PS Formation of the Volcanic Margins of West Greenland and North-Eastern Canada*

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Abstract

On the West Greenland and North-Eastern Canadian margins, as with many other volcanic passive margins (VPMs), a mantle plume has been proposed to elevate mantle temperatures sufficiently to account for the large volumes of magmatism observed. A number of observations made on both of these margins have been attributed to the passage of a mantle plume beneath this region (120-60Ma). Observations include the initiation of seafloor spreading in the Labrador Sea and Baffin Bay; the presence of large volumes of both extrusive and intrusive magmatism; the interpretation of seaward dipping reflectors (SDRs); the modelled underplating of the Davis Strait by a high-velocity body; and the presence of high 3He/4He ratios in picrites. The presence and role of mantle plumes during the formation of VPMs remains equivovcal, and cannot explain many of the larger scale features observed on the West Greenland and North-Eastern Canadian margins. Here we consider potential spatial and temporal mismatches between proposed hotspot track locations and independently dated geological events observed on the West Greenland and North-Eastern Canadian margins. These mismatches include; the timing of seafloor spreading initiation; location of seafloor spreading and the presence of 'pre-plume' coast parallel dyke swarms. These observations lead us to propose that the mantle plume hypothesis alone cannot satisfactorily explain the formation of all the geological features observed along these margins and that alternative mechanism(s) should be considered. Understanding the fundamental mechanisms involved in the formation of volcanic passive margins is critical in the reduction of exploration risk on such margins, as they place constraints on the structural and thermal evolution of the margin. This is particularly relevant as exploration activity extends further into frontier regions such as the West Greenland margin.

Formation of the volcanic margins of West Greenland and North-Eastern Canada: Background and Rationale

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Introduction

Aim: To provide insights into the thermal conditions present during the evolution of the West Greenland and North-Eastern Canadian Margins, though linking rifting patterns and fault localisation to the thermal conditions during margin formation, with a consideration of the larger scale tectonic setting.

Formation and Characteristics of VPMs

- Passive margins are produced by thinning of the lithosphere, resulting in continental breakup and eventually the initiation of seafloor spreading (Eldholm and Sundvor, 1979)
- Continental breakup can leave a complex transition from continental to oceanic crust.
- Volcanic Passive Margins (VPMs) are generally considered to be the products of continental breakup over an abnormally hot mantle (Geoffroy, 2005). This view is however challenged by other work (e.g. Simon et al 2009).
- Key features of VPMs (Geoffroy, 2005; Franke, 2013) include:
  - Thick igneous crust from both intrusive and extrusive rocks
  - High velocity zone in the lower crust
  - Seaward dipping reflectors

Geological Setting

- Continental rifting between Greenland and Canada probably initiated in the Early Cretaceous (Umpleby, 1979; Larsen, 1999).
- The Early spreading history of the Labrador Sea is poorly constrained, with the undisputed age of seafloor spreading in the Labrador Sea being Chron 27N (Danian) (Chalmers and Laursen, 1995).
- Large area affected by flood basalt volcanism during Chron 27N (60.9-61.3Ma) (Early Paleocene).
- Further volcanism occurred at 55.9-53.3Ma (Early Eocene), coincidental with a change in spreading direction.
- The West Greenland – Eastern Canadian margins bound the small oceanic basin of the Labrador Sea in the south to Baffin Bay in the north. These two small oceanic basins are linked via a transform fault system, through a bathymetric high known as the Davis Strait (McGregor et al., 2012).
- Along-margin variation in the amount of volcanism is observed along both the West Greenland and Eastern Canadian margins.
- The margins in the north and south of the study area display the least volcanism, whereas the margins around the Davis Strait are the most volcanic.
- On the volcanic segment of the margin we observe large volumes of both intrusive and extrusive igneous rocks (Storey et al., 1998), interpret seaward dipping reflectors (SDRs) (Chalmers et al., 1999) and infer mafic underplating to have occurred (Gerlings et al., 2009), resulting in its classification as a volcanic passive margins (VPM – Geoffroy, 2005).

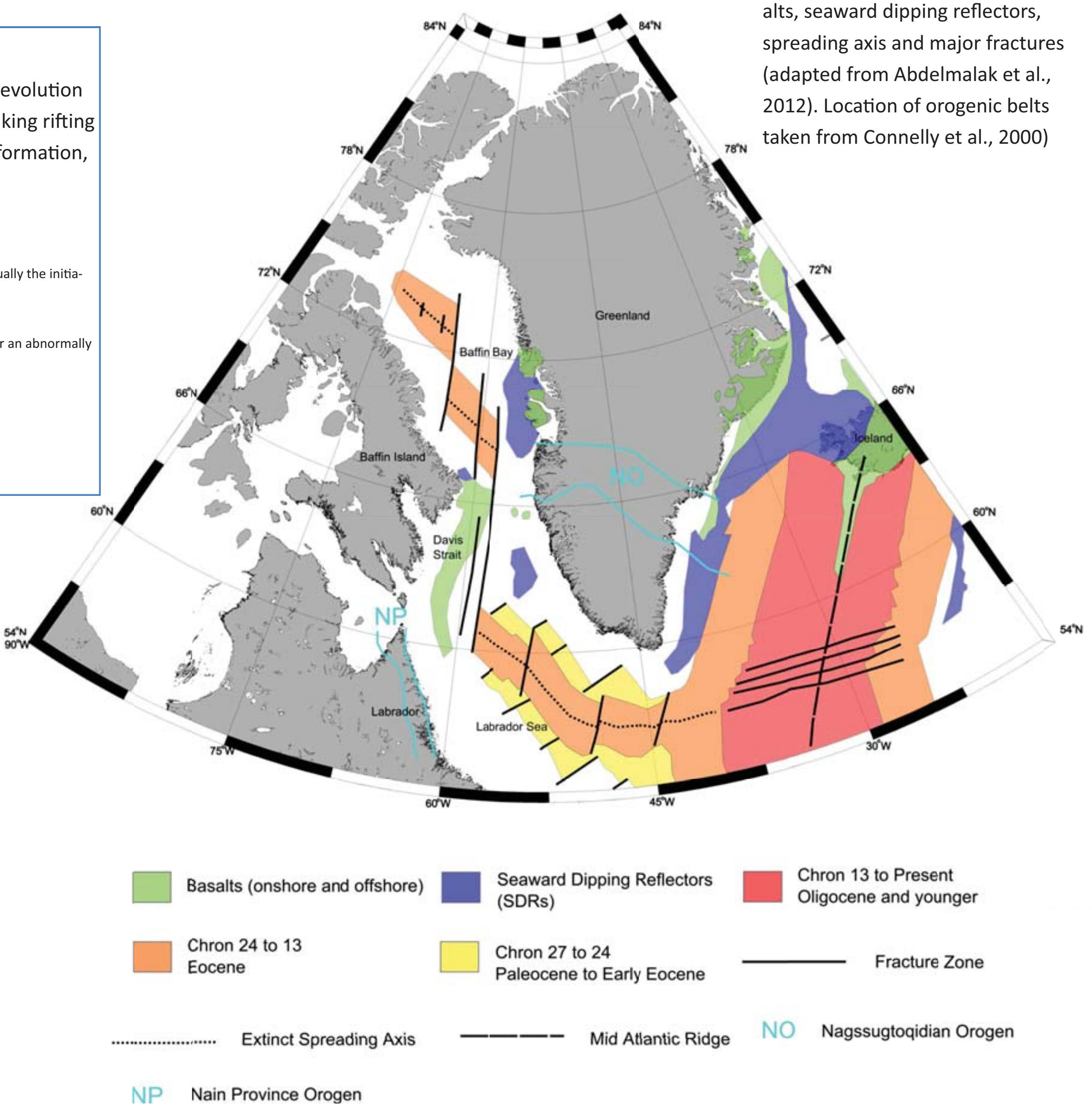

Figure 1. Age of the Seafloor in the North Atlantic and offshore West Greenland, along with the distribution of both on and offshore basalts, seaward dipping reflectors, spreading axis and major fractures (adapted from Abdelmalak et al., 2012). Location of orogenic belts taken from Connelly et al., 2000)

The Plume theory in West Greenland

The mantle plume theory is the most common mechanism proposed in the literature as an explanation for the formation of the volcanic margins of West Greenland and North-Eastern Canada (e.g. Chalmers, 1995).

Observations attributed to a Mantle Plume in Greenland:

- Onset of seafloor spreading in the Labrador Sea (Chalmers and Larsen, 1995; Gerlings et al., 2009).
- Major volcanism in West Greenland and Baffin Island (Chalmers and Larsen, 1995; Storey et al., 1998).
- Underplating of the Davis Strait by a high-velocity body (Gerlings et al., 2009).
- High $^{3}He/^{4}He$ (Graham et al., 1998) and low $^{187}Os/^{188}Os$ ratios in Picrites (Schaefer et al., 2000).
- Uplift of onshore sedimentary successions (Dam et al., 1998).
- High melting temperatures for picrites (Gill et al., 1992).
- Seismically observable volcanics for 400km east of Baffin Island (Funck et al., 2007).

Apparent mismatches between proposed plume and observations

When the hotspot tracks are considered, apparent mismatches between this theory and observations become apparent demonstrating the requirement for refinement of margin formation models (fig 2).

1. Seafloor Spreading initiating in the Southern Labrador Sea before the North

- Despite the debate regarding the exact date of seafloor spreading initiation in the Labrador Sea it is generally regarded that it was first initiated in the South Before the North (Strivastava, 1978) (Fig 1)
- The undisputed age of seafloor spreading in the Labrador Sea is Chron 27N (Danian) (Chalmers and Laursen, 1995). Even if this latest date is used it still significantly predates the closest location of the proposed plume to the Labrador Sea (Lawver and Müller, 1994))
- These interpretations imply that rifting first began in the southern, non-volcanic realm, which does not fit a model whereby a plume producing voluminous magmatism initiated seafloor spreading (Gerlings et al., 2009).
- If a plume were present during rifting, and subsequent seafloor spreading would be expected to start nearest to the plume and to propagate away from it.

2. Delayed initiation of seafloor spreading in Baffin Bay

- The timing of seafloor spreading in Baffin Bay is also contrary to what would be expected by the plume hypothesis. The hotspot track reconstruction of Lawver and Müller (1994) place the proto-Icelandic plume in the Baffin Bay area at ca.120-70Ma, whereas seafloor spreading did not initiate until much later at Chron 27-25 (52-62Ma) (Oakey and Chalmers, 2012), even though it is situated in close proximity to the alleged plume track for a prolonged period of time (Fig 2).

3. Absence of fully initiated seafloor spreading in the Davis Strait

- In the more volcanic Davis Strait seafloor spreading was never fully initiated as it was in the Labrador Sea and Baffin Bay (Suckro et al., 2013).
- Instead a 'leaky transform' system has developed (Funck et al., 2007). If a plume was the cause of the abundant volcanics here, the greatest beta factors, and thus seafloor spreading, would be expected in this region.
- It is not clear why should cause seafloor spreading in the distant Labrador Sea (Chalmers et al., 1995; Gerlings et al., 2009) but not at the Davis Strait which is situated much closer to the alleged plume.
- A transform fault system is not a prediction of the mantle plume model.

4. Coast parallel dyke swarms pre-plume arrival

- It has been suggested that the prolonged location of a plume could "pin" the position of subsequent spreading (Hill, 1993), through thermal and mechanical weakening of the lithosphere, which a subsequent stress field could exploit.
- Onshore coast parallel dykes have however been dated as early as the Jurassic (Larsen et al., 2009). This implies that the weakness exploited by subsequent continental breakup was already in place before the proposed plume was in the vicinity.

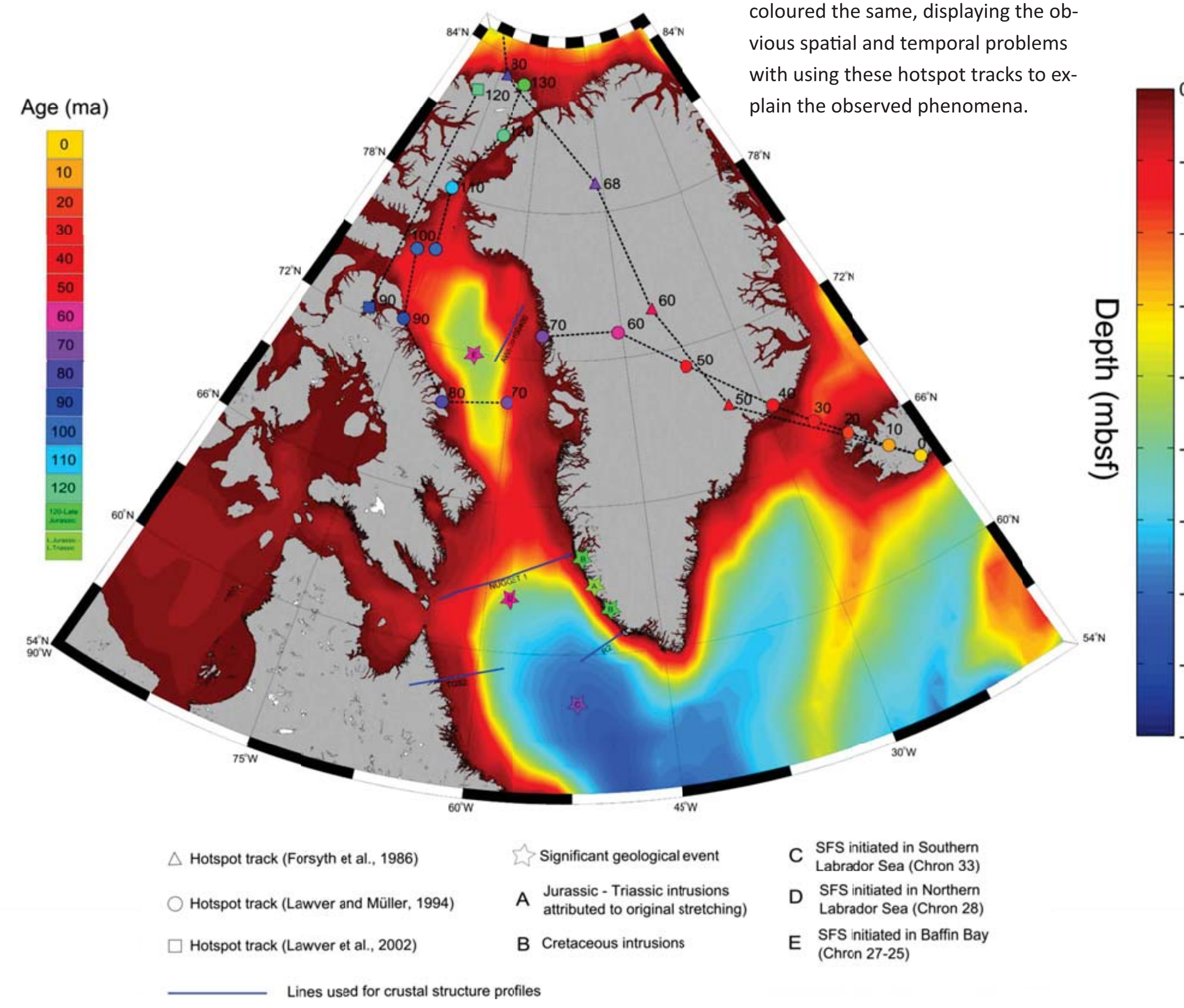

Figure 2. An overview of study area with proposed hotspot tracks and relevant geological events overlaid. Events occurring simultaneously are coloured the same, displaying the obvious spatial and temporal problems with using these hotspot tracks to explain the observed phenomena.

Rationale

- It can be seen from the apparent mismatches between the Plume theory and observations on the West Greenland and North Eastern Canadian Margins that our current understanding of the fundamental processes involved in VPM formation is insufficient.
- Margin formation models are often based upon observations at non-volcanic margins (Such as the Iberia-Newfoundland conjugate pair) which are unlikely to be applicable to VPMs.
- It is generally regarded that heat flow on VPMs was higher than their non-volcanic counterparts as an explanation for the abundant intrusive and extrusive rocks on such margins, but there is currently a need for independent confirmation that heat flow was higher in order to provide insights into the mechanisms operating during margin formation.

The Importance of understanding heat flow on VPMs

- Understanding the fundamental mechanisms involved in the formation of VPMs is critical in the reduction of exploration risk on such margins.
- The thermal history places constraints on the structural evolution of the margin.
- The thermal evolution of a margin is critical in understanding source rock maturation.
- This is particularly relevant as exploration activity extends further into frontier regions such as the West Greenland margin, where operating costs may be much higher than elsewhere.

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Formation of the volcanic margins of West Greenland and North-Eastern Canada: Data analysis and Interpretation

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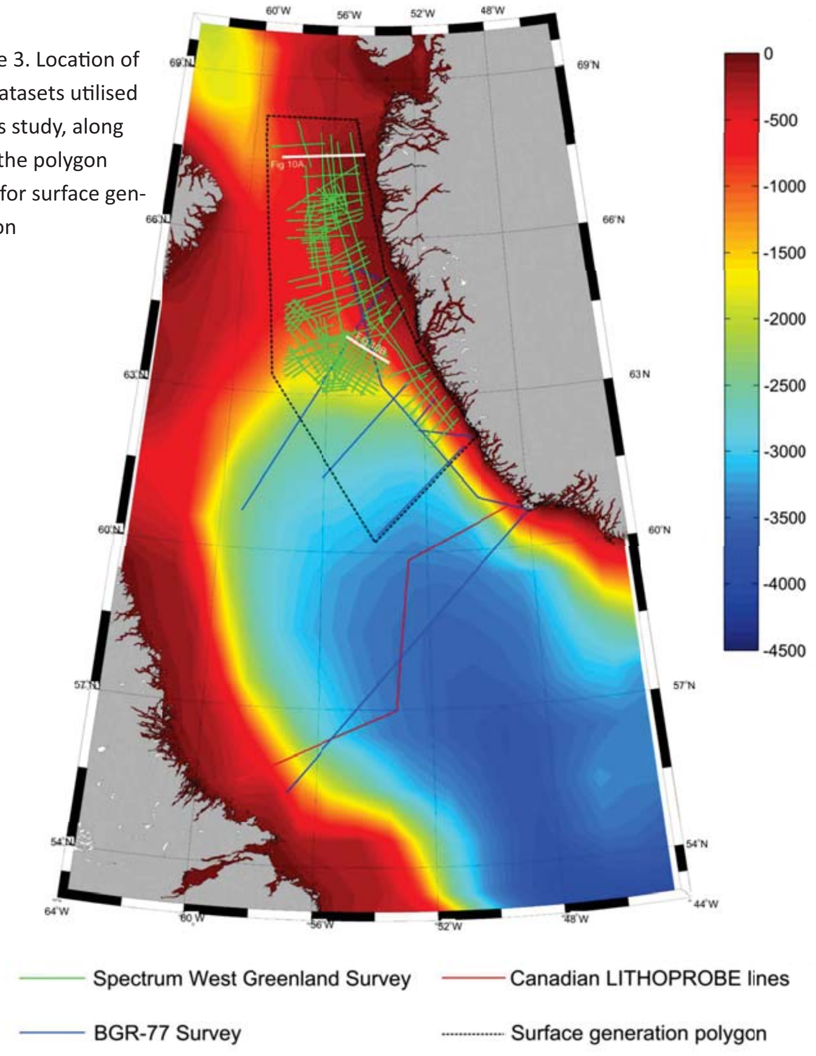
Figure 3. Location of the datasets utilised in this study, along with the polygon used for surface generation



Datasets

Our study utilises several seismic datasets including:

- **Spectrum West Greenland survey**, high quality dense 2D survey covering the West Greenland margin in the Davis Strait.
- **BGR-77 Survey,** medium quality, low density survey, good for overall margin structure in the Labrador Sea.
- **Canadian LITHOPROBE survey,** several older lines useful for large scale structures.

Methodology

- Seismic interpretation carried out in Petrel.
- Top syn-rift, top pre-rift (basement) and the seafloor horizons were traced across the data coverage area.
- 3D Surfaces were then generated from the interpreted horizons.
- Isochron maps between the surfaces were then generated.

Surface Boundary Polygons

- A boundary polygon is required by Petrel to generate surfaces.
- The quality and density of the data is highest around the Spectrum West Greenland Survey.
- An appropriate polygon area was chosen based upon inclusion of the volcanic/non-volcanic transition to study the effect upon fault localisation.

Interpretation of Surfaces and Isochron Maps

Current Bathymetry

- In both the Northern Labrador Sea and the Davis Strait the current Bathymetry appears to be heavily controlled by basement architecture (Fig 4 and 5).

Sediment Source

- The focus of sedimentary depocentres changes between the syn and post rift stages of margin development (Fig 7 and 8).
- This could be a reflection of dynamics related to margin evolution or it may be as a result of changing sediment sources.
- The small basins in the syn –rift of the Northern Labrador Sea no longer appear on the post-rift isochron, and the large area of sediment accumulation appears to have shifted south.

Implications for Rifting and margin formation

- A different rifting regime was operational in the Davis Strait area compared to the Northern Labrador Sea.
- This is observable in figure 7 where the syn-rift sedimentation in the Davis Strait is concentrated in one very large basin compared to in the Northern Labrador Sea where we can see that the syn-rift sedimentation occupies multiple smaller basins.
- The observed variation in rifting regime can be interpreted in terms of the degree of localisation, in that the extensional deformation in the Davis Strait is more concentrated upon fewer but much larger faults (i.e. more localised deformation in the Davis Strait compared to the Northern Labrador Sea).
- The degree of localisation can be related to the strength of the lithosphere, in that more localised faulting implies a weaker lithosphere.
- Enhancing the geothermal gradient is proposed as a 'strain softening' mechanism (Cowie et al., 2005), therefore the more localised deformation in the Davis Strait may provide further evidence for an enhanced heat flow during formation.

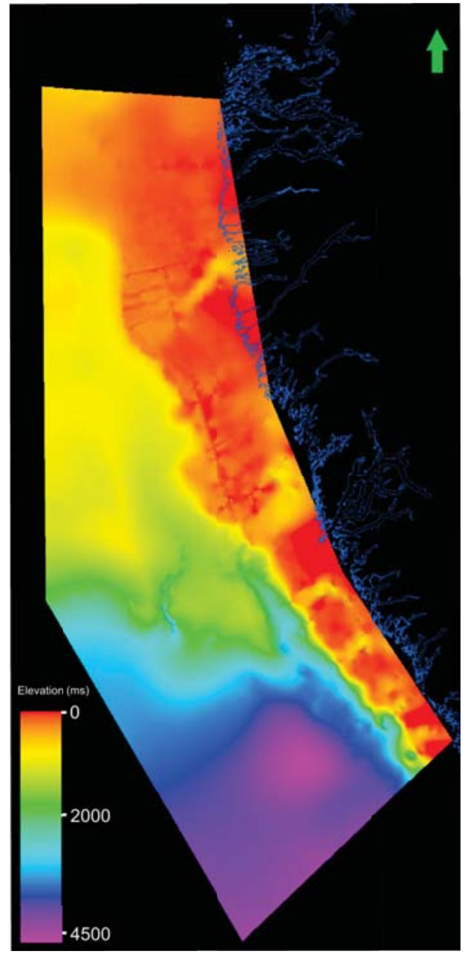


Figure 4. Depth (ms) to seafloor Surface

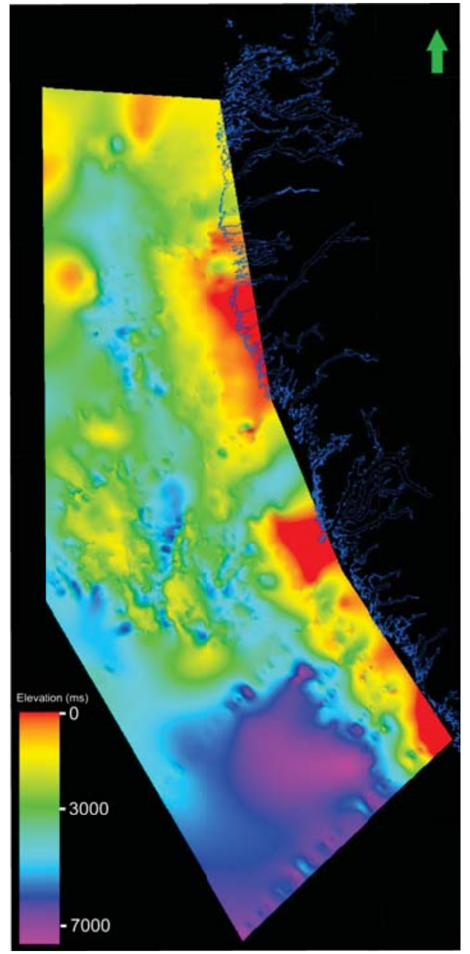


Figure 5.Depth (ms) to basement (top pre-rift) Surface

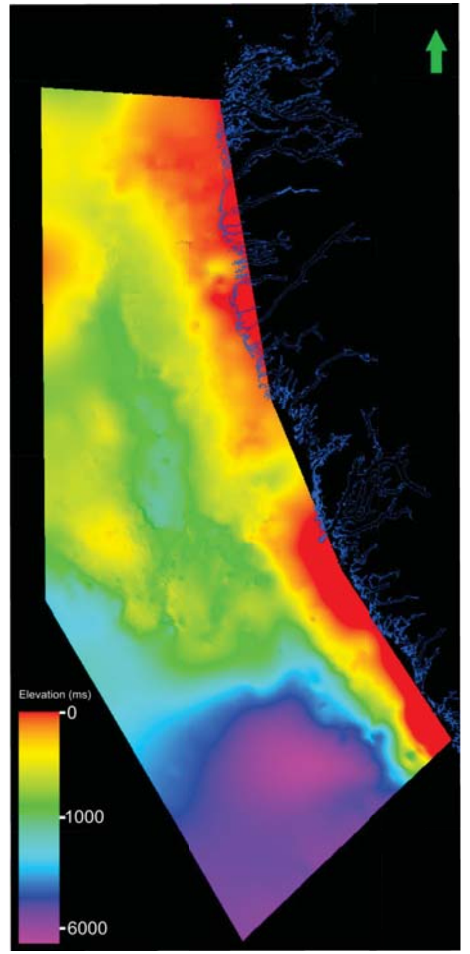


Figure 6. Depth (ms) to top syn-rift surface

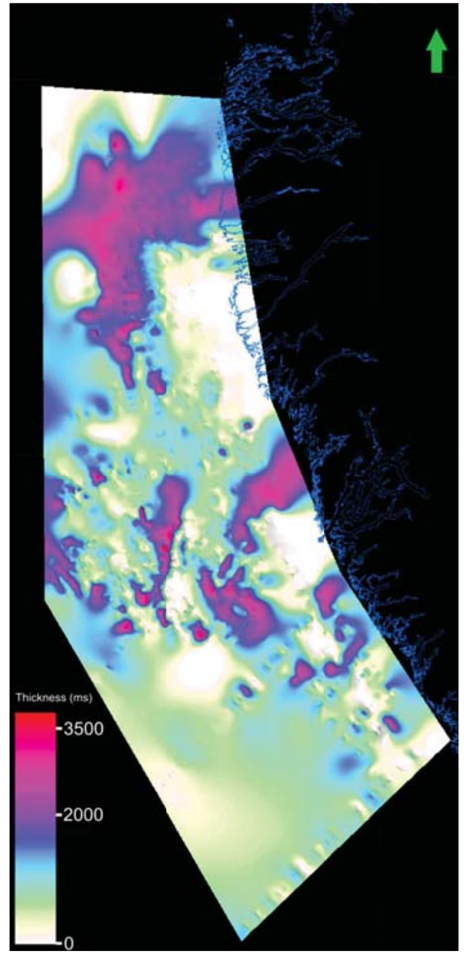


Figure 7. Thickness isochron of syn-rift sedimentation

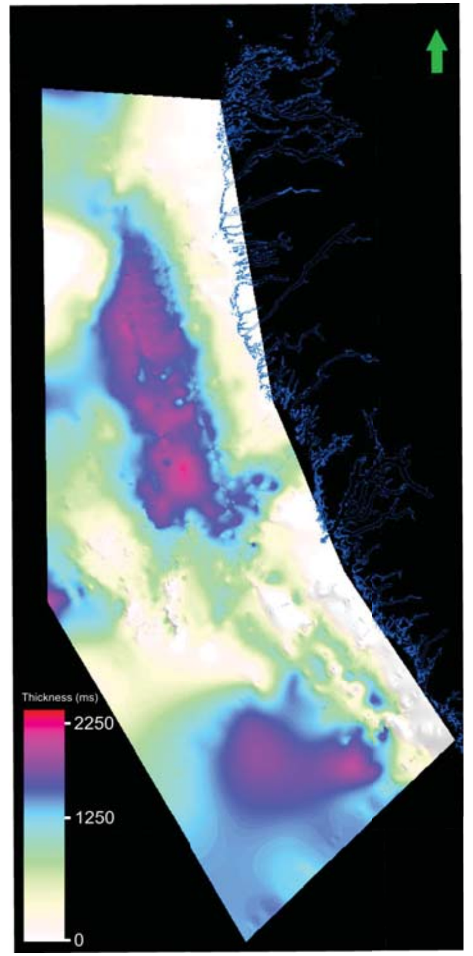


Figure 8. Thickness isochron of post-rift sedimentation

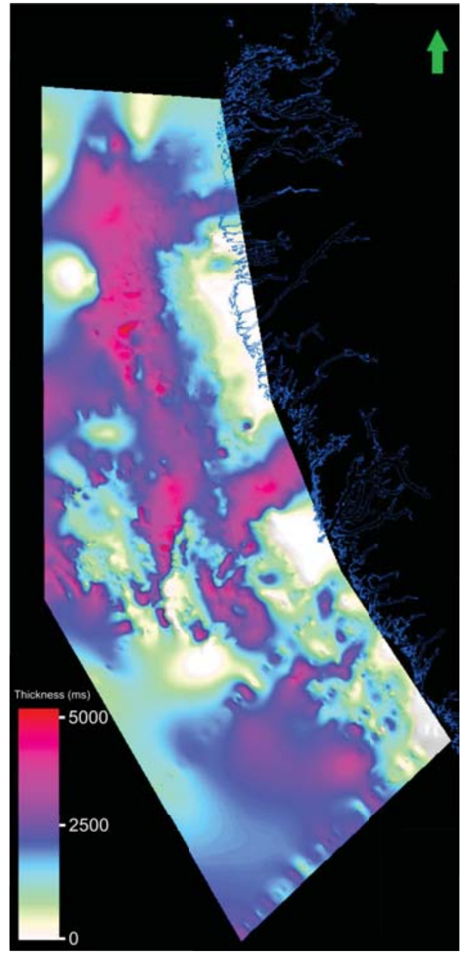


Figure 9. Thickness isochronof all sediments (post-rift and syn-rift)

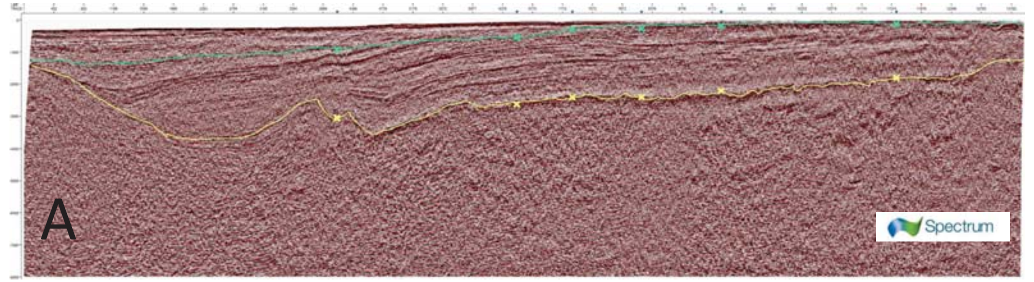


Figure 10A. Line A, located in the Eastern Davis Strait from the Spectrum West Greenland Survey displaying the structures typically observable in this area. Approximate location shown on Fig 3.

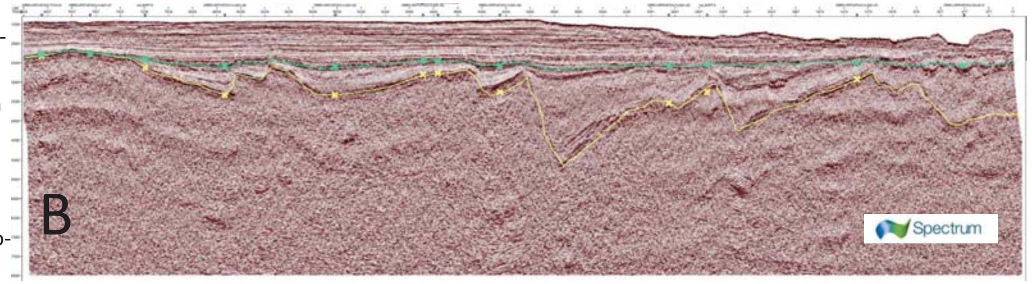


Figure 10B. Line B, located in the Northern Labrador Sea from the Spectrum West Greenland Survey displaying the structures typically observable in this area. Approximate location shown on Fig 3.

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Formation of the volcanic margins of West Greenland and North-Eastern Canada: Models and Conclusions

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Strain Localisation Mechanisms

The localisation of deformation onto larger structures can occur as a result of several mechanisms (Bellahsen et al 2003), known as strain softening mechanisms (Kearey et al., 2009).

- Elevation of the Geothermal gradient during rifting
- Heating by intrusions
- Interactions between the lithosphere and asthenosphere
- Other mechanisms that control fault and deformation behaviour during deformation

Our isochron maps (Fig 7 to 9) clearly show that extensional deformation was more localised in the Davis Strait area than the Labrador Sea. This does fit with the previous models suggesting that VPM formation requires a higher heat flow than the formation of a non-volcanic margins (e.g. Geoffroy, 2005), it does not however allow us to conclusively state that this localisation of deformation is certainly as a result of an elevated geothermal gradient. We can however conclude that along with the other evidence for an enhanced geothermal gradient provided by previous work (e.g. Chalmers et al., 1995) it is likely that it is as a result of an elevated geothermal gradient during margin evolution.

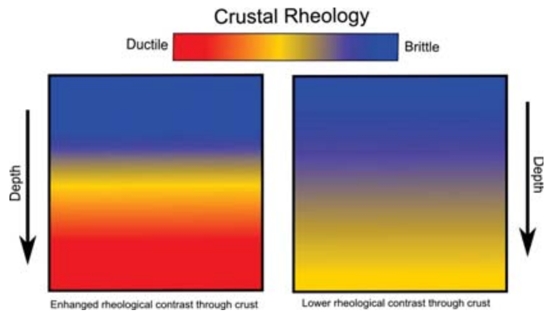


Figure 11. Schematic depiction of the concepts derived from the numerical and analogue models by Bellahsen et al., 2003. The models by Bellahsen demonstrated that the presence of a basal viscous layer localizes the deformation by creating faults with very large throw and that a lower strength viscous layer enhances the localisation of the deformation. Although the models by Bellahsen et al,. 2003 did not consider the effects of temperature, it is reasonable that an enhanced geothermal gradient would result in a greater brittle/ductile rheological difference throughout the crust.

Margin formation models

Having provided further evidence that the geothermal gradient was in fact elevated in the Davis Strait area several models can be considered as the causal factor behind this elevated heat flow during margin creation. These models are not implied to be mutually exclusive and in reality more than one may have been active.

Thermal anomaly in the mantle

The mantle plume theory is the most common explanation provided in the literature for the formation of this VPMs. This theory suggests that a thermal anomaly originating from deep in the Earth is responsible for the observations on the West Greenland Margin. Some previous work suggests that more than one plume may have been present (Gill et al., 1995).

Pros:

- Picrites are interpreted to be the product of high temperature melting, a plume could provide this heat.
- It has been claimed that the volumetrically extensive (22,000km^3) nature of the volcanism requires a plume (
- A non-circular plume head (as opposed to the circular geometry proposed by most work) could help explain some of the observations attributed to a mantle plume (Chalmers, 1997)
- Provides a simple explanation
- Lateral flow of plume material have been previously suggested which could help explain some of the observations (Sleep, 1997)

Cons:

- 'Additional ' heat may not be required to produce VPMs as can be seen by the other models presented herein.
- A clear hot spot track is not observable.
- Apparent spatial, temporal and geometric mismatches between observations and predictions of the plume theory (Fig 2, 1st poster).
- Although picrites are typically quoted as being the products of an elevated mantle temperature it can not be proven that they are not the product of a 'contaminated' source.

Stress concentration at Ridge-Transform Intersections (RTIs)

This model has previously been used to explain the location of hotspots at RTIs (Beutel, 2005) when plate tectonic theory would predict greatest amount of volcanism at the centre of ridge segments. According to the models produced by Beutel (2005) we should get melt produced in the areas indicated in red, and that increased transform strength increases the extensional stresses at RTIs. These increased stresses may result in adiabatic melting and a change in the geothermal gradient (Beutel, 2005).

Pros:

- No need to invoke large scale mantle dynamics for which there is no other evidence
- Geometry of the Davis Strait fits this model, not only in terms of offset spreading centres connected by a fault system but also in that the volcanic rocks are located near the intersections between the spreading centre terminations and the start of the fault zone.

Cons:

- This mechanism has been used to explain volcanism at RTIs which are considerably smaller than the volume of the melts on the West Greenland VPM
- May not be capable of producing adequate volumes of igneous material
- The original work by Beutel (2005) produces models which are capable of calculating relative amounts of stress rather than absolute values. The results therefore do not allow us to make any predictions regarding the volume of potential melts created.
- The models by Beutel are stress calculations (not strain). Strain calculations may be more relevant when relating to melt production.

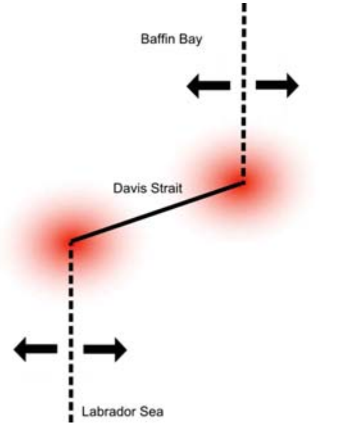


Figure 12. Schematic depiction of stress concentrations at RTIs (red shade) as it may be applied to the Davis Strait. Concept derived from the finite element numerical models by Beutel, 2005.

Small-scale convection

Small-Scale Convection (SSC) has been previously proposed as a mechanism capable of producing melt in extensional settings (Simon et al., 2009). SSC is proposed to be caused by lateral temperature gradients, which may provide an enhanced flux of material into a region of partial melting, therefore increasing magmatic productivity without the need for additional heat. This idea was recognised by Mutter et al., (1988) and its role in melt generation at extensional settings has been recently considered (Simon et al 2009)

Pros:

- No need to invoke large scale mantle dynamics for which there is no other evidence
- Modelling suggests it could provide an adequate mechanism in the formation of VPMs
- Complex transform systems such as in the Davis Strait could encourage the onset of small-scale convection
- Could occur alongside other mechanisms
- Multiple 'Leaky transform' faults (ref?) in the Davis Strait may have been capable of inducing numerous small scale complexities and lateral temperature gradients

Cons:

- May not be capable of producing the volumes of melt required for VPM formation
- Explains the later evolution of the margin but not the rift initiation. However the volcanics are dated considerably later than the onset of rifting so it could still provide an adequate explanation for VPM formation.

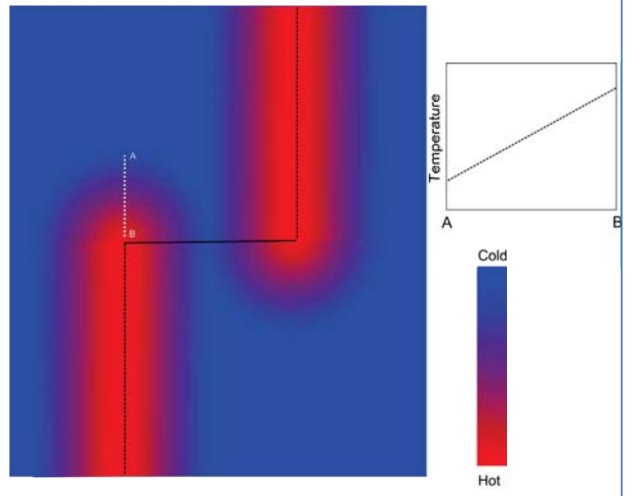
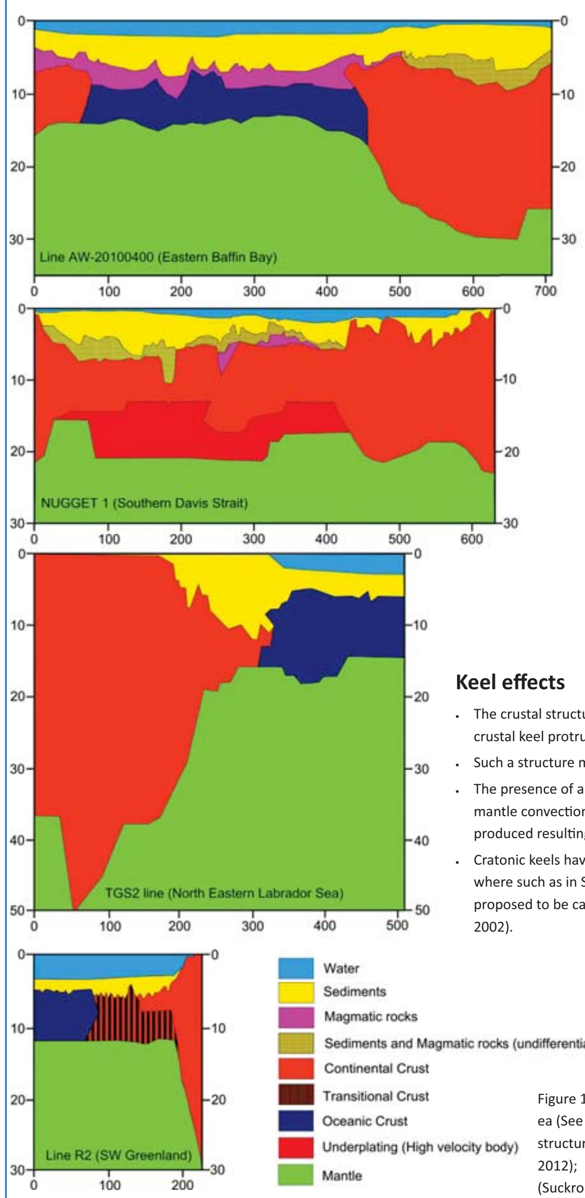


Figure 13. Schematic depiction of cooling newly created oceanic lithosphere and how it may be capable of producing lateral temperature gradients capable of initiating small-scale convection

The influence of continental lithospheric structure variations

The structure of the continental lithosphere could have influenced margin formation due to a number of mechanisms.



Insulating effects

Thicker continental lithosphere may provide a thermal blanket capable of insulating the mantle beneath. The prolonged presence of continental lithosphere over the Davis strait, compared to Baffin Bay and the Labrador Sea (where seafloor spreading was initiated) may have insulated material below, enhancing the effects of other mechanisms.

- Generic models have shown that this mechanism could work.
- Post initiation of seafloor spreading crust is significantly thinner in the Labrador Sea and Baffin Bay
- High heat flow related to seafloor spreading may have reduced the insulating properties of the crust.
- Unlikely to have been solely responsible for the formation of the VPM, but could have enhanced the effects of the other mechanisms.
- There may not be a significant enough difference in crustal structure and thickness between the Labrador Sea and Davis Strait (Fig 14), as the crust is still reasonably thick at the margins of the Labrador Sea.
- We can not be sure that the crust in the Davis strait has always been thicker, as we cannot accurately deduce when that underplated body was added to the crust (Fig 14).
- This does not provide a mechanism for rift initiation or margin formation.

Keel effects

- The crustal structure depicted on the TGS 2 line shows a large continental crustal keel protruding into the mantle down to 50km (Fig 14).
- Such a structure may be related to the orogenic belts (Fig 1).
- The presence of a large cratonic keel such as this could have focused mantle convection patterns in the Davis Strait allowing more melt to be produced resulting in VPM formation
- Cratonic keels have been known to influence asphenospheric flow elsewhere such as in SE Brazil (Assumpção et al., 2006), and have even been proposed to be capable of deflecting mantle plume material (Sleep et al., 2002).

Figure 14. Crustal structure at selected location in the study area (See Figure 2 for locations) derived using seismic velocity structure. NUGGET 1 (Funck et al., 2007); TGS2 line (Keen et al., 2012); R2 line (Chian and Louden, 1994); AWI-20100400 (Suckro et al 2012)

Conclusions

- The more localised faulting in proximity to the volcanic segment of the West Greenland Margin (in the Davis Strait) adds to the bank of evidence that heat flow during margin formation was higher in the volcanic segment of the margin, but the causal mechanism of this elevated heat flow remains unclear.
- This 'additional' heat is unlikely to have been provided by the presence of a mantle plume as suggested by most previous models of VPM formation, due to the apparent mismatches between the observations on the margin and the proposed plume locations.
- A more likely scenario is that one or a combination of the other mechanisms suggested here are responsible for the formation of this volcanic margin.

Future Work

- Extending the coverage of the seismic data available to this study would allow us to test whether the patterns of strain localisation noted in the current study area are observed elsewhere.
- This would be particularly beneficial for the West Greenland margin in Baffin Bay as this would allow us to investigate the symmetry (or asymmetry) of the rifting patterns either side of the Davis Strait
- Finding further evidence for or against these models will be the next stage of this research.
- The models proposed here may be a causal mechanism in the formation of other VPMs. Further work will works towards developing models which can be more universally applied to VPM formation.

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