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Full-fit reconstruction of the Labrador Sea and Baffin Bay

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Abstract

Reconstructing the opening of the Labrador Sea and Baffin Bay between Greenland and North America remains controversial. Recent seismic data suggest that magnetic lineations along the margins of the Labrador Sea, originally interpreted as seafloor spreading anomalies, may lie within the crust of the continent–ocean transition. These data also suggest a more seaward extent of continental crust within the Greenland margin near the Davis Strait than assumed in previous full-fit reconstructions. Our study focuses on reconstructing the full-fit configuration of Greenland and North America using an approach that considers continental deformation in a quantitative manner. We use gravity inversion to map crustal thickness across the conjugate margins, and assimilate observations from available seismic profiles and potential field data to constrain the likely extent of different crustal types. We derive end-member continental margin restorations following alternative interpretations of published seismic profiles. The boundaries between continental and oceanic crust (COB) are restored to their pre-stretching locations along small circle motion paths across the region of Cretaceous extension. Restored COBs are fitted quantitatively to compute alternative total-fit reconstructions. A preferred full-fit model is chosen based on the strongest compatibility with geological and geophysical data. Our preferred model suggests that (i) the COB lies oceanward of magnetic lineations interpreted as magnetic anomaly 31 (70 Ma) in the Labrador Sea, (ii) all previously identified magnetic lineations landward of anomaly 27 reflect intrusions into continental crust, and (iii) the Ungava fault zone in Davis Strait acted as a leaky transform fault during rifting. This robust plate reconstruction reduces gaps and overlaps in the Davis Strait and suggests that there is no need for alternative models proposed for reconstructions of this area including additional plate boundaries in North America or Greenland. Our favored model implies that break up and formation of continent–ocean transition (COT) first started in the southern Labrador Sea and Davis Strait around 88 Ma and then propagated north and southwards up to onset of real seafloor spreading at 63 Ma in the Labrador Sea. In the Baffin Bay, continental

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stretching lasted longer and actual break up and seafloor spreading started around 61 Ma (Chron 26).

1 Introduction

The Labrador Sea and Baffin Bay formed following Cretaceous rifting between Greenland and North America (Fig. 1). The relative motions between these two plates in the Palaeocene following the onset of seafloor spreading can be reconstructed based on the identification of seafloor spreading magnetic anomalies (Roest and Srivastava, 1989; Oakey and Chalmers, 2012). Reconstructing the relative motions of the Greenland and North American plates for times prior to seafloor spreading depends on accurately identifying the present-day extent of stretched continental crust along the conjugate margins and undoing this extension in the reconstruction. Uncertainties in the distribution of crustal types and identification of seafloor spreading anomalies have implications for plate tectonic reconstructions, in particular for the rifting and early seafloor spreading phases. Existing reconstruction models for the relative positions of Greenland and North America during Cretaceous continental rifting include Bullard et al. (1965), Rowley and Lottes (1988), Srivastava and Roest (1989), Dunbar and Sawyer (1989). These reconstructions were derived under assumptions that much of the crust in the COT was oceanic during chrons 28–31 time (70–64 Ma according to timescale from Gradstein et al., 2004) and that spreading anomalies could be used to constrain relative plate motions (Roest and Srivastava, 1989). This appears questionable in the light of subsequently collected seismic data, yet the anomaly identifications and reconstructions derived from these interpretations are still used within global-scale compilations (Torsvik et al., 2008; Müller et al., 2008; Seton et al., 2012). More recent reconstruction models only consider seafloor spreading since chron 27 (63 Ma), the earliest undebated spreading anomalies (Oakey, 2005; Oakey and Chalmers, 2012).

In this paper we investigate the full-fit configuration of Greenland and North America in the light of available geophysical and geological data. The distribution of crustal types in the margins of Labrador Sea and Baffin Bay were determined using interpreted seismic lines and other geophysical data to extract the limits of continental deformation. A map of crustal thickness was derived by inversion of gravity data constrained by Moho depth estimates from seismic refraction profiles and receiver functions. Next, the extended continental crust within the conjugate margins was restored to determine the pre-rift extent of each plate. These boundaries are used as quantitative constraints in generating new poles of rotation for the full-fit configuration of North America and Greenland. We show that previous reconstructions overestimate the amount of closure between the two plates. Our new reconstruction, incorporating more recent evidence of the extent of continental crust, reduces the gaps in the Labrador Sea and overlaps in Davis Strait and Baffin Bay which occurred in previous reconstructions of this region.

2 Regional tectonic models

Several authors have presented poles of rotations that describe the relative motions of Greenland and North America between the onset of Mesozoic rifting and cessation of seafloor spreading at chron 13 time (34 Ma). Rowley and Lottes (1988) generated stage poles of rotation of Greenland relative to North America in the framework of reconstruction of the North Atlantic and Arctic. This reconstruction took into account both onshore geology and offshore geological and geophysical data including magnetic anomalies, fracture zones and syn-rift extension data. Dunbar and Sawyer (1989) created another full-fit reconstruction for Central and North Atlantic including the Labrador Sea with a methodology similar to this study as it treats the continents as non-rigid in the rifting phase. They estimate continental extension from total tectonic subsidence rates of margins and seismic studies and restored the COB's to their pre-rift configurations. Roest and Srivastava (1989) and Srivastava and Roest (1999) introduced poles of rotation from the break up stage (118 Ma) up to end of seafloor spreading (49 Ma) in the Labrador Sea based on new interpretation of linear magnetic anomalies, gravity data and fracture zones in this area.

A more recent reconstruction for the opening of Labrador Sea and Baffin Bay was presented in Oakey (2005) and Oakey and Chalmers (2012), who combined Roest and Srivastava (1989) magnetic anomaly picks for chrons 27 to 13 (63 to 35 Ma) from the Labrador Sea with new picks from Baffin Bay. They present new poles of rotation for the 24R interval, which correlates with the start of seafloor spreading between Eastern Greenland and Europe, but no new poles for the earlier rifting. Significantly, these studies do not use spreading anomalies for chrons older than C27 on the grounds that these anomalies, used in the reconstructions of earlier authors, were located within the continent–ocean transition and are not true spreading isochrons. This debate is important both for reconstructions of the early seafloor spreading, and for delineating and restoring the extended continental crust within each margin, and is discussed further in the next section.

3 Tectonic setting

Rifting and the extension of the Labrador Sea started either in the Late Jurassic (160 Ma) based on dating of coast-parallel dykes in SW Greenland or the early Cretaceous (140 Ma), on the basis of distinguishing and dating syn-rift sediments from wells on both margins (Chain and Louden, 1994). These sediments were deposited on top of rift related volcanics in grabens and half grabens that formed during continental extension (Sandwell and Smith, 2009; Srivastava and Roest, 1999; Chalmers and Pulvertaft, 2001). Seafloor spreading in the Labrador Sea started along a branch of the Mid-Atlantic in either the Late Cretaceous or Early Paleocene times (Roest and Srivastava, 1989; Keen et al., 1993; Srivastava and Roest, 1999; Chian et al., 1995; Chalmers and Laursen, 1995; Chalmers and Pulvertaft, 2001; Keen et al., 2012), and ceased about 35 Ma (Chron 13) leaving an extinct spreading centre in the middle of the basin. The existence of oceanic crust in Baffin Bay was first shown in seismic refraction lines. Magnetic anomalies along these lines were determined in two different directions of NNW–SSE and NW–SE in this area. These linations were interpreted as

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Palaeocene and Eocene extinct spreading ridges (Keen and Barrett, 1972; Keen et al., 1974; Chalmers and Pulvertaft, 2001; Oakey, 2005).

The age of the earliest seafloor spreading magnetic anomalies within the Labrador Sea is controversial. The uncertainty originates from differing interpretations of the nature of crust within the COT between unequivocal continental and oceanic crust in both margins. Roest and Srivastava (1989) interpreted this zone as oceanic crust containing linear magnetic anomalies 31–33 formed during slow seafloor spreading (Fig. 2). Other authors interpreted this crust as serpentinized mantle or high velocity igneous crust overlain by thin oceanic basalts, highly fractured and hydrothermally altered (Chian and Louden, 1994; Lundin and Dore, 2011; Keen et al., 2012). Some other studies (Chian and Louden, 1994; Chian et al., 1995a,b; Reston, 2009; Dickie et al., 2011) conclude that seafloor spreading starts sometimes between chron 31 and chron 27. This interpretation is based on data derived from seismic lines, subsidence history and stratigraphic characteristics of both margins. Nonetheless, Chalmers (1991); Chalmers and Laursen (1995); Chalmers and Pulvertaft (2001) and Funck et al. (2007) interpret these anomalies as being a result of magmatic intrusion into highly thinned and stretched continental crust based on interpretation of reflection seismic profiles and that the oldest true seafloor spreading anomaly is chron 27 (Fig. 2).

The nature of the crust within the Davis Strait is also debated. Chalmers and Pulvertaft (2001) describe the entire crust in Davis Strait as continental while Srivastava (1983) described sedimentary basins flanking Davis Strait High as oceanic while they stated that the nature of the crust in basement high of Davis Strait could be described as continental.

Several studies (Funck et al., 2007, 2012; Keen et al., 2012) propose that the Ungava Fault Zone (UFZ) in Davis Strait acted as a leaky transform fault (Fig. 3) and this extensional phase thinned the continental crust allowing melted material from the proto-Iceland plume to penetrate and fill it as new oceanic crust (Storey et al., 1998; Funck et al., 2007) or as a mixture of continental crust and plume related material (Keen and Barrett, 1972).

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The Oakey and Chalmers (2012) reconstruction of chron 27–25 suggests a Paleocene extensional phase along the UFZ continued as a transpressional tectonic regime during the Eocene. In their model, this structural inversion leads to formation of the Davis Strait High, a structural feature that resulted from over-thrusting of Precambrian and Ordovician continental units onto Palaeogene volcanic rocks.

Uncertainty in the extent of continental crust and nature of the COT continues northward of Davis Strait in southern Baffin Bay mostly on the Greenland margin. Funck et al. (2012) interpret a northward extension of the UFZ as a continuation of the leaky transform fault. Remnants of continental crust or a transform fault associated with UFZ lay between this zone and normal oceanic crust of Baffin Bay (Chalmers and Pulvertaft, 2001; Funck et al., 2012). Another interpretation defines this zone as Paleocene oceanic crust (Oakey and Chalmers, 2012; Funck et al., 2012). In comparison, along the Baffin Island margin the continent–ocean boundary is much sharper, recognisable by a strong positive gravity high all along the margin (Fig. 4).

Both margins in the northernmost area of Baffin Bay have been interpreted as non-volcanic with basement highs and faulted continental crust, a rough basement of serpentinized mantle and submarine basalts within the interpreted COT, and smoother oceanic crust with only weak magnetic anomalies (Whittaker et al., 1997; Skaarup et al., 2006). Oceanic crust terminates in Northern Baffin Bay at about 76° N (Reid and Jackson, 1997; Oakey and Stephenson, 2008).

4 Methodology

4.1 Delineation of crustal types across the COT

The distribution of crustal types and the nature of the COT within the study area remain poorly constrained. For this reason, we investigate end-member cases for the extent of continental crust within the COT for each margin based on available seismic profiles, using a simple classification scheme similar to the approach of Crosby et al. (2011) (Fig. 5). We mapped the most landward position of “certain” oceanic crust and the most oceanward position of “certain” stretched continental crust. Determining these two boundaries relies upon interpretations of the crustal nature in seismic profiles along both margins in different studies. This interpretation is mainly based on changes in *P* wave velocity and crustal thickness and observation of detachment faults and seaward dipping reflectors (SDRs) along with information obtained from exploration wells wherever they exist. The nature of the intervening crust is open to interpretation. Importantly for our reconstructions, it is unclear how much of the material mapped within the present-day crust within these zones was part of the crust before the rifting, and how much was added, for example due to igneous intrusion or mantle exhumation. The crust underneath Davis Strait has been considered alternatively as totally continental (Chalmers and Pulvertaft, 2001; Gerlings et al., 2009) or mostly continental with a narrow strip of Paleocene oceanic crust in the southwestern boundary of Davis Strait High that could be the result of a Paleocene extensional phase (Funck et al., 2007, 2012; Keen et al., 2012; Oakey and Chalmers, 2012).

We generated alternative plate reconstructions using the end-member scenarios for the COT, allowing us to investigate the effect of uncertainty in the extent of continental crust on the full-fit reconstruction between Greenland and North America. These different models can be summarized as follows:

1. An extremely landward COB, based on the definition of Srivastava and Roest (1989). This model assumes that the COB lies at the edge of the continental shelf along the Greenland margin. The position of this boundary is less clear on the Labrador margin because thinned and extended continental crust is wider here (Srivastava and Roest, 1999). Further north, through the Davis Strait a more landward COB implies oceanic crust for the area and follows the continental shelf in both Greenland and Baffin Island margins.

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2. The most landward COB (within the limits of current seismic interpretations). The COB is located at the landward limit of the COT and assumes that the entire Davis Strait underlain with continental crust.

3. The same as (2) in the Labrador Sea and Baffin Bay, but assumes the existence of a narrow strip of oceanic crust described as Ungava leaky transform fault passing through the western edge of the Davis Strait High.

4. The most oceanward COB (within the limits of current seismic interpretations). The oceanward boundary of the COT was taken as the COB in the Labrador Sea and Baffin Bay. This model assumes the presence of continental crust across the entire Davis Strait.

5. The same as (4) but assuming the UFZ is a leaky transform fault and that the Davis Strait contains oceanic crust.

6. The COB falls within the COT permitted by seismic reflection data. In the Labrador Sea the COB is located landward of chron 31 (70 Ma) assuming this isochron as the first seafloor spreading anomaly in this region. This model is based on the assumption that Davis Strait is continental.

7. The same as (6) but with narrow strip of ocean crust in Davis Strait.

4.2 Generating the crustal thickness grid

We derived a map of crustal thickness for the Labrador Sea and Baffin Bay. This grid enables us to distinguish the boundary where the continental crust starts thinning at the onset of rifting and thus with recognising this limit it is possible to restore the COB to its pre-rift location. Generating the crustal thickness grid has been performed by inversion of gravity data using the method of Chappel and Kusznir (2008). The starting point for this method is the global free-air gravity anomaly compilation of Sandwell and Smith (2009). We estimated the gravity effects of bathymetry (Divins, 2004) (Fig. 6a)

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and sediment layers (Louden et al., 2004; Divins, 2003; Bassin et al., 2000; Fig. 6c) and subtracted these from the observed free-air gravity. The gravity effect of mantle thermal variations was estimated on the basis of seafloor age (Müller et al., 2008; Fig. 6d). The need to correct for mantle density variations is supported by the 2-D gravity model of Keen et al. (2012), who showed that a lower mantle density was necessary beneath the Labrador Sea compared to the flanking continents to match gravity and seismic observations. The remaining gravity signal is inverted using the method of Parker (1972) to derive a map of depth to the Moho (Fig. 7). A complete description of the workflow is provided in Appendix A. Crustal density, initial crustal thickness, and the seafloor age grid influence the results of this method so we performed sensitivity tests to investigate the influence of these parameters on the resulting crustal thickness. These sensitivity tests are discussed in detail in Appendix A and Fig. A1.

We took into consideration the possibility of a thickening of the crust in Davis Strait and southern Baffin Bay due to igneous material added to the continental lower crust during the passage of the proto-Icelandic plume beneath this area around 70 Ma (Lawver and Müller, 1994). Such igneous material has been interpreted along seismic lines 20 080 600 (Funck et al., 2012), 20 100 700 (Suckro et al., 2012), NUGGET line 1 (Funck et al., 2007) and NUGGET line 2 (Gerlings et al., 2009) as due to underplating, resulting in igneous crust and a high velocity zone and with a thickness varying between 1 to 9 km, postdating rifting. We eliminated these high velocity bodies from the crustal thickness grid to obtain more accurate depths to Moho during the rifting process. The restoration of COBs has been performed with a crustal thickness grid generated considering thick igneous crust in the northern Labrador Sea and Davis Strait.

The resulting crustal thickness grid (Fig. 7) shows that continental crustal thickness varies from 39 km in unstretched continental crust beneath the inland cratons of North America and Greenland to less than 9 km under extremely thinned and stretched continental crust adjacent to both margins. Figure 8 illustrates the comparison between Moho depths from seismic experiments and the Moho depth extracted from gravity inversion along each of the seismic profiles. We also compare our database of seismic refraction and receiver function depths with the Moho depth contained within the CRUST2 model of global crustal structure (Bassin et al., 2000). The comparison shows that the global grid gives typically deeper Moho compared with individual seismic profiles, and suggests that the gravity inversion method will yield more robust crustal thickness restoration.

A lithospheric thinning factor (γ) grid illustrates the implications for crustal stretching of our crustal thickness grid. The parameter γ is derived from the lithospheric stretching factor beta (β) and taking into account the addition of igneous material added to the crust during rifting:

$$\beta = \mathrm{tc0}/\mathrm{tc1} \tag{1}$$

Where tc is the initial unstretched continental crustal thickness and tc1 is the crustal thickness at present day.

The gamma factor γ is calculated using

$$\gamma = (1 - 1/\beta) \tag{2}$$

This factor is sensitive to addition of igneous material to crust as magmatic underplating and/or oceanic crust and thus is useful for showing the extent of thinned crust along rifted margins. Gamma varies from 0.5 for volcanic margins to 0.7 for normal and magma poor margins (Kuzsnir, 2009). Figure 9 shows the thinning factor grid for the entire study region overlain by COB lines for our preferred model. In the magma-starved south Labrador Sea COBs follow the 0.7 Gamma contour while it changes to 0.6 in the northern parts where rifting was accompanied by excess magmatism. In the Davis Strait the gamma grid shows a relatively thick crust with a thinning factor around 0.4-0.5. This over-thickened crust may reflect igneous crust or underplating in this area. Along the southern Baffin Bay volcanic margins, COBs correspond to gamma factors 0.6 to 0.7 on both margins. A 92 000 km^2 submarine fan complex referred to as the Baffin Fan covers most of this area (Fig. 9) (Harrison et al., 2011). This massive volume

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of sedimentary cover makes the gravity data unable to detect basin slope topography, which leads to greater uncertainty in computed crustal thickness in this region. Defining COBs in this area mainly relies on seismic profiles.

4.3 Restoring extended crust between UCCL and COB boundaries

For each model, the extended continental crust between the COB and UCCL was restored along each margin to a reference thickness of 35 km in the North America and 36 km in the Greenland (Fig. 11). The location of the UCCL in all models is fixed and the only difference is in the position of COBs along both margins. We used the stage poles of rotation of Roest and Srivastava (1999) for restoration, which represent the direction of the motion of extended continental crust during the rifting between Greenland and North America. These stage poles of relative motion were used to generate small circle motion paths between two limits of extended continental crust. Crustal thicknesses from the grid derived by gravity inversion are then extracted along these small circles to estimate the thickness of crust between two boundaries. Next, we calculate the length of this crust before extension and restore the crust to its initial reference thickness before being subjected to extension. Applying the change in crustal length along the given small circle gives the restored COB (RCOB). Repeating this process for all small circles along the margins results in a continuous model for the RCOB location.

4.4 Reconstruction of restored COBs

For each model described above, we use the generated RCOBs to compute poles of rotation for the pre-rift fit between Greenland and North America. The computation of Euler poles of rotation has been performed using the Hellinger (1981) least-squares fitting method. This method is typically applied to reconstructions of seafloor spreading using isochrons and fracture zones as constraints. Here, we apply the method to derive full-fit poles of rotation in the same manner as used for the Australia–Antarctic margins by Williams et al. (2011). The Euler pole of rotation calculated for the alter-

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native models from the beginning of rifting (120 Ma) to the start of seafloor spreading (chron 27, 63 Ma). All reconstructions are using crustal thickness grids derived from the gravity inversion method in which igneous crust added to the thinned continental crust is removed. North America is considered as the fixed plate in all reconstructions. The main input for geometrical fitting of the margins are the RCOBs, which constrain the amount of closure between the two plates. To constrain the lateral juxtaposition of Greenland and North America prior to rifting, we use older structural features and terranes mapped and correlated between these two continents as follows (Fig. 12):

1. Committee–Melville Orogeny (CMO) separating the Rae Craton in the north from mainly Palaeoprotrozoic Karrat Group of Greenland and Foxe fold belt in Baffin Island margins (Dawes, 2009).

2. Baffin and Disco Bugt suture zones (DBS) that closed at approximately 1.88 Gyr. The Baffin suture zone thrust the Meta Incognita microcontinent over the Cumberland Batholith in North America. Similarly, closure of the DBS in Greenland led to the expansion of the Aasiaant domain over the Rae craton.

3. Norde Isortoq suture zone (NIS) (1.86–1.84 Gyr) that formed due to collision of the Rae craton with the Archean North Atlantic craton along the northern boundaries of the latter.

4. Makovik and Ketilidian orogeny (MKO) (1.89–1.8 Gyr) separating mainly Palaeoproterozoic units of Labrador and west Greenland from Archean North Atlantic Craton.

5 Results

We carried out restoration and reconstruction of RCOBs for the all end-member models discussed above. Restored COB locations and small circle paths for model 1 and 7 are presented in Fig. 10; the restored COBs and small circle paths for the other proposed

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models can be found in Appendix B. Model 1 is very similar to the Srivastava and Roest (1989) model in terms of what they proposed as the location of COB, which put the COB in the most landward position compared to all other models. Model 7 resulted in the best fit amongst all examined models.

The most dramatic differences in the position of the RCOB occur in the Greenland margin in northern Labrador Sea near the Davis Strait. Davis Strait shows the greatest amount of extension in all models, which is mostly concentrated on the Greenland margin. The smallest amount of continental extension was observed in the model 1, where the most landward COB follows the continental slope (Fig. 10a). The amount of continental extension in this model varies between 6 and 100 km in both margins. This amount of extension is the least in comparison with the other models, implying less continental thinning.

The position of the restored COBs along both margins in Baffin Bay does not change significantly for all tested models. In all models, small circles show a NW–SE direction of extension and are perpendicular or highly oblique to the coastline.

Full fit reconstructions for our preferred model 7 and model 1 are shown in Fig. 12. Table 1 summarises the location of Euler poles for full-fit reconstructions and their errors for all models whereas Table 2 reviews the parameters used to calculate the rotation poles. See Appendix B for reconstructions for the other models presented here.

Model 1 shows a reasonable fit in the southern Labrador Sea and Baffin Bay but further north there is a major gap in the northern Labrador Sea near Davis Strait and an overlap north of Disco Island (Fig. 12). This model is very similar to the Srivastava and Roest (1989) reconstruction for the onset of rifting except that model 1 locates Greenland slightly further south relative to North America.

The most dramatic improvement in the fit reconstruction of model 7 is achieved in the northern Labrador Sea and Davis Strait, which are the two most problematic and controversial regions. This model reinforces the hypothesis of the existence of a narrow Palaeocene oceanic basin in that region.

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Our entire proposed models correlate juxtaposed Precambrian rocks in North America and Greenland margins well.

6 Discussion

6.1 Non-rigid Greenland–North America

Previous attempts to reconstruction Cretaceous rifting between Greenland and North America produce major gaps and/or overlaps, leading to some suggestions that the two plates need to be treated as non-rigid continents. Small amounts of Late Cretaceous-Early Palaeogene extension in Canada (Okulitch et al., 1990) was proposed for North America as a deforming plate for alleviating overlaps in Davis Strait e.g. Srivastava and Falconer (1982) and Lawver (1990). The evidence for this extension comes from on mapping features in the Hudson Strait and Foxe Channel (Jackson and Ianelli, 1981).

An alternative mechanism to improve the pre-rift fit has been to invoke deformation within Greenland. Studies in western Greenland that supports the existence of several shears zones within the boundaries of Nagssugtoqidian orogenic belt (the area between structural features 3 and 4 in Fig. 11) (Bak et al., 1975; Wilson et al., 2006). Beh (1975) and Srivastava and Faconer (1982) invoked a number of sinistral shear zones crossing central Greenland on the basis of information from Bak et al. (1975) and the physiography of the channels running through the Greenland. A similar shear zone has been contemplated in a recent Arctic reconstruction (Winefield et al., 2011). These structures have been mapped only in the Achaean and Proterozoic rocks near the margin and the continuation of these tectonic features inland and under the ice cover of the Greenland and any reactivation and displacement along these faults during Late Cretaceous rifting is as yet undocumented.

Our analysis suggests that full-fit reconstructions treating Greenland and North America as rigid blocks with deforming margins achieve a relatively good overall fit, including in areas such as Davis Strait where the distribution of crustal types remains

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unclear. Our preferred model 7, as well as the range of models presented here testing the sensitivity of our results to different starting assumptions, shows that internal deformation within Greenland and/or North America is not necessary to restore these plates to their configuration at the onset of rifting and opening of the Labrador Sea and Baffin Bay.

6.2 Comparing previous models and our preferred model

Figure 13 shows the comparison between the location of the Euler poles and their uncertainty ellipses of our alternative models together with the full-fit Euler poles from previous studies. The Euler poles resulting from different models proposed here vary within a very limited geographical range and their error ellipses mostly overlap. The pole resulting from model 1 is the closest to the rotation pole proposed by Srivastava and Roest (1989). This similarity can be explained by the almost identical interpretations of these models concerning the nature of crust adjacent to both margins. This model (model 1) and model 4, where the transitional crust is interpreted as oceanic crust, and Davis Strait as continental, are the two extremes of the range. Of the previously published models, the full-fit rotation pole of Rowley and Lottes (1988) is located closest to our preferred model (model 7).

6.3 Continental rift phase

Our reconstruction based on restoring extended continental crust gives us a full-fit reconstruction pole at the onset of continental rifting (~ 120 Ma). Since the oldest reliable seafloor spreading isochron within Labrador Sea is chron 27, the next more recent time for which we have a quantitatively constrained reconstruction is ~ 63 Ma (Oakey and Chalmers, 2012). We now use our preferred reconstruction and COT configuration to investigate the diachronous transition from continental rifting to the onset of formation of the transition zone and seafloor spreading, assuming a constant rate and direction

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of rotation of Greenland away from North America and considering possible deviations from this simple assumption.

Reconstruction from 120 to 85 Ma shows that extending continental crust during this time spans the entire region in between North America and Greenland. At 85 Ma, Baffin Bay is still underlain entirely by continental crust, but further south crust now contained within the COT of the Labrador margins has begun to form (Fig. 14a). By 69 Ma, large regions of the Labrador Sea are underlain by COT crust although, based on our preferred COBs from assimilation of seismic data, continental connection persists at the junction between the Labrador Sea and Davis Strait (Fig. 14b). Oblique opening of the Davis Strait around this time suggests that the oldest igneous crust within the UFZ, proposed as a leaky transform fault (Funck et al., 2007, 2012), could be Late Cretaceous in age. Unequivocal chron 27 seafloor spreading anomalies are observed in the Labrador Sea (Fig. 14c). The existence of oceanic crust in Baffin Bay, possibly younger than chron 27 (Late Palaeocene, Chron 26), has also been proposed (e.g. Suckro et al., 2012; Oakey and Chalmers, 2012) that is consistent with our model. The reconstruction of Oakey and Chalmers (2012) predicts that the earliest ocean crust in Baffin Bay formed during broadly NE–SW spreading, followed by a change to more oblique N–S extension between chrons 25 and 24 (57–54 Ma) (Fig. 14d). Reconstructions constrained by seafloor spreading anomalies and fracture zones suggest that this direction of relative motion persisted until the cessation of spreading between North America and Greenland around chron 13 time (Roest and Srivastava, 1989; Oakey and Chalmers, 2012; Suckro et al., 2012). Seafloor spreading within Baffin Bay and Labrador Sea occurred contemporaneously with strike-slip and transpressional deformation within the Davis Strait (Suckro et al., 2013).

The discussion above assumes a uniform rate and direction of relative motion during continental rifting and the formation of the transition zone. Other geological evidence is necessary to make such inferences. For example, Dossing (2011) presented a detailed study of the Fylla Structural Complex (Fig. 1) located on the western Greenland margin in the north Labrador Sea near the Davis Strait. The complex is composed of

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rift basins that initiated in the late-Early Cretaceous. Following a phase of major uplift, characterised by an erosional unconformity, further episodes of rifting occurred in the Campanian and Early Cenozoic. The inferred stress regime changes significantly between these different rift phases, with dominantly NE–SW extension in the late-Early Cretaceous followed a clockwise rotation on the extensional stress direction to E–W to ENE–WSW by the early Campanian.

Tectono-stratigraphic studies of the North American margin of the Labrador Sea also show an early rifting phase during the Early Cretaceous, characterized by widespread extensional faulting and formation of grabens and half-grabens (Dickie et al., 2012). Regional unconformities in the mid-Cretaceous (100–83 Ma) are considered too early to be related to continental breakup, and may instead be related to changes in the magnitude and/or direction of the stress field (Dickie et al., 2012 and references therein).

Subsidence curves calculated from wells in the Hopedale Basin (Fig. 1) consistently show the onset of rapid subsidence around 70 Ma, interpreted to coincide with the onset of seafloor spreading in the Labrador Sea.

A limitation of using crustal thickness restoration is that these data do not allow us to quantitatively constrain changes in plate motion during the rifting. Our reconstruction describes the overall motion between Greenland and North America from the beginning of rifting ($\sim$ 120 Ma) until the time of the earliest seafloor spreading anomaly (63 Ma), that varies from ENE–WSW in the southern Labrador Sea to NE–SW in Baffin Bay. The studies discussed above are consistent with the overall motion implied by our reconstruction while providing evidence for distinct stages within this overall motion. However, the available data are insufficient to constrain this in a quantitative manner. As shown for the Australian and Antarctic margin, reconstructions derived using the method used here is relatively insensitive to changes in the direction of relative plate motions (Williams et al., 2011). Hence our reconstruction forms a starting point for more detailed models of Cretaceous continental rifting between Greenland and North America.

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7 Conclusions

We derive a new full-fit reconstruction that restores the Greenland and North American plates to their configuration prior to Cretaceous rifting. In contrast to previous Early Cretaceous reconstructions, our study incorporates new interpretations of thinned and stretched crust in the margins of the Labrador Sea, Baffin Bay and Davis Strait as either continental or a transitional crust as a mixture of serpentinized mantle with slivers of continental crust and igneous material. We quantify the extension and thinning of continental crust and restore the COBs to their pre-rift configuration, and test the sensitivity of these results to different interpretations of the crustal types within the COT. The model that best fits the entire region (model 7) was generated with a COB within the bounds of all available seismic interpretations, and oceanward of magnetic anomalies previously interpreted as chron 31 in the Labrador Sea. Within, the best-fitting model the UFZ is considered as a leaky transform fault that produces a narrow strip of igneous crust through Davis Strait.

Our results imply that an acceptable fit between Greenland and North America can be achieved without the need for large-scale deformation within either these plates. Assuming a constant rate and direction of rifting from the beginning of rifting to the start of seafloor spreading, Our best defined model 7 shows the generation of post-rift material within the present-day COT started in the southern Labrador Sea and propagated northward.

Appendix A

Mapping crustal thickness by gravity inversion

We derived a map of Moho depth for the Labrador Sea, Davis Strait and Baffin Bay by inversion of gravity data, Our method follows an approach similar to that used by Greenhalgh and Kusznir (2007) and Chappel and Kusznir (2008) to map crustal thickness at continental margins of the northeast Atlantic. We estimate and strip away the gravity effects of sea water, sediment layers and density variations within the mantle based on variation in the age of oceanic lithosphere.

We use gravity data derived from satellite altimetry over the oceans (Sandwell and Smith, 2009), which incorporates the EGM08 gravity model for onshore areas. We calculated an onshore simple Bouguer correction using the EGM08 elevation model and a Bouguer correction density of 2.67 $g\,cc^{-1}$. For Greenland, the corrections also take into account the thickness of ice taken from (Bamber et al., 2001), and using a density for ice of 0.91 $g\,cc^{-1}$.

To estimate the gravity effect of the sediment layers, we use sediment thickness grids from Louden et al. (2004) for the Labrador Sea and Davis Strait. We merged this map with less detailed data for Baffin Bay taken from the compilations of Divins (2003) and Bassin et al. (2000). A 3-D distribution of sediment density was derived using a depth-density function based on the equations and empirically-derived constants given by Sawyer (1985).

A lithosphere thermal gravity anomaly correction was calculated by first deriving a 3-D model of the lithosphere temperature beneath the basin. Beneath oceanic lithosphere the thermal structure is estimated using a 1-D cooling model (McKenzie, 1978), which provides an adequate approximation to 2-D thermal models (Chappel and Kusznir, 2008). For the distribution of seafloor age we use a modified version of the age grid presented by Müller et al. (2008). The grid of Müller et al. (2008) contains ocean crust in the Davis Strait and along the Labrador Sea margins based on the interpretation of seafloor up to Chron 33 age from Roest and Srivastava (1989). As discussed in the main text, a synthesis of currently available seismic profile interpretations suggests much of this area is underlain by either stretched continental crust or the continent–ocean transition – see Figs. 2 to 5. We therefore mask the Müller et al. (2008) age grid to for these areas. Following Breivik et al. (1999) and Kimbell et al. (2004), we model the temperature in the region of stretched continental crust is modelled using a ramp between oceanic domain and a separate model for the lithosphere temperature under

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stable continental areas. In this way a 3-D grid of lithospheric temperature field is calculated at a resolution of 5 km. From this, we derive a 3-D density field and gravity field observed at the surface as described by Chappel and Kusznir (2008).

After application of all the gravity corrections described above, the remaining gravity signal is inverted using the method of Parker (1972) to derive a map of depth to the Moho. The results are influenced by a range of assumptions involved, notably the density contrast across the Moho, and the reference Moho depth. (the thickness of crust corresponding to zero bathymetry and zero long-wavelength free-air gravity; Alvey et al., 2008). We tested a range of parameter combinations (Fig. A1) and validated the results by plotting the gravity inversion depths against independent estimates of the Moho depth from seismic refraction profiles and receiver functions studies at onshore seismic stations. The lowest RMS difference between the gravity and seismic refraction was corresponds to a reference depth of 36 km and density contrast across the Moho of 500 $\mathrm{kg\,cm^{-3}}$ (the RMS for values of 38 km and 450 $\mathrm{kg\,cm^{-3}}$ are very similar). The reference depth is important for our purpose, since we use this value as the thickness of continental crust prior to extension in the cross-section area-balancing. We find the value used for the Zref has two counteracting affects on the location of the restored COB locations – larger Zref value yields a greater volume of continental within the margin (tending to move the RCOB location more oceanward), but then the larger Zref is also used in the area-balancing moves the RCOB (tending to move the RCOB landward).

Seismic data (e.g. Funck et al., 2007; Skaarup et al., 2006; Gerlings et al., 2009) show that the Davis Strait is heavily affected by magmatic addition related to the passage of the Iceland underneath the area during the early Paleocene. Chappel and Kusznir (2008) describe an approach to estimate the amount of magmatic addition based on stretching factors obtained from the gravity inversion crustal thickness. However, compression in this area, illustrated by observations and plate motions (Oakey and Chalmers, 2012), makes it complicated to estimate stretching factors for the earlier extension (and therefore volumes of magmatic addition) directly from present-day

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crustal thickness estimates. We can draw insights from direct comparison between our estimated Moho depths and the distribution of what previous authors interpret as underplating along seismic refraction profiles. For profiles across the Davis Strait, our preferred Moho depth typically lies shallower than the refraction Moho where underplating is interpreted beneath continental crust on NUGGET lines 1 and 2 (Funck et al., 2007; Gerlings et al., 2009); The preferred gravity Moho lies slightly above the base of the crust in the refraction profile presented by Suckro et al. (2013), although the gravity Moho falls significantly below the refraction interpretation at the western margin of the line. The implications of interpreted underplating within the Davis Strait for our reconstructions are discussed further in the main text.

Supplementary material related to this article is available online at: http://www.solid-earth-discuss.net/5/917/2013/sed-5-917-2013-supplement.zip.

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Table 1. Full-fit rotation parameters for alternative models of Greenland relative to North America (fixed) discussed in this paper. The Chron 27 pole of rotation derived from Oakey and Chalmers (2012) has also been represented.

Full-fit (120 Ma) Model	Latitude (deg)	Longitude (deg)	Angle (deg)	r (km)	$\hat{\kappa}$	dF	N	s
1	64.82	−122.51	−13.50	842.9	0.12	106	117	4
2	61.20	−125.95	−11.30	829.14	0.12	107	118	4
3	62.77	−126.54	−11.36	679.31	0.15	103	114	4
4	58.69	−134.21	−9.17	946.72	0.12	120	131	4
5	61.58	−128.56	−10.23	795.06	0.14	112	123	4
6	60.26	−128.70	−10.39	971.54	0.10	106	117	4
7	62.09	−127.99	−10.63	738.54	0.14	105	116	4
Chron 27	27.8	−150.0	−3.75					

Parameters are r, total misfit; $\hat{\kappa}$, estimated quality factor; dF, degree of freedom; N, number of data points; s, number of great circle segments.

Table 2. Rotation covariences for North America–Greenland reconstructions.

Model	a	b	c	d	e	f
1	9.10	3.03	1.94	2.25	−1.98	8.69
2	1.32	−5.46	3.33	2.59	−3.06	1.32
3	1.26	3.99	3.12	2.57	−2.95	1.25
4	1.22	−1.98	3.47	2.32	−3.85	1.60
5	1.08	−8.52	2.89	2.53	−3.62	1.35
6	1.27	−1.25	3.46	2.38	−3.28	1.46
7	1.41	2.65	3.60	2.14	−2.03	1.39

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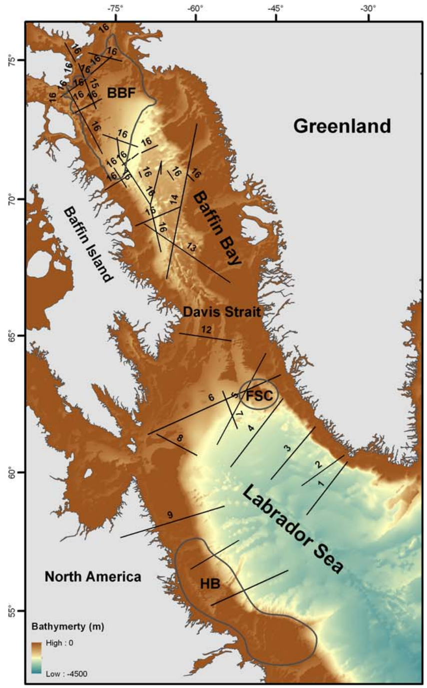

Fig. 1. Bathymetry of the Labrador Sea, Davis Strait and Baffin Bay. The seismic refraction and reflection lines discussed in this paper are shown as thick black lines 1: Chalmers, 1997 line BGR77-17; 2: Chian and Louden, 1994 line88R2; 3: Chalmers, 1997 line BGR77-21; 4: Chalmers, 1997 line BGR77-12; 5: Chalmers, 1997 line BGR77-6; 6: Funck et al., 2007 Nugget line1; 7: Gerlings et al., 2009 NAGGET line2; 8: Keen et al., 2012 line TGS1; 9: Keen et al., 2012 Profile1 (Gravity Profile); 10: Keen et al., 2012 line TGS3; 11: Chian et al., 1995 line90R1; 12: Suckro et al., 2012 line20 100 700; 13: Funck et al., 2012 line20 080 600; 14: Suckro et al., 2012 line20 100 400; 15: Harrison et al., 2011; line3c and Reid and Jackson, 1997 Line4; 16: Harrison et al., 2011. BBF – Baffin Bay Fan; FSC – Fylla Structural Complex; HB – Hopedale Basin.

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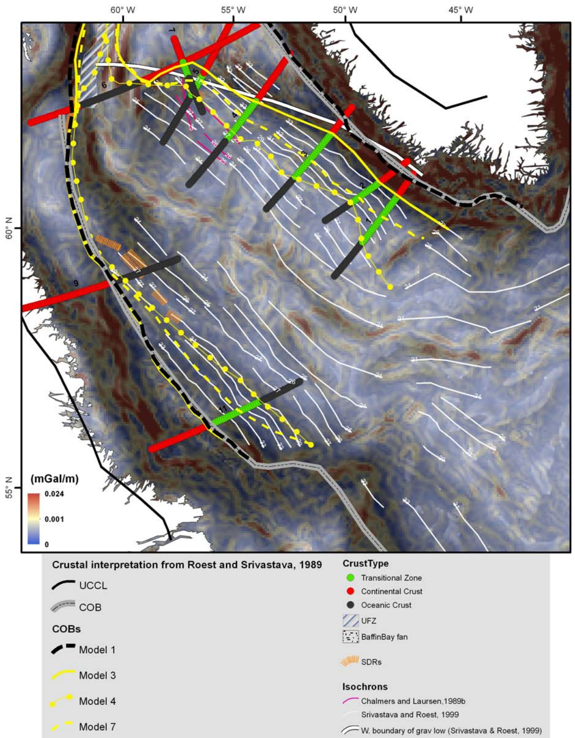

Fig. 2. Interpreted crustal structure and alternative COB models in the Labrador Sea shown overlying Bouguer gravity (derived from EGM08). UCCL (black) line is the same for all models. Four alternative COB interpretations are shown: Model 1 (dashed black line) based on (Roest and Srivastava, 1989) crustal interpretation. Model 3 (continuous thick yellow line) is the most landward COB (same as model 2 in the Labrador Sea). Model 4 (yellow line with circles) is the most oceanward COB (same as model 5 in the Labrador Sea). Model 7 (dashed yellow line) interprets the COB within the range of transitional zone (same as model 6 in the Labrador Sea). The numbering for seismic lines is the same as Fig. 1.

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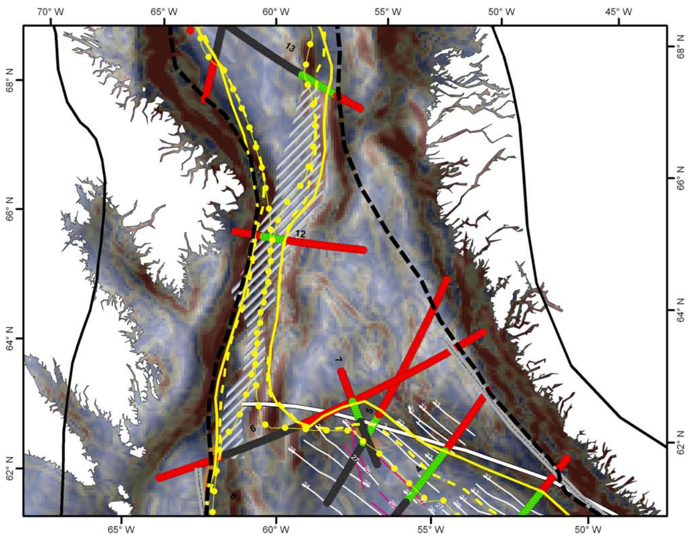

Fig. 3. Interpreted crustal structure and alternative COB models in the Davis Strait. Key as for Fig. 2

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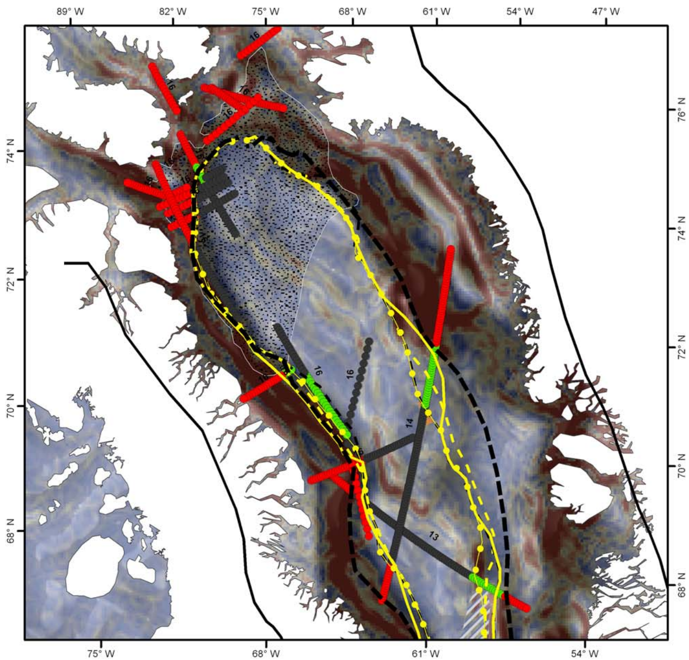

Fig. 4. Interpreted crustal structure and alternative COB models in Baffin Bay. Key as for Fig. 2.

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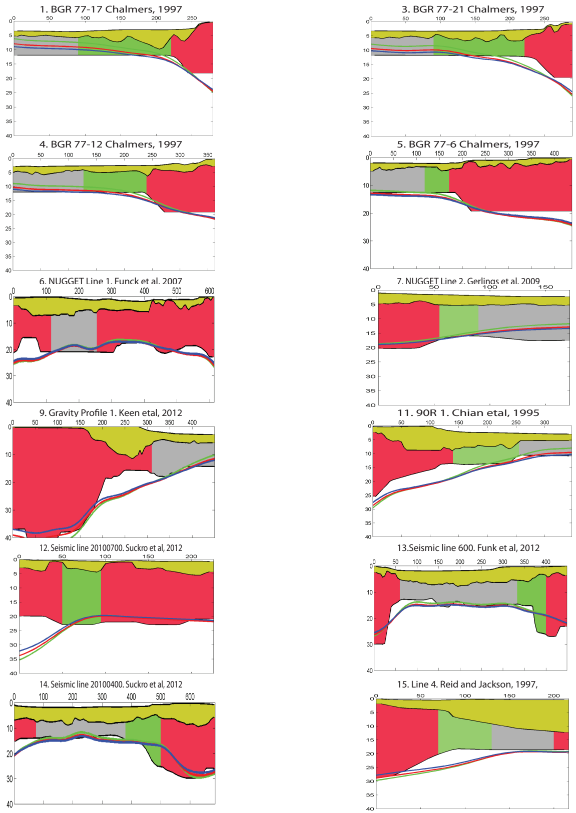

Fig. 5. Seismic profiles showing crustal type interpreted from different studies, locations shown in Figs. 1 to 4. Red – continental crust, green – transitional crust, grey – oceanic crust, yellow – sediments. Coloured lines show crustal thickness computed using gravity inversion; blue (for initial crustal thickness of 36 km and density of 500 $\mathrm{kg\,cm^{-3}}$), red (for initial crustal thickness of 38 km and density of 450 $\mathrm{kg\,cm^{-3}}$) and green (for initial crustal thickness of 40 km and density of 400 $\mathrm{kg\,cm^{-3}}$).

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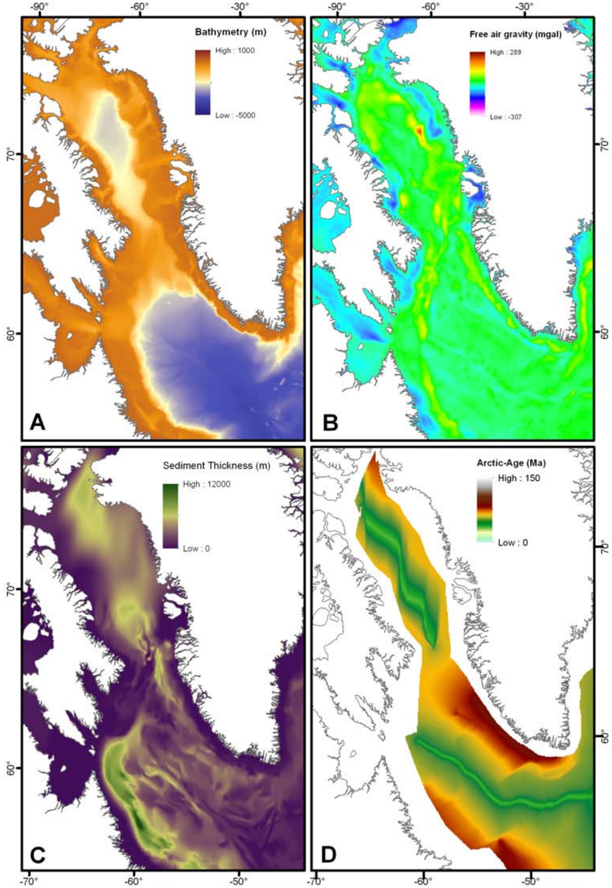

Fig. 6. Grids used to generate crustal thickness maps based on the gravity inversion method of Chappel and Kusznir (2008). **(A)**: Bathymetry (Louden et al., 2004), **(B)**: free air gravity (Sandwell and Smith, 2009), **(C)**: sediment thickness (Loudin et al., 2004; Divins, 2003; Laske et al., 1997). **(D)**: Age grid modified from Muller et al. (2008).

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Full-fit reconstruction of the Labrador Sea and Baffin Bay

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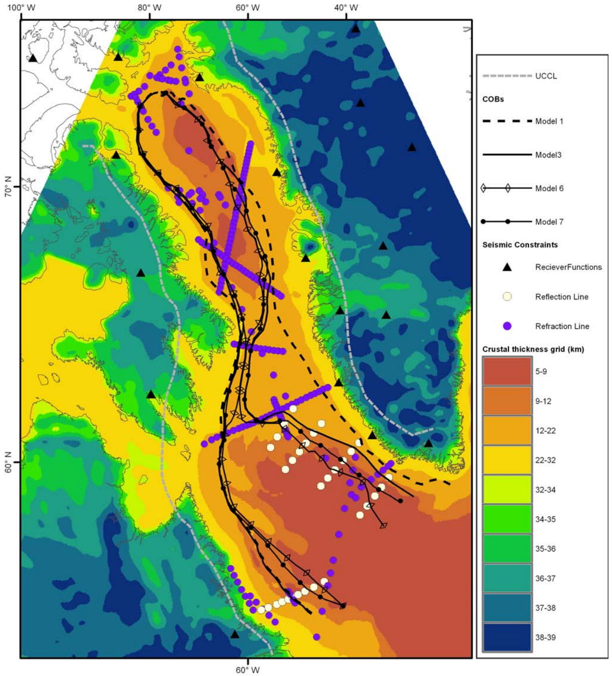

Fig. 7. Crustal thickness grid computed using gravity inversion method. Thickness of unstretched crust beneath inlands of Greenland and North America varies between 34–39 km.

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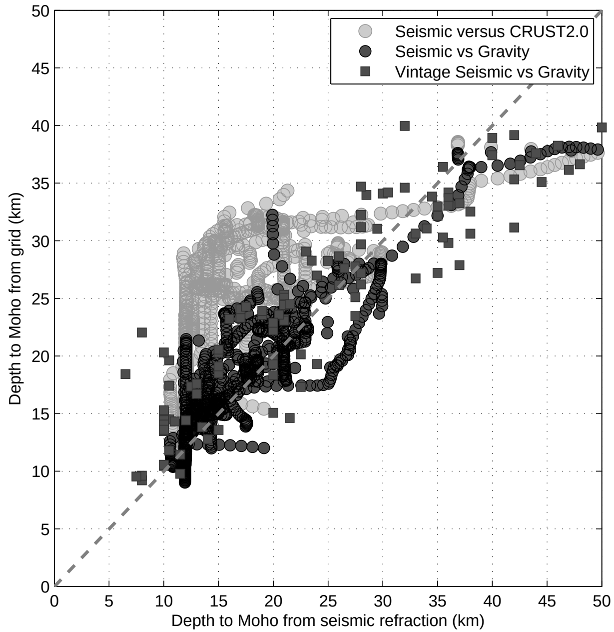

Fig. 8. Comparison of depth to Moho between independent seismic interpretations, global crustal thickness map (CRUST2 model)(Bassin et al., 2000), and our computed crustal thickness from gravity inversion. Dark grey circles show seismic depths versus gravity inversion derived Moho depths. Squares show the Moho depths from pre-2000 seismic studies versus gravity depth. Light grey circles show seismic depths versus CRUST2 model depths. Depths from CRUST2 model are typically deeper compared to regional seismic data. The grey dashed line is 1 : 1 trend.

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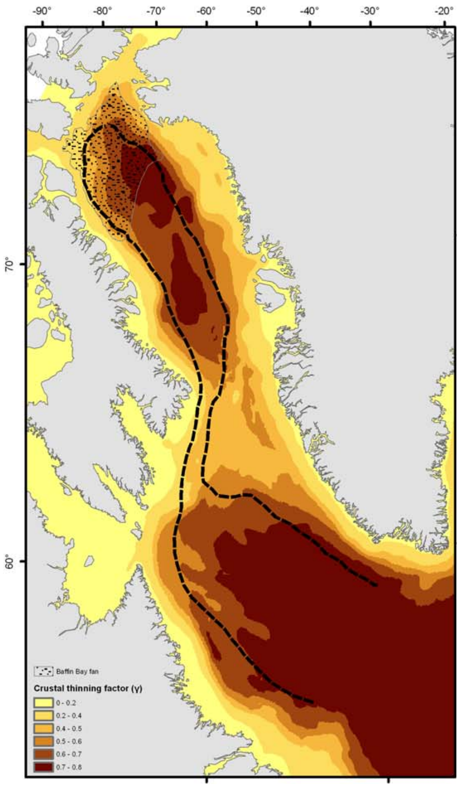

Fig. 9. Crustal thinning factor (γ) grid varies between 0 in unstretched continental crust to more than 0.7, which is the representative of volcanic addition in the form of magmatic underplating or oceanic crust. The thick dashed line is our preferred COB (model 7) that remains approximately at $\gamma = 0.5 - 0.7$.

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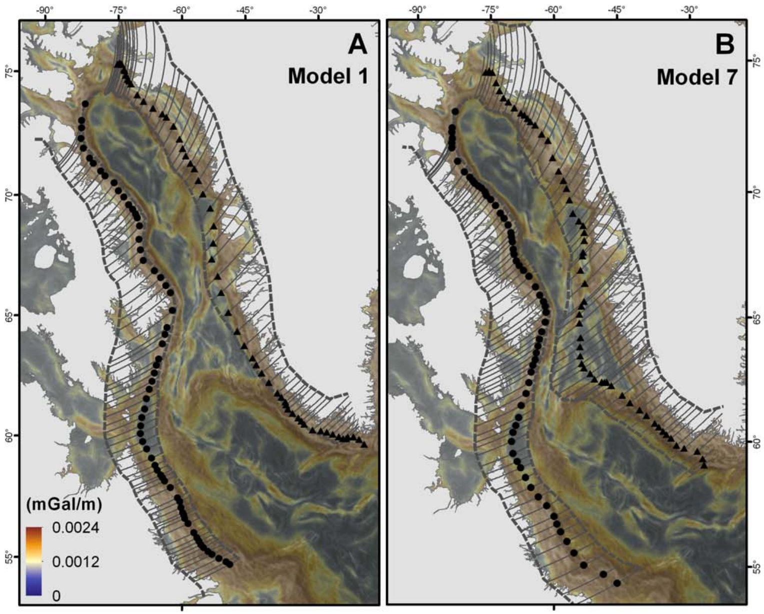

Fig. 10. Restored COBs on North America and Greenland margins together with small circle paths showing the direction of restoration. The dashed lines are the UCCL and COB lines before the restoration has been performed. The background is total horizontal gradient of Bouguer gravity map. Model 1: Srivastava and Roest (1989) COBs. Model 7: our preferred model assuming the COB in the range of COT, and UFZ as leaky transform fault in Davis Strait. Restored COB locations triangles – Greenland margin; circles – North American margin.

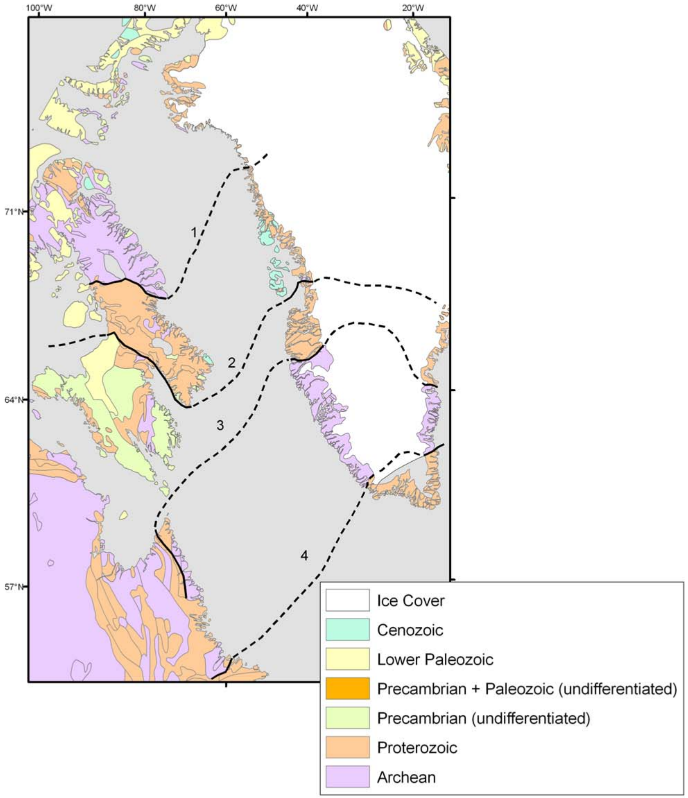

Fig. 11. Geological map of North America and Greenland (Bouysse, 2010) used for lateral correlation of two margins. We use sedimentary formations and rock units older than Palaeozoic to correlate the full-fit alignment of the conjugate margins. Numbers refer to structural features separating those units and formations that have been mentioned and discussed in more details in the main text.

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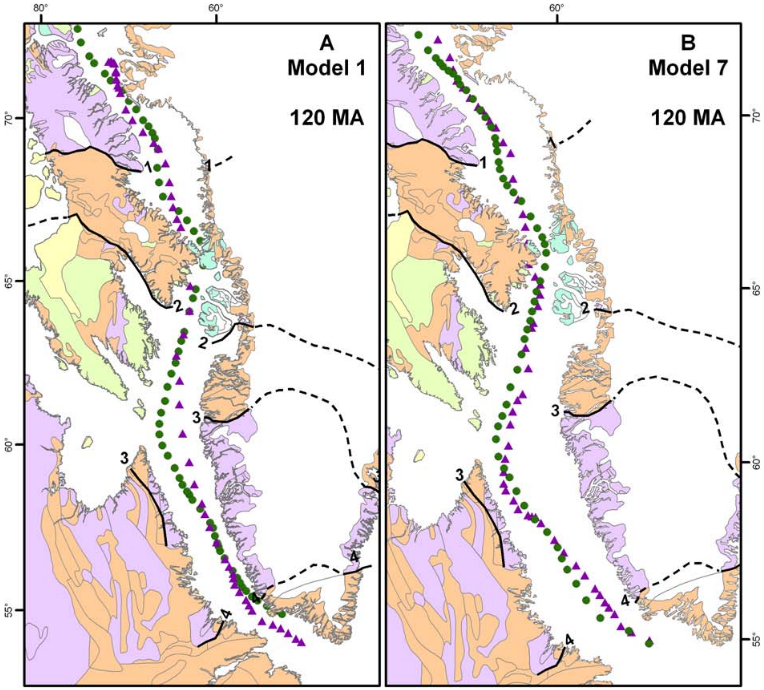

Fig. 12. Full-fit (120 Ma) plate reconstruction of North America- Greenland margins. North America restored COB – green circles, Greenland restored COB – purple triangles. **(A)** Model 1 results in a major overlap in the northern Labrador Sea near the Davis Strait. **(B)** Model 7 minimizes the mismatch in this area and results in a good fit in both the Labrador Sea and Baffin Bay. Structural lines are the same as Fig. 11 and represented here to show the lateral juxtaposing of the margins.

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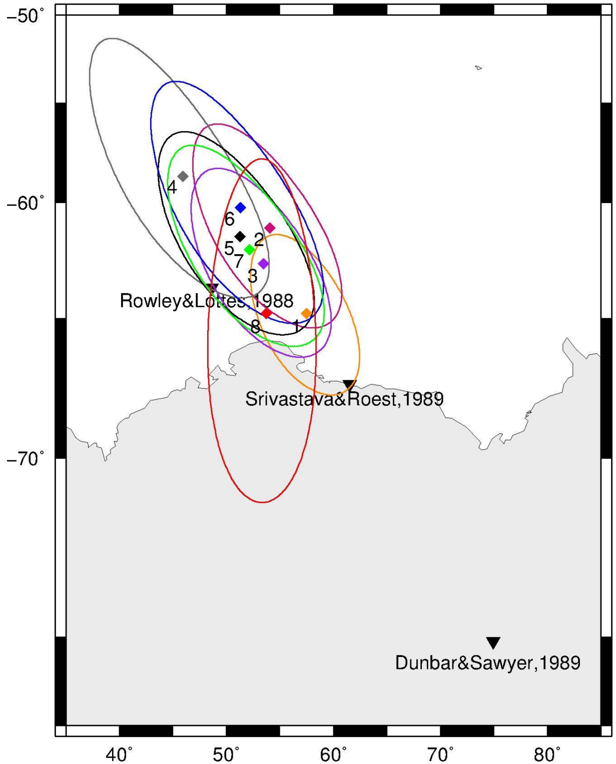

Fig. 13. Comparison of previously published and our computed Euler poles with 95 % uncertainty ellipses. The numbers represent the models described in the text.

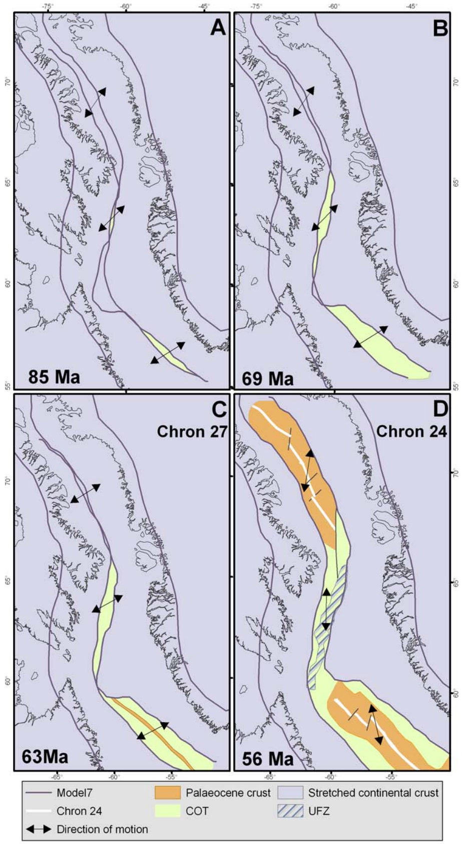

Fig. 14. Reconstruction of the rifting and seafloor spreading in the Labrador Sea and Baffin Bay. The models use rotation pole from model 7 for the rifting period (120 up to 63 Ma). Seafloor spreading (63 Ma and younger) has been reconstructed using Oakey and Chalmers (2012) poles of rotation.

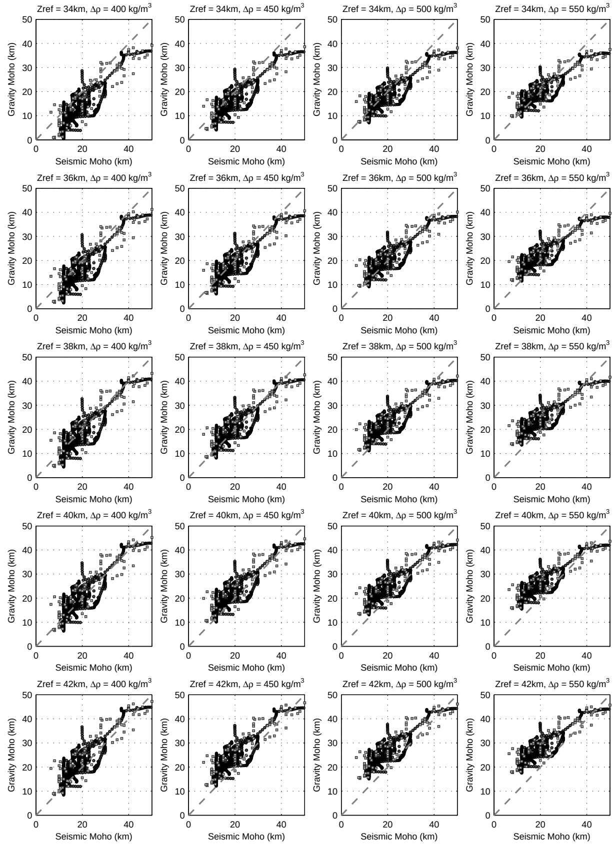

Fig. A1. Verification of the credibility of gravity inversion method and the resulted crustal thickness grid. The results were tested by different combination of reference Moho depths (Zref) and crustal densities ($\Delta\rho$). The gravity Moho in each combination (circles) have been plotted against the depth to Moho derived from independent seismic refraction profiles and receiver functions (squares) to examine their correspondence and validity.

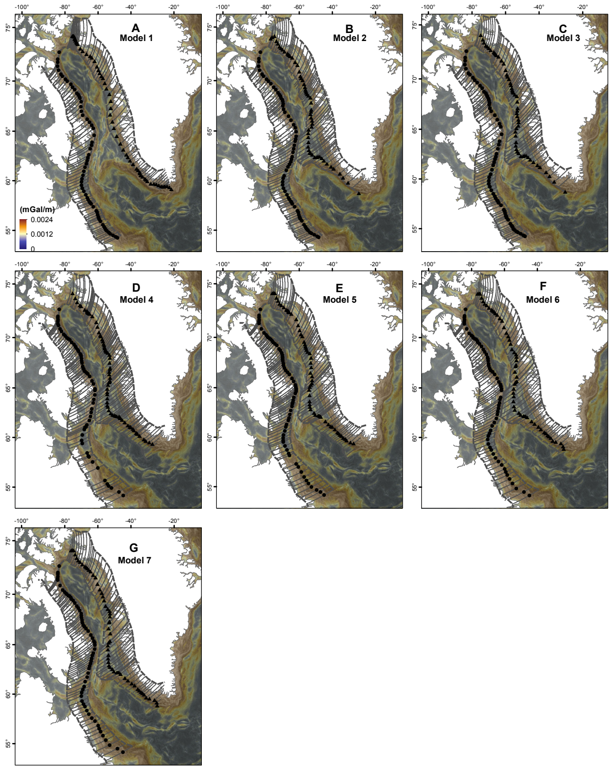

Fig. B1. Restoration of present-day COBs in to their pre-rift positions in conjugate margins. The restoration has been applied for the all 7 models in this study. UCCL lines and present-day COBs have been shown in grey dashed lines while the restored COBs come as black circles for the North America and black triangular for Greenland margin. Thin solid lines are small circle paths showing the direction of motion during the restoration process. The background map is total horizontal gradient of Bouguer gravity map corrected from EGM08 gravity model.

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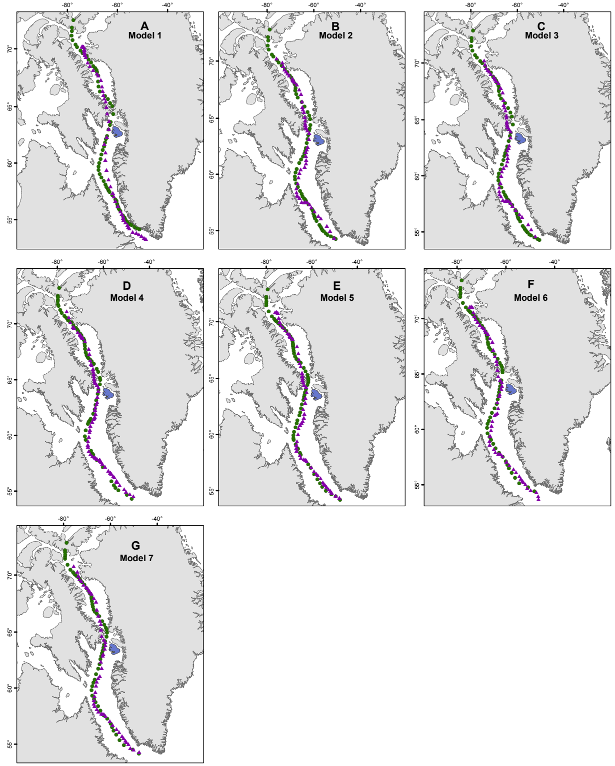

Fig. C1. Alternative Full-fit (120 Ma) plate reconstruction of North America–Greenland margins for all of the models tested in this study. North America restored COB has been shown in green circles while Greenland COB comes in purple triangles. Disco Island is highlighted in blue in all models to make the comparison easier.

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