Davis Strait Paleocene Picrites: Products of a Plume or Plates?

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NOTE: THIS PRELIMINARY VERSION OF OUR MANUSCRIPT IS STILL VERY ROUGH AND REPETITIOUS

"if [we] had more time, [we] would have written a shorter [manuscript]"

Abstract

THIS IS JUST OUR AGU ABSTRACT AND WILL NEED UPDATING

Voluminous, subaerial, ultra-depleted, 62 Ma, primary picritic lavas occur on both sides of Davis Strait separating Baffin Island and West Greenland. Temporally, the picrites are coeval with the initiation of sea-floor spreading in Labrador Sea and Baffin Bay around 62 Ma. Petrogenetically, the chemical characteristics of these picrites (MgO = 18-21 wt. %; K_2O = 0.01-0.20 wt. %; $^{87}Sr/^{86}Sr_i \approx 0.7030$; $\varepsilon Nd_i \approx +5.2$-8.6; $^{3}He/^{4}He \leq 49.5R_A$) demand only derivation by partial melting of highly depleted subcontinental lithospheric mantle (SCLM) at a pressure of ~ 4 GPa, followed by rapid ascent to the surface, but do not necessarily require high temperatures or high degrees of partial melting. Tectonically, these picrites formed in thick Archean and Paleoproterozoic cratonic terranes during Paleogene rifting between Greenland and North America. Structurally, the picrites are related to the major intersection of a NNW suture zone under Baffin Bay and the E-W trending Paleoproterozoic Nagssugtoqidian Fold Belt. During the late Mesozoic, ENE extension created normal faulted basins quasi-parallel with the NNW suture and thinned the mantle lithosphere. Elastic finite-element models and present day studies of crustal extension show that the thicker Nagssugtoqidian Fold Belt underwent less thinning and extension than the NNW suture zone in the Archean Rae craton. These extensional disparities occur at the orthogonal intersection of pre-existing ~E-W trending strike-slip faults in the thicker Nagssugtoqidian Fold Belt with the NNW thinned Archean suture zone, and likely resulted in the formation of one or more pull-apart basins. Because the strike-slip faults are ancient suture zones, trans-tension within these suture zones easily reached ~120 km, creating not only decompression melting in the SCLM, but also a pathway for the picritic melts to rapidly reach the surface. Such a purely tectonic model requires no spatially or temporally improbable deep mantle plume for generation of the Paleocene picrites of Davis Strait.

in the field, the Davis Strait picrites (DSPs) look like CFBs resting on continental crust, but regionally they lie on conjugate continental margins astride a sea-floor spreading centre and they have indisputable MORB tectonomagmatic indicators, so they are genetically MORBs

Outline

INTRODUCTION

- **Review – historical background, regional geology, the picrite petrogenetic problem**
- **Purpose – to reinterpret Davis Strait picrites as plate controlled**
- **Claim – Davis Strait picrites have nothing to do with any deep mantle plume**
- **Scope – picrites only, previously published observations + new finite-element model**

METHODS

- **Compilation of relevant geological, geophysical, petrological, geochemical, and geochronological data**

RESULTS

- **Volcanic stratigraphy**
- **Picrite geochronology**
- **Picrite petrology**
- **Picrite geochemistry**
- **Picrite tectono-magmatic indicator**

Geochem Discussion

- **Tectonic setting for Davis Strait picrites, including SCLM thickness and structure**

Geochem Results Motivate Model—can we bring deep melts to the surface?

Model Methods

Finite-element Model Results

- **The only new result to be fully described here is the finite-element model**

DISCUSSION

- **Finite-element model of Davis Strait picrite generation**
- **Why generally there is no mantle plume in Davis Strait**
- **Picrite petrogenesis in Davis Strait**
- **Origin of the overlying feldspar-phyric flood basalts**
- **Davis Strait and NAIP**
- **Broader implications**

CONCLUSIONS

- **Bulleted list of five principles underlying our interpretation**

- **Bulleted list of five specific conclusions**
- **Bulleted list of five general conclusions**

Final statement that Davis Strait picrites can be resolved in terms of the reigning plate-tectonic paradigm, thus no need for any deep mantle plume

Introduction

Review

Historical Background

Exactly one century ago, Holmes (1918) defined the Brito-Arctic petrographic province of related volcanic rocks as extending from western Scotland and Northern Ireland through the Faeroes Islands and Jan Mayen to Iceland, eastern Greenland, and western Greenland. However, Holmes appears to have been unaware that Sutherland (1853) had reported young volcanic rocks from southeastern Baffin Island, and that McMillan (1910, p. 424) had even noted a general stratigraphic correlation between southeastern Baffin Island and West Greenland ("…it would appear that these islands are formed of Cenozoic rocks, similar to those of Disco on the opposite side of Davis Strait"), suggesting that Holmes' Brito-Arctic petrographic province should have been somewhat larger, with its westernmost extremity on Baffin Island. In any case, most subsequent workers have included the Baffin Island volcanic rocks in the Brito-Arctic province, now known as the North Atlantic Igneous Province (NAIP).

Saunders et al. (1997) compiled some of the impressive dimensional and temporal characteristics for NAIP, including: area = $1.2*10^6$ km^2; volume = $5.5*10^6$ km^3; and age = 62 Ma to present. Clearly, NAIP magmatism has produced igneous rocks substantially in excess of the volumes required to construct oceanic crust of normal thickness, and it has done so at a latitude of 65-70^{o}N for ~62 million years. In some places, NAIP magmatism began with its volcanic products erupting onto what are now the terrestrial continental margins at its extremities (Baffin Island-West Greenland and East Greenland-Scotland), and it continues this so-called over-production today at the bathymetric anomaly on the Mid-Atlantic Ridge that is Iceland. Such prolonged over-productivity demands a significant and long-lived thermal and/or compositional and/or structural anomaly.

The concept of long-lived stationary hot spots began with Wilson's (1963) pre-plate-tectonic explanation for the origin of the Hawaiian volcanic chain. Subsequently, Morgan (1971) linked such hot spots to mantle plumes as a way for the Earth to dissipate heat and, in the process, also to produce volcanism. Such mantle plumes are buoyant cylinders (~1000 km in diameter) of fertile mantle peridotite, ascending through a static mantle from the core-mantle compositional and thermal boundary, impinging on the base of the lithosphere, and delivering their decompression melts to a single volcano or Large Igneous Province (LIP) on the surface of the Earth. Many workers have deduced that NAIP is a classic example of the effects of a deep-seated mantle plume (Fitton etc.).

Properties of mantle plumes include regional uplift prior to volcanism, high regional heat flow, and Bulk Earth / primeval mantle / OIB-type magma compositions. The plume model seems to offer an explanation particularly for intra-plate volcanism (oceanic islands and continental flood basalts) that are somewhat problematic for normal plate tectonic explanations. Problematic, also, is that little or no tomographic evidence exists for mantle plumes: in fact, the "evidence" for the plume is primarily the volcano or the LIP. In other words, a plume is essentially a hypothetical construct to explain an observation. Even so, the plume concept gained considerable acceptance through the latter part of the late 20th and early 21st Centuries.

As with other scientific hypotheses (Kuhn 1962), the plume paradigm began to accumulate anomalies. For each observation it could not explain, the plume hypothesis was modified and imbued with special properties that could "explain" the anomalies. Ironically, after several decades of expanding and patching the plume paradigm, and also through the counter-arguments of Anderson (2005), Foulger et al. (2005), and Foulger (2009), it is becoming clear that most, if not all, of the problematic inter-plate and intra-plate volcanoes and volcanic fields can have acceptable, shallow asthenospheric-lithospheric, plate tectonic explanations. The entire debate concerning deep mantle plumes is readily available at www.mantleplumes.org.

Regional Marine Geology

St-Onge et al. (2008) presented a compilation of the ocean-floor geology of the Labrador Sea - Davis Strait - Baffin Bay. The principal geological elements along this axis are:
(a) *Labrador Sea* – The main geological features of the Labrador Sea include thinned and faulted continental margins, seaward dipping reflectors of volcanic rocks along parts of both sides, and predominantly oceanic crust with magnetic lineations in the central axis, all overlain by younger sediments (Chalmers and Pulvertaft 2001; Louden et al. 2004). Sea-floor spreading may have begun as early as magnetic Chron 33 (79-72 Ma) (Roest and Srivastava, 1989), or as late as magnetic Chron 27 (62 Ma) (Chalmers and Laursen, 1995). The latter age estimate of 62 Ma is virtually identical to the age of basalts in the Davis Strait area (Storey et al. 1998). By magnetic Chron 13 (34 Ma), sea-floor spreading had ceased in the Labrador Sea, leaving behind an extinct spreading centre now filled by younger sediment.

(b) *Davis Strait* – The most significant geological features of Davis Strait are its unusual thickness and its structure. The bathymetric sill of Davis Strait is underlain by thick (up to 20 km) crust, characterized by a nearly continuous thin Paleogene basalt layer on top in the western part, a significant thickness of continental crust in the eastern part, and a thick magmatic underplated layer at the Moho in the central part (Funck et al. 2007; Gerlings et al. 2009). The most important structural element is the Ungava Fault Zone, which marks the northern limit of oceanic crust in the Labrador Sea, and which appears to have acted as a complex transfer zone linking the spreading axis in the Labrador Sea with a presumed spreading axis in Baffin Bay (Srivastava 1978; Skaarup et al. 2006; Funck et al. 2007). Offshore basalts from Davis Strait on the Baffin Island side (MacLean et al. 1978) and on the West Greenland side (Clarke 1975) show none of the depleted and picritic characteristics that the onshore volcanic rocks do, suggesting a significant change in both source and processes, respectively. The rapidly erupted and voluminous picrites appear to belong only to the earliest stages of volcanism in the Davis Strait area.

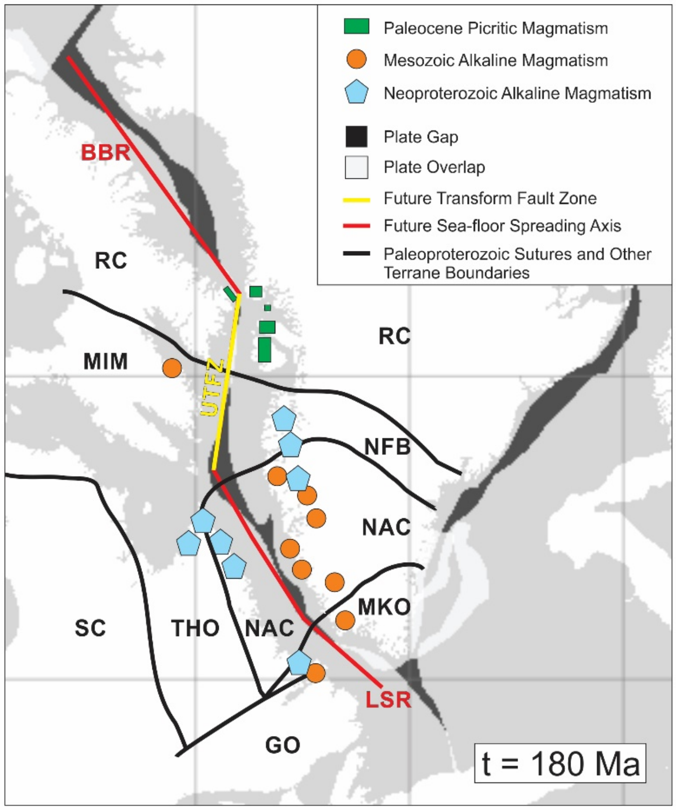


Figure 1. Schematic location of the Davis Strait picrites and relevant geological features, including ancient sutures and terrane boundaries, pre-Paleocene magmatism, mid-oceanic ridges, and a transform fault zone superimposed on the plate configuration for t = 180 Ma (after Scotese ***). *Abbreviations:* BBR - Baffin Bay Ridge; GO - Grenville Orogen; LSR - Labrador Sea Ridge; MKO - Makkovik-Ketilidian Orogen; MIM - Meta-Incognita Microcontinent; NAC - North Atlantic Craton; NFB - Nagssugtoqidian fold belt; RC - Rae Craton; SC - Superior Craton; THO - Trans-Hudson Orogen; UTFZ - Ungava Transform Fault Zone

(c) *Baffin Bay* – Despite the thick sediment cover in Baffin Bay, Barrett et al. (1971) and Keen et al. (1974) used seismic refraction, gravity, and magnetic data to detect the presence of a thin crust, and to deduce that Baffin Bay was a small ocean created by sea-floor spreading. Since then, work by others (e.g. Rice and Shade 1982; Reid and Jackson 1997) has essentially upheld this early view, but with the thick blanket of sediments, interpretation of the geophysical evidence is difficult.

Regional Terrestrial Geology

Many workers have noted the correlation of Precambrian geology between Baffin Island, northern Quebec, and Labrador on one side of Baffin Bay-Davis Strait-Labrador Sea and all of western Greenland on the other side (e.g., Bridgwater et al. 1973; St-Onge et al. 2007)(Fig. 1). In general terms, the various Archean and Proterozoic lithotectonic domains correlate reasonably well and provide convincing evidence that they were once continuous domains now separated by plate tectonics.

During the Phanerozoic, alkaline magmatism occurred on both sides of the Labrador Sea, consisting of rare lamproite, nephelinite, and carbonatite dykes along the coast of Labrador and northern Quebec, and more abundant gabbros, lamprophyres, kimberlites, and carbonatites in SW Greenland (Fig. 1). Summaries of the magmatic evolution of this region include those of Clarke (1977), Larsen et al. (1983), Upton (1988), Larsen and Rex (1992), Larsen (2006), Tappe (2007), and Tappe et al. (2017). The volumes of magma were small, but what is clear from these compilations is that SW Greenland, and to some extent northern Quebec and Labrador, had been stewing magmatically at least through the entire Jurassic and Cretaceous (~150 my), and perhaps very much longer. The significance of this Phanerozoic, and especially Mesozoic, magmatism is that igneous activity did not suddenly begin 62 Ma ago in the Labrador Sea and Davis Strait region, but rather it appears to have been the culmination of a long sluggish period of tectonic and magmatic pre-processing. In this respect, the Labrador Sea spreading centre resembles the East African Rift which has been opening for ca. 40 my, and producing magmas, but without yet developing any oceanic crust (Wood and Guth no date; Rosenthal et al. 2009; Beutel et al. 2010).

On both sides of Davis Strait (Baffin Island – Cape Searle to Cape Dyer; West Greenland – Svartenhuk, Ubekendt, Nuusuuaq, Disko), but nowhere else along the Baffin Bay-Davis Strait-Labrador Sea axis, occur deposits of sedimentary and volcanic rocks of Late Cretaceous – Early Cenozoic age (ca. 100-60 Ma) resting directly on rocks of Paleo-Proterozoic age (ca. 1850 Ma) belonging to the collisional Trans-Hudson Orogen (Fig. 2). Kidd (in Baird et al. 1953) recorded the sedimentary and volcanic stratigraphy along the coast from Cape Searle to Cape Dyer. Burden and Langille (1990) provided detailed stratigraphic and palynological descriptions on the Baffin sediments (Aptian to Cenomanian, and Paleocene) and Henderson et al. (1976) have described the sedimentary rocks of similar ages, lithologies, and flora in West Greenland. The significance of this depositional basin in Davis Strait is that it represents a prolonged (ca. 40 my) extensional event prior to the eruption of the volcanic rocks. Clarke and Pedersen (1976) summarized the volcanic sequence in West Greenland. Clarke (1965, 1968) emphasized the strong volcanic and sedimentary stratigraphic, as well as petrological, similarities between Baffin Island and the much better studied succession in West Greenland. Clarke and Upton (1971) provided the first detailed geological description of the volcanic rocks on Baffin Island. Wilson and Clarke (1965) offered the first plate-tectonic connection between Baffin Island and West Greenland, suggesting the volcanic rocks were related to a branch of the Mid-Atlantic Ridge extending through Labrador Sea, Davis Strait, and Baffin Bay.

Davis Strait Picrites

LeBas (2000) defined picrites as volcanic rocks with MgO contents of 12-18 wt.%. In this paper, we use the term picrite for all basaltic rocks with MgO > 12 wt%. Rare occurrences of picrites in basalt lava piles have simple explanations in terms of accumulation of olivine in high-level magma chambers, but thick sequences consisting exclusively of picrites are petrogenetically problematic. On Baffin Island, the volcanic sequence is nowhere more than 750 m thick, but it consists entirely of picritic tholeiites, it thins inland, and judging from the giant cross-bedding in the hyaloclastite breccias, it appears to have source to the northeast. In West Greenland, the thickness of the volcanic pile exceeds 2000 m, it consists of an underlying picritic tholeiitic unit up to 1000 m thick, and an overlying unit of feldspar-phyric flood basalts, it thins inland, and also from the orientation of the giant cross-bedding in the hyaloclastite breccias, it appears to have a source to the southwest.

Since 1965, many authors have contributed to the understanding of the picritic volcanic rocks on Baffin Island (Table 1). The high MgO concentrations of these picrites are similar to the compositions of initial melts from mantle peridotites at 3 GPa (Clarke 1968, 1970), and thus they appear to be unmodified partial melts of the peridotite mantle and excellent candidates for being primary magmas. These picrites have major-element chemistry like komatiites (Viljoen and Viljoen 1969), but trace-element chemistry like MORBs (Engel et al. 1965). O'Nions and Clarke (1972) made the connection between low concentrations of LILE and low $^{87}Sr/^{86}Sr_i$ and a depleted mantle source. Building on the work of Robillard et al. (1993), Stuart et al. (2003) used $^{3}He/^{4}He$ data to postulate two mantle sources for the Baffin Island picrites. They proposed that the majority of the melt comes from a depleted upper mantle in the asthenosphere, but that a smaller high $^{3}He/^{4}He$ component comes from a lower mantle reservoir.

Since the 1940s, many authors have also contributed to the understanding of the picritic rocks of central West Greenland (e.g., Munck 1942; Noe-Nygaard 1942; Drever 1956; Clarke 1971; Clarke and Pedersen 1976; Larsen and Pederson 2009). These contributions have gradually evolved from simple descriptions of the picrite occurrences to petrogenetic interpretations involving major implications for mantle dynamics.

Collectively, the Davis Strait picrites represent a "hotspot", or more neutrally, a positive volcanic volume anomaly (PVVA) or a melt extraction anomaly (Foulger 2003), on the complex sea-floor spreading axis that extends approximately 2400 km from the triple junction with the Mid-Atlantic Ridge to the northern end of Baffin Bay. More specifically, in their pre-sea-floor spreading reconstruction, Oakey and Chalmers (2012, Fig. 12) show a ridge-transform intersection lying approximately equidistant between the picrites of Disko Island and the picrites of Baffin Island, and Hosseinpour et al. (2013) show that the Baffin Island picrites and the Svartenhuk picrites are juxtaposed and adjacent to a major change in orientation of the plate boundaries. *We regard these singular spatial relationships to be significant in terms of the origin of the extensive picrite volcanism.*

<u>Purpose</u>

Currently, all published interpretations for the origin of the DSPs invoke some form of mantle plume: two plumes (one for Davis Strait and one for Iceland; Gill et al. 1995); one migrating Iceland plume (Lawver and Müller 1994); or one quasi-stationary Iceland plume (e.g., Ganerod et al. 2010). Larsen and Pedersen (2009a) stated the petrogenetic problem for these rocks very well: “The very large volume of picrites in the Paleocene volcanic section in West Greenland and Baffin Island is unusual and must have formed under conditions rarely fulfilled at other times and places.” In all existing models for the origin of the Davis Strait picrites, these rock compositions connote high temperatures, and high temperatures connote mantle plumes. But the reigning Earth science paradigm is that of plate tectonics, and as such, we are obliged to attempt first to interpret our observations in those terms, resorting only to other processes if it cannot be shown that plate tectonics works. With this in mind, we believe that picrites connote an open magmatic plumbing system to depths of 100-125 km, and such open magmatic plumbing systems connote favourable configurations of plates (RTIs, triple junctions, other plate tectonic singularities (PTSs)). As an alternative to the now, essentially default, plume models, we expand on the work of Clarke (2007, 2008, 2017), Beutel and Clarke (2017), and Peace et al. (2017) to make the case for an exclusively plate-tectonic-controlled origin for the Davis Strait picrites.

<u>Claim</u>
The Late Mesozoic-Early Cenozoic separation of Greenland from North America was controlled by lithospheric thickness and strength, and the Davis Strait picrites are the unique products of catastrophic decompression melting created during the rupture of the sub-continental lithospheric mantle.

<u>Scope</u>
We use already published petrological, geochemical, and geochronological data, combined with a detailed examination of crustal structures and a new finite-element model, to make inferences about picrite petrogenesis. Our work is restricted to the picrites, and does not include any detailed consideration of the significant volume of feldspar-phyric flood basalts overlying the picrites in West Greenland.

Results

In this section, we address each significant feature of the DSPs, *one at a time*, first presenting the critical observations and then commenting on their significance in terms of their origin, both petrologically and tectonically.

Davis Strait Picrite Volcanic Stratigraphy

The entire Phanerozoic stratigraphic section in central West Greenland is up to 3000 m thick, and consists of Late Cretaceous and Paleocene unconsolidated clastic sediments overlain by picritic hyaloclastite breccias, thin subaerial picritic lava flows, and thick subaerial feldspar-phyric tholeiites. On the opposite side of Davis Strait, the Phanerozoic stratigraphic section on southeastern Baffin Island is approximately 800 m thick, and consists of Paleocene unconsolidated clastic sediments, overlain by picritic hyaloclastite breccias, and thin subaerial picritic lava flows.

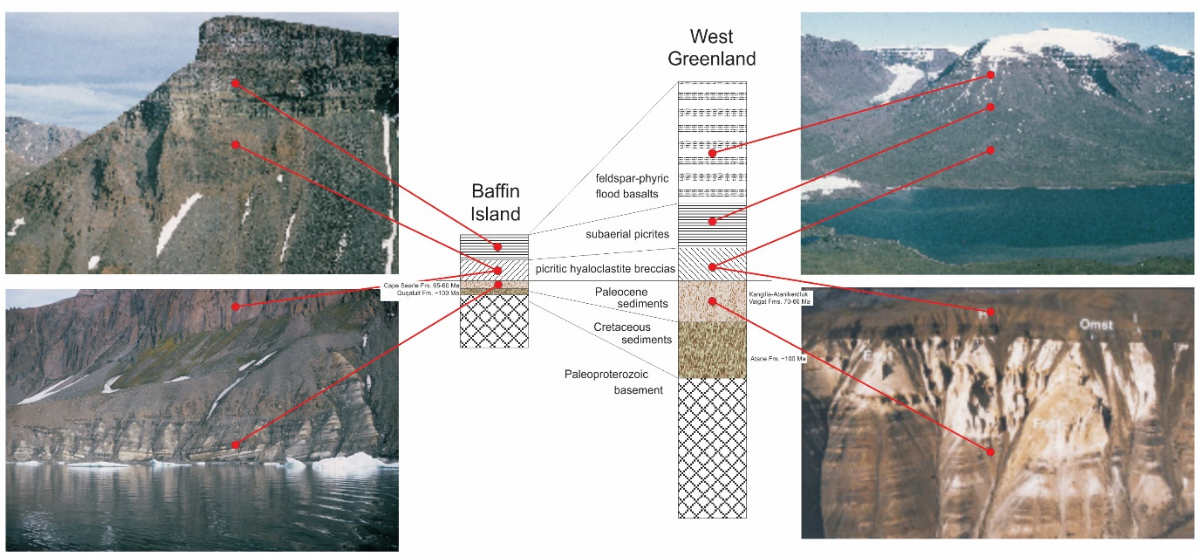


Figure 2. Schematic comparison of Baffin Island and West Greenland stratigraphic sections. For scale, the entire volcanic section in West Greenland is approximately 2000 m, but thicknesses of all units vary considerably depending on locality. Field photo of West Greenland sediments from Dam (2009, with permission).

In essence, the Baffin Island section is a miniature mirror-image of the middle part of the West Greenland stratigraphic section. The high aspect-ratio, coast-clinging, geometry of both picrite occurrences (Table 1), and absence of evidence for any central volcanic structure, suggest that these picrites may be related to one or more NNW-trending fissures. At least the terrestrial part of this volcanic province falls short of the 100,000 km^3 threshhold for a LIP, so we refer to it as a Baby LIP (BLIP), one that did not reach full maturity.

	Max Length	Max Width	Max Thickness	References
Baffin Island	90 km	10 km	750 m	Clarke and Upton (1971); Francis 1985; Robillard et al. (1992)
West Greenland	200 km	50 km	1000 m	Clarke and Pedersen (1976); Larsen and Pedersen (2009); Larsen et al. (2016)

Table 1. Physical Dimensions of Davis Strait Picrites.

<u>Davis Strait Picrite Geochronology</u>

Dykes and other small-volume intrusions of highly alkaline magmas intruded along what are now the coasts of Baffin Island, Labrador, and southwest Greenland during Jurassic and Cretaceous time (Tappe et al. 2007, 2017; Heaman et al. 2015). Subsequently, at ~62 Ma, the high-volume eruption of terrestrial Davis Strait picrites occurred simultaneously with MORBs produced at the initiation of sea-floor spreading in the northern Labrador Sea (Larsen et al. 2016).

<u>Davis Strait Picrite Petrology</u>

The picrites on both sides of Davis Strait are almost exclusively remarkably unaltered, fine-grained, rocks. They contain high modal abundances of olivine microphenocrysts and phenocrysts ($Fo_{84\text{-}93}$), generally averaging less than 2 mm in length. In thicker flows, gravity settling has produced greater concentrations of olivine grains in the lower half of the flow. In the basal hyaloclastite breccias, much of the glass is still fresh, and the olivine grains show skeletal quench textures, indicating disequilibrium growth at the time of eruption. Further petrological details are available in Francis (1985) and Larsen and Pedersen (2009).

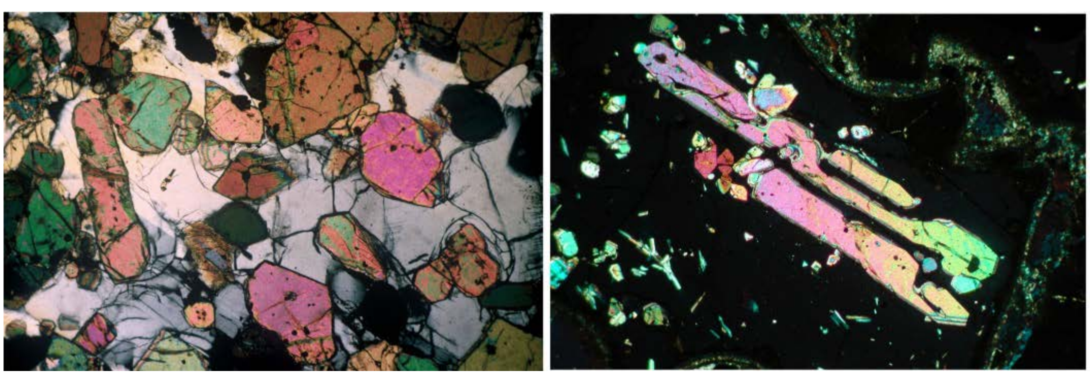


Figure 3. Picrite petrography – retake some photomicrographs for BI and WG

Davis Strait Picrite Geochemistry

LeBas (2000) chemically re-defined the term "picrite" to be basaltic rocks with 12 < MgO < 18 wt. %, and with total alkalies less than 3 wt. %. This definition unfortunately includes only some of the Paleocene olivine-rich lavas of Davis Strait. According to LeBas (2000), some of those Davis Strait rocks with MgO > 18 wt. % are komatiites, but the additional constraints placed on TiO_2 and total alkalies would leave the rest of them unclassified. Because the term "picrite" has been used for the MgO-rich, olivine-rich, volcanic rocks of Davis Strait for more than 60 years, we will continue to use it here for all rocks with MgO > 12 wt. % (Fig. 3.5).

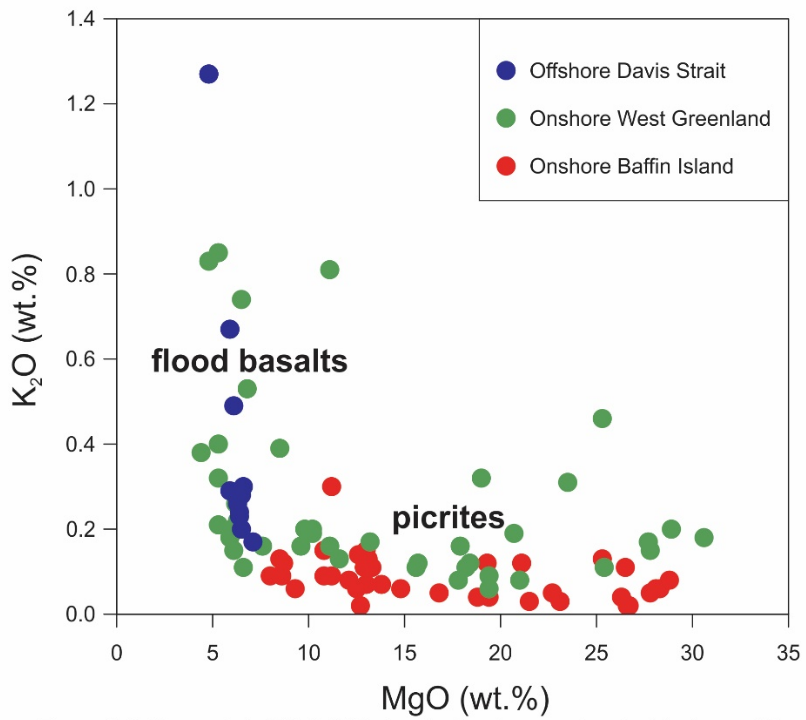


Figure 3.5. Binary plot of MgO-K_2O showing two key geochemical features of the Davis Strait picrites: the high MgO contents typical of primary magmas, and the low K_2O contents typical of highly depleted mantle sources. Data from Clarke (1969) and Park et al. (1971).

But, high MgO contents are only one of the remarkable geochemical features of the Davis Strait picrites; LILE and HFSE incompatible-element concentrations, and many radiogenic isotopic ratios, lie at the extremities of the ranges of world-wide basalt compositions (Table 2).

Parameter	Primitive Mantle	Extreme DSP	DSP Mantle Source	Reference(s)
K_2O (wt.%)		0.01	strongly depleted	Clarke (1970); Francis (1985)
La (LREE)	1*chondrite	3*chondrite	strongly depleted	O'Nions and Clarke (1972)
$^{87}Sr/^{86}Sr_i$	0.7047	0.7028	strongly depleted	O'Nions and Clarke (1972)
εNd_i	0	+10	strongly depleted	Graham et al. (1998)
$^{206}Pb/^{204}Pb$		18	strongly depleted	Graham et al. (1998)
$^{208}Pb/^{204}Pb$		37.5	strongly depleted	

$^{187}Os/^{188}Os$	0.130	0.127	depleted	Dale et al. (2009)
$^{3}He/^{4}He$		$49.5R_A$	strongly depleted*	Graham et al. (1998);
				MORE REFS NEEDED ABOVE

Table 2. Summary of principal geochemical features of Davis Strait picrites.

The first indication of the highly unusual chemical compositions of the Davis Strait picrites is their low K_2O contents ($0.01 < K_2O < 0.20$) (Clarke 1970; Francis 1985; Larsen and Pedersen 2009b; Starkey et al. 2009), immediately suggesting a strongly depleted source mantle. Concomitant with the low K_2O are the strong depletions in the LILE incompatible trace elements (e.g., Rb, LREE, U, Th), making them among the most LILE-depleted Phanerozoic basaltic rocks on Earth (Fig. 3.75). Similarly, the incompatible high field-strength elements (HFSE) such as the REEs, Y, and Zr have low concentrations. In addition, extreme values for isotopic ratios ($^{87}Sr/^{86}Sr_i = 0.7028$; $\varepsilon Nd_i = +10$; $^{206}Pb/^{204}Pb_i = 18.0$; $^{187}Os/^{188}Os_i = 0.1230$; $^{3}He/^{4}He = 49.5*R_A$) are collectively consistent with ancient depletion of the LILE parent elements in the mantle source for these picrites (Kent et al. 2004; Class and Goldstein 2005; Wittig et al. 2008), including uranium as the parent of ^{4}He (Anderson 1998).

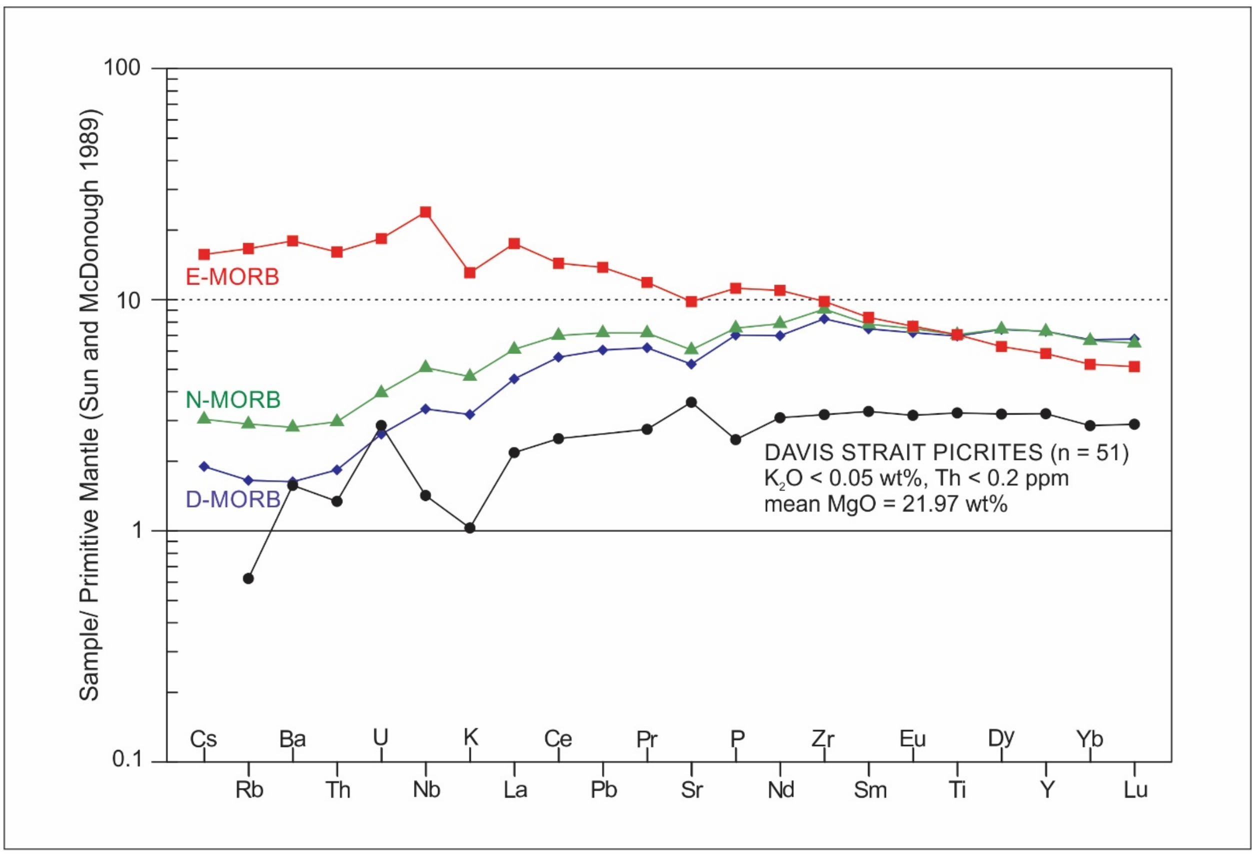


Figure 3.75. Spider diagram comparing the 51 most depleted picrite samples from Baffin Island and West Greenland (Starkey et al. 2009) with the means for D-MORB (depleted), N-MORB (normal), and E-MORB (enriched) of Gale et al. (2012).This plot supports the claim that the Davis Strait picrites are among the most depleted basaltic rocks on Earth.

We deduce that the source for these strongly depleted picrites must have been a highly depleted sub-continental lithospheric mantle (SCLM), and because this type of mantle is so buoyant (O'Hara et al. 1975), it is unlikely to ever have gone down to the core-mantle boundary and re-ascend as a plume. A strongly depleted buoyant SCLM is a much simpler and more probable source for the Davis Strait picrites than a depleted mantle recycled from the core-mantle boundary.

Davis Strait Picrite Tectono-magmatic Signature

One of the standard techniques of igneous petrology is to relate the rocks under investigation to comparable rocks elsewhere. In the early stages of studying the Davis Strait picrites, Clarke (1970) and O'Nions and Clarke (1972) used the depleted LILE concentrations and REE patterns to draw parallels with 'deep oceanic tholeiites' and 'abyssal basalts' (later to become known as MORBs). The advent of tectono-magmatic discrimination diagrams (Pearce and Cann 1973) involved the use of major- and trace-element plots to distinguish basalts from different tectonic settings (MORBs, island arcs, continental arcs, within-plate oceanic and continental, etc.). All such diagrams unanimously show the Davis Strait picrites to be MORBs, and Figure 4 illustrates perhaps the most objective and reliable one (Agrawal 2008), using a combination of five immobile high field-strength elements (La-Sm-Yb-Nb-Th) and discriminant function analysis to place these picrites firmly in the MORB field. In greater detail, Robillard et al. (1992) recognized the presence of both N-MORBs and E-MORBs in the Baffin Island rocks, suggesting slightly different mantle sources. However, to label these picrites simply as MORBs is to obscure the fact that they are unique amongst MORBs. As indicated above, these rocks are severely depleted in incompatible trace elements (both LILE and HFSE). To underscore this uniqueness, we refer to them as highly depleted MORBs (or HD-MORBs).

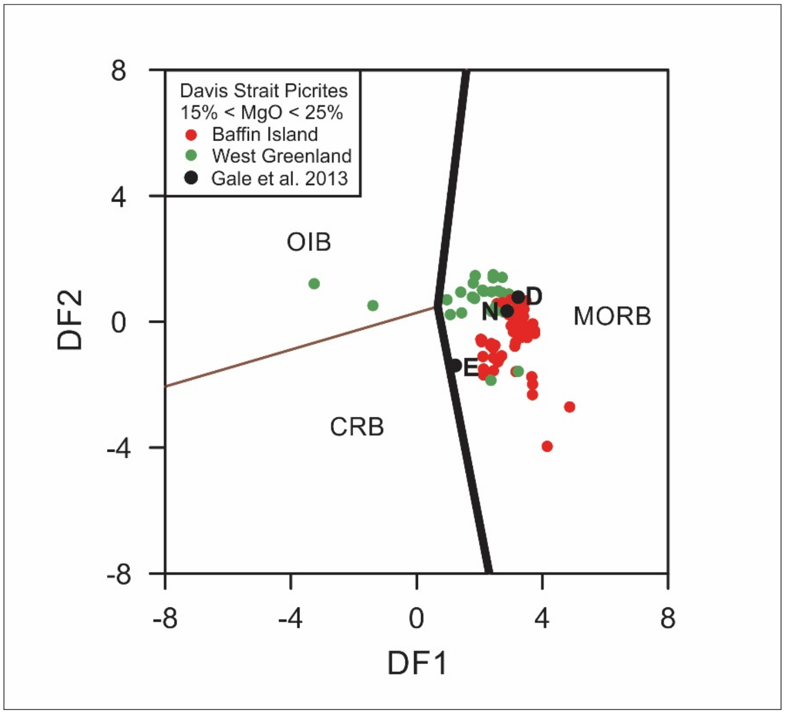


Figure 4. Tectono-magmatic indicator diagram (Agrawal et al. 2008) that applies discriminant function analysis to La-Sm-Yb-Nb-Th. The bold boundary separates unlikely plume-related MORBs from possible plume-related within-plate basalts. Sources of data: Baffin Island (Starkey et al. 2009); West Greenland (Larsen and Pedersen 2009). D-, N-, and E-MORB means from Gale et al. 2013.

To conclude this section, we note several implications that are relevant to the origin of the Davis Strait picrites:

1. the Davis Strait picrites have compositions placing them at, or beyond, the limits of most MORBs and hence we refer to them as highly depleted MORBs (HD-MORBs)

2. these HD-MORBs have paradoxically erupted onto Precambrian basement on Baffin Island and West Greenland (in simple terms, they represent the spilling over of mid-ocean ridge-generated basalts onto the conjugate continental margins)

3. MORBs of any type, and especially HD-MORBs, are the least likely of any compositional or tectonic type of basalt to be associated with a deep mantle plume

Discussion

Tectonic Setting for Davis Strait Picrites

In general terms, although the Davis Strait picrites are MORBs that rest on conjugate margins astride the Labrador Sea-Baffin Bay spreading axis, more specifically the picrites lie precisely at the intersection of the initial positions of the Baffin Bay spreading centre and a change in thickness and structural fabric of the continental lithosphere (Oakey and Chalmers 2012) (Fig. 1).

Tectonics (notes for further development by the authors)

- eruption of the DSP follows a long (40-150 my) period of subsidence, crustal thinning, and alkali magmatism in the Labrador Sea axis – these are clear initial signs of the LS-DS-BB spreading centre, à la East African Rift where there are "two rifts that are separated enough to justify giving them separate names, but near enough to suggest that they are genetically related" (Wood and Guth 2***), (sounds like Labrador Sea and North Atlantic!!)
- subsidence, basin formation, and sediment accumulation prior to initiation of DSP, are inconsistent with uplift associated with arrival of a hot mantle plume
- Ungava Fault Zone is a major transform that offsets the incipient spreading axis (now) by 850 km and is sub-parallel to the boundary with the Trans-Hudson Orogen, a major Proterozoic structural discontinuity in the crust – DSP represent a magmatic production anomaly on the LS-BB spreading centre – it can't be just an accident that it occurs right at the PTS
- DSPs occur precisely at a PTS, places that are known for complex extensional tectonics, so what further need is there for a plume? – Okham's Razor / principle of parsimony – PTSs are an integral part of plate tectonics, but plumes are not (they are independent of the PT paradigm)
- include mention of "excess" volcanics at the complementary LS ridge-UFZ transform, but they are less prominent because they are entirely submarine
- spatial-temporal improbability of plume hitting the DS PTS - a mantle plume, originating at the core-mantle boundary, knowing nothing about the rifting lithosphere far above, nevertheless from a range of 3000 km, makes a direct hit on a 1-dimensional rift, which had already been tectonically and magmatically active for 40-150 my, and not only on the 1-dimensional rift but right at the 0-dimensional PTS, and spurred that PTS into hotspot volcanic activity - a very improbable strike indeed on the base of the lithosphere, both spatially and temporally
- there is physical evidence of "excess" magmatism in DS, but that need not mean excess melting (as might be the result of higher T and a plume, or more fertile mantle (NOT!), just focussed eruption at a PTS)
- there is no direct physical-chemical evidence that points to a plume, but there is overwhelming evidence that points to a strongly DM that must have permanently resided in the lithosphere
- tectonic deduction – well-known lithospheric thinning for decompression melting extensional plumbing system for magma ascent are sufficient conditions to explain DSP hotspot – no plume needed

In general terms, supercontinents break up along planes of greatest weakness in response to stresses applied to their bases by convective overturn in the asthenosphere (Wilson 1961). Such is the case in modern rifts such as the East African Rift (Daly et al. 1989; Beutel et al. 2010; Daoud et al. 2011), and in older rifts such as the Atlantic (Beutel 2009; Hansen et al. 2009; Buiter and Torsvik 2014, Petersen and Schiffer 2016). At irregular intervals along those rifts, asymmetric LIPs may develop on the conjugate margins (e.g., Parana-Etendeka 132 Ma, CAMP 200 Ma, NAIP 60 Ma), including the Davis Strait picritic BLIP in the relatively small Labrador Sea-Davis Strait-Baffin Bay aulacogen. The underlying causes for these LIPs must be examined on a case-by-case basis, but in general the spatial association of conjugate margin LIPs with mantle plumes is either non-committal (Buiter and Torsvik 2014), or highly suspect (Julian and Foulger 2015), concerning the role of deep mantle plumes. More likely, these LIPs should be considered simply as positive volcanic volume anomalies (PVVAs) along an already established volcanic axis, where the excess volcanism is controlled by the structural state of the SCLM. We now consider what the pre-rifting lithospheric state was in Davis Strait, both its thickness, and its structures.

Lithospheric Thickness

Prior to any stresses being applied to its base, the thickness of the SCLM is at its maximum ($SCLMt_{max}$). As convective stresses are applied to its base, the SCLM undergoes ductile deformation and thins, whereas the crust undergoes brittle deformation and develops normal faults. At some point in this extensional process, the SCLM and crust rupture, bringing to an end to the stretching and initiating sea-floor spreading. The problem is to try to determine what $SCLMt_{max}$ was when only the stretched version, $SCLMt_{min}$, is now available. Two approaches are possible: geological and geophysical.

Geological: As noted above, the Labrador Sea axis was a locus of episodic small-volume alkaline magmatism (lamprophyres, kimberlites, lamproites) for ca. 500 my before rifting occurred (Tappe et al. 2007). A combination of observed mantle inclusions and theoretical petrogenetic considerations can provide some insight into the thickness of the SCLM in this region prior to any significant thinning. (Obviously, the older the alkaline igneous rocks, such as the ~600 Ma kimberlites (Tappe et al. 2012), the more reliable may be the estimate of $SCLMt_{max}$). In addition, Bernstein et al. (2013) examined highly depleted dunite nodules in a 1.7 Ga Ma diamond-bearing lamprophyre dyke immediately east of Disko Island, and determined that highly depleted SCLM extended into the diamond stability field (>150 km) in the Proterozoic. Also, based on the geothermobarometry of mantle xenoliths (Sand et al. 2009), Tappe et al. (2012) determined that the 600 Ma kimberlites originated in the asthenosphere, immediately below a highly depleted SCLM, at depths of ca. 225 km, and the 160 Ma kimberlites originated in the same asthenospheric position immediately below a thinned depleted SCLM at depths of ca. 175 km.

Geophysical: As noted above, any attempt to measure the thickness of the lithosphere in the vicinity of Labrador Sea today can only determine $SCLMt_{min}$. Thus we can only use results from seismic tomography along lines that are removed from the rift and infer that these thicknesses were uniform from North America to Greenland prior to the onset of rifting. Faure et al. (2011) used seismic architecture of the Archean to determine that kimberlites originated beneath the LAB located at depths of 225-240 km. In a series of papers, Darbyshire (2005), Darbyshire and Eaton (2010), Darbyshire et al. (2013), and Gilligan et al. (2016) have determined an SCLM thickness of 240 km under Baffin Island, and in the vicinity of Hudson Bay there are no systematic differences between the thicknesses of SCLM (185-260 km) in Archean and Proterozoic domains, but in the Hudson Bay region, the Paleoproterozoic SCLM appears to be thickest. If this finding applies to the Nagssugtoqidian Fold Belt, then we might infer that it is a significant impediment to rupture and rifting.

Lithospheric Structures

As noted in the introduction to this section, rifting of continents tends to follow pre-existing planes of weakness in the lithosphere. Such planes of weakness may include metamorphic fabric, lithospheric-scale faults, and suture zones.

Metamorphic fabric: In central West Greenland, there is a boundary between the Rinkian Orogen of the Archean Rae craton with a predominantly N-S metamorphic fabric, and the Paleoproterozoic Nagssugtoqidian fold belt with a predominantly E-W metamorphic fabric. Of particular relevance here is that the southern end of the Paleocene picrite province in West Greenland appears to be pinned at this Paleoproterozoic suture. These nearly orthogonal metamorphic fabrics suggest that the rifting in Davis Strait and Baffin Bay may have been facilitated by the N-S fabric in the Rae craton, and that its extension southward was impeded by the E-W fabric in the Nagssugtoqidian fold belt.

Lithospheric-scale faults: do we have any significant reactivated faults that are relevant? If so, add here

Suture zones: The Archean-Paleoproterozoic history of what is now Greenland-Baffin Island-Quebec-Labrador was complex, involving at least four Archean cratonic blocks (Rae, North Atlantic, Meta Incognita, Superior) and the Paleoproterozoic reworked collision zones between them (Trans-Hudson, Nagssugtoqidian, …) (van Gool et al. 2002; Corrigan et al. 2009; St-Onge et al. 2009; Eglington et al. 2013). The result is that by 1750 Ma, these cratonic blocks had become integrated into Laurentia and remained together until the Mesozoic when rifting began. That rifting exploited existing weaknesses in Laurentia, including the Paleoproterozoic suture zones (Tesauro et al. 2015), the most important of which were the E-W boundary between the Rae craton and the Nagssugtoqidian fold belt, and the N-S boundary between the North Atlantic craton and the Trans-Hudson Orogen. In addition, van Gool et al. (2002) determined that a Paleoproterozoic triple junction lay beneath Davis Strait, one suture of which extended northward into what is now Baffin Bay. Thus when Paleozoic-Mesozoic extensional forces began to operate on the lithosphere, these relatively weak lithospheric sutures could have controlled the ultimate path of the rift. In Baffin Bay and Labrador Sea, the rifting exploited similarly oriented sutures, but in Davis Strait, a transfer zone between the Labrador Sea and Baffin Bay rifts developed into the Ungava Transform Fault Zone (Suckro et al. 2013). It is precisely between the southern end of the Baffin Bay rift and the transfer zone that developed the Davis Strait picrites.

Summary

As determined from petrogenetic considerations, from geothermobarometry on peridotite inclusions in lamprophyres and kimberlites, and from seismic tomography, the pre-rifting thickness of the SCLM in the vicinity of Davis Strait was 185-260 km. As determined from peridotite inclusions in lamprophyres and kimberlites, the SCLM was also highly depleted. Such depleted roots are relatively cold, neutrally buoyant, and mechanically strong (Darbyshire and Eaton 2010). Furthermore, from geodynamic considerations, this part of Laurentia consisted of four main cratonic blocks separated by relatively weak suture zones, the locations of which had a significant bearing on the development of the Mesozoic-Cenozoic rift.

Evidence for Thick Lithosphere in the Baffin Bay-Davis Strait-Labrador Sea Complex:

Currently, the Baffin Bay-Davis Strait-Labrador Sea corridor is a series of failed oceanic spreading centers and transfer zones bounded by the Paleoproterozoic continents of Greenland and North America. The thickness of the lithosphere at the onset of spreading and the formation of the picrites ($SCLMt_{min}$) must be gleaned from the present day thickness of extant continental lithosphere adjacent to the spreading zone and older magmatism that reveals a deep source. This will determine the likelihood the Peterson and Schiffer (2016) model applying to the region and the availability of SCLM at ~120 km depth to create the picrites.

Present Day: Assuming that the Archean and Paleoproterozoic lithosphere bounding Baffin Bay and the Davis Strait have not been significantly altered, the pattern of lithospheric thickness in Greenland and Baffin Island are a good proxy for the depth to the SCLM prior to extension. In a series of papers, Darbyshire (2005), Darbyshire and Eaton (2010), Darbyshire et al. (2013), and Gilligan et al. (2016) have used tomography to find an SCLM thickness of 240 km under Baffin Island and Darbyshire (XXXX) tomographically mapped a thickened lithosphere in Greenland between ~65N and 71 N. This thickened area of lithosphere in Greenland corresponds to the thickened lithosphere under Baffin Island when the plates are reconstructed, and also approximately corresponds to the tectonic boundaries of the South Nagsuggtoquidian suture zone and the northern Rinkian? (REF) suture zone (FIGURE) (St. Onge et al, 2009; Ucisik et al., 2008; Connelly et al., 2006; James and Dunning , 2000). The area of thickened lithosphere in Baffin Island and Greenland also corresponds with the area of least crustal thinning during the Mesozoic/Cenozoic extension event (Artemieva and Thybo, 2008 and Hosseinpour et al., 2013). (FIGURE)

Past: As noted above, the Labrador Sea axis was a locus of episodic small-volume alkaline magmatism (lamprophyres, kimberlites, lamproites) for ca. 500 my before rifting occurred (Tappe et al. 2007). A combination of observed mantle inclusions and theoretical petrogenetic considerations can provide some insight into the thickness of the SCLM in this region prior to any significant thinning. (Obviously, the older the alkaline igneous rocks, such as the ~600 Ma kimberlites (Tappe et al. 2012), the more reliable may be the estimate of $SCLMt_{max}$). In addition, Bernstein et al. (2013) examined highly depleted dunite nodules in a 1.7 Ga Ma diamond-bearing lamprophyre dyke immediately east of Disko Island, and determined that highly depleted SCLM extended into the diamond stability field (>150 km) in the Proterozoic. Also, based on the geothermobarometry of mantle xenoliths (Sand et al. 2009), Tappe et al. (2012) determined that the 600 Ma kimberlites originated in the asthenosphere, immediately below a highly depleted SCLM, at depths of ca. 225 km, and the 160 Ma kimberlites originated in the same asthenospheric position immediately below a thinned depleted SCLM at depths of ca. 175 km.

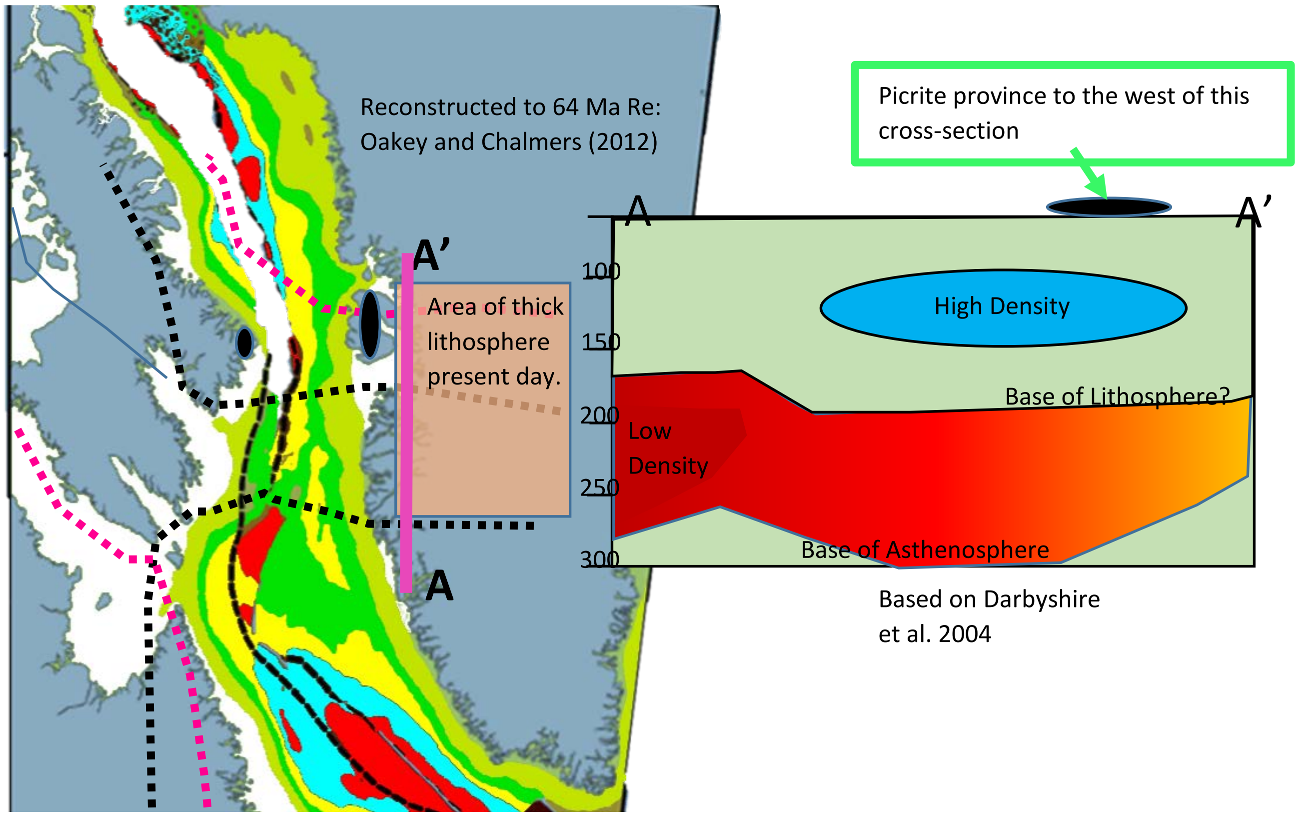


FIGURE: Colors indicate the degree of lithospheric thinning; red is the most thinning, yellow/green is the least (e.g. Artemieva and Thybo, 2008 and Hosseinpour et al., 2013). Black ovals represent location of picrite flows.

Crustal thickness prior to extension:

Based on the above evidence, it is apparent that prior to the extension that began in the Jurassic, the North American-Greenland lithosphere was around 200 km thick and that the lithosphere between the southern Nagssugtoqidian suture and the northern Rinkian suture zone was likely significantly thicker than the crust to the North and South (perhaps 250 km) (REFS—include Peace at al.).

Effect of Tectonic Inheritance and Melt Generation

When the relative motion between Greenland and North America became trans-tensional in the Jurassic it is likely that extension started at the base of thick lithosphere as proposed by Peterson and Schiffer (2016) and illustrated by the kimberlites (Tappe et al., 2012). However, given the degree of total crustal thinning (Artemieva and Thybo, 2008 and Hosseinpour et al., 2013) and the lack of oceanic sea floor, it is clear that the thickened area of the Davis Strait and the Nagssugtoqidian mobile belt did not undergo as much extension as the adjacent Baffin Bay and Labrador Sea (Peace et al., 2017 REFS). The areas of continental extension that do exist are also much narrower in scope than the basins that would later host the oceanic spreading centers.

Why the area of the Nagssugtoqidian mobile belt belts did not extend as much as the adjacent crust is likely due to the suture zones that defined the amalgamation of the terranes in the Paleoproterozoic. Despite some inconsistencies and discussion between authors on the exact location and relationship, sutures to the North and South of the Davis Strait appear to be oriented dominantly parallel to the present day Baffin Bay/Labrador Sea (NNW) whereas the sutures in and just North of the Davis Strait are E-W (REFS). The assumption is that sutures are more likely to be zones of weakness, thus extension (even at depth) would be concentrated along appropriately oriented sutures (NNW) whereas the sutures in the Davis Strait and just to the north would be oriented inappropriately to allow for easy extension. Furthermore, the thickened crust in the Nagssugtoqidian mobile belt likely inhibited extension.

Thickened crust in the Nagssugtoqidian mobile belt is key to generating picrites as deep SCLM is needed to source them. However, thickened lithosphere with ~E-W sutures may have had a second role in generating picrites, the thick lithosphere and E-W sutures likely inhibited the propagation of rifts at depth and this resulted in increased extensional stress. Basic fracture mechanics states that stress is concentrated at crack tips, the longer and narrower the crack the greater the stress (REF). If the crack is propagating under a given stress and it is unable to continue propagating as a result of changing conditions in the lithology or stress relief mechanisms (RTI Beutel REF), extensional stress will increase at the crack tip until either the crack propagates or some other stress relief is found.

Mechanical Proposal for Getting Deep Melts to the Surface: Because of the configuration of the Archean and Nagssugtoqidian mobile belt we propose that the NNW trending suture zones

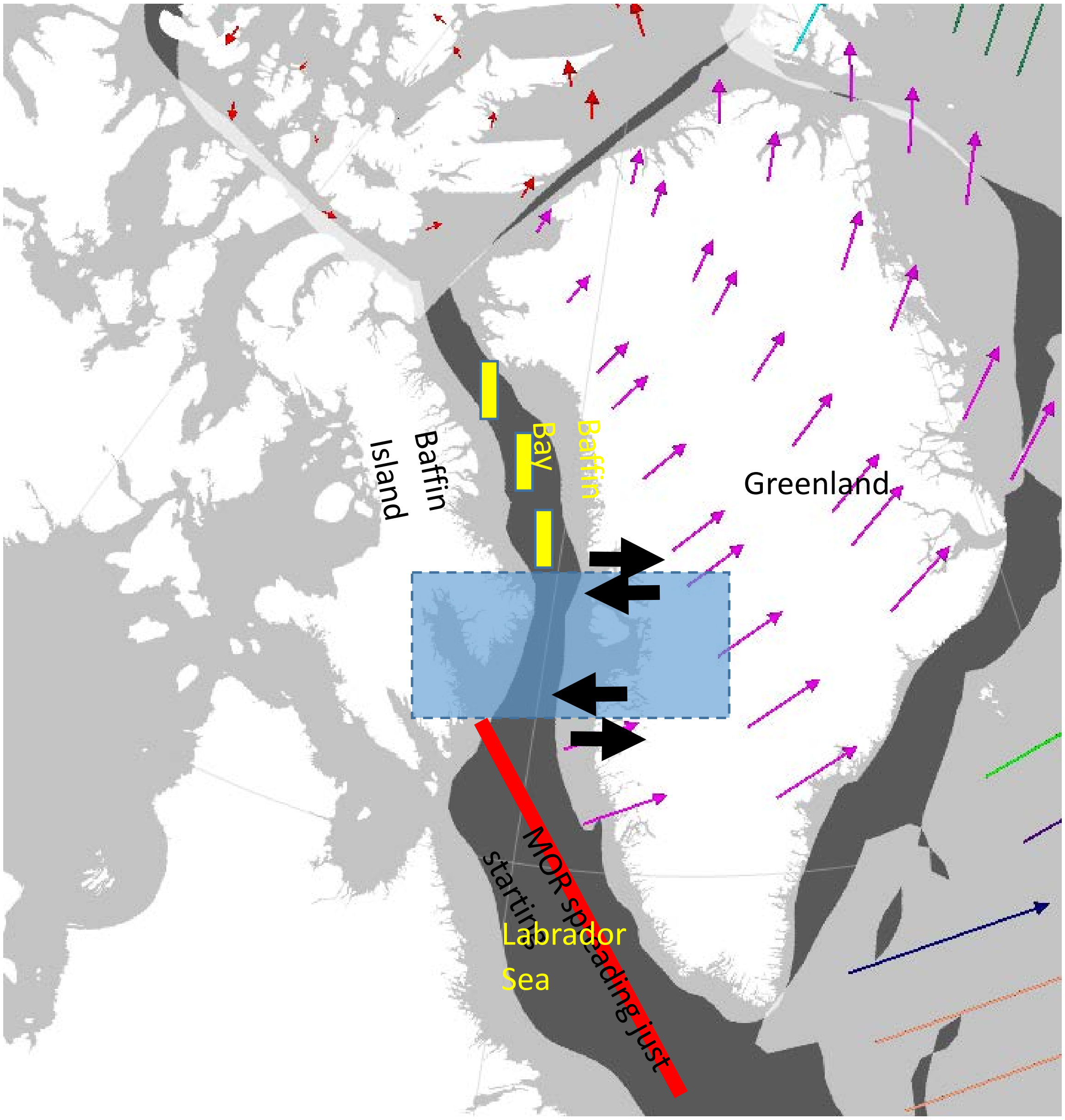


Figure M: Relative motion and strain partitioning at 63 Ma. Base figure made using Gplates to show plates in their positions relative to a fixed North America as per the Scotese (DATE) and Oakey and Chalmers (2012). Thin arrows show the relative plate motion to a fixed North America, thicker black arrows show the relative motion on the edges of the proposed thickened area of the Davis Strait and Disko Area (blue box) as per strain portioning. Yellow blocks show likely cartoon configuration of continental basins above a thinned crust in Baffin Bay while the thick red line indicates that sea-floor spreading had likely started or was about to start in the Labrador Sea.

acted as cracks that propagated into the Nagssugtoqidian mobile belt, these 'cracks' thinned the lithosphere from the bottom up (with concurrent rifting of the surface) until sea-floor spreading occurred. While a N-S suture in the northern Nagssugtoqidian mobile belt eventually failed, the rifting was not able to advance through the entirety of the belt. This led to a geodynamic situation where the areas that were significantly thinned would have been able to

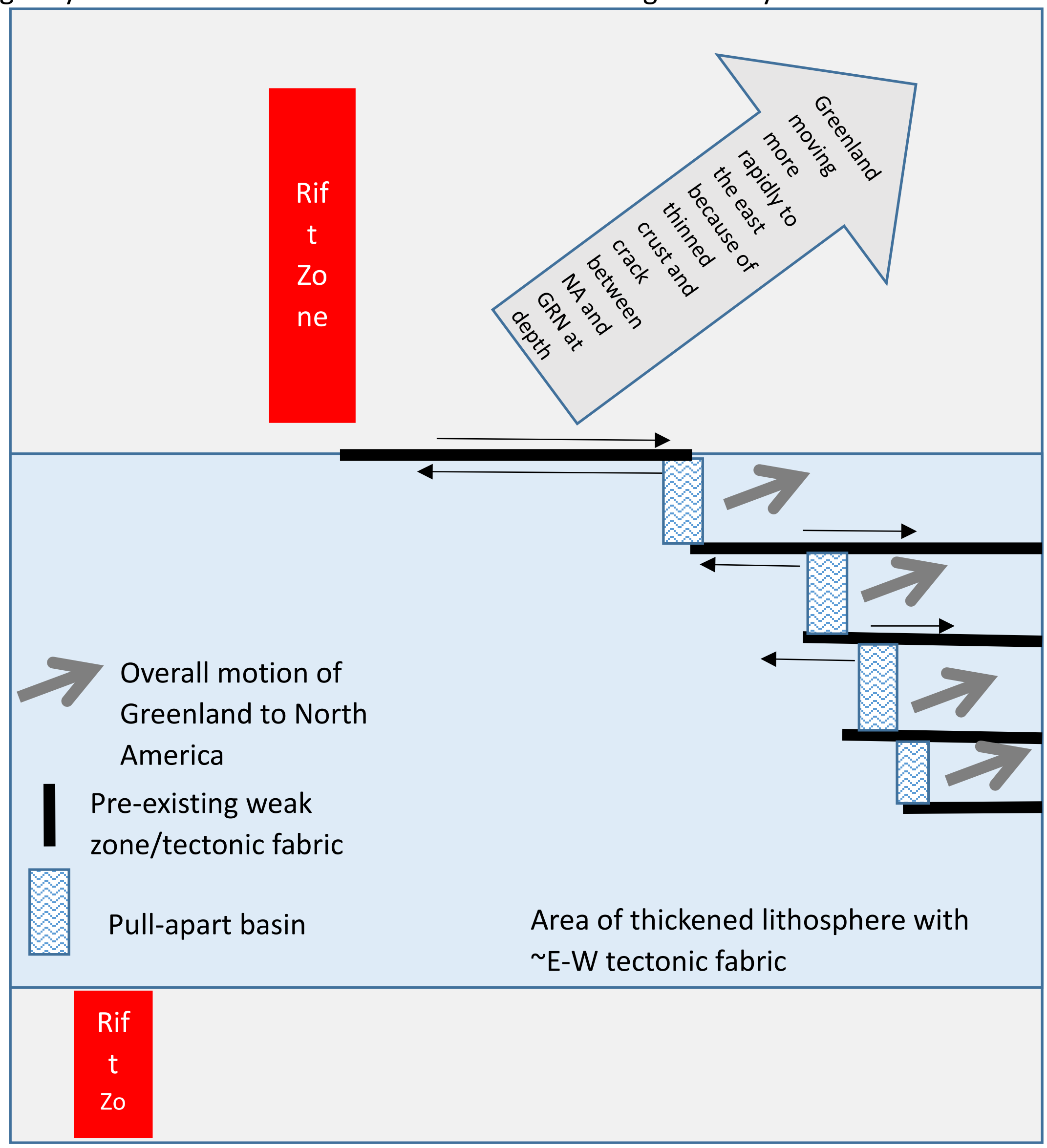


Figure N: Cartoon of proposed lithospheric scale structures in the area of the Disko Bugt just North of Davis Strait.

move more rapidly than the thickened crust in the Davis Strait and just to the North. Figure M is a cartoon of the likely relative motions due to strain partitioning between North America and Greenland near the Davis Strait at 63 Ma. We hypothesize that this unique configuration in conjunction with the strong E-W tectonic fabric within the thickened block presents one way to get the deep melts to the surface—by creating pull-apart basins between the shear zones (FIGURE N).

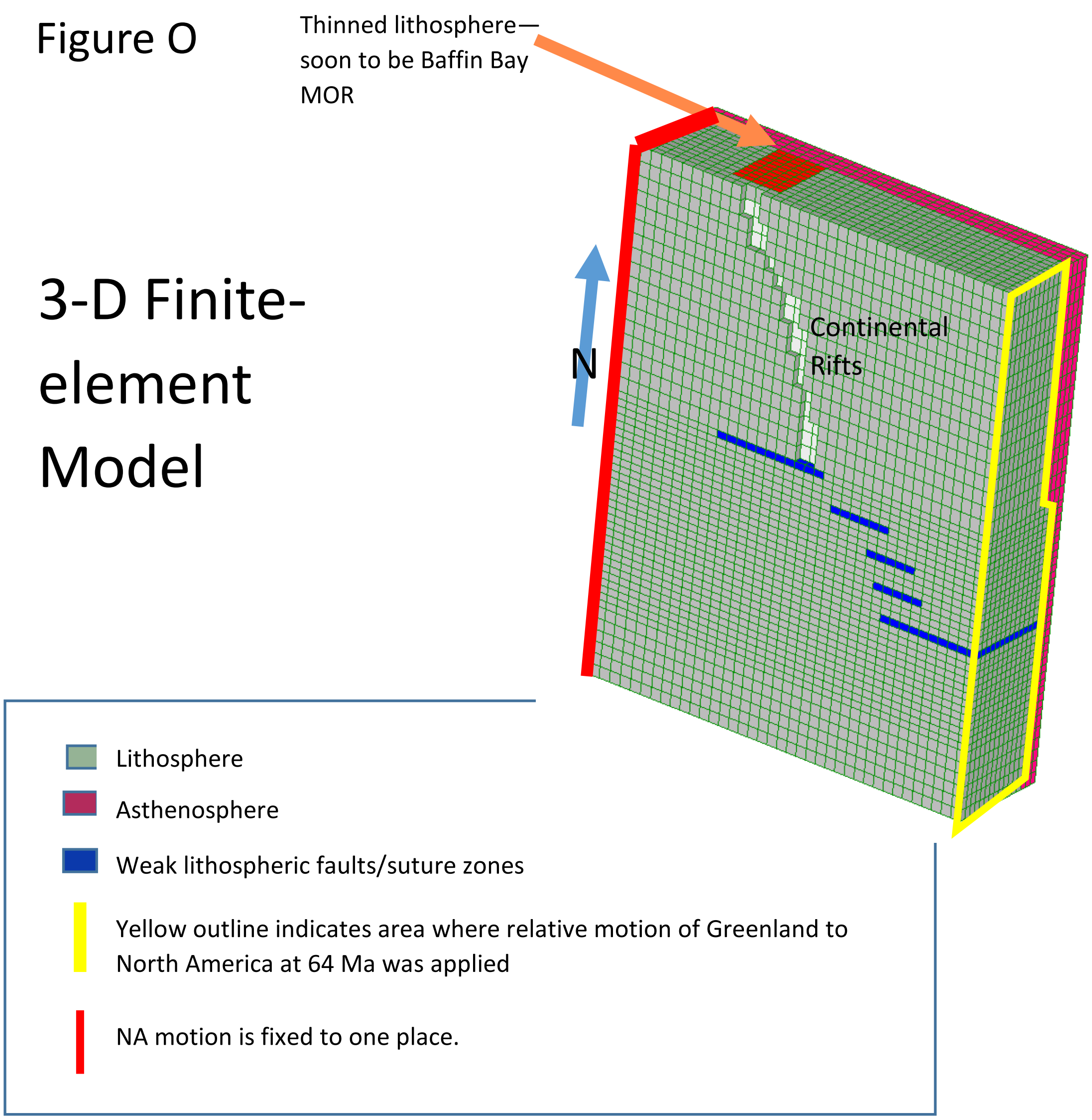
Finite-Element Modelling of Davis Strait

To test whether it is viable to bring melts rapidly to the surface we constructed an elastic finite-element model of a likely configuration of tectonic elements around Davis Strait/Disko Bugt area at the time of the picrite emplacement at 63 Ma. Elastic finite-element models show what the instantaneous stress would be given a constructed framework of elements (representing the material) and an applied force. They do not show long term changes in the structures or elements but simply show where stress is concentrated and its relative magnitude. Displacement can also be modelled, but without fluid flow magma cannot be modelled, instead we are using the model to determine whether it is viable to generate an extensional stress field in the area of the picrites and that that stress field could extend to 130 km depth.

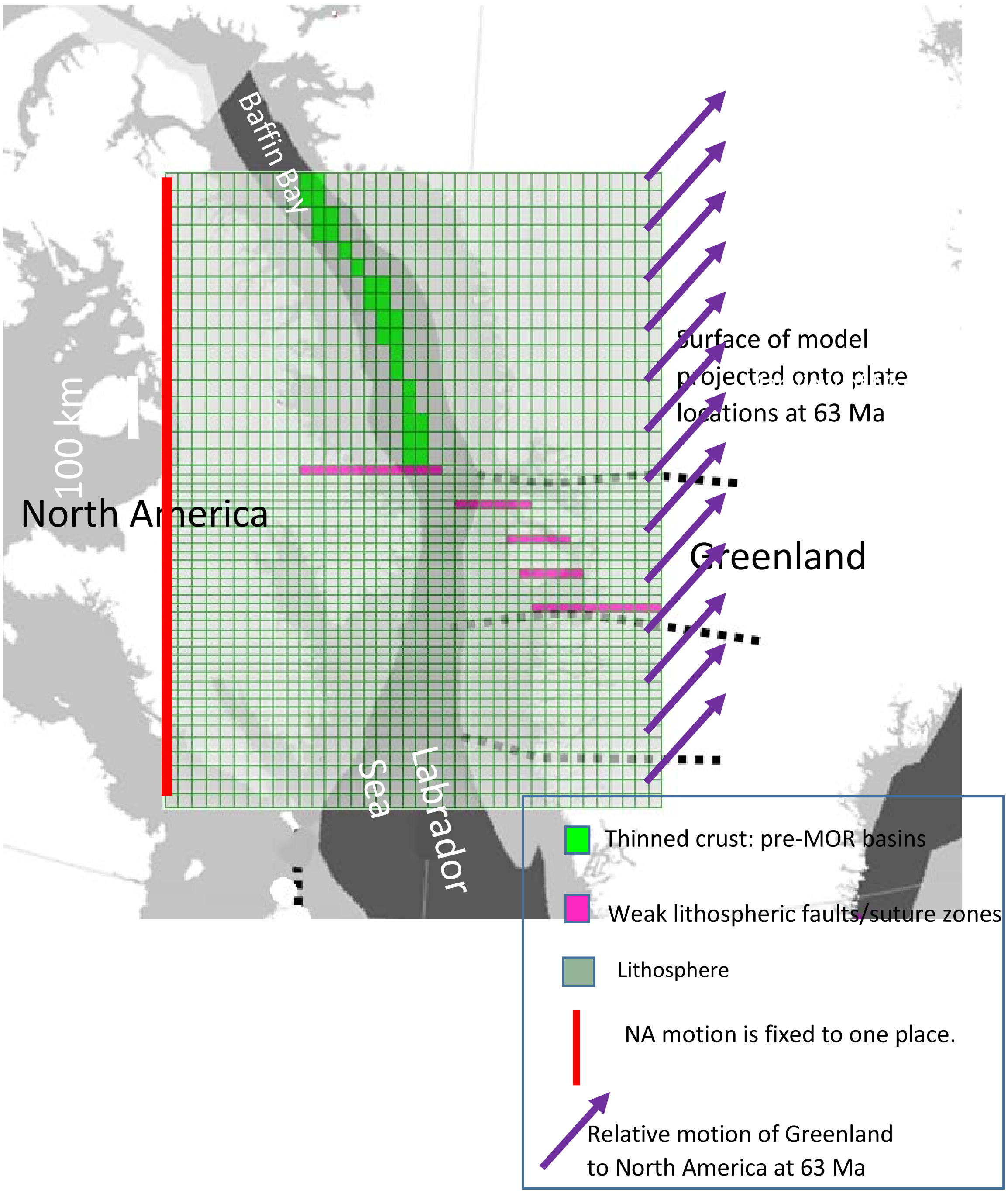
The model:

The model consists of solid elements of varying sizes connected by nodes which may or may not have stresses associated with them. It is assumed that the original elastic lithospheric thickness for Nagssugtoqidian mobile belt and is between 150-250 km (Teasuro et al., 2015, see earlier) with an elastic strength of between 10^9 and 10^7 Pa (Teasuro et al., 2015). Because of the thinning that had been occurring in the area between North America and Greenland for at least 100 m.y., we modelled the lithosphere as ~150 km thick on the margins of Baffin Bay and ~170 km thick through the Disko Bugt/Davis Strait area. The entire model was underlain by modelled asthenosphere, which, in the absence of a viscous element, was modelled as extremely weak with an elastic constant of 10^3 Pa. As seen in Figure O, our model consists of thinned lithosphere under the present day Baffin Bay oceanic crust with several continental rift basins overlying the thinned lithosphere. In the area of the thickened Nagssugtoqidian mobile belt we modelled several E-W lithospheric scale weak zones as per the strong E-W tectonic fabric and sutures zones described in (Dossing et al., 2011; Hollis et al, 2006, Garde et al., 2002 REF). The relative motion of Greenland to a fixed North America was applied to the right side of the model, while North America was modelled as fixed. The relative location of the tectonic features was based on the GPlates reconstruction of the plate positions in conjunction with the information from (REFS). Multiple tests were run of different scenarios to determine what was the product of model constraints vs tectonic structures (see appendix). This is a simple model with no variation in density or strength within the lithosphere aside from the suture zones. Lithospheric variations were not modelled because lateral and vertical variations in strength can cause changes in the stress field and we do not have detailed enough information at this time to reconstruct the lithosphere exactly. Further research examining the possible configurations and their effect on the stress distribution would be helpful. Thus, this model is simply testing the scope and likelihood of large scale extensional stresses existing just before the formation of the Baffin Bay mid-ocean ridge.

FIGURE O.



Model



Baffin Bay
100 km
North America
Surface of model projected onto plate locations at 63 Ma
Greenland
Labrador Sea
Thinned crust: pre-MOR basins
Weak lithospheric faults/suture zones
Lithosphere
NA motion is fixed to one place.
Relative motion of Greenland to North America at 63 Ma

Results: Elastic finite-element models of the Baffin Bay-Davis Strait intersection at 63 Ma indicate that large differential stress concentrations occur from the surface to the base of the elastic lithosphere between a series of offset E-W faults.

The 3-D finite-element model results show that at the surface, extension associated with the incipient rift dominates the crust with some extension between the ends of the tectonic faults in the Nagssugtoqidian mobile belt. However, as soon as a depth in which the incipient MOR has brought asthenosphere into the area under what is now Baffin Bay, there is very little stress associated with the incipient rift itself and most of the stress is concentrated between the tips of the E-W suture zones (FIGURE P,Q). The configuration of the extensional stresses indicates that a trans-tensional stress field has been concentrated between the pre-existing suture zones to a depth of ~150 km.

Figure P

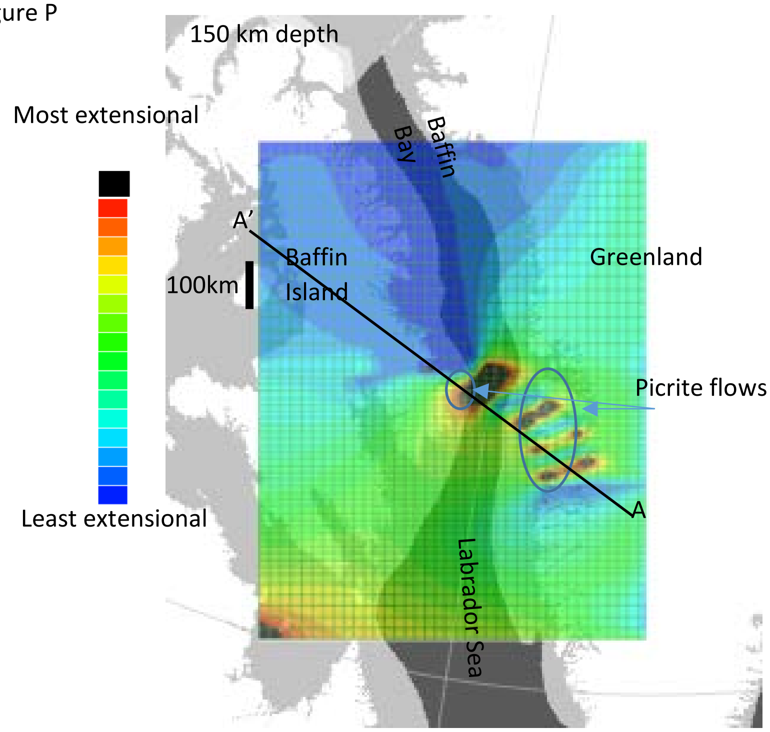


Figure Q

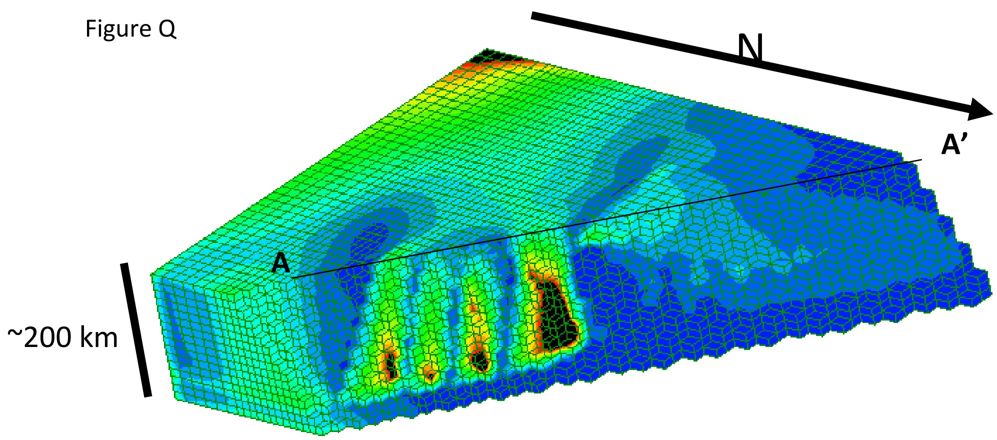


Figure P shows the map view of the extensional stress concentration results of the finite-element model at 150 km depth. Blue is least extensional and red—black is the most extensional. These results are overlain on the reconstructed continental outlines from 63 Ma using Oakey and Chalmers (2012) poles. Blue ovals indicate the location of the picrites at the surface.

Figure Q is a cutaway of the same 3-D model showing the stress concentrations in three-dimensions looking south along a cross-section from A-A'. The color scale is as in Figure P with blue being the least extensional and red-black being the most.

Finite-element analysis

1) Displacement between the E-W Paleoproterozoic Nagssugtoqidian mobile belt and the Rae craton to the north despite the same force being applied to the edge is caused by the weak NNW boundary under Baffin Bay that has filled with asthenosphere just prior to mid-ocean ridge spreading. The lack of resistance allows the Greenland lithosphere adjacent to Baffin Bay undergo more translation than the Greenland lithosphere in the Nagssugtoqidian belt still being held tightly to North America with a thick, strong craton.
2) This creates a relative motion difference between the Rae Craton to the North and the Nagssugtoqidian mobile belt belts.
3) As expected from our understanding of fracture mechanics in which stress is concentrated at crack tips, extensional stress is concentrated at all crack ends.
4) The stress orientation of the stress at 63 Ma is such that instead of crack propagation along E-W faults, trans-tensional fractures and complicated strain partitioning would occur. This was type of complicated structure was noted in the surface deformation in Frye(?) Island in the Davis Strait.)
5) Based on previous studies, the E-W suture zones and tectonic fabric are only located in the area of the Nagssugtoqidian mobile belt.
6) Concentrated extensional stress due to the intersection of the tectonic fabric, the relative motion between the Nagssugtoqidian and Rae craton, and the formation of the weak crust associated with incipient rift development, will exist at all depths in the elastic lithosphere.
7) Therefore, trans-tension between E-W tectonic fabrics could have occurred to a depth of 150 km and over an area large enough to bring picrites from that depth directly to the surface everywhere they are seen on the surface in the Davis Strait-Baffin Bay area.

Summary: What do the elastic finite-element models show?

The finite-element results presented here are not a unique solution for generating and bringing picrites to the surface, instead they illustrate that: 1) in thick cratonic lithosphere stresses reach to the depth of the elastic lithosphere, which can be up to 200-250 km (Teasuro et al., 2015); 2) inherited tectonic structures exert strong control on deformation and magma ascent (Peterson and Schiffer, 2016); 3) therefore no super heating due to a plume is necessary to bring deep/hot melts to the surface in thick lithosphere; and 4) specifically, the Davis Strait picrites are easily brought to the surface because of tectonic forces rather than via a plume (which makes no geochemical sense).

Why there is probably no deep-mantle plume in Davis Strait

Intelligently designed mantle plumes can explain every physical, chemical, and temporal aspect of a LIP or an oceanic island (Lundin 2013; Lustrino 2017). In addition, unless plumes drive plates, there are far too many LIPs associated with plate-tectonic singularities (triple junctions, RTIs, ridge-transfer zones) for the association to be statistically random (Julian and Foulger 2015). Instead of relying on a plume theory without any unequivocal evidence, we should be addressing the more challenging problem of using our reigning plate tectonics paradigm to try to explain each LIP. For the following reasons, we believe that a deep mantle plume is highly unlikely to have been responsible for the formation of the Davis Strait picrites:

1. the Davis Strait volcanics occur after a protracted (40-140 my) prelude of subsidence, crustal thinning, and alkali magmatism in the Labrador Sea axis – clearly these are the initial signs of the spreading centre and melting of the base of the lithosphere, as in the East African Rift (refs), that ultimately became the Labrador Sea and Baffin Bay (and in which the Davis Strait picrites simply represent a positive volcanic volume anomaly (PVVA) on that spreading axis)
2. plume advocates must be consistent – if they want picrites to mean a very hot plume, they have to accept significant regional uplift with arrival of the plume, but instead there was Mesozoic rift-related magmatism and late Cretaceous-Paleocene sedimentary basin formation immediately prior to picrite eruption;
3. the Davis Strait picrites are too remote from the central axis of most postulated plume models to result in unfractionated primary magma compositions (Gill et al. 1995);
4. a single plume migrating from the Siberian Traps and Sverdrup Basin, through Davis Strait, and on its way to become Iceland, appears far too conveniently in Davis Strait at precisely the time sea-floor spreading begins in Labrador Sea;
5. the smaller Davis Strait member of a double plume is unlikely to have been hotter and faster and shorter in duration and bearing an interrupting discontinuity between 56-54 Ma, than the larger Iceland member (ref)
6. picrites require an open plumbing system for rapid ascent more than they need excess heat;
7. the Davis Strait picrites are highly depleted, and must have had their source in a strongly depleted, low-density, buoyant, upper mantle, and that mantle material would have been unlikely to have been forced down to the core-mantle boundary and re-ascend as a plume, as suggested by Kerr et al. (1995);
8. the Davis Strait picrites are unique HD-MORBs, but any MORBs are the most unlikely types of basalt to be associated with mantle plumes (Presnall 2008) - the heavy solid line on Figure 4 separates MORBs on the right from within-plate basalts on the left;
9. the *spatial* probability (p_s) of any given 2000 km diameter plume arriving at the base of the lithosphere, and being close enough to contribute to the pending volcanism in Davis Strait, is area of plume/area of Earth = 3115900/510000000 = 0.006;

10. the *temporal* probability (p_t) of any plume leaving the core-mantle boundary 92 my ago, and arriving at the base of the lithosphere just in time to coincide with the onset of sea-floor spreading in northern Labrador Sea 62 my ago, any time in the 150 my history of crustal extension in the Labrador Sea area, is, say 1/150 = 0.007;
11. thus, the *combined* spatial and temporal probability of any mantle plume arriving at just the right place (close enough to produce magmatism at the RTI), and at just the right time in the ≥ 140 my history of rifting (as the Labrador Sea floor was beginning to form) is the product p_t*p_s = 0.00004, far too low to make *any* plume hypothesis credible for production of the Davis Strait picrites.

In general, of all the extant plume models advanced for the Davis Strait picrites (refs), at best only one can be correct; at worst, no plume model is correct, or even necessary. The antidote for severe cases of *plumitis* is www.mantleplumes.org. Having taken this remedy, we prefer to explain the Davis Strait picrites purely in terms of tectonic processes.

Davis Strait Picrite Petrogenesis

More than 75 years have elapsed since the pioneering work of Munck (1942) and Noe-Nygaard (1942) on the volcanic rocks of West Greenland. In those days, neither plate tectonics nor mantle plumes were known, and since that time we have learned much about the physical, chemical, and temporal features, and thus constraints, relevant to the origin of the picritic rocks. Any petrogenetic-tectonic model for them must explain as many as possible of the following parameters:

Physical

1. giant cross-beds in hyaloclastite breccias on both sides of Davis Strait show seaward provenance, i.e. the magma source is offshore in Baffin Island and West Greenland
2. coast-parallel linear belts on both sides of Davis Strait stretching NNW for 100-200 km parallel to the Baffin Bay spreading axis
3. thick stratigraphic sequences exclusively of picrites indicates they cannot be the cumulate products of high-level magma chambers
4. terrestrial picrites occur in Baffin Island and West Greenland, but the more voluminous(?) and more widespread(?) feldspar-phyric flood basalts occur only in West Greenland and Davis Strait
5. the southern terminus of the picritic rocks is spatially related to the BBSC-UTFZ PTS (Oakey and Chalmers (2012) or the change in orientation of the plate boundary (Hosseinpour et al. 2013)
6. southern terminus of picrite belt closely related to Nagssugtoqidian suture
7. seismic tomography indicates 200-240 km thick lithosphere prior to thinning Tappe (2012) kimberlites, Darbyshire (2010, 2013)
8. how strong was the lithosphere? – Paleoproterozoic sutures may control Mesozoic rifting (van Gool, St-Onge, Eglington 2013, Corrigan 2009)

Chemical

1. peridotite nodules in kimberlites are depleted (Tappe 2012 and others)
2. high MgO concentrations in picrites indicate rapid ascent of primary picrite magmas from ~120 km depth
3. CMAS projection shows a P*f* (final pressure of partial melting) about 4 GPa
4. HFSE tectono-magmatic designation of the Davis Strait picrites as MORB compositions
5. ultra-depleted incompatible trace elements means ultra-depleted and buoyant SCLM source
6. extreme isotopic compositions of picrites also indicative of ancient ultra-depleted SCLM (Tappe 2012)

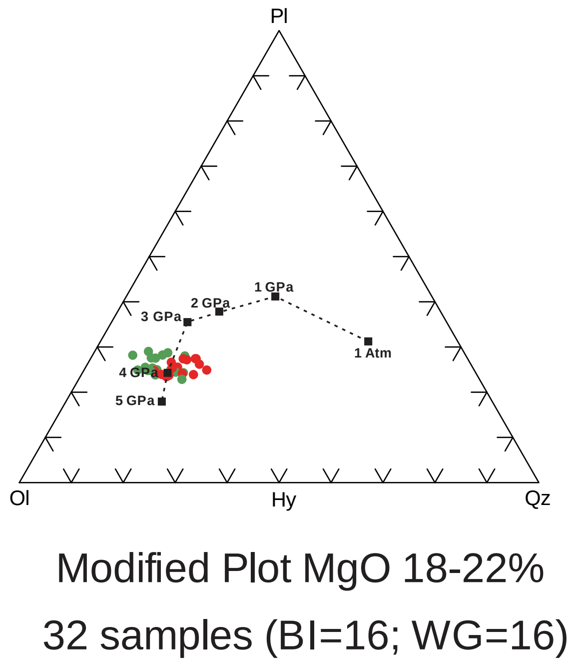
Temporal

1. general lack of weathering and erosion between lava flows indicates short period of volcanic activity
2. 62-61 Ma very short time interval for eruption of > 22,000 km^3 of picrites.
3. 62-61 Ma coincides with the onset of sea-floor spreading in Labrador Sea (and presumably Baffin Bay)
4. 62-61 Ma coincides with Oakey and Chalmers (2012) WSW-ENE motion

Davis Strait Picrite T-P Conditions of Mantle Partial Melting

Much has been written about picrites and their origin as the result of high temperatures of melting of mantle peridotite (e.g., Herzberg et al. 2007; Hole and Millett 2016; Spice et al. 2016). As a consequence, considerable attention has been directed to devising a plethora of geothermometers (e.g., Fo content of olivine, Ni in olivine, Al in olivine, fractionation of REEs) in an effort to determine the “excess” temperatures for picrites, and more generally whether “hotspots” are truly hotter than MORBs. The results vary widely, ranging from 0-300 C^{o} (e.g., Green and Falloon 2005, ***). From these sorts of thermal arguments, it is only one short and simple step from the imagined high temperatures of melting for picrites to their origin in hot mantle plumes (Larsen and Pedersen 2009). The real problem is that the picrites (DSP, BPIP), and presumed associated high temperatures, are out on the presumably cooler periphery of the putative plume. However, what matters is not the absolute temperature of melting, but what the temperature of the mantle is relative to its solidus.

The apparent high temperatures of picrites are inseparable from decompression melting at high pressures, and rapid ascent of the melts from those high pressures. (Clarke 1970, Francis 1985, Natland 2008 http://www.mantleplumes.org/Greenland.html). If the focus is placed on the pressure of melting, rather than the temperature, deduced pressures range from 3 GPa (Clarke 1970) to 3.8-4.7 GPa (Herzberg and O’Hara (2002) to 5.9-7.1 GPa (Hole and Millett 2016). Two consequences of melting at these pressures, followed by rapid ascent, are preservation of the primary magma compositions and retention of the mantle potential temperature of melting. Indeed, Hole and Millett (2016) state that “*P*f and by inference lithospheric thickness, must have been the dominant control on the extent of melting for the Vaigat Formation” in West Greenland (where *P*f is the final pressure at which melting takes place, and where ascent of the magma begins).



5.

Figure 5. CMAS projection of 32 picrites with 18 < MgO < 22 wt. % (Starkey, Larsen & Pedersen, Robillard) into the plane Ol-Pl-Qz (after Herzberg and O'Hara 1998) showing the positions of the experimentally-determined pressure-dependent invariant points (in GPa). The bulk chemical compositions of the picrites are similar to the melt compositions in equilibrium with mantle peridotite at pressures ~ 4 GPa (120 km depth).

Figure 5 shows 32 Davis Strait picrites with 18 < MgO < 22 wt % plotted on the CMAS pseudo-ternary phase diagram of Herzberg and O'Hara (1998). These primary magma picrite compositions cluster in the vicinity of 4 GPa, indicating that they could have been in equilibrium with mantle peridotite at that pressure. Our view is that, if gradual decompression (without heating) of the asthenosphere is an acceptable mechanism for producing conventional MORBs, then more rapid decompression (also without heating) of the SCLM at P ~ 4 GPa can produce the picritic MORBs of Davis Strait. This deduction about the depth of partial melting is consistent with Herzberg and O'Hara (2002), Harzberg and Asimow (2008, 2015), and Hole and Millett (2016). We expand on the petrogenetic and tectonic implications below.

Petrogenetic Statement: "Many continental large igneous provinces lie on the edges of continents and clearly formed in association with continental breakup." (Foulger 2007). The opening of the Atlantic is no exception (Parana, CAMP, Iceland LIPs), including the Davis Strait BLIP in the relatively small Labrador Sea aulacogen. In a well-documented tectonic setting of prolonged (≥ 140 my) lithospheric thinning and continental rifting, the Davis Strait picrites represent a positive volcanic volume anomaly, and a strongly depleted compositional anomaly, spatially and genetically related to a structural anomaly (RTI), coeval with sea-floor spreading along an otherwise unremarkable, and ultimately, failed Labrador Sea-floor spreading axis. Any thick volcanic sequence, consisting exclusively of picrites, requires a parental magma with MgO

= 18-22%. Most researchers agree that the parental Davis Strait picrites are also primary magmas (unmodified partial melts of the mantle) erupted rapidly from pressures of ~4 GPa to prevent polybaric fractionation of olivine (Clarke 1970; Francis 1985; Gill et al. 1992; Herzberg and O'Hara 1998, 2002; Larsen and Pedersen 2009). The enhanced extensional environment in the vicinity of the PTS permitted both the enhanced decompression melting of the depleted buoyant SCLM and the open plumbing system to the surface required by a thick sequence of strongly depleted N-MORB picrites. The source of the E-MORB picrites in BI and WG, and the overlying feldspar-phyric tholeiites in WG, may have been asthenospheric mantle, and the WG feldspar-phyric basalts may reflect a more restricted plumbing system (consistent with Clarke 1970, Larsen and Pedersen 2009 and Larsen et al. 2016*). We also predict the existence Skaergard/Rhum-like magma chambers/layered intrusions associated with the overlying flood basalts. Furthermore, with no deep mantle plume required to account for the positive volcanic volume anomaly in Davis Strait, the Davis Strait volcanism was probably largely independent of the formation of the North Atlantic Igneous Province (NAIP).

We attach major petrogenetic significance to the close observed spatial relationship between the Davis Strait picrites and the BBR-Nagssugtoqidian Fold Belt transfer/accommodation zone. Beutel and Anderson (2007) used finite-element analysis to show that such plate tectonic singularities (PTSs) can be sites of enhanced tensional forces and development of seamounts - a natural example is the Mid-Atlantic Ridge-Atlantis RTI that is spatially associated with an additional 2 km thickness of basalts on the ocean floor (Carbotte et al. 2016) and the development of volcanoes at the intersection of the ridge an offsetting faults in northern Iceland (Foulger and Anderson 2005; Mariotto et al. 2015). In these cases, the important spatial coincidence is PVVA-RTI, not PVVA-Plume. This demonstrated coincidence of a PVVA with a PTS does not require a further hypothetical coincidence of a mantle plume to generate magmatism. We also attach petrogenetic significance to the close temporal relationship between the picritic MORBs in Davis Strait and more ordinary MORBs in Labrador Sea. The important temporal coincidence is PVVA-initiation of sea-floor spreading, not PVVA-plume arrival. Thus, we suggest that the Davis Strait picrites in Baffin Island and West Greenland represent the products of partial melting of a highly depleted, buoyant, SCLM caused by enhanced pressure reduction at the BBR-Davis Strait PTS to produce relatively catastrophic (Presnall et al. 2002; Presnall 2008 www.mantleplumes.org/NoRidgePlumes.html) and top-down(?) decompression melting. The tensional forces at this PTS were also responsible for providing the relatively unobstructed pathways needed for rapid eruption and preservation of the primary magma compositions.

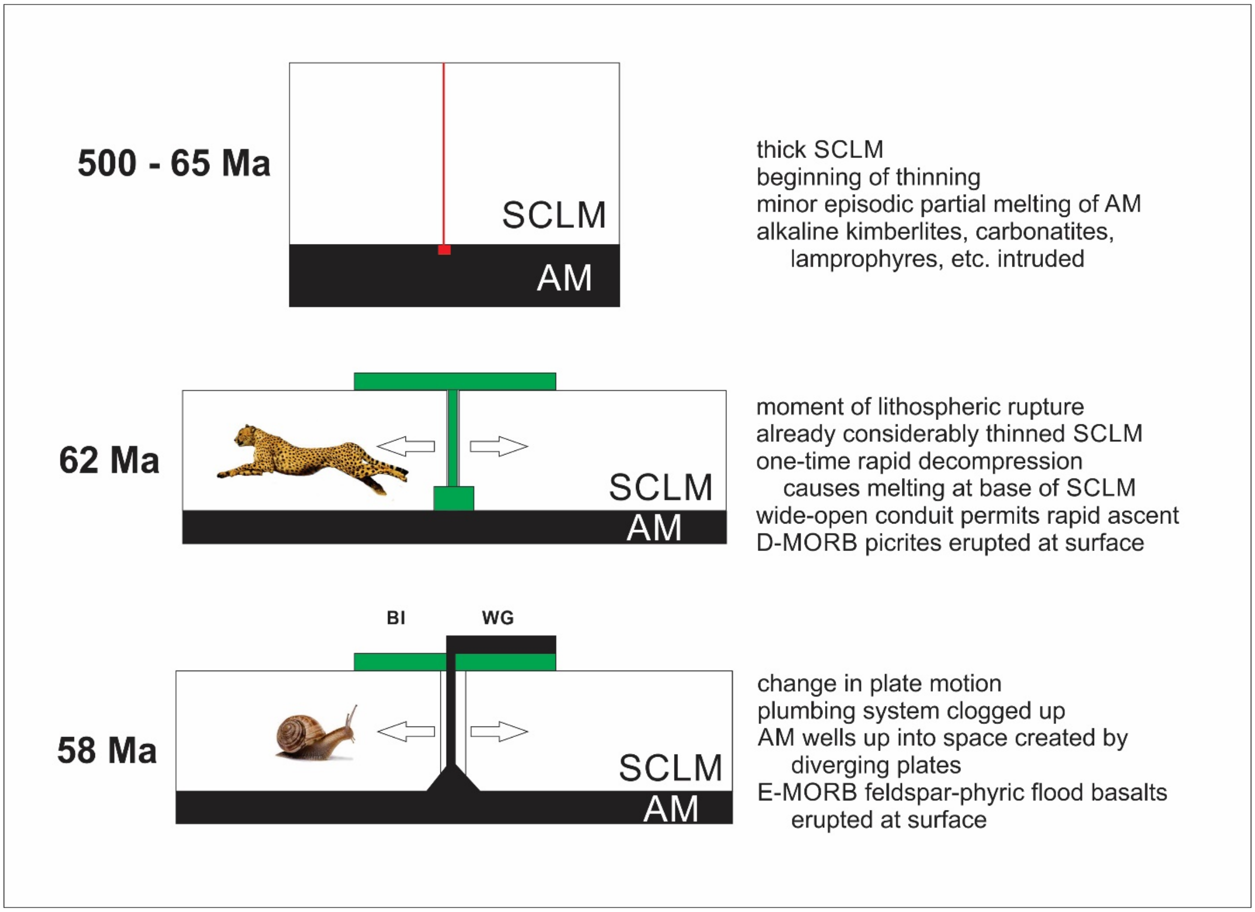


Figure 8+. Summary of magmatic history of Labrador Sea – Davis Strait.

Generating Deep Melts:

The concept of sutures zones acting as guides to subsequent rifting is not a new one (e.g. Dunbar and Sawyer, 1988) nor is the idea that they may help focus magmatism (e.g. REF, Peterson and Schiffer, 2016). However, that suture zones can focus deeper, sub-crustal melts is a concept that is not widely discussed. Recent work by Peterson and Schiffer (2016) determined that the thickness of the lithosphere in the suture zone affects the depth and timing of melting; thinner lithosphere concentrates stress rapidly and develops rifts prior to magmatism while thicker lithosphere results in deep lithospheric melting and magmatism prior to oceanic spreading. Further, deep, small volume alkaline eruptions have been determined to be associated with trans-tensional faulting along pre-existing suture zones in Archaean and Proterozoic cratons suggesting that lithosphere scale extension reaches to extreme depths (e.g. Jelsma et al. 2004 and White et al., 1995). Thus, thick lithosphere and trans-tensional stress have been previously demonstrated to cause deep melting of the lithosphere and may be assumed to be possible mechanisms for generating melt from SCLM. Add BUOYANT MELTING Raddick et al 2002…

Origin of the Overlying Feldspar-phyric Flood Basalts in West Greenland

In West Greenland, a thick sequence of olivine-poor, feldspar-phyric, flood basalts overlies the picrites, and these flood basalts appear to constitute most or all of the submarine basaltic sequences. These rocks are typical olivine-poor MORBs and represent magmas that have equilibrated to low-pressure conditions, meaning that the magmatic plumbing system had become restricted, and that there must have been high-level magma chambers developed, as happened in East Greenland (Skaergaard) and in the BPIP (Rhum). Our principal objective has been to explain the origin of the Davis Strait picrites, but two other major questions concern the origin of the overlying flood basalts. Those questions are: 1. what processes caused the switch from exclusively olivine-rich picrites to exclusively olivine-poor tholeiites?; and 2. why are these extensive olivine-poor flood basalts present only in on-shore West Greenland and in Davis Strait, but not on Baffin Island?

Larsen and Pedersen (2009JPet) have offered an answer to the first question, namely "The change midway in the volcanic succession from picrites to basalts is seen throughout the volcanic province from Disko to Svartenhuk Halvo. The sudden establishment of long-lived magma chambers must be due to a change in the regional plate-tectonic conditions." To which we would simply add, if the relatively minor change from picrites to flood basalts is attributable to regional plate conditions and restriction of the picrite plumbing pathway, why not also the relatively major change from volcanically inactive to volcanically active conditions?

The change from deep sourced picrites to shallower magma chambers and basalts occurred after spreading had been established in Labrador Sea and Baffin Bay and the Ungava transform fault had formed between the two. This would effectively decrease the stress between North America and Greenland and cause a change in the relative motion of Greenland (DALY QUOTE). This would change the stress state that had allowed for the creation of the deep extensional stresses that tapped the picrites. Further, as the lack of surface picrites and voluminous kimberlites world-wide suggests, deep conduits to the SCLM are not stable.

The answer to the second question may be that Baffin Island was simply too remote from the active magmatic axis by the time of the eruption of the olivine-poor flood basalts. Those flood basalts reached only as far as what is now the offshore Baffin Island part of Davis Strait (MacLean et al. 1978).

Davis Strait and NAIP

The Davis Strait picrites are identical to volcanic rocks in NAIP, except for the entire spectrum of physical, chemical, and temporal parameters. Because the Davis Strait picrites are plate-, and not plume-, related, there is no over-arching necessity to force similarities between them and volcanic rocks in East Greenland and the North Atlantic. In our view, the Davis Strait picrites are the products of the unique tectonic conditions that prevailed in Davis Strait, only, at 62 Ma ago, and have no need to parallel the development of any other volcanic rocks in the region.

If there is no plume in Davis Strait, this restricts the westernmost influence of the Iceland plume to East Greenland, but perhaps there is no plume in Iceland either (Kent 2004). Need to develop this section…

Broader Implications

<u>The East African Rift as a Modern Analogue of the Labrador Sea – Davis Strait – Baffin Bay</u>

Rifting of old continents to form new intervening oceans follows a general pattern of magmatic and structural events. The late Mesozoic-early Cenozoic Labrador Sea – Davis Strait – Baffin Bay system, a fossil propagated rift, preserves in time what the actively propagating rift system in East Africa (Ayalew et al. 2016; Hagos et al. 2016; Mèdge et al. 2016), currently shows in space (Fig. below). As for Davis Strait, most petrogenetic models for the Afar region, and other Gondwanan CFB provinces, involve one, or more, deep mantle plumes (Furman 2007; Natali et al. 2016), although Natali et al. 2017 concede "the rapid ascent of high-MgO magmas through open-feeding systems preferentially located at the intersection of multiple extensional tectonic lineaments, where the paroxysmal tectonomagmatic activity was focused". The Afar plumists face the same space-time probability problem as the Davis Strait plumists, i.e., what is probability of intersection of a plume with a plate tectonic singularity??

Figure 9+. Map of the Afar Triangle region, inverted vertically (after Wood and Guth, no date). Yellow labels (Africa), white labels (North America).

Magmatic Events: A rifting continent may show several discrete stages of magmatism as the rift develops. The first stage, lasting for tens or hundreds of millions of years, consists of small volume, volatile-rich, highly alkaline lamprophyres, lamproites, kimberlites and carbonatites, as in the East African Rift system (Beutel et al 2010; Furman 1995; Rosenthal et al. 2009) and along the margins of West Greenland, Labrador, Quebec, and Baffin Island (Clarke 1977; Digonnet et al. 2000; Heaman et al. 2015; Larsen et al. 2009; Tappe et al. 2006, 2007, 2008, 2012, 2017). The mantle source of these magmas lies somewhere in the vicinity of the lithosphere-asthenosphere boundary (LAB). An optional second stage, if the plate configurations are favourable for the relatively unrestricted passage of magma, and lasting a few million years, consists of flood basalts erupted onto one or both of the conjugate margins, as at the Afar triangle triple junction (Wood and Guth no date) and in Davis Strait (Clarke 1970). Such positive volcanic volume anomalies (PVVAs) can also occur at other tectonic singularities such as ridge-transform intersections (Carbotte et al. 2016; Mariotto et al. 2015). The third, and normally final, major stage of magmatism, lasting as long as sea-floor spreading occurs, consists of the production of MORBs and development of new oceanic crust. The source of these basaltic magmas is probably the thinned and decompressed asthenospheric mantle (Doré and Lundin 2015; Williamson et al 1995). As the magmatism winds down, a fourth magmatic stage may produce small volumes of highly fractionated products such as lamprophyres in West Greenland (Clarke et al. 1983).

Structural Events: In response to tensional forces in the lithosphere created by convection cells in the asthenosphere, the ductile lower lithosphere thins, and the brittle upper lithosphere fractures. Those brittle fractures can include normal faulting to produce a rift basin, transfer zones between adjacent developing basins, strike-slip faults that may become transform faults when sea-floor spreading begins, and lithospheric-scale rupture when the cratons ultimately separate (Alsulami et al. 2015; Døssing 2013; Lundin and Doré 2005; Nemčok et al. 2016; Wilson et al. 2006). The precise path/s that these structural elements follow through the craton is/are the planes of greatest weakness in the lithosphere. Those weak planes may be anisotropic fabrics in the crust, or ancient sutures resulting from former craton collisions. In East Africa, the position of the modern rift system is determined by Proterozoic shear zones (Daly et al. 1989; Beutel et al. 2010; ***add more refs***). In the Labrador Sea region, the position of the rift system is determined by Paleoproterozoic suture zones (St-Onge et al. 2009; van Gool et al. 2002).

Plate Tectonic Singularities PTS: Maybe not so singular?

We attach major petrogenetic significance to the close observed spatial relationship between the Davis Strait picrites and the BBR-Aasiaat domain transfer/accommodation zone. Beutel and Anderson (2007) used finite-element analysis to show that such plate tectonic singularities (PTSs) can be sites of enhanced tensional forces and development of seamounts - a natural example is the Mid-Atlantic Ridge-Atlantis RTI that is spatially associated with an additional 2 km thickness of basalts on the ocean floor (Carbotte et al. 2016) and the development of volcanoes at the intersection of the ridge an offsetting faults in northern Iceland (Foulger and Anderson 2005; Mariotto et al. 2015). In these cases, the important spatial coincidence is PVVA-RTI, not PVVA-Plume. This demonstrated coincidence of a PVVA with an "RTI" does not require a further hypothetical coincidence of a mantle plume to generate magmatism. We also attach petrogenetic significance to the close temporal relationship between the picritic MORBs in Davis Strait and more ordinary MORBs in Labrador Sea. The important temporal coincidence is PVVA-initiation of sea-floor spreading, not PVVA-plume arrival. Thus, we suggest that the Davis Strait picrites in Baffin Island and West Greenland represent the products of partial melting of a highly depleted, buoyant, SCLM caused by enhanced pressure reduction at the BBSC-UTFZ PTS to produce relatively catastrophic (Presnall et al. 2002; Presnall 2008 www.mantleplumes.org/NoRidgePlumes.html) and top-down(?) decompression melting. The tensional forces at this PTS were also responsible for providing the relatively unobstructed pathways needed for rapid eruption and preservation of the primary magma compositions. Thus, an analogy between both ongoing kimberlite production along continental transfer and trans-tensional zones (REF) and voluminous volcanism along mid-ocean ridge ridge-transform intersections can be made. Leading one to wonder if trans-tensional stresses, tectonic inheritance, and PTSs are less of a singularity and more of an ubiquitous answer.

Conclusions

We conclude that the Davis Strait picrites are exclusively the products of plate-tectonic interaction. We base this conclusion on five well-established and uncontroversial tectonic and petrogenetic principles:

1. supercontinent rifting paths follow pre-existing zones of weakness in the lithosphere;
2. intersection of a developing rift with strong lithosphere can create enhanced extensional forces;
3. such enhanced extension may lead to catastrophic fracture, resulting in extensive decompression melting, even in a depleted SCLM;
4. highly depleted SCLM must be the source for the picrites, but such depleted mantle is so buoyant that it could never have gone down to the core-mantle boundary; and
5. thick picrite sequences mean rapid ascent of primary magmas through fractures related to the enhanced extensional environment.

In addition, we conclude that:

1. the new oceanic crust in Labrador Sea and Baffin Bay, and "excess" volcanism in Davis Strait simply represent a normal magmatic continuation of the Mesozoic magmatism;
2. the "excess" magmatism in DS, spilling over onto both continental margins, and the picritic compositions, representing unfractionated primary magmas, from a 4GPa → 3GPa decompression in the mantle, can <u>both</u> be the result of *the same single factor*, namely a pressure-reducing and unobstructed plumbing system to the surface provided by enhanced extensional forces at the DS plate-tectonic singularity;
3. the unparallelled depletions in LILE and the Sr-Nd-He isotopic signatures of the DS picrites are the signatures of a highly depleted, low density, subcontinental lithospheric mantle that was highly buoyant and could not have been forced down to the CM boundary, only to rise again as a plume;
4. the temporal interruption of magmatism between 58 and 56 Ma in WG is related to changes in plate motion, not discontinuities in a plume; and
5. the thick feldspar-phyric flood basalts, sitting on top of the picrites, are less depleted more normal asthenosphere-derived MORBs.

Finally, we generally conclude that:

1. the plume spatial-temporal connection to Davis Strait picrites is highly improbable ($p=0.00004$);
2. the plate spatial-temporal connection to Davis Strait picrites is very strong;
3. the tectonic setting and the thick picrite sequence are inextricably linked, and thus no deep mantle plume is necessary;
4. there is no connection between Davis Strait volcanism and volcanism in East Greenland and points farther east, i.e., there is no single entity called NAIP; and
5. in purely logical terms, a-plumism is no less valid than plumism, and therefore under the ruling plate tectonics paradigm, *plate tectonics should be the default explanation for LIPs*, particularly for those lying on, or straddling, rifted continental margins, and that reliance on tailor-made deep mantle plumes should only be used as a last resort for other LIPs.

Acknowledgements

In 1963, J. Tuzo Wilson published his famous Hawaii hotspot paper, and was undergoing his own personal transformation from believing in an expanding Earth to formulating what shortly thereafter became known as plate tectonics. He was also full of other ideas, not least of which was conjecturing that basaltic rocks on southeasternmost Baffin Island might have a connection through "continental drift" to the better known volcanic rocks of central West Greenland. To this end, he created the opportunity to investigate the Baffin Island volcanics in the summer of 1964 (Wilson and Clarke 1965). A year after that publication, in 1966, Tuzo penned yet another famous paper "Did the Atlantic close and re-open?" (Wilson 1966). Although he could not have guessed in 1964 that, in Davis Strait, he was already standing on another example of closing and re-opening, we are pleased to provide additional support for his idea in this paper. In recognitions of his enormous contributions, we dedicate this paper to the memory of Tuzo Wilson, a co-founder of hotspots and plate tectonics, and sole discoverer of transform faults and Wilson cycles.

List of Abbreviations

BB – Baffin Bay
BBR – Baffin Bay Ridge
BI – Baffin Island
CMB – core-mantle boundary
DS – Davis Strait
DSP – Davis Strait Picrites
GPa – gigaPascals
LAB – lithosphere-asthenosphere boundary
LILE – large-ion lithophile elements
LREE – light rare-earth elements
LS – Labrador Sea
LSR – Labrador Sea Ridge
PT – plate tectonics
PTS – plate tectonic singularity
PVVA – positive volcanic volume anomaly
RTI – ridge-transform intersection
UTFZ – Ungava Transform Fault Zone
WG – West Greenland

References (incomplete)

Alsulami, S., Paton, D. A., and Cornwell, D. G. 2015 Tectonic variation and structural evolution of the West Greenland continental margin. American Association of Petroleum Geologists Bulletin 99, 1689-1711.

Anderson, D. L. 1998 The helium paradoxes Proceedings of the National Academy of Sciences, USA 95, 4822-4827.

Ayalew, D., Jung, S., Romer, R. L., Kersten, F., Pfänder, J. A., and Garbe-Schönberg, D. 2016. Petrogenesis and origin of modern Ethiopian rift basalts: constraints from isotope and trace element geochemistry. Lithos 2580-259, 1-14.

Beutel, E. K. 2009. Magmatic rifting of Pangaea linked to onset of South American plate motion. Tectonophysics 468, 149-157.

Beutel, E. K. and Clarke, D. B. 2017 Paleocene Picrites of Davis Strait: Products of a Plume or Plates? American Geophysical Union Abstract ***

Beutel, E. K. 2005 Stress-induced seamount formation at ridge-transform intersections. Geological Society of America Special Paper 388, 581-593.

Buiter, S. J. H. and Torsvik, T. H. 2014. A review of Wilson Cycle plate margins: a role for mantle plumes in continental break-up along sutures? Gondwana Research 26, 627-653.

Burke, K. and Cannon, J. M. 2014. Plume-plate interaction. Canadian Journal of Earth Sciences 51, 208-221. dx.doi.org/10.1139/cjes-2013-0115

Clarke, D. B. 1970. Tertiary basalts of Baffin Bay: possible primary magma from the mantle. Contributions to Mineralogy and Petrology 25, 203-224.

Clarke, D.B., 1977. The Tertiary volcanic province of Baffin Bay. Geological Association of Canada, special Paper 16, 445-460.

Clarke, D. B. 2007 The Davis Strait BLiP: a unique magmatic afterTHOt. In St-Onge, M. R. and Scott, D. J., GAC-MAC Trans-Hudson Field Trip, A Geological Transect of the Trans-Hudson Orogen from the Superior Craton to the Rae Craton, Geo-Briefing Book, Volume 2, Day 9 Davis Strait, 34 pp.

Clarke, D. B. 2008 The Davis Strait BLIP: tenuous relationships to deep mantle plume activity and NAIP. International Geological Congress Abstracts 33, 1339810.

Clarke, D. B. 2017 The Davis Strait BLIP: a retrospective reconciliation of igneous petrogenesis and plate tectonics. Geological Association of Canada – Mineralogical Association of Canada, Abstract ***

Clarke, D.B., Cameron, B.I., Muecke, G.K. and Bates, J.L., 1989. Early Tertiary basalts from the Labrador Sea floor and Davis Strait region. Canadian Journal of Earth Sciences 26, 956-968.

Clarke, D.B. and Pedersen, A.K., 1976. Chapter 12: Tertiary volcanic province of West Greenland. *In*, Geology of Greenland, eds. A. Escher and W.S. Watt, pp. 364-385.

Clarke, D.B. and Upton, B.G.J., 1971. Tertiary basalts on Baffin Island: field relations and tectonic setting. Canadian Journal of Earth Sciences 8, 248-258.

Class, C. and Goldstein, S. L. 2005 Evolution of helium isotopes in the Earth's mantle. Nature 436, 1107-1112.

Daoud, M. A., Le Gall, B., Maury, R. C., Rolet, J., Huchon, P., and Guillou, H. 2011. Young rift kinematics in the Tadjoura rift, western Gulf of Aden, Republic of Djibouti. Tectonics 30, TC1002, doi:10.1029/2009TC002614.

Foulger, G. R., Anderson, D. L, and Natland, J. H. 2003 An alternative model for Iceland & the North Atlantic Igneous Province. http://www.mantleplumes.org/Penrose/PenPDFAbstracts/Foulger_Gillian_abs.pdf

Francis, D. 1985 The Baffin Bay lavas and the value of picrites as analogues of primary magmas. Contributions to Mineralogy and Petrology 89, 144-154.

Funck, T., Jackson, H. R., Louden, K. E. and Klingelhöfer, F. 2007. Seismic study of the transform-rifted margin in Davis Strait between Baffin Island (Canada) and Greenland: What happens when a plume meets a transform. Journal of Geophysical Research 112, B04402, doi:10.1029/2006JB004308.

Furman, T. 2007. Geochemistry of East African Rift basalts: an overview. Journal of African Earth Sciences 48, 147-160.

Ganerød, M., Smethurst, M. A., Torsvik, T. H., Prestvik, T. Rousse, S., McKenna, C., van Hinsbergen, D. J. J., and Hendriks, B. W. H. 2010 The North Atlantic Igneous province revisited. Geophysical Journal International 182, 183-2

Geoffrey, L., Callot, J-P., Scaillet, S., Skuce, A., Gélard, J. P., Ravilly, M., Angelier, J., Bonin, B., Cayet, C, Perrot, K., and Lepvrier, C. 2001. Southeast Baffin volcanic margin and the North American – Greenland plate separation. Tectonics 20, 566-584. **IT IS, AFTER ALL, SEPARATION OF *PLATES* SO WHY ISN'T THE VOLCANISM ALSO?**

Gerlings, J., Funck, t., Jackson, H R., and Louden, K. E. 2009 Seismic evidence for plume-derived volcanism during formation of the continental margin in southern Davis Strait and northern Labrador Sea. Geophysical Journal International 176, 980-994.

Gill, R. C. O., Holm, P. M. and Nielsen, T. F. D. 1995 Was a short-lived Baffin bay plume active prior to initiation of the present Icelandic plume? Clues from the high-Mg picrites of West Greenland. Lithos 34, 27-39.

Gill, R. C. O., Pedersen, A. K., and Larsen, J. G. 1992 Tertiary picrites in West Greenland: melting at the periphery of a plume? Geological Society Special Publication No. 68, 335-348.E

Graham, D. W., Larsen, L. M., Hanan, B. B., Storey, M., Pedersen, A. K., and Lupton, J. E. 1998 Helium isotope composition of the early Iceland mantle plume inferred from the Tertiary picrites of West Greenland. Earth and Planetary Science Letters 160, 241-255.

Hagos, M., Koeberl, C., and van Wyk de Vries, B. 2016. The Quaternary volcanic rocks of the northern Afar Depression (northern Ethiopia): perspectives on petrology, geochemistry, and tectonics. Journal of African Earth Sciences 117, 29-47.

Hastie, A. R., Fitton, J. G., Kerr, A. C., McDonald, I., Schwindrofska, A., and Hoernle, K. 2016 The composition of mantle plumes and the deep Earth. Earth and Planetary Science Letters 444, 13-25.

Heaman, L. M., Pell, J., Grütter, H. S., and Creaser, R. A. 2015 U-Pb geochronology and Sr/Nd isotope compositions of groundmass perovskite from the newly discovered Jurassic Chidliak kimberlite field, Baffin Island, Canada. Earth and Planetary Science Letters 415, 183-199.

Herzberg, C. and O'Hara, M. J. 1998 Phase equilibrium constraints on the origin of basalts, picrites, and komatiites. Earth Science Reviews 44, 39-79.

Herzberg C. and O'Hara, M. J. 2002 Plume-associated ultramafic magmas of Phanerozoic age. Journal of Petrology 43, 1857-1883.

Hole and Millett 2016 Mantle potential temperature and NAIP Journal of Petrology ***

Holm, P. M., Hald, N., and Nielsen, T. F. D. 1992 Contrasts in composition and evolution of Teriary CFBs between West and East Greenland and their relations to the establishment of the Icelandic mantle plume. Geological Society Special Publication No. 68, 349-362.

Hosseinpour, M., Muller, R. D., Williams, S. E., and Whittaker, J. M. 2013 Full-fit reconstruction of the Labrador Sea and Baffin Bay. Solid Earth 4, 461-479. doi: 10.5194/se-4-461-2013

Julian, B. and Foulger, G. 2015. Hotspots in hindsight. Geological Society of America Special Publication 514, 105-121.

Keen, C. E., Dickie, K., and Dehler, S. A. 2012. The volcanic margins of the northern Labrador Sea: Insights to the rifting process. Tectonics 31, TC1011, doi:10.1029/2011TC002985.

Keir, D., Bastow, I. D., Pagli, C. and Chambers, E. L. 2013. The development of extension and magmatism in the Red Sea rift of Afar. Tectonophysics 607, 98-114.

Kent, A. J. R., Stolper, E. M., Francis, D., Woodhead, J., Frei, R., and Eiler, J. 2004 Mantle heterogeneity during the formation of the North Atlantic Igneous Province: Constraints from trace element and Sr-Nd-Os-O isotope systematics of Baffin Island picrites. Geochemistry Geophysics Geosystems 5, doi:10.1029/2004GC000743

Kerr, A. C., Saunders, A. D., Tarney, J. Berry, N. H. and Hards, V. L. 1995 Depleted mantle-plume geochemical signatures: No paradox for plume theories. Geology 23, 843-846.

Larsen, L. M., Heaman, L. M., Creaser, R. A Duncan, R. A., Frei, R., and Hutchison, M. 2009 Tectonomagmatic events during stretching and basin formation in the Labrador Sea and the Davis Strait: evidence from age and composition of Mesozoic to Palaeogene dyke swarms and West Greenland. Journal of the Geological Society of London 166, 999-1012. doi: 10.1144/0016-76492009-038

Larsen, L. M. and Pedersen, A. K. 2009a Petrology of the Paleocene picrites and flood basalts on Disko and Nuussuaq, West Greenland. Journal of Petrology 50, 1667-1711.

Larsen, L. M. and Pedersen, A K. 2009b West Greenland was hot – how else can you make 22,000 km^3 of picrites? www.mantleplumes.org/GreenlandHot.html Accessed 20170328

Larsen, L. M., Pedersen, A. K., Tegner, C., Duncan, R. A., Hald, N., and Larsen, J. G. 2016 Age of Tertiary volcanic rocks on the West Greenland continental margin: volcanic evolution and event correlation to other parts of the North Atlantic Igneous Province. Geological Magazine 153, 487-511.

Lawver, L. A. and Müller, R. D. 1994 Iceland hotspot track. Geology 22, 311-314.

Le Bas, M. J. 2000 IUGS reclassification of the High-Mg and picritic volcanic rocks. Journal of Petrology 41, 1467-1470.

MacLean, B., Falconer, R.K.H. and Clarke, D.B., 1978. Tertiary basalts of western Davis Strait: bedrock core samples and geophysical data. Canadian Journal of Earth Sciences 15, 773-780.

Mège, D., Purcell, P., Bézos, A., Jourdan, F., and La, C. 2016. A major dyke swarm in the Ogaden region south of Afar and the early evolution of the Afar triple junction. Geological Society of London, Special Publications 420, 221-248.

Natali, C., Beccaluva, L., Bianchini, G., Ellam, R. M., Savo, A., Siena, F., and Stuart, F. M. 2016. High-MgO lavas associated to CFB las indicators of plume-related thermochemical effects: the case of ultra-titaniferous picrite-basalt from the Northern Ethiopian-Yemeni Plateau. Gondwana Research 34, 29-48.

Natali, C., Beccaluva, L., Bianchini, G., and Siena, F. 2017. Comparison among Ethiopia-Yemen, Deccan, and Karoo continental flood basalts of central Gondwana; insights on lithosphere versus asthenosphere contributions in compositionally zoned magmatic provinces. Geological Society of America, Special Paper 526, 191-215.

Natland, J. H. 2008 Eruptive temperatures of the Paleogene picrites of West Greenland and Baffin Bay. www.mantleplumes.org/Greenland.html Accessed 20090803

Nemčok, M., Sinha, S. T., Doré, A. G., Lundin, E. R., Mascle, J. and Rybár, S. 2016 Mechanisms of microcontinent release associated with wrenching-involved continental break-up: a review. Geological Society London, Special Publications 431, 323-359.

Oakey, G. N. and Chalmers, J. A. 2012 A new model for the Paleogene motion of Greenland relative to North America: plate reconstructions of the Davis Strait and Nares Strait regions between Canada and Greenland. Journal of Geophysical Research 117, B10401, doi: 10.1029/2011JB008942

Peace, A. L., Foulger, G. R., Schiffer, C., and McCaffrey, K. J. W. 2017. Evolution of Labrador Sea-Baffin Bay: Plate of plume processes. Geoscience Canada ***

Petersen, K.D., and Schiffer, C., 2016. Wilson cycle passive margins: Control of orogenic inheritance on continental breakup: Gondwana Research, 39, 131-144. doi: 10.1016/j.gr.2016.06.012

Presnall, D. C. 2008 No plumes along mid-ocean ridges. http://www.mantleplumes.org/WebpagePDFs/NoRidgePlumes.pdf Accessed 20170808

O'Hara, M. J., Saunders, M. J., and Mercy, E. L. P. 1975 Garnet peridotite, primary ultrabasic magma and eclogite; interpretation of upper mantle processes in kimberlite. Physics and Chemistry of the Earth 9, 571-604.

O`Nions, R.K. and Clarke, D.B., 1972. Comparative trace element geochemistry of Tertiary basalts from Baffin Bay. Earth and Planetary Science Letters 15, 436-446.

Peace, A., Foulger, G., McCaffrey, K., and Schiffer, C. 2016 Labrador Sea and Baffin Bay opening and magmatism explained by plate processes and lithospheric structure. (unpublished manuscript)

Peace, A., McCaffrey, K. Imber, J, Hobbs, R., van Hunen, J., Foulger, G., and Gerdes, K. 2014 Formation of the West Greenland volcanic margin: exploring alternatives to the plume hypothesis. 4th Atlantic Conjugate Margins Conference, 161-162.

Robillard, I., Francis, D., and Ludden, J. N. 1992 The relationship between E- and N-type magmas in the Baffin Bay lavas. Contributions to Mineralogy and Petrology 112, 230-241.

Sand, K. K., Waight, T. E., Pearson, D. G., Nielsen, T. F. D., Makovicky, E., and Hutchison, M. T. 2009. The lithospheric mantle below southern West Greenland: A geothermobarometric approach to diamond potential and mantle stratigraphy. Lithos 112S, 1155-1166. doi:10.1016/j.lithos.2009.05.012

Sleep, N. H. (no date) Origins of the plume hypothesis and some of its implications. http://www.mantleplumes.org/P%5E4/P%5E4Chapters/SleepP4AcceptedMS.pdf Accessed 20170805

Spice Fitton Kirstein 2016 Temperature variation in Iceland plume over time G3

St-Onge, M. R., van Gool, J. A. M., Garde, A. A., and Scott, D. J. 2009 Correlation of Archeaean and Palaeoproterozoic units between northeastern Canada and western Greenland: constraining the pre-collisional upper plate accretionary history of the trans-Hudson orogen. The Geological Society, London, special Publications 318, 193-235.

Starkey, N. A., Stuart, F. M., Ellam, R. M., Fitton, J. G., Basu, S., and Larsen, L. M. 2009 Helium isotopes in early Iceland plume picrites: constraints on the composition of high $^{3}He/^{4}He$ mantle. Earth and Planetary Science letters 277, 91-100.

Storey, M., Duncan, R. A., Pedersen A. K., Larsen, L. M., and Larsen H. C. 1998 $^{40}Ar/^{39}Ar$ geochronology of the West Greenland Tertiary volcanic province. Earth and Planetary Science Letters 160, 569-586.

Storey, M., Duncan, R. A., and Tegner, C. 2007 Timing and duration of volcanism in the North Atlantic Igneous Province: implications for geodynamics and links to the Iceland hotspot. Chemical Geology 241, 264-281.

Stuart, F. M., Lass-Evans, S., Fitton, J. G., and Ellam, R. M. 2003 High 3He/4He ratios in picritic basalts from Baffin Island and the role of a mixed reservoir in mantle plumes. Nature 424, 57-59.

Suckro, S. K., Gohl, K., Funck, T., Heyde, I., Schreckenberger, B., Gerlings, J., and Damm, V. 2013 The Davis Strait crust – a transform margin between two oceanic basins. Geophysical Journal International 193, 78-97.

Tappe, S., Foley, S. f., Jenner, G. A., Heaman, L M., Kjarsgaard, B. a., Romer, R. L., Stracke, A., Joyce, N., and Hoefs, J. 2006 Genesis of ultramafic lamprophyres and carbonatites at Aillik Bay, Labrador: a consequence of incipient lithospheric thinning beneath the North Atlantic Craton. Journal of Petrology 47, 1261-1315. doi:10.1093/petrology/eg1008

Tappe, S., Foley, S. F., Stracke, A., Romer, F. L., Kjarsgaard, B. A., Heaman, L. M., and Joyce N. 2007 Craton reactivation on the Labrador Sea margins: $^{40}Ar/^{39}Ar$ age and Sr-Nd-Hf-Pb isotope constraints from alkaline and carbonatite intrusives. Earth and Planetary Science Letters 256, 433-454.

Tappe, S., Foley, S. F., Kjarsgaard, B. A., Romer, R. L., Heaman, L. M., Stracke, A. and Jenner, G. A. 2008 Between carbonatite and lamproite – Diamondiferous Torngat ultramafic lamprophyres formed by carbonate-fluxed melting of cratonic MARID-type metasomes. Geochimica et Cosmochimica Acta 72, 3258-3286.

Tappe, S., Steenfelt, A., and Nielsen, T. 2012 Asthenospheric source of Neoproterozoic and Mesozoic kimberlites from the North Atlantic craton, West Greenland: new high-precision U-Pb and Sr-Nd isotope data on perovskite. Chemical Geology 320-321, 113-127.

Tappe, S., Romer, R. L., Stracke, A., Steenfelt, A., Smart, K. A., Muehlenbachs, K., and Torsvik, T. H. 2017 Sources and mobility of carbonate melts beneath cratons, with implications for deep carbon cycling, metasomatism and rift initiation. Earth and Planetary Science Letters 466, 152-167.

Upton, B. G. J. 1988 History of Tertiary igneous activity in the N Atlantic borderlands Geological Society Special Publication No 39, 429-453.

White and McKenzie 1989 Magmatism at rift zones JGR

White, R. S. and McKenzie, D. 1995 Mantle plumes and flood basalts. Journal of Geophysical Research 100, 17543-17585

White, R. S., Spence, G. D., Fowler, S. R., McKenzie, D. P, Westbrook, G. K., and Bowen, A. N. 1987 Magmatism at rifted continental margins. Nature 330, 439-444.

Williamson, M-C., Courtney, R. C., Keen, C. E., and Dehler, S. A. 1995 The volume and rare earth concentrations of magmas generated during the finite stretching of the lithosphere. Journal of Petrology 36, 1433-1453.

Wilson, J. T. 1961. Discussion of R. S. Dietz: Continent and ocean basin evolution by spreading of the sea floor. Nature 192, 125-128.

Wilson, J. T. 1963 A possible origin of the Hawaiian Islands. Canadian Journal of Physics 41, 863-870.

Wilson, J. T. 1966. Did the Atlantic close and re-open? Nature 211, 676-681.

Wilson, J. T. and Clarke, D. B. 1965. Geological expedition to Capes Dyer and Searle, Baffin Island, Canada. Nature 205, 349-350.

Wilson, R. W., Klint, K. E. S., van Gool, J. A. M., McCaffrey, K. J. W., Holdsworth, R. E, and Chalmers, J. A. 2006 Faults and fractures in the central West Greenland: onshore expression of continental break-up and sea-floor spreading in the Labrador – Baffin Bay Sea. Geological Survey of Denmark and Greenland Bulletin 11, 185-204.

Wood, J. and Guth, A. (no date) East Africa's Great Rift Valley: A Complex Rift System www.geology.com/articles/east-africa-rift.shtml Accessed 20170328