceanic crust clearly show significant thickening of postrift wedge (Figure 5) from approximately 0.1 second TWTT in the northeast nearshore to 1.5 second TWTT in the southwest. This thickening is most evident in the Mid-Miocene to Quaternary packages (Figure 5). The thickness variation is unrelated to rifting but deposition of postrift packages into topography created by the emplacement of the basalt.

3.4 Nuuk West Province (NWP)

The Nuuk West Province has a number of strike-slip structures that trend broadly in a NE-SW orientation and are associated with the Ungava transform fault (Figure 1). In terms of this province length, the Nuuk West Province is about 550 km long from the Fylla complex structure to the Sisimut basin and has a width of 150 km in the north and 260 km in the south (Table 1). The geometry in the south of the Nuuk West Province is remarkably different from that to the north. Instead of a relatively unfaulted flexure, the south is dominated by a number of basement highs (Hecla, Manlitsoq, Kangamuit, Fylla) separated by grabens and half-grabens, different from the faulted north.

The absence of the Paleocene Basalt (PB) in this area (except on the Hecla and Maniisoq Highs) allows the identification of Top Acoustic Basement (Bs) with greater certainty. Cretaceous rifting is again interpreted in this region and the interpretation in this work suggests a series of isolated, large (> 7 km) rift basins during this phase (Figure 6). The Late Cretaceous package is more uniformly distributed and is mappable across at least some of the basement highs suggesting postrift sedimenta in most of the margin (Figure 6). The nature of this unit however is rather variable. Within the Lady Franklin and Nuuk (Figure 6); Sisimiut (Figure 7); and South Fylla Structures Complex (Figure 8) basins there is demonstrable thickening of strata into rift faults typical of synrift intervals. In contrast, many of the basin faults within the Cretaceous grabens (e.g. Cape Farewell) show no thickening (Figure 8). This may be an indication of how extension was progressively localised onto a limited number of faults during the rift episode. Thick basalts are deposited on both flank of the Hecla High (Figure 6) and a flower structure is interpreted within the Sisimiut basin (Figure 7). Sediments of postrift package were probably deposited during thermal subsidence resulting in onlapping of sediments onto the topography highs. In the Hecla High, postrift strata are thin and post Mid- Miocene in age in contrast to the thick (~1.0 second TWTT) postrift packages of the Fylla Structures Complex Area (Figure 6). The postrift sedimentary succession are thicker (~2.0 second TWTT) in the Sisimiut and Kangamiut basins than in the (FSCA) and Hecla basins (Gregersen and Skaarup, 2007). In addition, the eastern side of Sisimiut basin is characterized by non-deposition of sediment resulting in the absence of Mid-Miocene to present day (Figure 8).

3.5 Cape Farewell Province (CFP)

The Cape Farewell Province shows faults up to 200-400 km in length and typical throws of 0.5 seconds TWTT (Figures 1 and 8). The (SFSCA) is 400 km long and 100 km wide, whereas the Cape Farewell is approximately 400 km long and 200 km wide (Table 1). One of the faults has a throw of 1.5 second TWTT that may be the result of reactivation during the late stage of rifting in Late Cretaceous (Figure 8). The Cape Farewell Province also marks a significant narrowing in the width of the continental margin as the transition from attenuated continental crust into full oceanic crust occurs over ~80 km (rather than >250 km as is the case further north. On the continental crust the rifting geometry is dominated by relatively planar faults and rotated faults blocks (Figures 1 and 8). The imaging of the footwall cut-offs suggest faults remain planar and show no evidence of a listric geometry with depth. From stratal thickening it is evident that the faults were active during the Cretaceous, similarly to basins in the north. However, the fault throws are significantly smaller (maximum observed throws are <0.5 second TWTT) in contrast to reactivated faults with throws of 1.5 second TWTT. This difference in fault geometry is also reflected in a change of fault orientation. Faults in the southern Nuuk West Province are dominated by a broadly north-south orientation whereas in Cape Farewell they have a NW-SE orientation.

In the more distal portion of the basin, the lower section is characterized by low amplitude reflectivity suggestive of oceanic crust at ~ 8 seconds TWTT (Figure 8). In addition, the presence of ~ 80 km wide magnetic (70 Ma) and (60 Ma) at the south and north respectively further justifies the presence of the oceanic crust (*cf*. Chalmers and Laursen 1995; Figures 1 and 8). The seismic character of the area between the attenuated continental crust containing the rift faults and the oceanic crust is rather enigmatic and may be either Seaward Dipping Reflector (SDR), basaltic intrusions; this is interpreted as the transition zone (Figure 8). It is onlapped by the Upper Cretaceous unit and then overlain by Paleocene basalts that are attributed to break-up related magmatism. These volcanic rocks appear to mask all internal reflections at a transition zone of c. 80 km observed between the oceanic and continental crust. The west section of the transition zone has high amplitude reflectors that may be seaward dipping reflections (Figure 8), and this, coupled to a positive gravity anomaly above it, suggests that it is a late stage volcanic event that may have been the pre-cursor to break-up. Overlying the entire section (Figure 8), including the oceanic and continental crust, is a postrift sequence with a rather constant thickness of ~1.3 second TWTT, reflecting a uniform subsidence across the margin. The exceptions are postrift packages of Palaeocene to Eocene ages, which show local onlap onto both the margin to the east and a volcanic edifice on the ocean crust.

4.0 Discussion.

4.1 Models of the Tectonic Development of the West Greenland margin

The development of the West Greenland margin involved deposition of thick sediment wedges during rifting, faulting of the rift sequence, and erosion of fault scarps that formed during early lithospheric extension by postrift sedimentation. The regional erosion during the latter stage is revealed by Mid-Eocene and Early Miocene unconformities. The rift event interpreted in this study area occurred intermittently with the emplacement of volcanic rocks during the Palaeocene and Eocene. Categorically, the pre-rift packages are flanked by an irregular dome structure in Cape Farewell; the dome is interpreted as a remnant of the oceanic crust or serpentine zone (Figure 9), and it is shown as chaotic and high-amplitude reflection at a deeper stratigraphic level on the seismic data (Figure 8). Furthermore, we surmise that the boundaries of the oceanic crust are delimited by a probably zone of SDRs developed prior the initial opening of the oceanic crust. Neogene uplift, post seafloor spreading are dated ~11-10 Ma and 7-2 Ma (cf. Chalmers, 2000; Green et al., 2011; Japsen et al., 2006). These observations all suggest a rather complex and variable margin evolution.

We propose a tectonic model that integrates the seismic interpreted faulting and overall basin geometry with the key stage of tectonic development (Figure 9):

I. Rifting stage (145-130 Ma): NE-SW extension across the West Greenland margin. This rift produced rotated fault blocks that formed horsts and grabens in the Cape Farewell, Baffin Bay and Nuuk West Provinces. The basin geometry in Disko West Province at this stage is not covered by the available seismic data. However, deposition of Cretaceous age strata onshore suggests that the province was affected by this rift stage. Late stage rifting comprises an early magmatic pulse during which the margin was intruded by dykes in Nuuk West and probably Disko West.

II. Magma-poor phase (80-70 Ma): recorded as the development of a continental-ocean transition zone that presumably includes attenuated continental crust in the Cape Farewell and Baffin Bay provinces or serpentinised zone. Possible thermal subsidence occurs on other areas across the West Greenland margin. The margin underwent postrift thermal subsidence as materialised by the marine mudstones of Kangeq sequence, which show little evidence of extension prior to the onset of seafloor spreading at 60 Ma (Chalmers 2012).

III. Seafloor spreading (70-60 Ma): Seafloor spreading started in the south of Cape Farewell Province (70 Ma) and is likely to have propagated to the northwest of Cape Farewell Province (61 Ma) and then transferred to Baffin Bay via the Ungava fault zone to form oceanic crust at (60 Ma) (See figure 9). The presence of a Magnetic high suggests uniform stretching of the lithosphere in Cape Farewell. Disko West and Baffin Bay showed magnetic low implying slow seafloor spreading on an underlying strongly extended continental crust and/or serpentinised mantle (Reid and Jackson, 1997). We propose that the cessation of seafloor spreading occurred during (48 Ma) and at (33 Ma) in Cape Farewell and Baffin Bay Provinces respectively, corroborating the works of Chalmers and Pulvertaft (2001) and Oakey and Chalmers (2012). The shift in spreading axis was from NNE in Palaeocene to NNW in Eocene in Baffin Bay (See also Oakey and Chalmers, 2012). This is attributed to an anticlockwise rotation of spreading axis by the oceanic crust or a shift in magmatic intrusion from West to East Greenland. Hence, the margin subsided after the breakup in the Davis Strait in Palaeocene to Late Eocene times, supporting the model of postrift subsidence reported onshore Disko and Nuussuaq basins (cf. Green et al., 2011).

4.2 Magmatism and influence of the mantle plume

For the study area, there continues to be a debate whether the Eocene and Palaeocene volcanism events are the product of multiple mantle plumes or a single mantle plume. The separation and movement of the Greenland and Canada cratons were probably influenced by the migration of a mantle plume that may have caused transient thermal uplift, extension and subsequent plate movements (Harrison et al., 1999). Several authors favoured a single plume hypothesis for the emplacement of all the volcanic provinces (Larsen et al., 1999; Nielsen et al., 2002; Storey et al., 1998; Torsvik et al., 2001). The geochemistry of early picrites of West Greenland are similar to subaerial Icelandic basalts and are formed by similar greater degrees of melting of their source mantle than their Icelandic counterparts (Holm et al., 1993). The volcanic eruption of the West Greenland picrites occurred ~5-6 Ma earlier than the start of volcanism in eastern Greenland (Gill et al., 1995). A possible scenario describing the plume dynamics under West Greenland is that the ~ 60 Ma events involves volcanism from a fast moving upper mantle plume that rapidly spreads out horizontally on encountering the base of the lithosphere (*cf.* Larsen et al., 1999; Nielsen et al., 2002). Palaeomagnetic reconstructions show that mantle and crust processes are linked via complex and enigmatic cause-and-effect relationships (Torsvik et al., 2001).

Our data analysis supports the notion that the West Greenland plume formed at ~60 Ma as suggested by earlier workers (e.g. Storey et al, 1998). Critically, there was early rifting along the whole margin during a magma-poor phase with more extension recorded in the south. The evidence is for a plume that is present at the transfer zone rather than at the area of greatest extension. Subsequently, the plume played a minor role in rift initiation and development. Therefore, we suggest that the role of the plume was less significant than proposed by previous authors. The plume may have contributed to the cessation of rifting in the study area. Our model proposes that the West-Greenland volcanic margin developed after a period of amagmatic extension during the Cretaceous in accord with the work of Abdelmalak et al. (2012). Consequently, the area was subjected to regional uplift in the Danian (65–60Ma) before the extrusion of pre-breakup magmatic rocks.

4.3 Contribution to understanding of lithospheric stretching

Based on the model defined in section 4.1, we propose a) multiphase extension and continental breakup for the West Greenland margin and that b) individual basins within West Greenland comprise both magma-poor and rich basins. The seismic stratigraphic division from this work is consistent with the classification of Schenk (2011). As the transition from rifting to drifting is marked by the breakup unconformity (BU) of Falvey (1974) and Franke (2013); the BU in this study is the mid-Miocene horizon. Angular unconformities with erosional truncation on seismic profiles were interpreted as the Rift Onset Unconformity (ROU) in line with the definition of Falvey, (1974). In the study area, the ROU is the Top Cretaceous Horizon. The nature and position of the Ocean-Continent Transition (OCT) is marked by the presence of Seward Dipping Reflectors (SDR). Structurally, the interpretation of compressional and inversion structures accompanied by strike-slip faulting and local transtensional faults and flexures are expression of the Eurekan orogeny (Gregersen et al., 2013). However, the identification of the transition between synrift and postrift settings may not always be reflected by a simple breakup unconformity (Alves et al., 2009; Soares et al., 2012). These authors show that the "breakup unconformity" is a Lithospheric Breakup Surface (LBS) that is not always developed as an unconformity and that the entire lithosphere is involved in the breakup process, not only the continental crust. The complex nature of the transition phase, which is stratigraphically between the demonstrable synrift and postrift phases, in this study is a reflection that the simple concept of the breakup unconformity is not applicable. Hence, the mid-Miocene (BU) may only indicate basinward shift of the extensional locus and not the end of rifting processes along West Greenland margins (Falvey 1974; Soares et al., 2012).

Our model offers supporting evidence for the occurrence of a passive continental margin comprised of both magma-rich and magma-poor lithospheric extension. Since most passive margins develop in response to lithospheric extension, passive margins can be classified into two end-members depending on the volume of extension-related magmatism (Franke, 2013). Baffin Bay and Labrador Sea are magma-rich margins characterized by SDRs at their ocean-continent transition. Keen et al (2012) showed that the Labrador Sea is exemplified by the presence of excess magmatism, SDRs, and volcanic plateau and thick igneous crust. This agrees with the classification of Funck et al (2007) and Gerlings et al (2009). In contrast, Skaarup et al (2000) proposed that the Labrador Sea is a non-volcanic margin. From this work, the Davis Strait is interpreted as a magma-poor margin that is defined by a wide area of highly attenuated crust where the upper crust is deformed by planar faults. Unlike other magma-poor passive margins, the detachment over which the fault soles was not interpreted. Therefore, the West Greenland to the north and south are magma-rich margins while centrally it is magma-poor margin. This highlights that single margins can be highly variable and these simple end members are not always applicable.

The role of mantle plumes in the evolution of magma-rich margins has been a subject of debate. Crustal rifting can evolve in conjunction with a plume head as: a) where the plume head triggers the rift evolution by a circular uplift in which the earliest and widest rift is expected to be close to the plume head and the width of the rift decreases away from the plume; and b) where the rift starts farther from the plume with a consistently decreasing width of the rift toward the plume (Franke, 2013). Examples include Iberia–Newfoundland, the Equatorial Atlantic Ocean, and East Antarctica–Australia. We have shown that extension along the West Greenland was less dependent on the mantle plume and that continental extension and break-up is not always associated with large amounts of volcanism.

The evolutionary model presented in this paper has implications for all aspects of hydrocarbon prospectivity in West Greenland. Reservoir intervals are likely to be present in synrift strata deposited in the observed half grabens of substantial size as well as postrift clastic deposits (Table 1). These intervals include the fluvio-deltaic sandstones of the Cretaceous Atane Formation in the Nuussuaq basin, the mid-Cretaceous to Paleocene marine slope channel sandstones and the marine canyon sandstones equivalent to the incised valley fill sandstones of the Paleocene Quikavsak Member (Dam et al., 2009; Dam et al., 1998). The deposition of these intervals, and the facies variations within them, will be intimately controlled by the basin and fault architecture that we have presented (Figure 9). Of equal importance as reservoir distribution is the trapping mechanisms, which within our interpretation are likely to include both structural and stratigraphic plays. Early rotated faults blocks, grabens and their horsts are important structural trap forming three-way closure. Additional trapping mechanism may include Upper Cretaceous compressional structures and rollover four-way closures formed by synrift packages (Figure 6).

The Paleocene was a time of widespread volcanic activity in the central part of the Davis Strait (Larsen and Pulvertaft, 2000; Pedersen and Larsen, 2006), when several kilometres of plume-related volcanic rocks were extruded regionally. Consequently, basalts extruded into Cretaceous strata are going to alter both reservoir and basin scale heat flow scenarios. The synvolcanic strata of the Baffin Bay Province may be of interest for hydrocarbon exploration activity (Pedersen et al., 2002) with the stratigraphic position of volcanic rocks is playing a role on reservoir scale source rock maturation. The Neogene was a time of widespread clastic input along north Atlantic passive margins, indicative of Neogene uplift that has been documented from many onshore locations around the Arctic and north Atlantic (Japsen et al., 2005; Japsen and Chalmers, 2000). The implications of such uplift are poorly constrained on other margins but are likely to influence sediment supply, geometry of stratigraphic traps and may also alter regional heat flows (Paton et al., 2008).

5.0 Conclusion

We present a new structural framework for the West Greenland margin. This reveals a long and complex evolution, and in particular demonstrates:

- Rifting margin in Early Cretaceous with synrift packages intercalated with volcanic sills. The Palaeocene basalt occurred in the Disko West, south Baffin Bay and the north Cape Farewell Provinces. These extrusive rocks are connected with the breakup stage during the development of the West Greenland margin.
- The architecture of faults in the Davis Strait High suggests continuity between the structures of Labrador Sea and Baffin Bay. Strike-slip faults in the Davis Strait acted as transfer zones for displacement during seafloor spreading during and after volcanic activity.
- Incipient rifting on the West Greenland margin was unaffected by the mantle plume. Seafloor spreading started in the Cape Farewell, propagated to the north West and later slowly to Baffin Bay where the underlying continental crust is strongly extended over a probable serpentinised mantle.
- The basins on the West Greenland margin such as the Sisimiut, Kangamiut and Melville Bay Graben have significant potential for hydrocarbon reservoir and seal in thick Cretaceous strata. Structural traps include half grabens and grabens with further potential in possibly inverted structures.
- The West Greenland margin is characterized by magma-rich and poor basins.

In conclusion, tectono- stratigraphic packages studied from seismic reflection and borehole data interpretation has permitted the basin architecture to be established and allowed us to construct a model for the tectonic development of West Greenland basins. The West Greenland margin shows complex tectono-stratigraphy and the along margin variability, in particular the variation of magma-poor to magma-rich margin, the relatively small influence of plume emplacement, and the significant variation in rift architecture along the margin has a significant impact on the hydrocarbon potential resources. Hence, the boarder basin geometry have more accommodation space for sediments and higher potential for hydrocarbon accommodation than their narrow counterparts.

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Figure 1: Regional tectonic framework map of the West Greenland study area at Top Cretaceous level. Generated by data integration of, 2D seismic data (GEUS and TGS), Structural Provinces after Knutsen et al., (2012). Global Seafloor Fabric and Magnetic chrons from Roest & Srivastava 1989 (dotted dark blue lines; C21-C33); and Chalmers and Laursen 1995 (dotted red lines; C27). Seafloor from Müller 2008 which has been modified to fit data seismic. Continental-Oceanic Transition zone (COT) has been characterized by Seaward Dipping Reflectors (SDRs), basalts and dikes. Ungava Transform Fault Zone (UTFZ), Fylla Structures Complex Area (FSCA) and South Fylla Structures Complex Area (SFSCA)

Figure 2: Generalized stratigraphic column of the West Greenland margin (this paper) differential subsidence and uplift among these basins have been established.

Figure 3: (a) Reflection terminations used for the seismic interpretation in this study. (b) Interpreted seismic examples from the study area showing applied reflection termination on a sequence boundary showing onlap, toplap, downlap and erosional truncation. (c) Chronostratographic interpretation in this study.

Figure 4: Seismic profile line 1 (line position in Figure 1) showing the interpreted sedimentary units in north Baffin Bay Province. Synrift sediments of lower and upper Cretaceous are in Melville Bay and Kivioq basins. Transition time include the Paleocene and Eocene sediments and postrift sediments from Mid-Miocene to present. The oceanic crust exposed at c. (6.0 second TWTT) southwest of Kivioq ridge. A Continental-Oceanic Transition (COT) zone is at c. (4.5 Second TWTT) and characterized by SDRs and basalt. Half right part is Kan92 of (GEUS) seismic data and other half on the right is reprocessed BB08RE11 (TGS) seismic data.

Figure 5: Seismic profile line 2 (line position in Figure 1) showing the interpreted sedimentary units of synrift in the Disko West Province including Paleocene Basalt and early Eocene sediments. Postrift from Mid- Miocene to present sediments. Cretaceous synrift sediments masked by a basalt layer. The approximate position of (COT) zone occurs at c. (4.5 second TWTT). The oceanic crust exposed at c. (3.8 second TWTT) southwest of Aaisaa basin.

Figure 6: Seismic profile line 3 (line position in Figure 1) showing the interpreted sedimentary units in the Nuuk West Province. Synrift sediments of lower and upper Cretaceous in Sisimint Basin. Transition time includes the Paleocene and early Eocene sediments and postrift sediments from Mid- Miocene to present. The basin characterized by flower structures as part of the (UTFZ) and Paleocene dikes in the lower Cretaceous sediment.

Figure 7: Seismic profile line 4 (line position in Figure 1) showing the interpreted sedimentary units in the Nuuk West Province. Synrift sediments of lower and upper Cretaceous in Nuuk and Lady Franklin Basins. Transition time includes the Paleocene to Mid-Miocene sediments. Postrift sediments from Mid- Miocene to present. Paleocene dikes in the lower cretaceous sediment.

Figure 8: Seismic profile line 5 (line position in Figure 1) showing the interpreted sedimentary units in Cape Farewell Province. Synrift sediments of lower and upper Cretaceous in (SFSCA). Transition time includes the basalt of Early Paleocene to Mid-Miocene. Postrift sediments from Mid- Miocene to present as well as oceanic crust formation. The oceanic crust is flanked by high-amplitude reflections which might be a (COT) zone. This (COT) zone occurs at c. (6.0 second TWTT).

Figure 9: West Greenland basin evolution model.

Table 1: Summarizing the major basins geometries and thicknesses of west Greenland continental margin

Table 1: Summarising the major basins geometries and thicknesses of west Greenland continental margin

West Greenland provinces	Basins geometry			Synrift sediment thicknesses	Transition sediment thicknesses	Postrift sediment thicknesses
Baffin Bay Province	Basin Name	Length Km	Width Km	TWTT, Second	TWTT, Second	TWTT, Second
	Melville	310	50	2.50	1.35	1.00
	Kivioq	200	25	1.41	1.00	2.00
	Upemavik	80	50	0.98	1.00	2.15
Disko West	Aasiaa	30-100	350	n	1.60	2.00

Province	Disko high	40-60	280	n	0.50	0.14
	Nuussuaq	130	60	1.0	n	n
Nuuk West Province	Sisimiut	120	100	2.40	1.30	1.10
	Ikimurt	120	40	2.12	1.04	1.00
	Kangamuit	110	50	2.14	1.1	1.20
	Maniisoq high	80	60	1.02	0.22	0.75
	Nuuk west	200	80	2.53	0.8	1.21
	Lady franklin	180	80	3.67	1.2	1.00
	Fylla Structures Complex	110	100	1.55	0.80	1.5
	Helca high	120	55	1.87	0.5	1.06
Cape Farewell Province	South Fylla Structures Complex	400	100	1.05	0.75	0.95
	Cape Fairwell	400	200	0.80	0.96	1.5

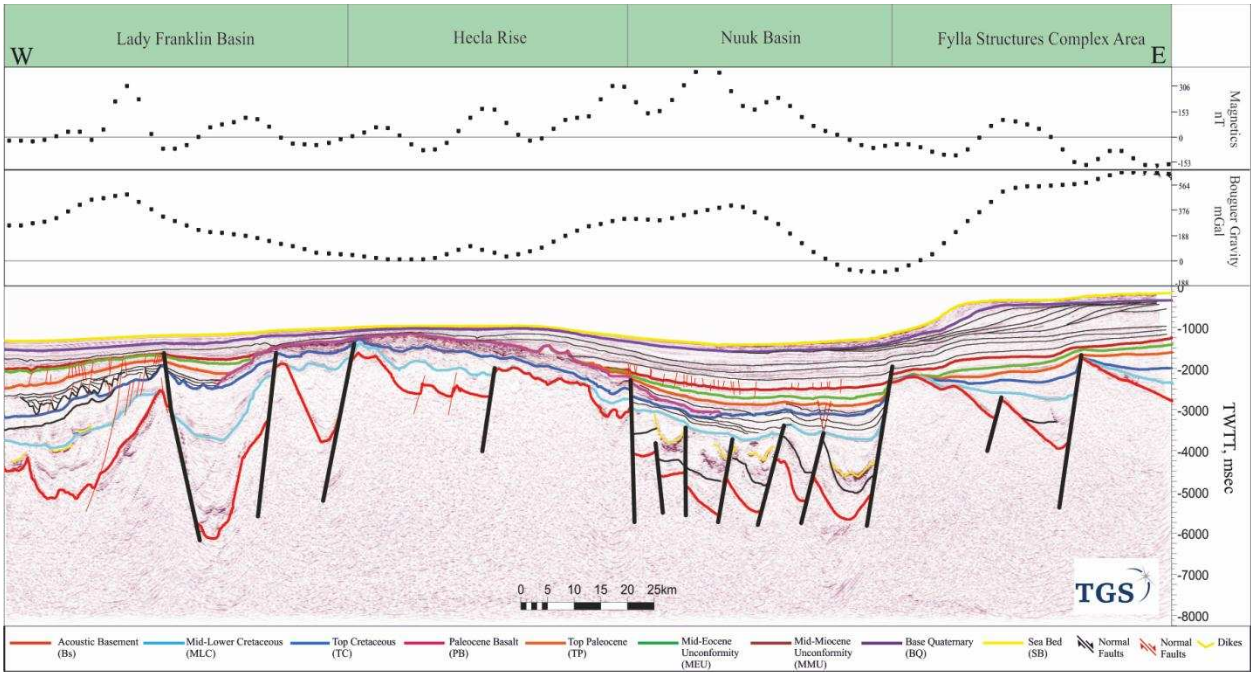

Lady Franklin Basin
Hecla Rise
Nuuk Basin
Fylla Structures Complex Area
W
E
Magnetics nT
Bouguer Gravity mGal
TWTT, msec
0 5 10 15 20 25km
TGS
Acoustic Basement (Bs)
Mid-Lower Cretaceous (MLC)
Top Cretaceous (TC)
Paleocene Basalt (PB)
Top Paleocene (TP)
Mid-Eocene Unconformity (MEU)
Mid-Miocene Unconformity (MMU)
Base Quaternary (BQ)
Sea Bed (SB)
Normal Faults
Normal Faults
Dikes

Fig 7

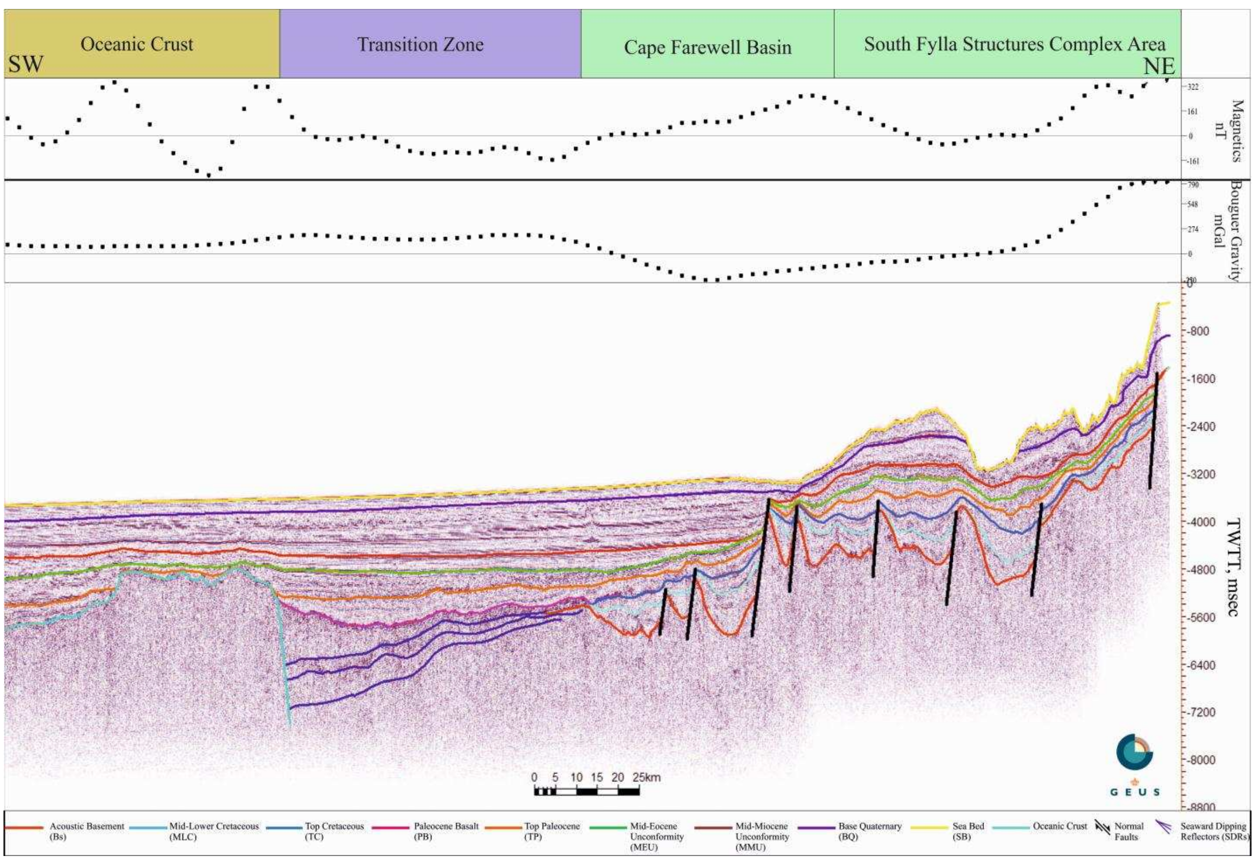

Oceanic Crust
Transition Zone
Cape Farewell Basin
South Fylla Structures Complex Area
SW
NE
Magnetics nT
Bouguer Gravity mGal
TWTT, msec
0 5 10 15 20 25km
GEUS
Acoustic Basement (Bs)
Mid-Lower Cretaceous (MLC)
Top Cretaceous (TC)
Paleocene Basalt (PB)
Top Paleocene (TP)
Mid-Eocene Unconformity (MEU)
Mid-Miocene Unconformity (MMU)
Base Quaternary (BQ)
Sea Bed (SB)
Oceanic Crust
Normal Faults
Seaward Dipping Reflectors (SDRs)

Fig 8

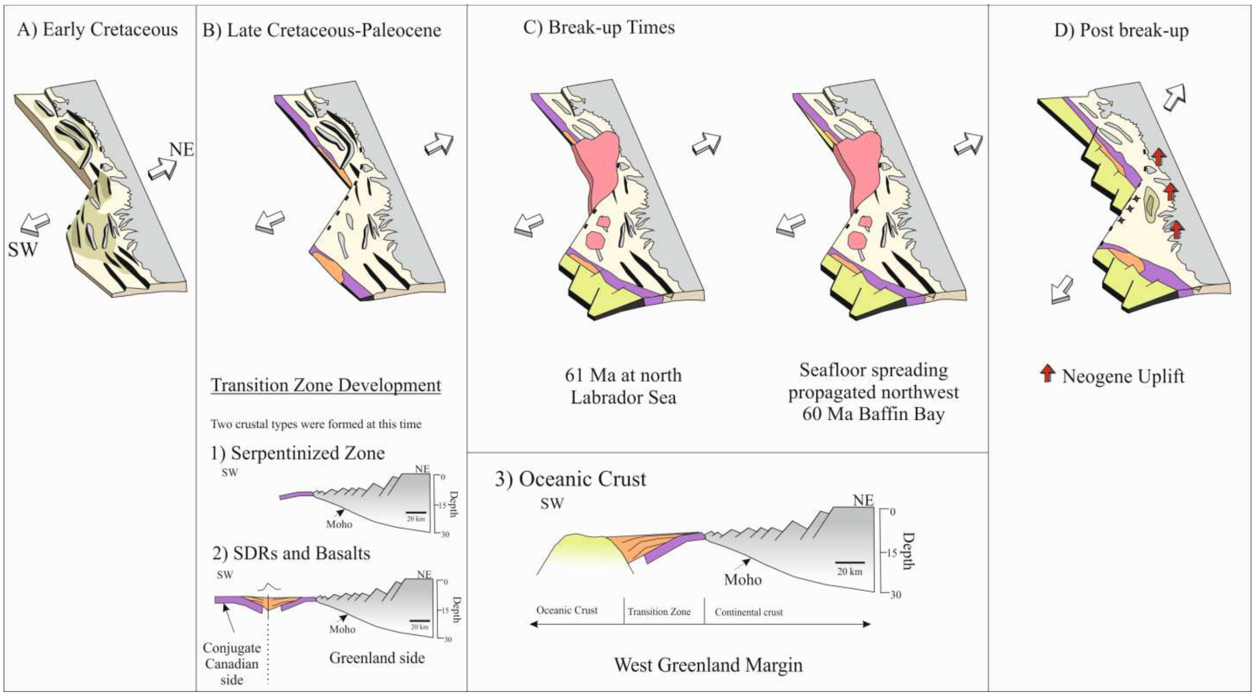

A) Early Cretaceous
NE
SW
B) Late Cretaceous-Paleocene
Transition Zone Development
Two crustal types were formed at this time
1) Serpentinized Zone
SW
NE
Moho
20 km
Depth
0
15
30
2) SDRs and Basalts
SW
NE
Moho
20 km
Conjugate
Canadian
side
Greenland side
C) Break-up Times
61 Ma at north
Labrador Sea
Seafloor spreading
propagated northwest
60 Ma Baffin Bay
3) Oceanic Crust
SW
NE
Moho
20 km
Depth
0
15
30
Oceanic Crust
Transition Zone
Continental crust
West Greenland Margin
D) Post break-up
Neogene Uplift

Fig 9

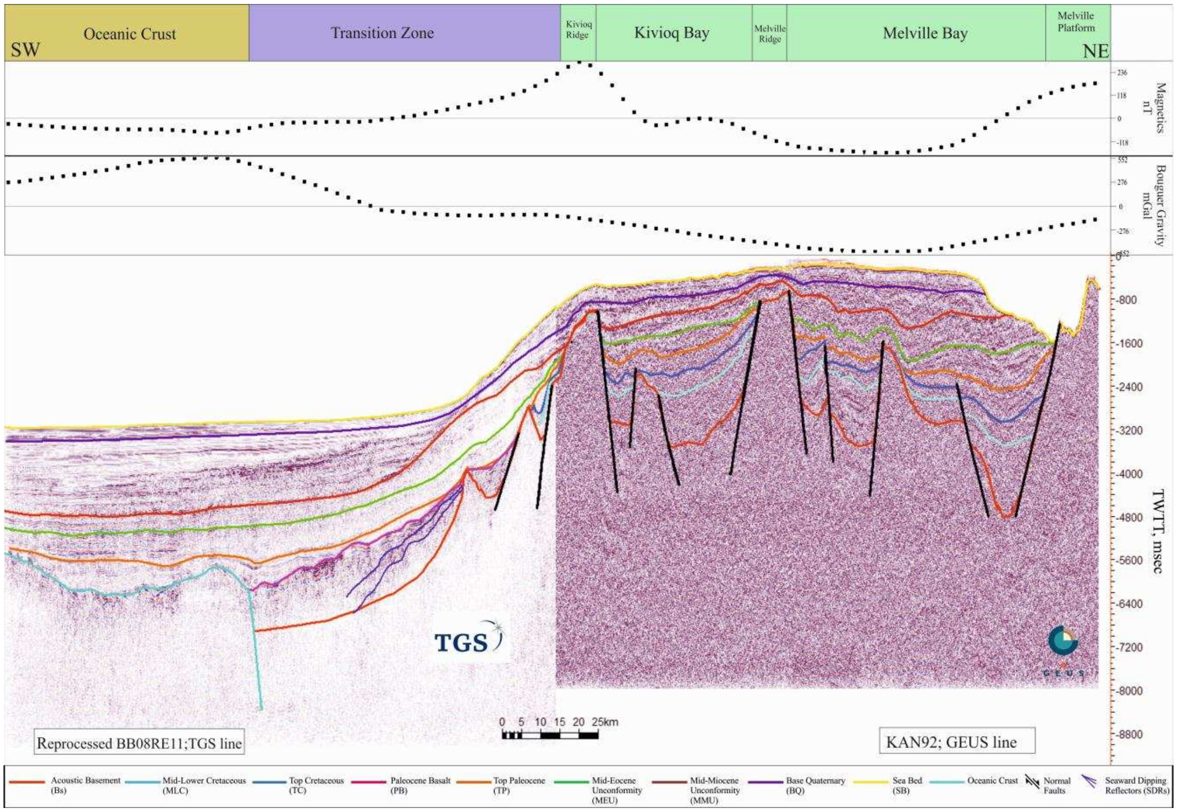

Oceanic Crust
SW
Transition Zone
Kivioq Ridge
Kivioq Bay
Melville Ridge
Melville Bay
Melville Platform
NE
Magnetics nT
Bouguer Gravity mGal
TWTT, msec
TGS
Reprocessed BB08RE11;TGS line
KAN92; GEUS line
0 5 10 15 20 25km
Acoustic Basement (Bs)
Mid-Lower Cretaceous (MLC)
Top Cretaceous (TC)
Paleocene Basalt (PB)
Top Paleocene (TP)
Mid-Eocene Unconformity (MEU)
Mid-Miocene Unconformity (MMU)
Base Quaternary (BQ)
Sea Bed (SB)
Oceanic Crust
Normal Faults
Seaward Dipping Reflectors (SDRs)

Fig 4

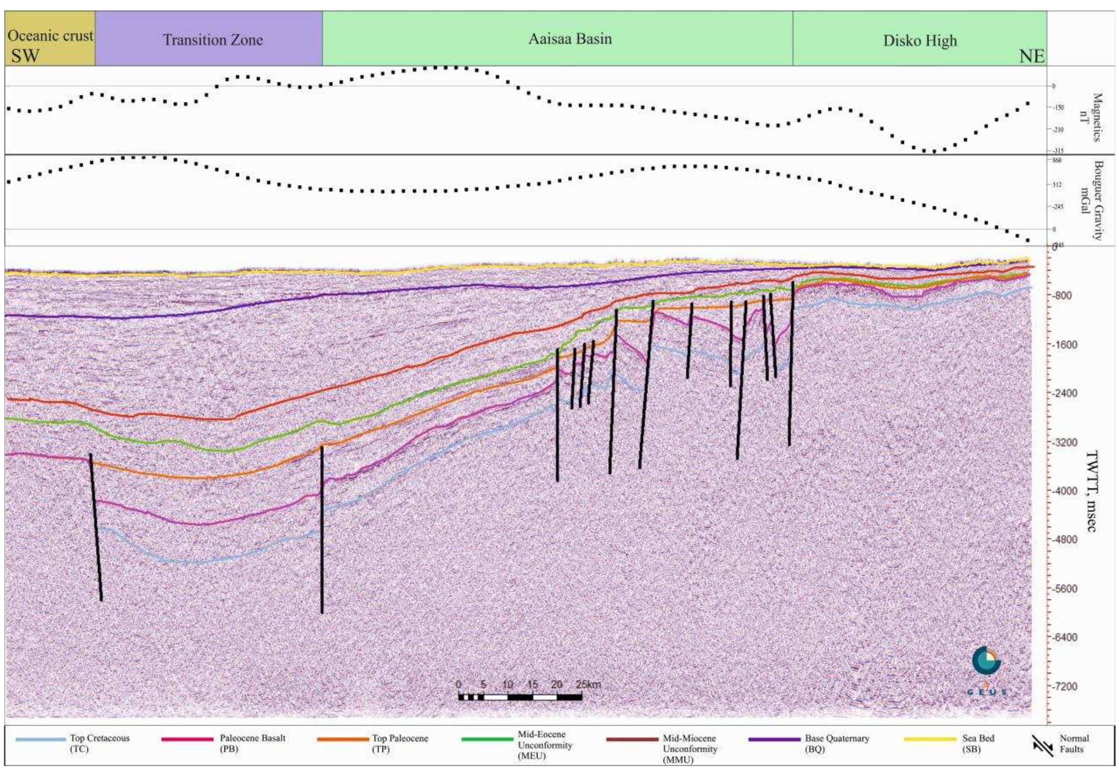

Oceanic crust
SW
Transition Zone
Aaisaa Basin
Disko High
NE
Magnetics nT
Bouguer Gravity mGal
TWTT, msec
0 5 10 15 20 25km
Top Cretaceous (TC)
Paleocene Basalt (PB)
Top Paleocene (TP)
Mid-Eocene Unconformity (MEU)
Mid-Miocene Unconformity (MMU)
Base Quaternary (BQ)
Sea Bed (SB)
Normal Faults

Fig 5

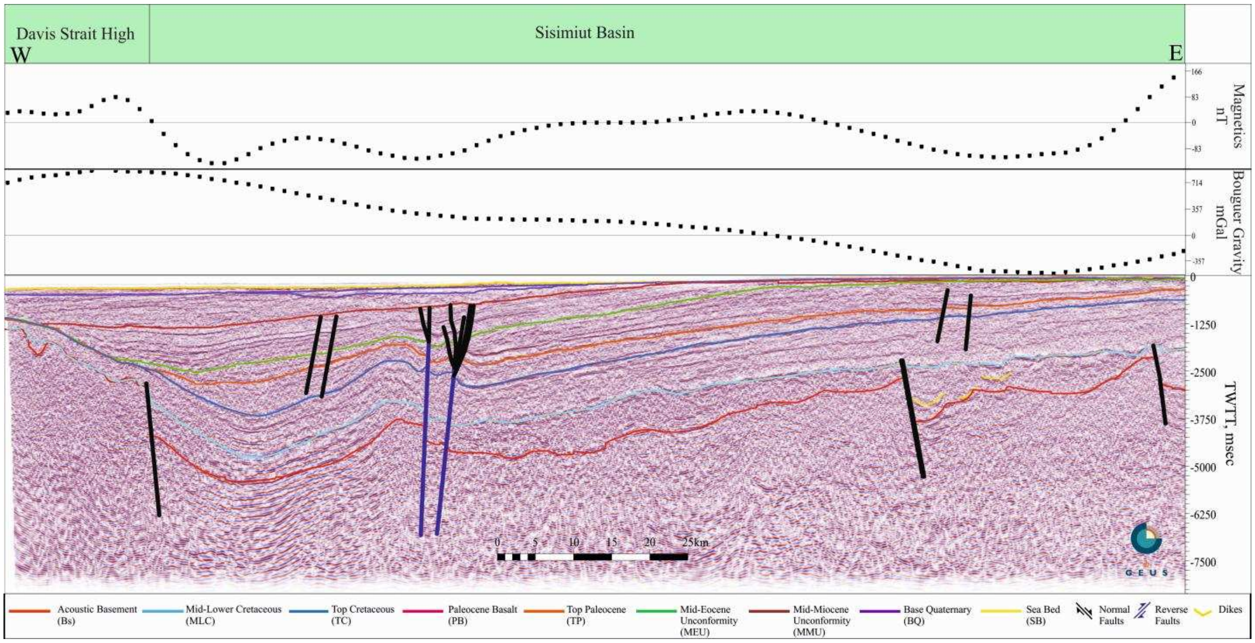

Davis Strait High
Sisimiut Basin
W
E
Magnetics nT
166
83
0
-83
Bouguer Gravity mGal
714
357
0
-357
0
-1250
-2500
-3750
-5000
-6250
-7500
TWTT, msec
0 5 10 15 20 25km
GEUS
Acoustic Basement (Bs)
Mid-Lower Cretaceous (MLC)
Top Cretaceous (TC)
Paleocene Basalt (PB)
Top Paleocene (TP)
Mid-Eocene Unconformity (MEU)
Mid-Miocene Unconformity (MMU)
Base Quaternary (BQ)
Sea Bed (SB)
Normal Faults
Reverse Faults
Dikes

Fig 6

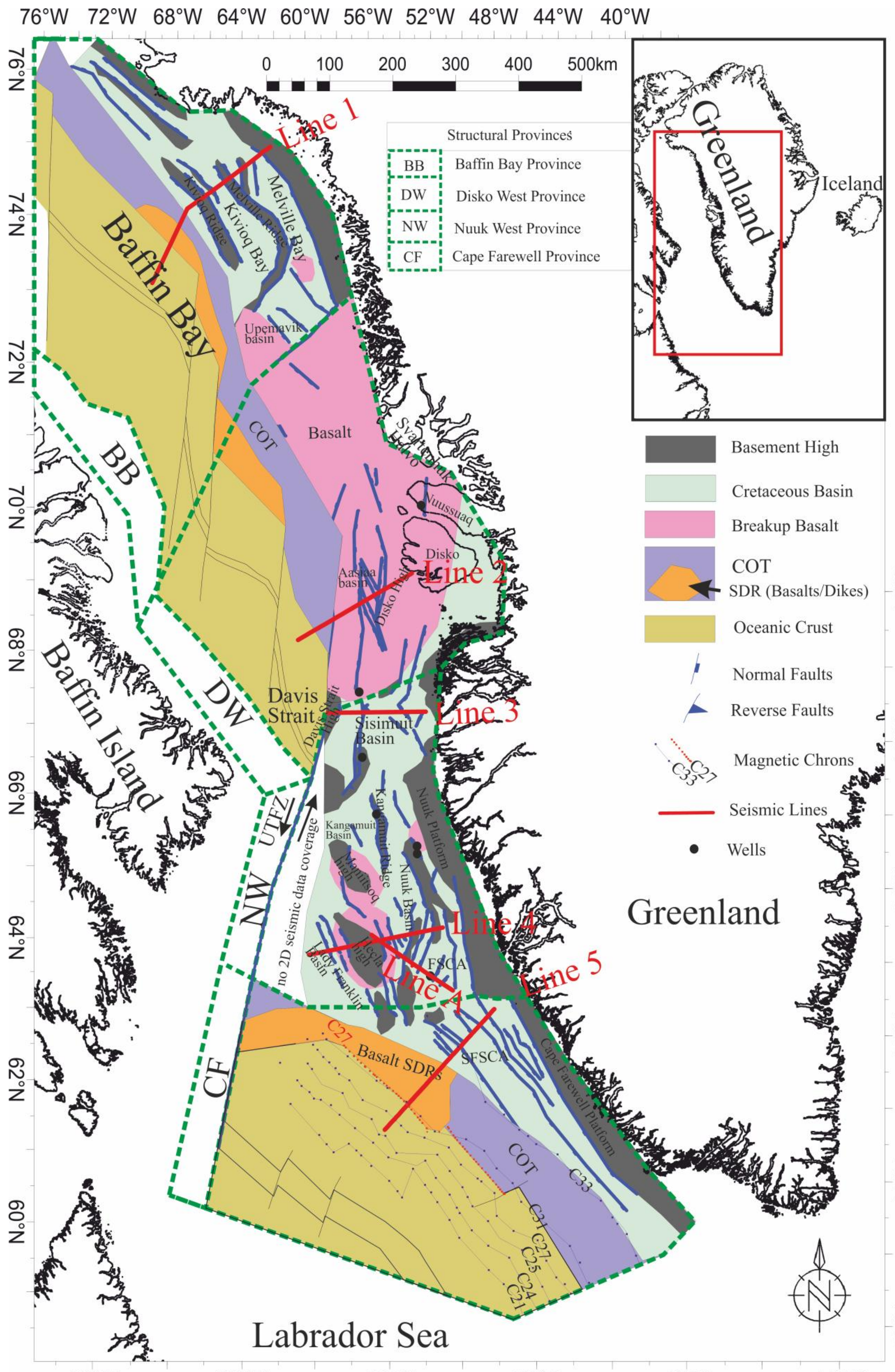

Structural Provinces
BB Baffin Bay Province
DW Disko West Province
NW Nuuk West Province
CF Cape Farewell Province
Greenland
Iceland
Basement High
Cretaceous Basin
Breakup Basalt
COT
SDR (Basalts/Dikes)
Oceanic Crust
Normal Faults
Reverse Faults
Magnetic Chrons
Seismic Lines
Wells
Line 1
Line 2
Line 3
Line 4
Line 5
Line A
Baffin Bay
Baffin Island
Davis Strait
Labrador Sea
Greenland
Basalt
Basalt SDRs
no 2D seismic data coverage
UTFZ
Sisimiut Basin
Nuuk Platform
Cape Farewell Platform
Melville Bay
Kivioq Bay
Upernavik basin
Nuussuaq
Disko
FSCA
SFSCA
0 100 200 300 400 500km

Fig 1

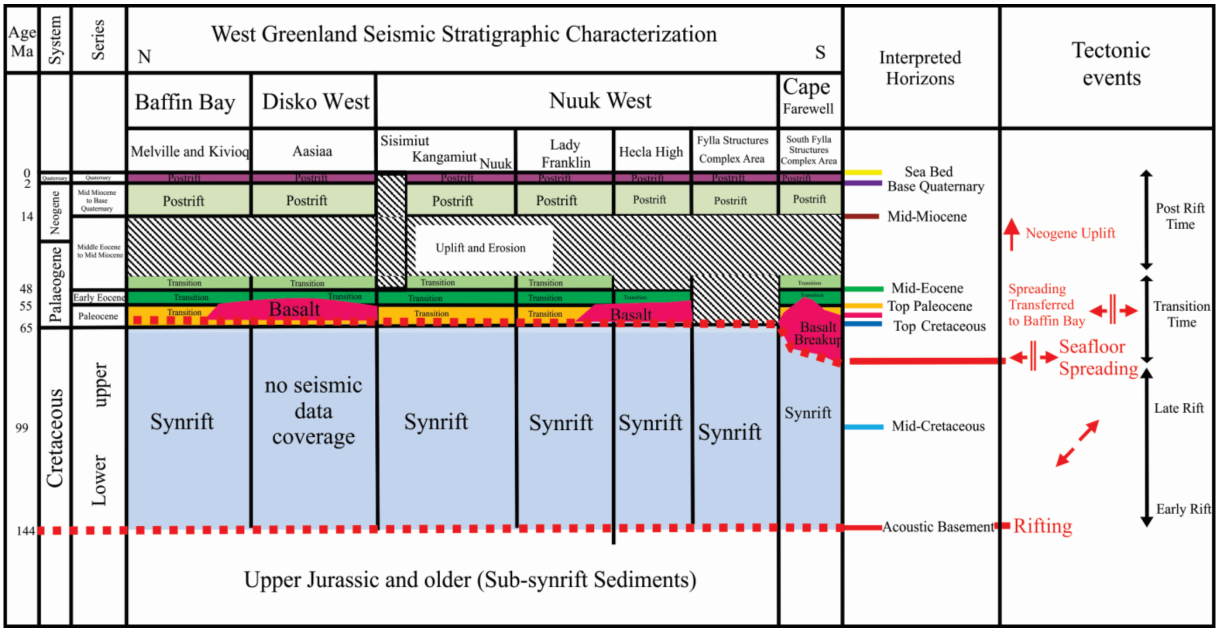

Age Ma
System
Series
West Greenland Seismic Stratigraphic Characterization
N
S
Interpreted Horizons
Tectonic events
Baffin Bay
Disko West
Nuuk West
Cape Farewell
Melville and Kivioq
Aasiaa
Sisimiut
Kangamiut
Nuuk
Lady Franklin
Hecla High
Fylla Structures Complex Area
South Fylla Structures Complex Area
0
2
14
48
55
65
99
144
Quaternary
Neogene
Palaeogene
Cretaceous
Mid Miocene to Base Quaternary
Middle Eocene to Mid Miocene
Early Eocene
Paleocene
upper
Lower
Postrift
Uplift and Erosion
Transition
Basalt
Basalt Breakup
Synrift
no seismic data coverage
Upper Jurassic and older (Sub-synrift Sediments)
Sea Bed
Base Quaternary
Mid-Miocene
Mid-Eocene
Top Paleocene
Top Cretaceous
Mid-Cretaceous
Acoustic Basement
Neogene Uplift
Spreading Transferred to Baffin Bay
Seafloor Spreading
Rifting
Post Rift Time
Transition Time
Late Rift
Early Rift

Fig 2

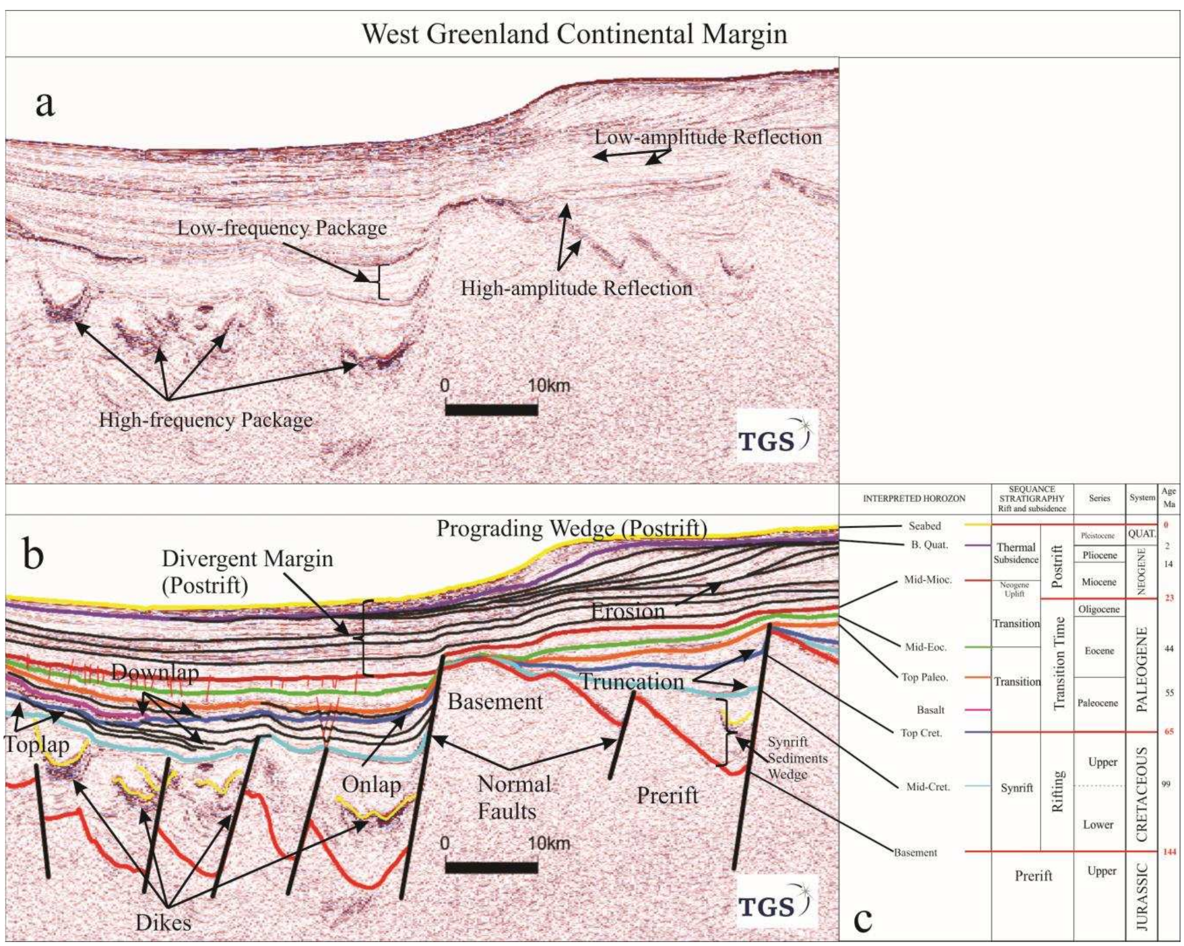
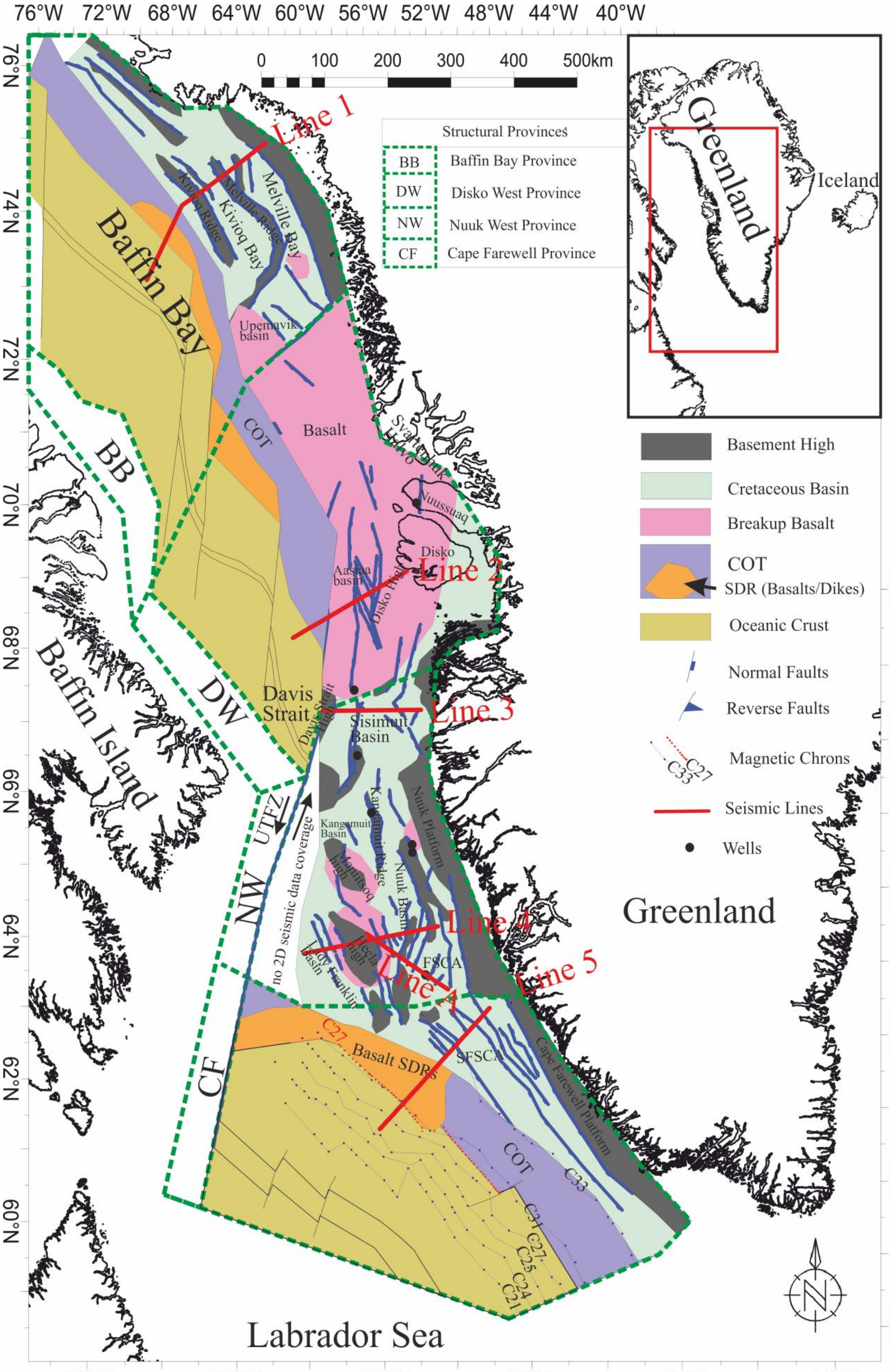

West Greenland Continental Margin
a
Low-amplitude Reflection
Low-frequency Package
High-amplitude Reflection
High-frequency Package
0
10km
TGS
b
Prograding Wedge (Postrift)
Divergent Margin (Postrift)
Erosion
Downlap
Toplap
Basement
Truncation
Onlap
Normal Faults
Prerift
Synrift Sediments Wedge
Dikes
0
10km
TGS
c
INTERPRETED HOROZON
SEQUANCE STRATIGRAPHY Rift and subsidence
Series
System
Age Ma
Seabed
B. Quat.
Mid-Mioc.
Mid-Eoc.
Top Paleo.
Basalt
Top Cret.
Mid-Cret.
Basement
Thermal Subsidence
Neogene Uplift
Postrift
Transition
Transition Time
Synrift
Rifting
Prerift
Pleistocene
Pliocene
Miocene
Oligocene
Eocene
Paleocene
Upper
Lower
Upper
QUAT.
NEOGENE
PALEOGENE
CRETACEOUS
JURASSIC
0
2
14
23
44
55
65
99
144

Fig 3



Line 1
Line 2
Line 3
Line 4
Line 5
Line A
Structural Provinces
BB Baffin Bay Province
DW Disko West Province
NW Nuuk West Province
CF Cape Farewell Province
Greenland
Iceland
Baffin Bay
Baffin Island
Davis Strait
Labrador Sea
Basalt
COT
Basalt SDRs
Basement High
Cretaceous Basin
Breakup Basalt
COT
SDR (Basalts/Dikes)
Oceanic Crust
Normal Faults
Reverse Faults
Magnetic Chrons
Seismic Lines
Wells
no 2D seismic data coverage
UTFZ
Sisimiut Basin
Nuuk Platform
Nuuk Basin
Cape Farewell Platform
FSCA
SFSCA
Upernavik basin
Melville Bay
Kivioq Bay
Disko
Nuussuaq
0 100 200 300 400 500km

Fig 1

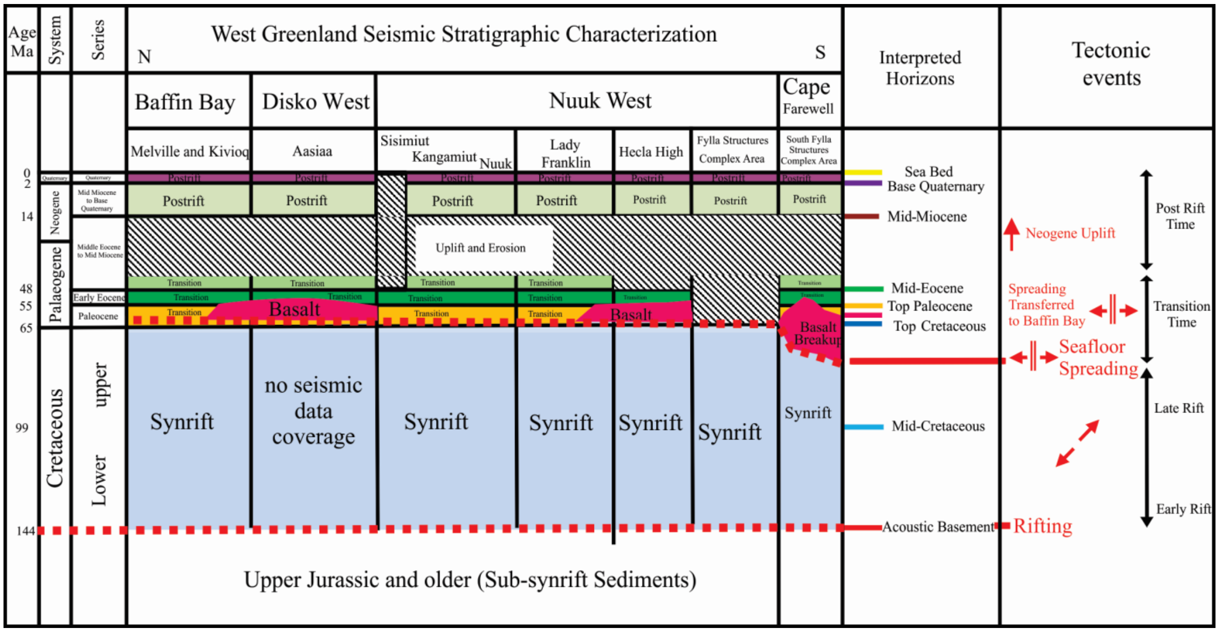

West Greenland Seismic Stratigraphic Characterization
Interpreted Horizons
Tectonic events
Baffin Bay
Disko West
Nuuk West
Cape Farewell
Synrift
no seismic data coverage
Uplift and Erosion
Basalt
Sea Bed
Base Quaternary
Mid-Miocene
Mid-Eocene
Top Paleocene
Top Cretaceous
Mid-Cretaceous
Acoustic Basement
Neogene Uplift
Spreading Transferred to Baffin Bay
Seafloor Spreading
Rifting
Post Rift Time
Transition Time
Late Rift
Early Rift
Upper Jurassic and older (Sub-synrift Sediments)

Fig 2

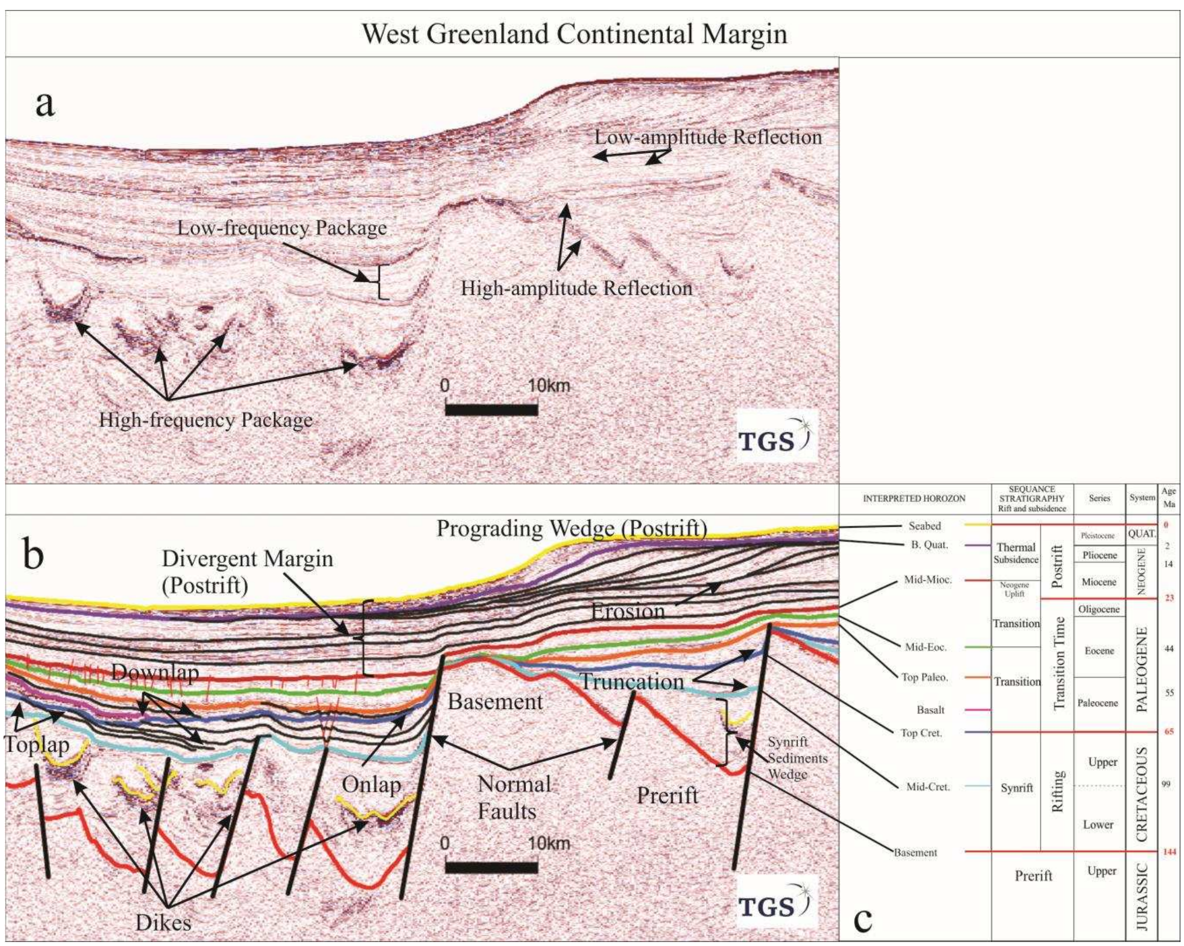

West Greenland Continental Margin
Low-amplitude Reflection
Low-frequency Package
High-amplitude Reflection
High-frequency Package
Prograding Wedge (Postrift)
Divergent Margin (Postrift)
Erosion
Downlap
Truncation
Basement
Toplap
Onlap
Normal Faults
Prerift
Synrift Sediments Wedge
Dikes
TGS

Fig 3

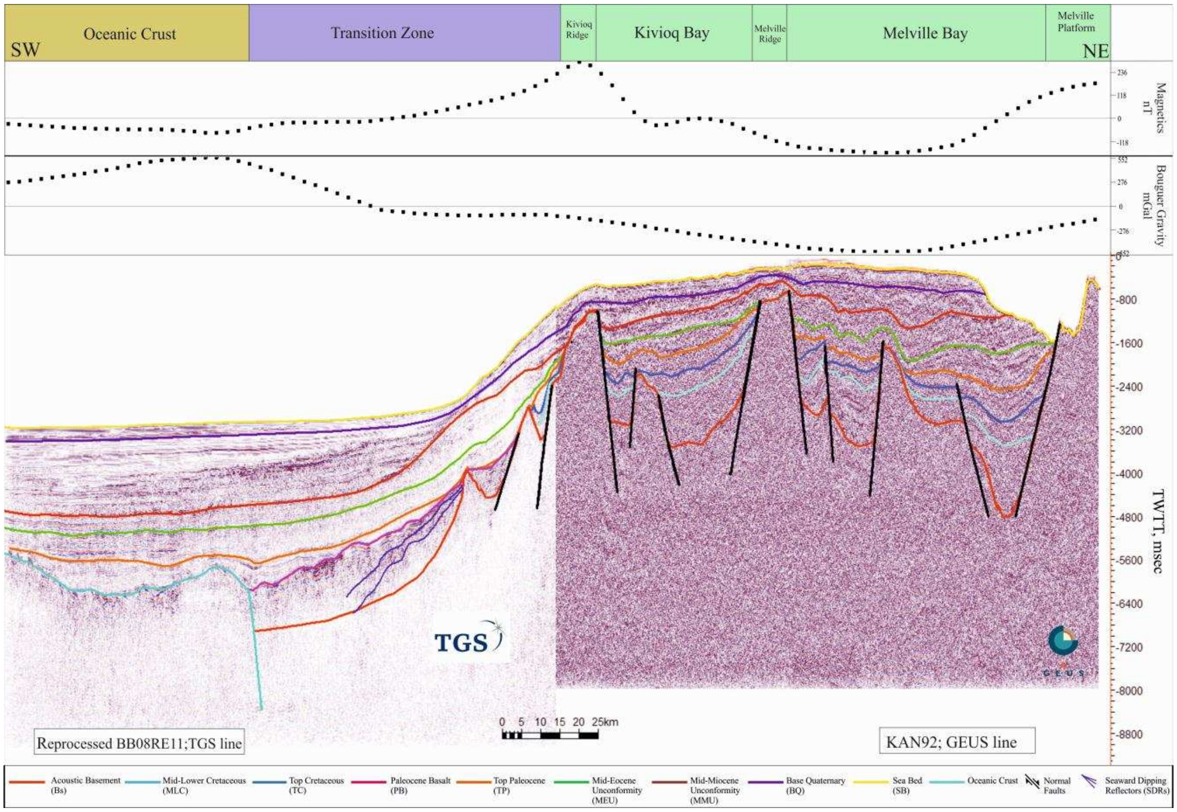

Oceanic Crust
Transition Zone
Kivioq Ridge
Kivioq Bay
Melville Ridge
Melville Bay
Melville Platform
SW
NE
Magnetics nT
Bouguer Gravity mGal
TWTT, msec
TGS
GEUS
0 5 10 15 20 25km
Reprocessed BB08RE11;TGS line
KAN92; GEUS line
Acoustic Basement (Bs)
Mid-Lower Cretaceous (MLC)
Top Cretaceous (TC)
Paleocene Basalt (PB)
Top Paleocene (TP)
Mid-Eocene Unconformity (MEU)
Mid-Miocene Unconformity (MMU)
Base Quaternary (BQ)
Sea Bed (SB)
Oceanic Crust
Normal Faults
Seaward Dipping Reflectors (SDRs)

Fig 4

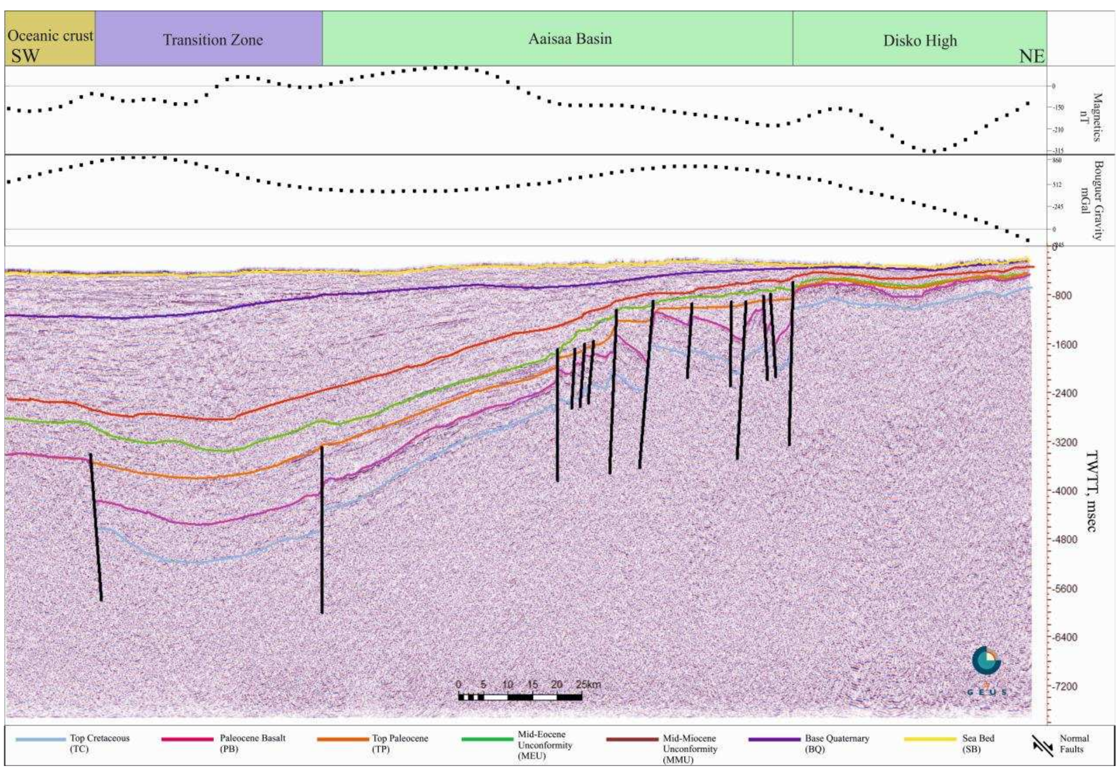

Oceanic crust
SW
Transition Zone
Aaisaa Basin
Disko High
NE
Magnetics nT
Bouguer Gravity mGal
TWTT, msec
0 5 10 15 20 25km
GEUS
Top Cretaceous (TC)
Paleocene Basalt (PB)
Top Paleocene (TP)
Mid-Eocene Unconformity (MEU)
Mid-Miocene Unconformity (MMU)
Base Quaternary (BQ)
Sea Bed (SB)
Normal Faults

Fig 5

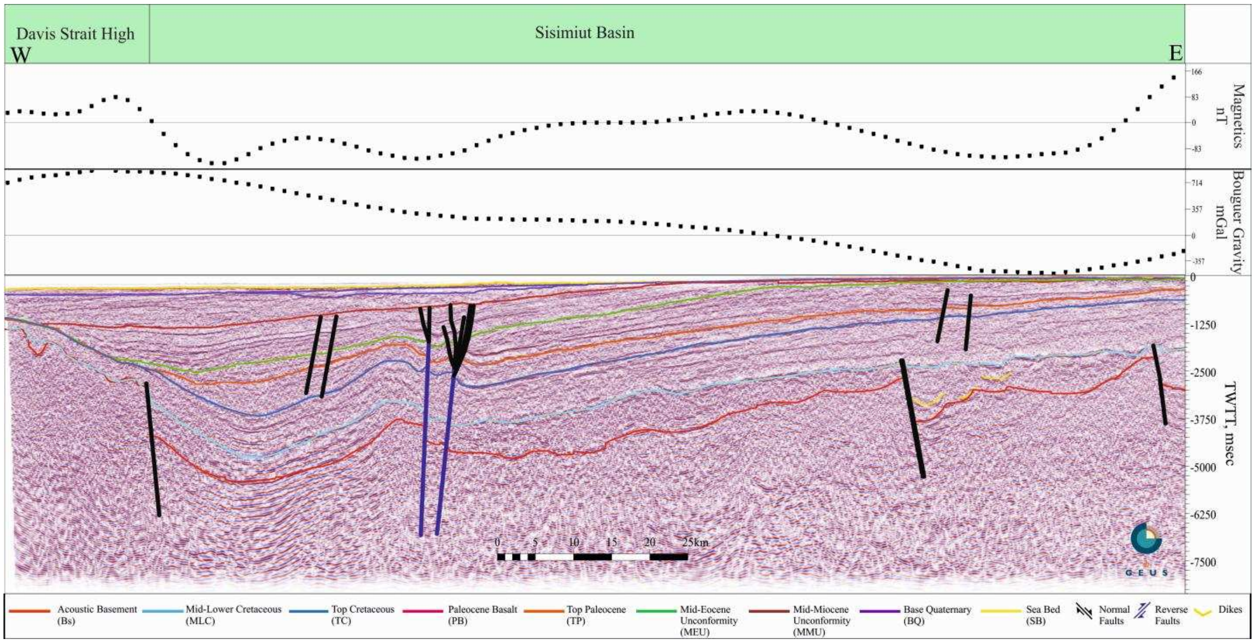

Davis Strait High
Sisimiut Basin
W
E
Magnetics nT
166
83
0
-83
Bouguer Gravity mGal
714
357
0
-357
0
-1250
-2500
-3750
-5000
-6250
-7500
TWTT, msec
0 5 10 15 20 25km
GEUS
Acoustic Basement (Bs)
Mid-Lower Cretaceous (MLC)
Top Cretaceous (TC)
Paleocene Basalt (PB)
Top Paleocene (TP)
Mid-Eocene Unconformity (MEU)
Mid-Miocene Unconformity (MMU)
Base Quaternary (BQ)
Sea Bed (SB)
Normal Faults
Reverse Faults
Dikes

Fig 6

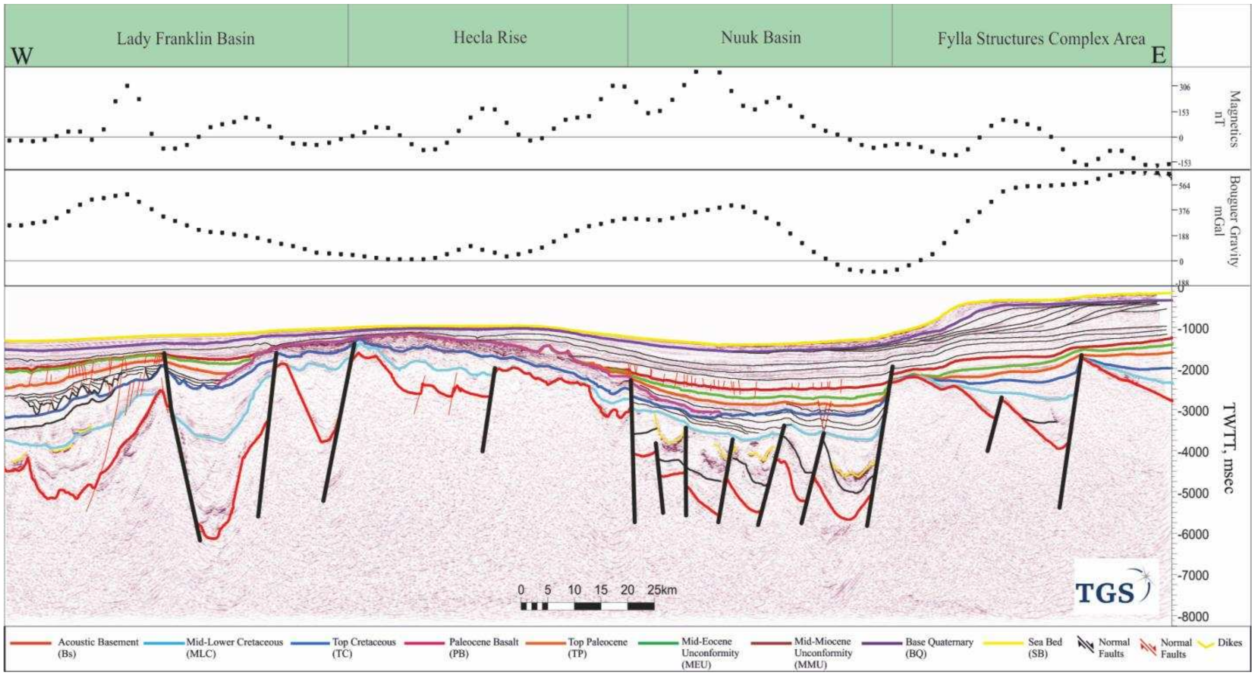

Lady Franklin Basin
Hecla Rise
Nuuk Basin
Fylla Structures Complex Area
W
E
Magnetics nT
Bouguer Gravity mGal
TWTT, msec
0 5 10 15 20 25km
TGS
Acoustic Basement (Bs)
Mid-Lower Cretaceous (MLC)
Top Cretaceous (TC)
Paleocene Basalt (PB)
Top Paleocene (TP)
Mid-Eocene Unconformity (MEU)
Mid-Miocene Unconformity (MMU)
Base Quaternary (BQ)
Sea Bed (SB)
Normal Faults
Normal Faults
Dikes

Fig 7

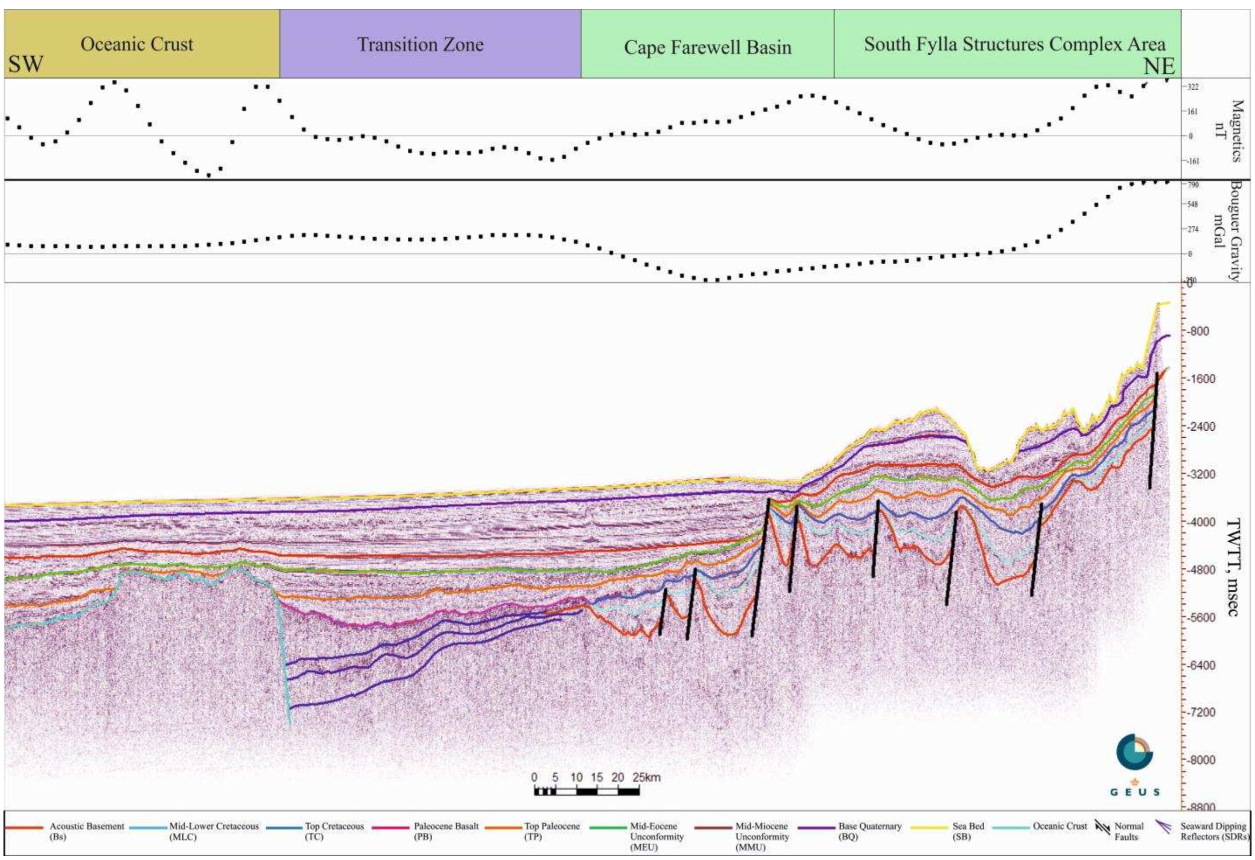

Oceanic Crust
Transition Zone
Cape Farewell Basin
South Fylla Structures Complex Area
SW
NE
Magnetics nT
Bouguer Gravity mGal
TWTT, msec
0 5 10 15 20 25km
GEUS
Acoustic Basement (Bs)
Mid-Lower Cretaceous (MLC)
Top Cretaceous (TC)
Paleocene Basalt (PB)
Top Paleocene (TP)
Mid-Eocene Unconformity (MEU)
Mid-Miocene Unconformity (MMU)
Base Quaternary (BQ)
Sea Bed (SB)
Oceanic Crust
Normal Faults
Seaward Dipping Reflectors (SDRs)

Fig 8

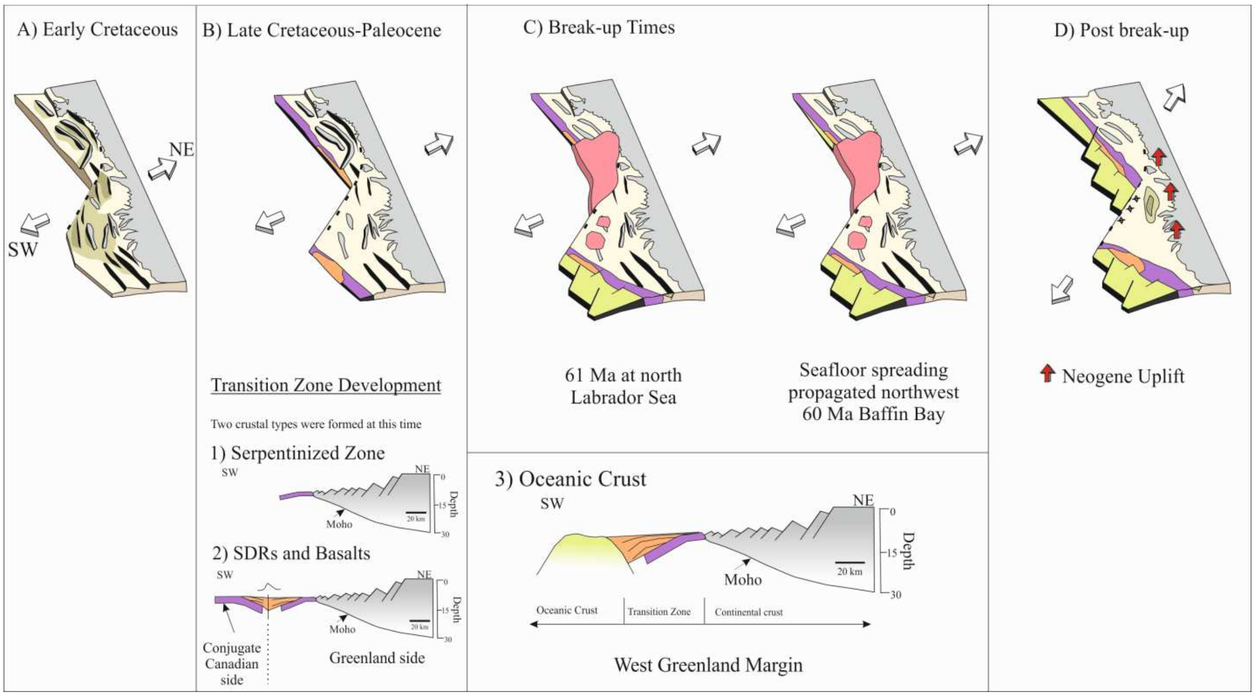

A) Early Cretaceous
NE
SW
B) Late Cretaceous-Paleocene
Transition Zone Development
Two crustal types were formed at this time
1) Serpentinized Zone
SW
NE
Moho
20 km
Depth
0
15
30
2) SDRs and Basalts
SW
NE
Moho
20 km
Conjugate Canadian side
Greenland side
C) Break-up Times
61 Ma at north Labrador Sea
Seafloor spreading propagated northwest 60 Ma Baffin Bay
3) Oceanic Crust
SW
NE
Moho
20 km
Depth
Oceanic Crust
Transition Zone
Continental crust
West Greenland Margin
D) Post break-up
Neogene Uplift

Fig 9