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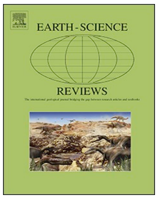

Davis Strait Paleocene picrites: Products of a plume or plates?

D. Barrie Clarke[a,*], Erin K. Beutel[b]

[a] Department of Earth Sciences, Dalhousie University, Halifax, Nova Scotia B3H 4R2, Canada
[b] Department of Geology and Environmental Geosciences, College of Charleston, Charleston, SC 29424, USA

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ABSTRACT

Voluminous, subaerial, ultra-depleted, 62 Ma, primary picritic lavas lie on conjugate volcanic margins on both sides of Davis Strait separating Baffin Island and West Greenland. Temporally, these picrites erupted just prior to, and coeval with, the initiation of sea-floor spreading in Labrador Sea and Baffin Bay. 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; $^3He/^4He \leq 49.5R_A$) are those of D-MORBs that demand derivation only by partial melting of highly incompatible-element 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 near Paleoproterozoic suture zones in the SCLM of thick Paleoproterozoic cratonic terranes during Paleogene rifting between Greenland and North America. Structurally, the picrites are related to the major intersection of a NNW-trending lithospheric thinning under Baffin Bay and the ~E-W-trending thickened lithosphere of the Paleoproterozoic Nagssugtoqidian Fold Belt. During the late Mesozoic, ENE extension that thinned the mantle lithosphere and created normal-faulted basins. 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 Baffin Bay lithosphere. These extensional disparities occurred at the orthogonal intersection of pre-existing ~E-W-trending strike-slip faults in the thicker Nagssugtoqidian Fold Belt with the incipient spreading under Baffin Bay, 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 depths of ~120 km, not only creating adiabatic decompression melting in the SCLM, but also forming an open pathway for the picritic melts to rapidly reach the surface. This purely tectonic model requires no spatially or temporally improbable deep mantle plume for generation of the Paleocene picrites of Davis Strait.

1. Introduction

1.1. Historical background

More than a 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 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 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. 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 the 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

Abbreviations: AM, asthenospheric mantle; BB, Baffin Bay; BLIP, Baby Large Igneous Province; BBR, Baffin Bay Ridge; BI, Baffin Island; CMB, core-mantle boundary; DS, Davis Strait; DSP, Davis Strait Picrites; GPa, gigaPascals; HFSE, high field-strength element; LAB, lithosphere-asthenosphere boundary; LILE, large-ion lithophile element; LIP, Large Igneous Province; LREE, light rare-earth element; LS, Labrador Sea; LSR, Labrador Sea Ridge; MORB, mid-ocean ridge basalt; PT, plate tectonics; PTS, plate tectonic singularity; PVVA, positive volcanic volume anomaly; REE, rare-earth element; RTI, ridge-transform intersection; SCLM, sub-continental lithospheric mantle; UTFZ, Ungava Transform Fault Zone; WG, West Greenland

[*] Corresponding author.
E-mail address: clarke@dal.ca (D.B. Clarke).

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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°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 apparent 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 in the lithosphere and/or asthenosphere.

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 persistent hot spots to deep 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 a 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 (e.g., Fitton et al., 1997; Larsen et al., 2016).

Properties of mantle plumes should include regional uplift prior to volcanism, high regional heat flow, and Bulk Earth/primitive 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.

As with other scientific hypotheses (Kuhn, 1962), the plume model began to accumulate anomalies. For each observation it could not explain, the plume hypothesis was modified and imbued with special properties that could account for 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 over deep mantle plumes is available at www.mantleplumes.org.

1.2. Regional marine geology

St-Onge et al. (2009) compiled the ocean-floor geology of the Labrador Sea - Davis Strait - Baffin Bay region (Fig. 1). 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; Williamson et al., 1995). 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 crust are its unusual thickness and its structure. 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 Paleoproterozoic 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 spreading axis in Baffin Bay (Funck et al., 2007; Skaarup et al., 2006; Srivastava, 1978; Suckro et al., 2013). Offshore basalts from Davis Strait on the Baffin Island side (Clarke et al., 1989; 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 the source and probably also the processes. The voluminous picrites appear to belong only to the earliest stages of volcanism in the Davis Strait area. (c) *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 in Baffin Bay, and deduced that it was a small ocean created by sea-floor spreading. Since then, work by others (e.g. Oakey and Chalmers, 2012; Reid and Jackson, 1997; Rice and Shade, 1982) has essentially upheld this early view, but with the thick blanket of younger sediments, interpretation of the geophysical evidence is difficult.

1.3. 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., 2009) (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 Mesozoic-Cenozoic plate-tectonic activity.

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), Larsen and Rex (1992), Larsen and Dalhoff (2006), Tappe et al. (2007, 2017), and Upton (1988). 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 magmatically active 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 at 62 Ma 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 a variety of alkaline magmas, but without yet developing any oceanic crust (Beutel et al., 2010; Rosenthal et al., 2009; Wood and Guth, n.d..

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 thick 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

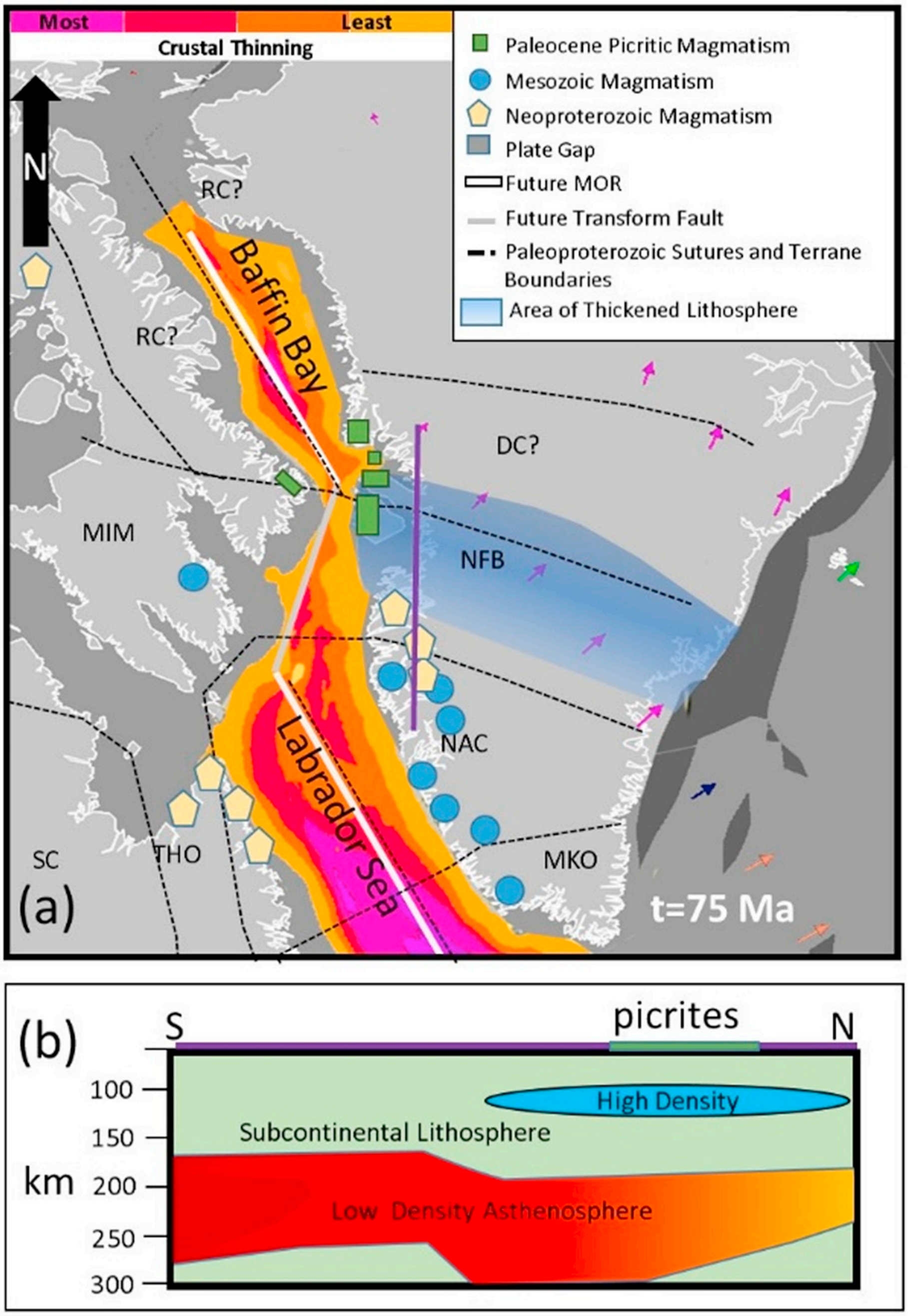


Fig. 1. (a) Schematic location of the Davis Strait picrites and relevant geological features at $t = 75$ Ma, including ancient sutures and terrane boundaries, small-volume Paleoproterozoic magmatism (ultramafic lamprophyres, carbonatites), small-volume Mesozoic magmatism (ultramafic lamprophyres, carbonatites, kimberlites, nephelinites, melilitites), mid-oceanic ridges, and a transform fault zone. Arrows indicate plate motion relative to a fixed North America generated by Gplates (Scotese, 2016). 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. Lithospheric thinning information from Artemieva and Thybo (2008) and Hosseinpour et al. (2013). The area of thickened lithosphere is based on Artemieva and Thybo (2008), Darbyshire et al. (2004), Lebedev et al. (2018), Tappe et al. (2006), and Wittig et al. (2008, 2010). (b) Cross-section along the western margin of Greenland from NAC to just north of the Nagssugtoqidian Fold Belt (purple line on the map).

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 that the volcanic rocks may be related to a branch of the Mid-Atlantic Ridge extending through Labrador Sea, Davis Strait, and Baffin Bay.

1.4. Davis Strait picrites

Le Bas (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 successions have simple explanations in terms of accumulation of olivine in high-level magma chambers, but thick volcanic sequences consisting exclusively of picrites are petrogenetically problematic. On Baffin Island, the volcanic sequence is nowhere >750 m thick, but it consists entirely of picritic tholeiites, it thins inland, and judging from the giant cross-bedding in the basal 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 basal 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. 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 may be unmodified partial melts (primary magmas) of a peridotite mantle. These primary picrites (mean composition of 32 primary picrites shown in Fig. 7: SiO_2 45.81, TiO_2 0.91, Al_2O_3 10.84, Cr_2O_3 0.24, FeO_T 10.65, NiO 0.11, MnO 0.18, MgO 20.15, CaO 9.40, Na_2O 1.18,

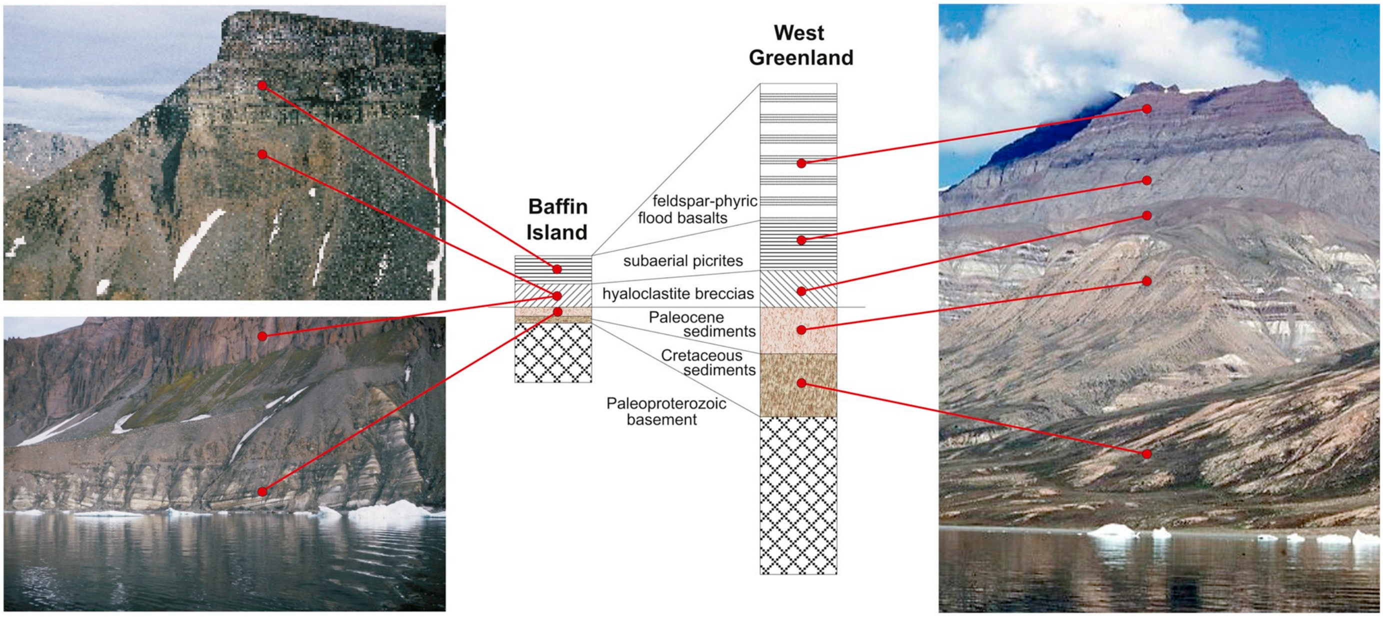


Fig. 2. Schematic comparison of the stratigraphic sections on Baffin Island (Cape Searle, lower left, and southeast of Durban Island, upper left) and West Greenland (Paatuut, Nuusuuaq Peninsula, right). For scale, the vertical height of the cliff on Baffin Island is approx. 600 m, and the vertical height of the section on Nuusuuaq is approx. 1000 m. Cretaceous sediments on Baffin Island include the Quqaluit Formation, and in West Greenland the Atane Formation). Paleocene sediments on Baffin Island include the Cape Searle Formation, and in West Greenland the Kangilia-Antanikerdluk Formation.

K_2O 0.07, P_2O_5 0.08) have major-element compositions similar to komatiites (Viljoen and Viljoen, 1969), but without spinifex textures (http://www.alexstrekeisen.it/english/vulc/spinifex.php), and trace-element compositions similar to MORBs. O'Nions and Clarke (1972) made the connection between low concentrations of large-ion lithophile elements (LILE) and low $^{87}Sr/^{86}Sr_i$ and an incompatible-element depleted, and relatively refractory, mantle source. The terms “fertile” and “depleted” are relative terms that may apply independently to major and trace elements. A minor melting event might have strongly depleted LILE, but not the major elements, in the residual mantle.

Building on the work of Robillard et al. (1992), Stuart et al. (2003) used $^3He/^4He$ 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 $^3He/^4He$ 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., Clarke, 1968; Clarke and Pedersen, 1976; Drever, 1956; Larsen and Pedersen, 2009a, 2009b; Munck, 1942; Noe-Nygaard, 1942; Pedersen et al., 2017). 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 a melt extraction anomaly (Foulger and Natland, 2003; Foulger et al., 2003), or more neutrally, a positive volcanic volume anomaly (PVVA), 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.

1.5. Purpose

Currently, all published interpretations for the origin of the Davis Strait picrites 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., Ganerød et al., 2010; Holm et al., 1992). Larsen and Pedersen (2009b) stated the petrogenetic problem for these rocks very cogently: “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, their high-MgO bulk compositions connote high temperatures, and high temperatures commonly connote mantle plumes and deep mantle sources. But the reigning Earth science paradigm is that of plate tectonics, and as such, we should first attempt to interpret our observations in those terms, resorting only to other processes if it cannot be shown that plate tectonics works. As an alternative to the now, essentially default, plume models, we expand on the work of Beutel and Clarke (2017), Clarke (2007, 2008, 2017), and Peace et al. (2018) to make the case for an exclusively plate-tectonic-controlled origin for the Davis Strait picrites.

1.6. Claim

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 adiabatic decompression melting created during the rupture of the subcontinental lithospheric mantle. With this in mind, we believe that these 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, or other plate tectonic singularities (PTS)).

1.7. Scope

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 in Davis Strait. 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.

2. Features of the Davis Strait picrites

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

2.1. 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 tholeiitic flows (Fig. 2). The picritic volcanic rocks are known as the Vaigat Formation (Pedersen et al., 2017). 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.

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 well short of the 100,000 km^3 threshhold for a LIP, so we refer to it as a BLIP (Baby LIP), one that did not reach full maturity.

2.2. Geochronology

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 (Heaman et al., 2015; Tappe et al., 2007, 2017). Subsequently, at ~62 Ma, the high-volume eruption of terrestrial Davis Strait picrites occurred just prior to, or simultaneously with, MORBs produced at the initiation of sea-floor spreading in the northern Labrador Sea (Larsen et al., 2016).

2.3. Petrography

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 ($Fo_{84–93}$), generally averaging < 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 (Fig. 3). Further petrological details are available in Francis (1985), Larsen and Pedersen (2009a) and Pedersen et al. (2017).

2.4. Geochemistry

Le Bas (2000) chemically re-defined the term “picrite” to be basaltic rocks with $12 < MgO < 18$ wt%, and with total alkalies < 3 wt%. This rather narrow definition excludes many of the olivine-rich Paleocene lavas of Davis Strait. According to Le Bas (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 > 60 years, we will continue to use it here for all volcanic rocks with MgO > 12 wt% (Fig. 4).

But, high MgO contents are only one of the remarkable geochemical features of the Davis Strait picrites; large-ion lithophile elements (LILE), high field-strength elements (HFSE), and many radiogenic isotopic ratios, lie at, or near, the extremities of the ranges of world-wide basalt compositions (Table 2).

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), suggesting a strongly LILE-depleted source mantle. Concomitant with the low K_2O are the strong depletions in the LILE incompatible trace elements (e.g., Rb, light rare-earth elements (LREE), U, Th), making them among the most LILE-depleted Phanerozoic basaltic rocks on Earth (Fig. 5). Similarly, the incompatible high field-strength elements (HFSE), such as the REEs, Y, and Zr, also have low concentrations. In addition, extreme values for isotopic ratios ($^{87}Sr/^{86}Sr_i = 0.7028$; $\varepsilon Nd_i = +10$; $^{206}Pb/^{204}Pb_i = 18.0$; $^{187}Os/^{188}Os_i = 0.1230$; $^3He/^4He = 49.5{*}R_A$) are collectively consistent with an ancient depletion of the relatively incompatible parent elements (Rb, Sm, U, Re) in the mantle source for these picrites (Anderson, 1998; Class and Goldstein, 2005; Kent et al., 2004; Wittig et al., 2008).

We support our deduction about the depleted nature of the source mantle with the evidence from peridotite xenoliths contained in ultramafic lamprophyres and kimberlites in West Greenland. Sand et al. (2009) and Wittig et al. (2008) described the SCLM beneath the adjacent North Atlantic Craton (NAC) as being up to 220 km thick 600 my ago, and as consisting of depleted dunite, harzburgite, and wehrlite above a depth of 180 km, and more fertile lherzolite and garnet lherzolite below a depth of 180 km. Furthermore, Re—Os systematics indicate that depletion of the upper SCLM occurred in the Archean (> 2.5 Ga) (Wittig et al., 2008, 2010). This stratigraphy of the SCLM suggests that the LIL E-depleted peridotites may be the source of the depleted picrites in the vicinity of Davis Strait. Byerly and Lassiter (2014) showed that isotopically ultra-depleted (convecting mantle) peridotite is capable of contributing to MORB petrogenesis.

This type of depleted mantle is so buoyant (O'Hara et al., 1975; O'Reilly et al., 2009) that it is unlikely to ever have descended to the core-mantle boundary and risen as a plume. A LILE-depleted, relatively 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.

2.5. Tectono-magmatic signature

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 (rare-earth element) patterns to draw parallels

Table 1
Physical dimensions of Davis Strait picrites.

	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 (2009a); Larsen et al. (2016); Pedersen et al. (2017)

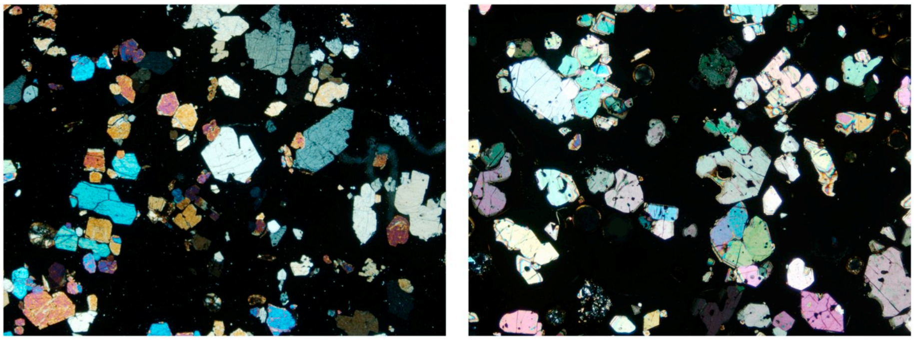


Fig. 3. Subaqueous picritic hyaloclastite breccias under crossed-polarized light. All birefringent grains are olivine enclosed in rapidly quenched isotropic glass. Left: Sample DX-35 from Padloping Island, Baffin Island (Clarke, 1965, 1970; Clarke and Upton, 1971). Right: Sample 658 from Svartenhuk Peninsula, West Greenland (Clarke, 1968, 1970). FoV = 6 mm.

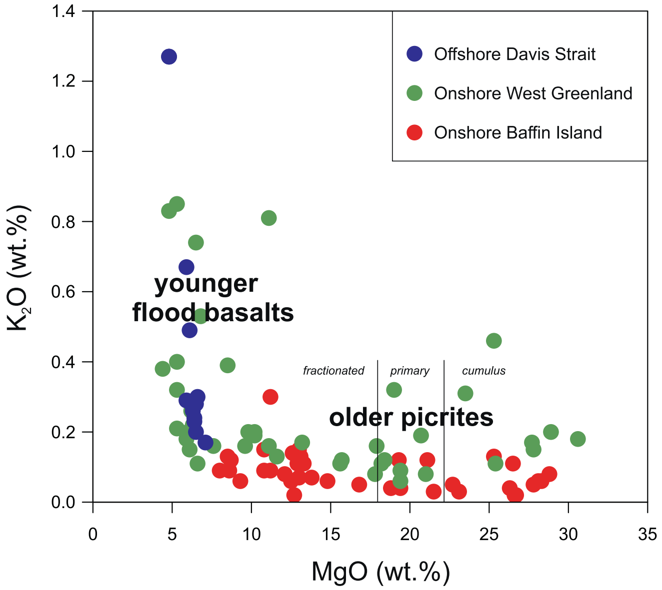


Fig. 4. Binary variation diagram of MgO-K_2O showing the two key geochemical features of the Davis Strait picrites: the high MgO contents typical of primary magmas, and the low K_2O contents typical of highly depleted mantle sources. Data from Clarke (1968) and Park et al. (1971).

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 show the Davis Strait picrites to be MORBs, and Fig. 6 illustrates perhaps the most objective and reliable one (Agrawal et al., 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 uniquely depleted (both LILE and HFSE) among MORBs, and to underscore this uniqueness, we refer to them as highly depleted MORBs (or HD-MORBs).

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 and Cretaceous-Tertiary sediments on Baffin Island and West Greenland; and
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 (Green and Falloon, 2015; Hastie et al., 2016).

2.6. Davis Strait picrite petrogenetic model

2.6.1. Constraints on melt generation

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 the Davis Strait picrites must explain as many as possible of the following features:

2.6.2. Physical

1. coast-parallel linear belts of volcanic rocks on both sides of Davis Strait, stretching NNW for 100–200 km parallel to the Baffin Bay spreading axis
2. giant cross-beds in hyaloclastite breccias on both sides of Davis Strait show seaward provenance, i.e. the magma source is offshore for Baffin Island and West Greenland
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

Table 2
Summary of principal geochemical features of Davis Strait picrites. Depleted mantle values compiled from Class and Goldstein (2005) and Salters and Stracke (2004).

Parameter	Trace-element depleted mantle	Extreme Davis Strait picrite	Davis Strait picrite mantle source	Reference
K_2O (wt%)	~0.09	0.01	strongly depleted	Clarke (1970); Francis (1985)
La (ppm)	2.67	0.7	strongly depleted	O'Nions and Clarke (1972)
$^{87}Sr/^{86}Sr_i$	0.7027	0.7028	depleted	O'Nions and Clarke (1972)
εNd_i	+9	+10	depleted	Graham et al. (1998)
$^{206}Pb/^{204}Pb$	18.28	18	depleted	Graham et al. (1998)
$^{187}Os/^{188}Os$	0.130	0.127	depleted	Dale et al. (2009)
$^{3}He/^{4}He$	50 R_A	49.5R_A	strongly depleted	Graham et al. (1998); Stuart et al. (2000)

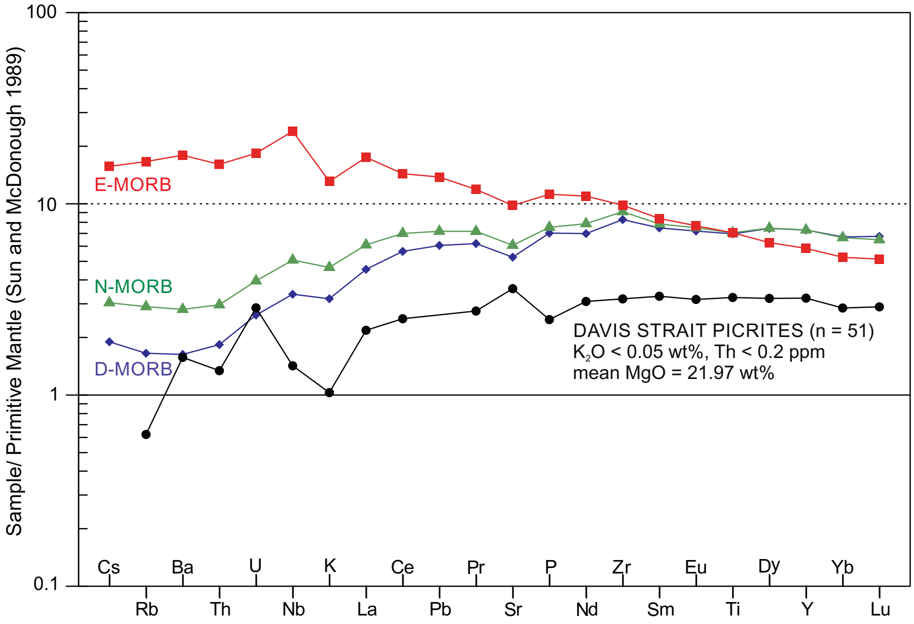


Fig. 5. Spider diagram comparing the 51 most depleted picrite samples from Baffin Island and West Greenland (Starkey et al., 2009) with the means for D-MORB (depleted mid-ocean ridge basalt), N-MORB (normal mid-ocean ridge basalt), and E-MORB (enriched mid-ocean ridge basalt) of Gale et al. (2013). The Davis Strait picrites are among the most depleted basaltic rocks on Earth. The erratic behaviour of the most incompatible elements may be the result of contamination (Larsen and Pedersen, 2009a), where the crustal concentrations of these elements can be one or two orders of magnitude greater than those in the picritic magmas.

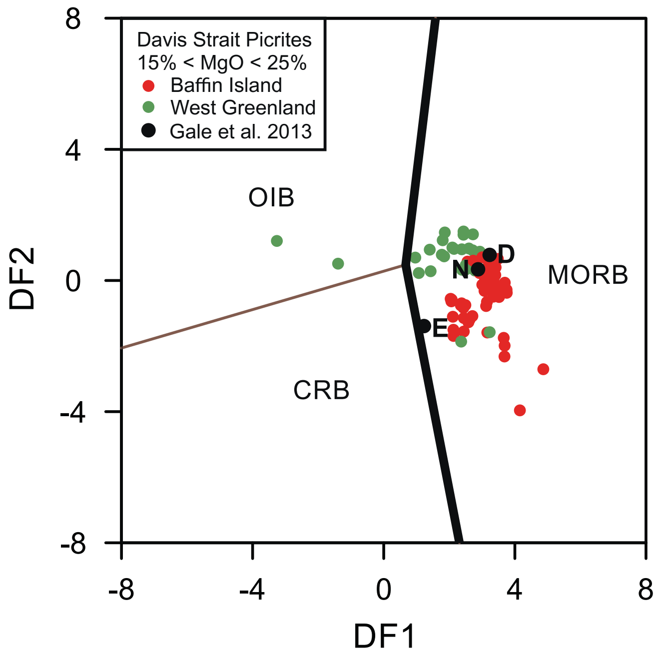


Fig. 6. Tectono-magmatic indicator diagram that applies discriminant function analysis to La-Sm-Yb-Nb-Th concentrations (Agrawal et al., 2008). The bold boundary separates unlikely plume-related MORBs from possible plume-related within-plate basalts. Sources of data: Baffin Island (Starkey et al., 2009); West Greenland (Larsen and Pedersen, 2009a). DF1 and DF2 are the two main discriminant functions, CRB is continental rift basalt, OIB is oceanic island basalt, and the D-, N-, and E-MORB are the depleted-, normal-, and enriched-mid-ocean ridge basalt means, respectively, from Gale et al. (2013).

basalts occur only in West Greenland and in Davis Strait

5. the southern terminus of the picritic rocks is spatially related to the Baffin Bay spreading centre-Ungava transform fault PTS (Oakey and Chalmers, 2012), or to the change in orientation of the plate boundary (Hosseinpour et al., 2013)
6. the southern margin of picrite belt is closely related to Nagssugtoqidian suture
7. seismic tomography indicates 200–240 km thick lithosphere prior to thinning (Darbyshire and Eaton, 2010; and Darbyshire et al., 2013; Tappe et al., 2012)
8. Paleoproterozoic sutures may control Mesozoic rifting (Corrigan et al., 2009; Eglington et al., 2013; St-Onge et al., 2009; Van Gool et al., 2002)

2.6.3. *Chemical*

1. high MgO concentrations in picrites indicate rapid ascent of primary picrite magmas from ~100 km depth (Clarke, 1970; Falloon et al., 2007; Francis, 1985)
2. extreme isotopic compositions of picrites also indicative of an ancient LILE-depleted peridotite source mantle
3. HFSE tectono-magmatic designation of the Davis Strait picrites as MORB compositions
4. ultra-depleted incompatible trace elements in the picrites suggests a depleted, relatively refractory, and relatively buoyant source
5. peridotite nodules in regional Phanerozoic lamprophyres and kimberlites are variably depleted in major elements (Sand et al., 2009; Tappe et al., 2012; Wittig et al., 2008)

2.6.4. *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

2.6.5. *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; Natland, 2008; 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 (Falloon et al., 2007). The results vary widely, ranging from 0 to 300 C° (e.g., Green and Falloon, 2005; Herzberg and O'Hara, 2002; Hole and Millett, 2016). 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, 2009b). The real problem is that the picrites (Davis Strait, British Paleocene Igneous Province (BPIP)), and presumed associated high temperatures, are out on the presumably cooler periphery of any 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 adiabatic decompression melting at high pressures, and rapid ascent of the melts from those high pressures (Clarke, 1970, Falloon et al., 2007, Francis, 1985, Natland, 2008http://www.mantleplumes.org/Greenland.html). In this matter of rapid rate of ascent, the Davis Strait picrites are similar to two other olivine-rich igneous rocks, namely komatiites (Huppert and Sparks, 1985) and kimberlites (Peslier et al., 2008). If we place the focus on the pressure of melting, rather than on the temperature, deduced pressures range from 3 GPa (Clarke, 1970; Falloon et al., 2007) to 3.8–4.7 GPa (Herzberg and O'Hara (2002) to 2.8–3.5 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).

Figure 7 shows 32 Davis Strait picrites with $18 < \text{MgO} < 22$ 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 adiabatic decompression of the asthenosphere is an acceptable mechanism for producing conventional MORBs, then more rapid adiabatic decompression 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), Falloon et al. (2007), and Herzberg and Asimow (2008, 2015). Furthermore, we are in full agreement with the following two insightful statements concerning the composition and origin of the picritic magmas. "The West Greenland picrites are extremely primitive, with a source more depleted in incompatible element systematics and radiogenic isotope rations than in any other post-Archean CFB province." (Holm et al., 1992); and "Therefore, it is proposed that before the onset of magmatism on Baffin Island, the lithosphere was already significantly thinned, allowing for extensive decompression melting." (Hole and Millett, 2016). We expand on the petrogenetic and tectonic implications below.

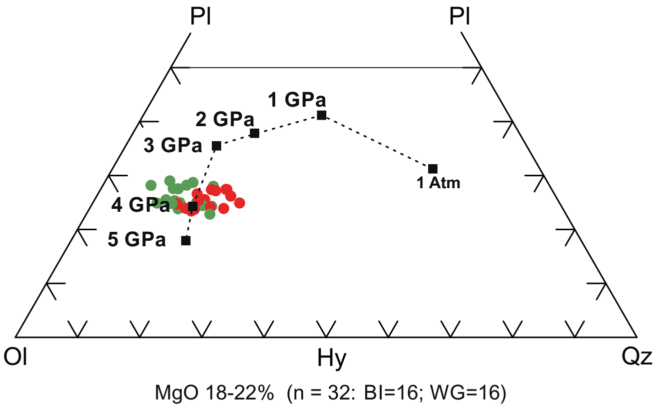


Fig. 7. CMAS projection of 32 picrites with $18 < \text{MgO} < 22$ wt% (Larsen and Pedersen, 2009a; Robillard et al., 1992; Starkey et al., 2009) into the plane Ol-Pl-Qz (after Herzberg and O'Hara, 1998) showing the positions of the experimentally-determined pressure-dependent invariant points (in GPa). The bulk chemical compositions of the picrites are similar to the melt compositions in equilibrium with mantle peridotite at pressures of ~ 4 GPa (120 km depth). Symbols: red – Baffin Island; green – West Greenland.

2.6.6. *Picrite petrogenetic statement*

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, as shown in Fig. 3) 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, 2009b). The enhanced extensional environment in the vicinity of the PTS permitted both the enhanced adiabatic decompression melting of the depleted buoyant SCLM and the open plumbing system to the surface required by a thick sequence of HD-MORB picrites. The source of the E-MORB picrites in Baffin Island (BI) and West Greenland (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, 2009b, and Larsen et al., 2016).

Constraints on the mantle source for the picritic magmas include: (i) Major-element composition fertile enough to produce picritic magma; (ii) Trace-element composition (especially LILEs) highly depleted; and (iii) Osmium isotopic composition recording an Archean depletion event. We choose to regard this source mantle as being the residuum of a *minor* melting event in the Archean that effectively stripped the LILEs, leaving a more refractory lherolitic or even harzburgitic residuum. If the Archean melting event in Davis Strait had left a harzburgitic residuum, a metasomatic or refertilization event might be required prior to the generation of the Paleocene picritic magmas. On the other hand, Wilson et al. (2003) appealed to the partial melting of a hydrated depleted refractory harzburgitic SCLM to produce the 3.3 Ga ultra-depleted Commondale komatiites in South Africa, wherein the introduction of water alone simply lowered the refractory mantle solidus. However, any such aqueous fluid is likely to carry LILEs and thus reduce the degree of strong depletion in subsequent partial melts, as suggested for some boninites (Smithies, 2002). Such a metasomatic event might also change the highly depleted isotopic ratios and upset the osmium model age.

"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 Ocean is no exception (Parana, CAMP, and 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.

We attach major petrogenetic significance to the close observed *spatial* relationship between the Davis Strait picrites and the Baffin Bay Ridge – Nagssugtoqidian Fold Belt RTI/transfer/accommodation zone. Beutel and Anderson (2007) used finite-element analysis to show that such plate tectonic singularities (PTS) can be sites of enhanced tensional forces and development of seamounts – two examples are the Mid-Atlantic Ridge-Atlantis ridge-transform intersection 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 and 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 can represent the products of partial melting of a depleted, buoyant, SCLM caused by enhanced pressure reduction at the Baffin Bay Ridge-Davis Strait PTS to produce relatively catastrophic (Presnall et al., 2002; Presnall, 2008www.mantleplumes.org/NoRidgePlumes.html;) 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.

2.7. Further arguments against a deep-mantle plume in Davis Strait

Mantle plumes can be designed to 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 et al., 2015). Instead of relying on a plume theory without any unequivocal evidence, we should be addressing the more challenging problem of using the reigning plate tectonics paradigm to try to explain each LIP. For the following reasons, we think 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 began erupting 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, as in the East African Rift, 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. If picrites indicate a very hot plume, regional uplift should be associated 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, arrived too conveniently in Davis Strait at precisely the time sea-floor spreading began in Labrador Sea.
5. The smaller Davis Strait member of a putative double plume is unlikely to have been hotter and faster and shorter in duration and bearing an interrupting discontinuity between 56 and 54 Ma, than the larger Iceland member (Gill et al., 1995).
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 (Fig. 6), but any MORBs are the most unlikely types of basalt to be associated with mantle plumes (Green and Falloon, 2015; Presnall, 2008).
9. 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 too low to make any plume hypothesis credible for production of the Davis Strait picrites.

In general, of all the existing plume models advanced for the Davis Strait picrites, at best only one can be correct; at worst, no plume model is correct, or even necessary. In this case, we prefer to explain the Davis Strait picrites purely in terms of tectonic processes.

3. Davis Strait tectonic setting

In this section, we describe the unique tectonic setting of the Davis Strait picrites and suggest that the generation and transport of the picritic magmas are intimately tied to the pre-existing Paleoproterozoic structures combined with the extension during break-up.

3.1. Paleoproterozoic assembly of North America and Greenland

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) (Corrigan et al., 2009; Eglington et al., 2013; Jackson and Berman, 2000; St-Onge et al., 2009; Van Gool et al., 2002). The result is that by 1750 Ma, these cratonic blocks had become integrated into Laurentia and remained together until the Mesozoic rifting began.

Given the age of the orogenies, the extent of ice cover, and the possible complexities, it is not surprising that some discrepancies in the mapped locations of the suture zones exists (Connelly and Thrane, 2005). However, basic reconstructions show that Greenland consists of the North American Craton to the south, a wide suture zone of reworked Archean craton (Nagssugtoqidian suture) in the middle, and the Rae juvenile Paleoproterozoic crust to the north (Corrigan et al., 2009; Eglington et al., 2013; Jackson and Berman, 2000; St-Onge et al., 2009; Van Gool et al., 2002).

3.2. Post-assembly tectonic history

After the assembly of North America, Greenland and North America moved as one cratonic unit for almost 2 billion years. During that time, the western margin of Greenland/North America remained relatively quiet with diamond-bearing kimberlites (at 1.2 Ga), and ultramafic lamprophyres and carbonatites (~600 Ma) being the only major magmatic events prior to the onset of extension at about 165 Ma (Engstrom and Klint, 2014; Tappe et al., 2008). The onset of continental extension at around 165 Ma was marked by the intrusion of numerous alkali volcanic events parallel to the Paleoproterozoic sutures that eventually became Labrador Sea (Fig. 1). Based on the geochemistry of the eruptives through time, Tappe et al. (2007) suggested that at least 30 km of SCLM was removed under the present day Labrador Sea prior to the onset of continental extension around 160 Ma. The alkali volcanics, including lamprophyres, had sources in the convecting asthenospheric mantle and erupted through depleted subcontinental mantle lithosphere during times of extension (Tappe et al., 2012).

In general terms, supercontinents break up along planes of greatest weakness in response to stresses applied to their bases (Wilson, 1961). Such is the case in modern rifts such as the East African Rift (Beutel et al., 2010; Daly and Chorowicz, 1989; Daoud et al., 2011), and in older rifts such as the Atlantic (Beutel, 2009; Buiter and Torsvik, 2014; Hansen et al., 2009; 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

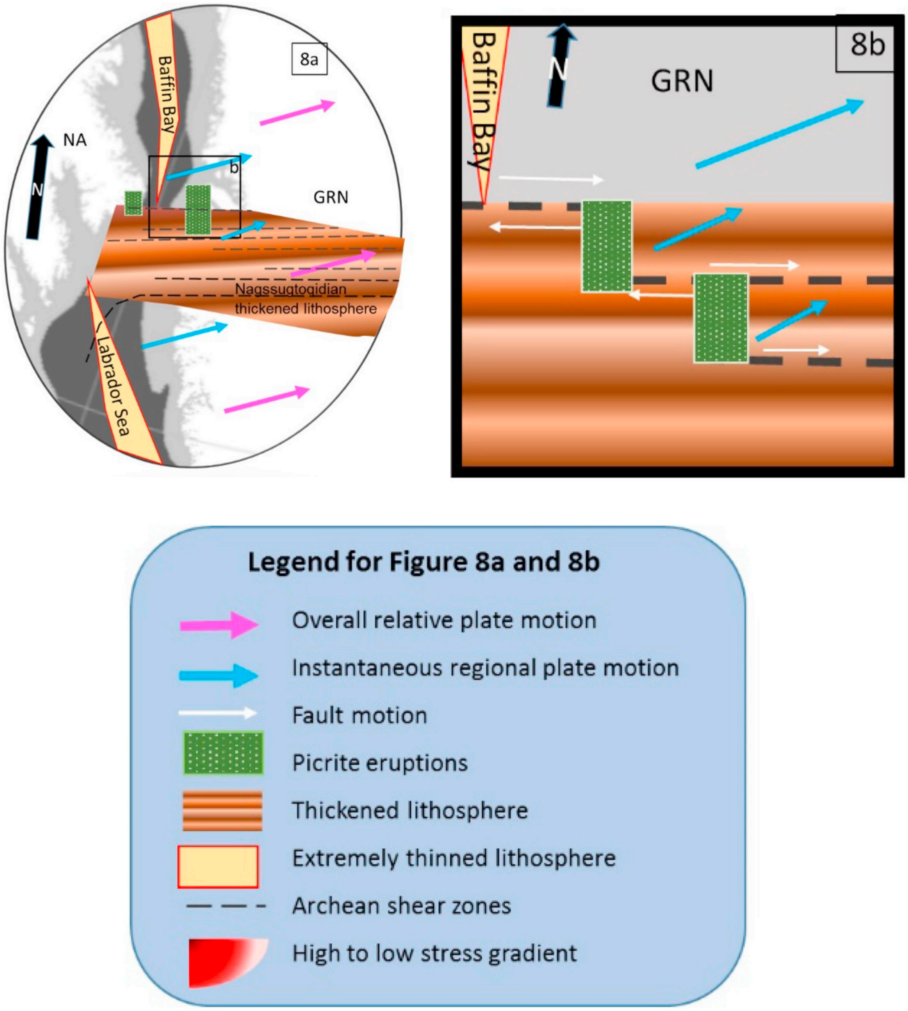


Fig. 8. Schematic representation of the proposed lithospheric-scale structures in the vicinity of Davis Strait at 63 Ma. The thickened lithosphere of the Nagssugtoqidian Fold Belt resists motion relative to the thinned lithosphere to the north and south. This differential motion is especially critical because of the pre-existing ~E-W sutures/zones of weakness that further result in strain partitioning and the formation of pull-apart basins. Fig. 8a: At 63 Ma the rifting in the Labrador Sea and Baffin Bay has localized along the incipient mid-ocean ridge systems, while the Nagssugtoqidian Fold Belt remains thick and strong because of the E-W lithospheric scale sutures and fabric (shown in the stereonets that measure the orientation of the dominant pre-Cenozoic fabric). The blue arrows indicate the relative instantaneous relative motion of Greenland that results from and in the differential thinning. The location and relative size of the observed picrite provinces are also shown. Fig. 8b: Once the lithosphere had been thinned to the point of mid-ocean ridge formation in Baffin Bay, all resistance to the separation of Greenland from North America would be focused along the intact Nagssugtoqidian and create the pull-apart basins along the suture zones.

spatial association of conjugate margin LIPs with mantle plumes is either non-committal (Buiter and Torsvik, 2014), or highly suspect (Julian et al., 2015). 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.

3.2.1. *State of the lithosphere at the time of the picrite eruption*

Recent work by Petersen and Schiffer (2016) determined that the thickness of the lithosphere in a suture zone affects the depth and timing of melting; thinner lithosphere concentrates stress rapidly and develops rifts prior to magmatism, whereas thicker lithosphere results in deep lithospheric melting and magmatism prior to oceanic spreading. Furthermore, 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; White et al., 1987; White and McKenzie, 1989, 1995). Thus, thick lithosphere and trans-tensional stress can cause deep melting of the lithosphere and may be the mechanism for generating melt from SCLM.

Prior to any stresses being applied to its base, the thickness of the SCLM is at its maximum (SCLMt$_{max}$). As extension increases, 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 must 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 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, suggesting erosion of the SCLM (Tappe et al., 2012).

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 use results from seismic tomography only along lines that are remote 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 lithosphere-asthenosphere boundary (LAB) located at depths of 225–240 km. 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 (Wittig et al., 2008). In that case, the Nagssugtoqidian Fold Belt is a significant impediment to rupture and rifting.

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 in LILE. Such depleted roots are relatively cold, positively buoyant, and mechanically strong (Darbyshire and Eaton, 2010). Furthermore, from geodynamic considerations, this part of Laurentia consists of three to 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. Tappe et al. (2012) also found evidence for erosion under the ~N-S weakness associated with the Torngat orogeny under the present-day Labrador Sea prior to the Cenozoic. This evidence suggests that the lithosphere was thinned under ~N-S zones of weakness, but not as much under the Nagssugtoqidian mobile belt in the Davis Strait region.

Fig. 8 shows that, in addition to differences in thickness, the Nagssugtoqidian mobile belt and the North Atlantic Craton and Rae Craton had different lithospheric-scale features (e.g., Keen et al., 2012; Peace et al., 2014, 2018; Wilson et al., 2006). According to Peace et al. (2018) and Wilson et al., (2006), the dominant fabric in the North Atlantic craton is variable and the only identifiable faults/fractures tend to run N-S; however, the dominant fabric in the Nagssugtoqidian Fold Belt is ~E-W. Thus, the sutures and tectonic fabrics south of Davis Strait and Nagssugtoqidian appear to be oriented dominantly parallel to the present day Baffin Bay/Labrador Sea (NNW) and the Paleoproterozoic Torngat Orogen, whereas the area around Davis Strait and the picrites is dominated by the Nagssugtoqidian orogenic belt and the ~E-W-oriented sutures and deformation (e.g. Bridgwater et al., 1990; Peace et al., 2014, 2018; St-Onge et al., 2009; Wilson et al., 2006) (Fig. 8). The complicated Nagssugtoqidian collision zone includes a mid-ocean ridge, a double subduction zone, and a micro-continent (e.g., Garde et al., 2002; Sanborn-Barrie et al., 2017). Multiple ~E-W suture zones, therefore, exist within the overall strongly ~E-W fabric of the Nagssugtoqidian (e.g., Døssing, 2011; Garde et al., 2002; Hollis et al., 2006; Klint et al., 2013; Wilson et al., 2006). Furthermore, Sanborn-Barrie et al. (2017) have identified Proterozoic shear motion parallel to the fabric, which was then reactivated in the Mesozoic (e.g., Peace et al., 2018; Wilson et al., 2006). The ~E-W fabric is so pervasive that it also appears in satellite images and in shear wave splitting of the region (Ucisik et al., 2008). Whereas the southern boundary of the Nagssugtoqidian is well documented, its northern boundary has long been inferred to lie somewhere under the volcanics of the Disko Bugt (Corrigan et al., 2009; Eglington et al., 2013; Jackson and Berman, 2000; St-Onge et al., 2009; Van Gool et al., 2002). However, recent work by Connelly and Thrane (2005) and Nicoli et al. (2018) has moved the boundary to just north of the picrite terranes where it merges with the ~E-W Rinkian fold belt (Fig. 8). North of the Rinkian fold belt there is little information available on the tectonic fabric of the Rae/Disko craton as it is covered by ice.

3.2.2. *Observed tectonics and deformation during rift initiation*

Prior to the Jurassic, Greenland and North America mostly moved as a single block, although periods of extension and trans-tension may have resulted in the emplacement of alkaline and kimberlite magmatism at ~1374 Ma, ~590 Ma and ~150 Ma (Tappe et al., 2007). Based on the geochemistry of the isolated magmatism between 150 Ma and 65 Ma, Tappe et al. (2007) proposed a change in the tectonics which may be related to the eventual break-up between North America and Greenland and the formation of the Labrador Sea spreading ridge. Specifically, Tappe et al. (2007) identified a bottom-up thinning of the lithosphere beneath the eventual Labrador Sea between 150 Ma and 100 Ma. This is the type of thinning predicted by Petersen and Schiffer (2016), who modelled thick craton-style lithosphere extending from the bottom up during extension versus thinner crust that was more likely to extend on the surface first. Wilson et al. (2006) documented surficial evidence for the extensional NE motion of Greenland relative to North America on NW- and N-trending faults along the west coast of Greenland. The age of onset of these motions is uncertain but it appears that they began in the Cretaceous and continued through the early Paleocene and the opening of the Labrador Sea. By 63 Ma, the Labrador Sea mid-ocean ridge spreading was propagating northward toward the southern boundary of the Nagssugtoqidian thickened crust of Davis Strait (e.g., Alsulami et al., 2015; Oakey and Chalmers, 2012). In the north, under Baffin Bay, mid-ocean ridge spreading began by around 62 Ma (e.g., Alsulami et al., 2015; Oakey and Chalmers, 2012), suggesting that MOR spreading was imminent or underway, similar to the Red Sea today. Davis Strait (and the Nagssugtoqidian Fold Belt) was a boundary between the two ocean basins that never underwent the level of extension needed for the formation of oceanic spreading (Artemieva and Thybo, 2008; Hosseinpour et al., 2013) (Fig. 1). The picrites were emplaced along the northern margin of the Nagssugtoqidian orogen and at the tip of the southward propagating Baffin Bay mid-ocean ridge at ~62 Ma (Larsen et al., 2016) (Figs. 1, 8).

3.2.3. *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 Petersen and Schiffer (2016) and illustrated at the surface by the kimberlites (Tappe et al., 2012). However, given the degree of total crustal thinning (and the lack of oceanic lithosphere), it is clear that the thickened area of Davis Strait and the Nagssugtoqidian mobile belt did not undergo as much extension as the adjacent Baffin Bay and Labrador Sea (Keen et al., 2012; Peace et al., 2014, 2018; Wilson et al., 2006).

Both Wilson et al. (2006) and Peace et al. (2018) noted that during the first phase of rifting it appeared that the relic ~E-W (ENE)-trending shear zones were reactivated in conjunction with new N—S— and NW-trending fractures. This reactivation reflects an ongoing strain partitioning caused by the oblique relative motion between North America and Greenland, and provides insight into the formation of the picritic lava flows. Given their short temporal duration, the picrites on Baffin Island and in the Disko Bugt area represent a geologically instantaneous response to short-lived stress situations. Fig. 8a illustrates the relative motions that resulted in the formation of the picrites, and Fig. 8b illustrates in more detail the proposed motion and results. At 63 Ma the Baffin Bay lithosphere thinned to the pre-MOR state, essentially making it a long narrow crack propagating toward the Nagssugtoqidian thickened lithosphere. Basic fracture mechanics states that stress is concentrated at crack tips, and the longer and narrower the crack, the greater the stress (e.g., Scholz et al., 1993). If a crack is propagating under a given stress, and if it is unable to continue propagating as a result of changing conditions in the lithology or stress relief mechanisms (Pollard and Aydin, 1984), extensional stresses will increase at the crack tip until either the crack propagates or some other stress relief develops. Because the Nagssugtoqidian was initially thicker and could accommodate the relative NE extensional stress through reactivation of the lithosphere scale suture zones, it did not thin and therefore was subject to intense extensional stress where the incipient Baffin Bay MOR crack propagated against the thickened lithosphere (Fig. 8b). The intense stresses would have two results: 1. increased melting at depth (e.g., Petersen and Schiffer, 2016); and 2. formation of lithospheric

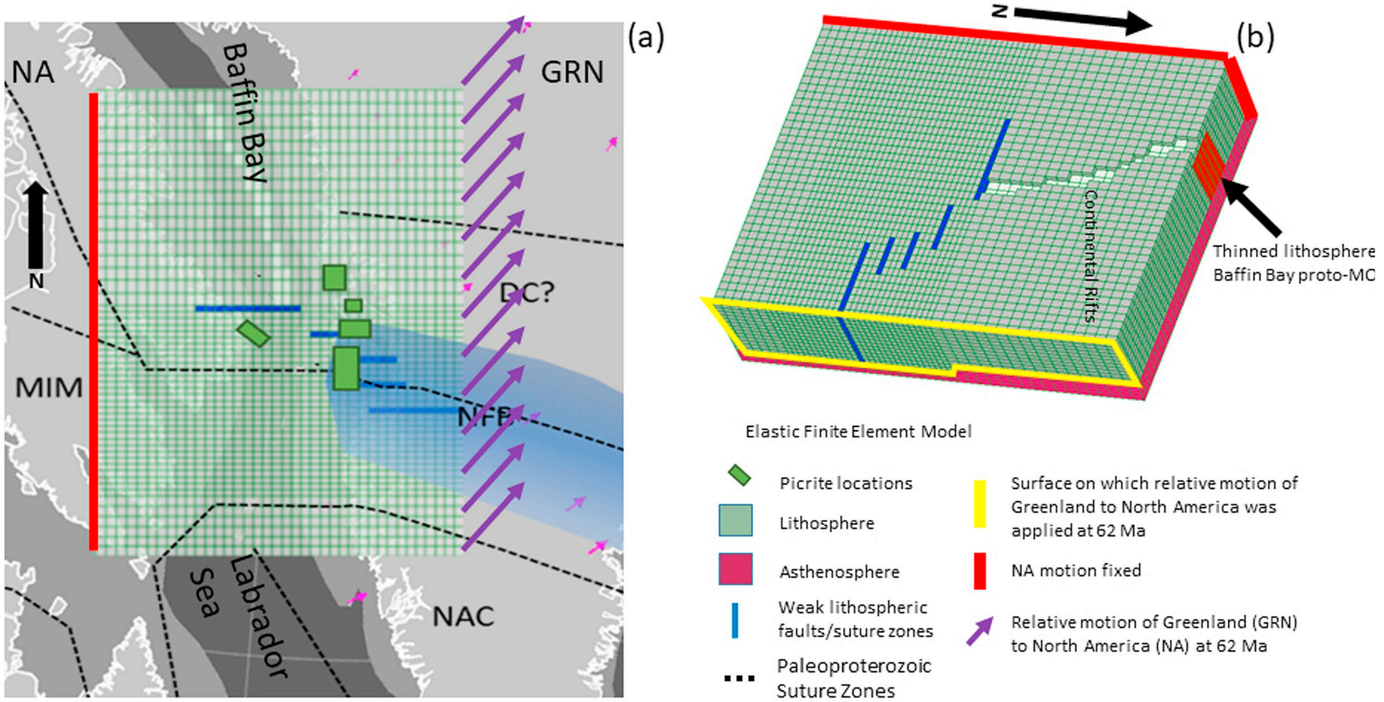


Fig. 9. Finite-element model. (a) Map view of 3-D finite-element model overlain on plate position at 62 Ma generated by Gplates (Scotese, 2016). Abbreviations as in Fig. 1. The green grid is the top of the 3-D model, and the size of each grid element varies between 8 km and 16 km. The grid has closer spacing and a change in anisotropy through the thickened section to approximate the change in tectonic fabric. The purple arrows indicate the relative motions between a fixed North America and a mobile Greenland at 62 Ma, based on Oakey and Chalmers (2012). (b) Three-dimensional view of the finite-element grid showing the missing/thinned crust at the surface and the variations in lithosphere thickness, based on present-day measurements and understanding of the formation of mid-ocean ridges (Artemieva and Thybo, 2008; Darbyshire et al., 2004; Lebedev et al., 2018; Tappe et al., 2006; Wittig et al., 2008).

scale trans-tensional structures (Lundin and Doré, 2018). As previously shown, the shear zones in the Nagssugtoqidian extend through the lithosphere as a whole, thus we propose the following sequence of events:

Step 1: Thinning of lithosphere under Baffin Bay, and reactivation of shear zones in Nagssugtoqidian orogenic belt.

Step 2: Baffin Bay thins dramatically making the Greenland lithosphere north of the Nagssugtoqidian move to the NE faster than the Greenland lithosphere adjacent to Davis Strait (intact Nagssugtoqidian).

Step 3: Dextral trans-tension concentrated along the ~E-W Nagssugtoqidian sutures in Davis Strait. Stress is greatest along the northern boundary where the plate motion stress is augmented by the crack tip that is the incipient Baffin Bay MOR.

Step 4: Because of the structure of the lithosphere and the dominance of the lithospheric scale ~E-W shear zones, the trans-tensional extension opens lithospheric-scale pull-apart structures within, or at discontinuities, particularly where there are overlaps or offsets of the shear zones. (Fig. 8b).

Step 5: The extensional pull-apart stress reaches into the lithosphere to depths of ~120 km or more resulting in the formation of melts at this depth. Within the Nagssugtoqidian, the lithosphere consists of highly depleted SCLM (subcontinental lithospheric mantle) at ~120 km that may or may not have already begun to melt.

Step 6: The melted SCLM then travels very rapidly to the surface along the trans-tensional features where it is erupted as picrites.

Step 7: After a relatively short period of massive picrite volcanism (~1 my), the base of the lithosphere erodes and convection brings more fertile asthenospheric mantle into the trans-tensional features to undergo more conventional adiabatic decompression melting, but the magma ascent rates are lower and feldspar-phyric flood basalts erupt.

The picrites are located only on the far eastern edge of Baffin Island and along the western portion of Greenland just north of Davis Strait (Fig. 1). They likely dominate the eastern portion of the southern tip of Baffin Bay, because the Nagssugtoqidian is dominant on the east and controls the deformation of Greenland, whereas on the western side of Baffin Bay the Meta Incognita terrane likely strongly influenced the deformation patterns. Whereas various options exist for the larger emplacement on the east side of the Davis Strait, including the much larger influence/presence of the Nagssugtoqidian in Greenland, it could also be the result of the westward drift (e.g. Cuffaro and Doglioni, 2007; Doglioni et al., 2015) of the lithosphere causing the melt to pool against Greenland's root before rising to the surface. However, the eruptive cycle is short and the plate motion is slow, and thus the distribution of picrites appears to be the result of the pre-existing features, rather than the motion of the lithosphere relative to the mantle. To the south of Davis Strait, the Labrador Sea rifting would encounter the Nagssugtoqidian where the sutures turn to the south (Fig. 1), which would not result in the same plate interaction or development of picrites.

In summary, Fig. 8 shows that there were likely two NNW-trending areas of thinned and extending crust to the north and south of Davis Strait which was under trans-tension at the time and, being more resistant to the NE motion of Greenland, had reactivated suture zones along its north and south boundaries. Essentially, the NW-trending suture zones were acting as cracks offset by a thickened and ~E-W faulted block. Whereas extensive thinning had occurred under the Labrador Sea and Baffin Bay for them to become proto-MORs, it did not occur in the thickened lithosphere of Davis Strait. Thus, when resistance to motion between North America and Greenland dropped significantly because of the development of the magmatic rifts, stress increased dramatically across the thickened lithosphere of Davis Strait.

4. Davis Strait finite-element structural model

4.1. Finite-element model parameters and methodology

To test whether it is viable to bring picritic partial melts rapidly to the surface, we constructed an elastic finite-element model of the likely configuration of tectonic elements around the 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 where stress is concentrated and its relative magnitude. Displacement can also be modelled but, without fluid flow, magma cannot be modelled. Instead, we use 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 a depth of at least 120 km.

We used the elastic finite-element modelling program LISA and constructed a three-dimensional grid that consists of solid elements of varying sizes connected by nodes that may or may not have stresses associated with them (Appendix A). Fig. 9 shows that 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 above (Døssing, 2011; Garde et al., 2002; Hollis et al., 2006; Klint et al., 2013; Wilson et al., 2006). Given the constraints of the modelling program, we determined that using E-W sutures rather than moderately trending ENE sutures would introduce fewer errors (angles of motion were adjusted accordingly). The relative motion of Greenland to a fixed North America was applied to the right side of the model. The relative location of the tectonic features was based on the GPlates reconstruction of the plate positions in conjunction with the information from Seton et al. (2012). Multiple tests were run of different scenarios to determine the effects of model constraints vs tectonic structures (Appendix A).

This model simply tests the scope and likelihood of large scale extensional stresses existing just before the formation of the Baffin Bay mid-ocean ridge. The Appendix shows the effect of different configuration of the model. Further research examining the possible configurations and their effect on the stress distribution would be helpful.

4.2. Finite-element model results and discussion

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 shear zones (Fig. 10). 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.

A detailed examination of the finite-element model reveals the following points:

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 to 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 difference in lithospheric thickness creates a difference in relative motion between the Rae Craton to the north and the Nagssugtoqidian mobile belt.
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 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 type of complicated structure was noted in the surface deformation in other parts of the Nagssugtoqidian Orogen and Fylla Bank (e.g., Døssing, 2011; Wilson et al., 2006).
5) Based on previous studies, the ~E-W suture zones and tectonics dominate in the area of the Nagssugtoqidian mobile belt e.g. (Døssing, 2011; Garde et al., 2002; Geoffroy et al., 2001; Hollis et al., 2006; Wilson et al., 2006).
6) Concentrated extensional stress resulting from 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, can exist at all depths in the elastic lithosphere.
7) As a result, 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 at the Davis Strait-Baffin Bay intersection.

Our finite-element model for Davis Strait is not a unique solution for generating and bringing picrites to the surface, but it does illustrate that:

1) in thick cratonic lithosphere, stresses reach to the depth of the elastic lithosphere, which can be up to 200–250 km thick (Tesauro et al., 2015);
2) those tensional stresses can result in adiabatic decompression melting at those depths; and
3) inherited tectonic structures exert strong control on deformation and magma ascent rates (Petersen and Schiffer, 2016; Tappe et al., 2018).

Under these conditions, magmatism is solely a product of plate interaction, and no mantle plume is necessary to bring deep/hot melts to the surface in thick lithosphere.

5. Broader implications

Our plate tectonic model for the origin for the picrites of Davis Strait picrites has implications beyond just the picrites in Davis Strait, in particular for the overlying feldspar-phyric flood basalts, and the dubious status of NAIP as a single plume-generated LIP.

5.1. Origin of the overlying feldspar-phyric flood basalts in West Greenland

The mirror-like symmetry involving the sedimentary and picritic sequences in Baffin Island and West Greenland stands in stark contrast to the total asymmetry involving the overlying feldspar-phyric flood basalts in West Greenland (Fig. 2). These flood basalts are typical olivine-poor

E-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 occurred in East Greenland (Skaergaard) and in the BPIP (Rhum). Our principal objective in this paper has been to explain the origin of the Davis Strait picrites, but two major questions

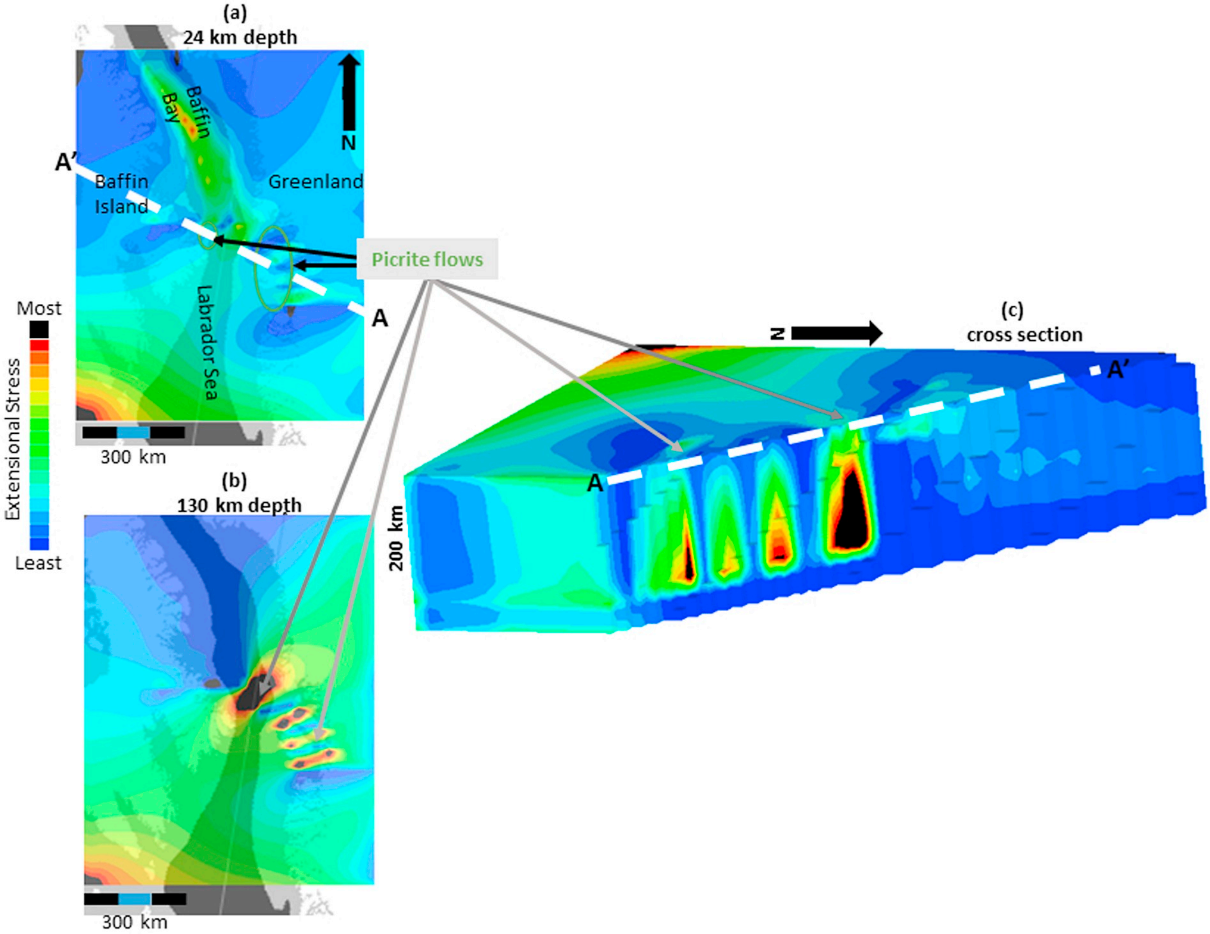


Fig. 10. Finite-element results, presented as extensional principal stress concentrations. Black is the greatest extensional stress concentration; blue is a result of the overall stress state, most of the stresses are extensional. The few compressive stresses are 60 times smaller than the larger extensional stresses, and do not appear in these images. (a) Stress pattern at 24 km depth. (b) Stress pattern at 130 km depth. (c) Cross-section through the picrite occurrences on Baffin Island and West Greenland showing distribution of extensional stresses and possibility of generating picritic primary magmas by adiabatic decompression melting at depths of 120–150 km.

concern the origin of these overlying flood basalts (Fig. 11). 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?

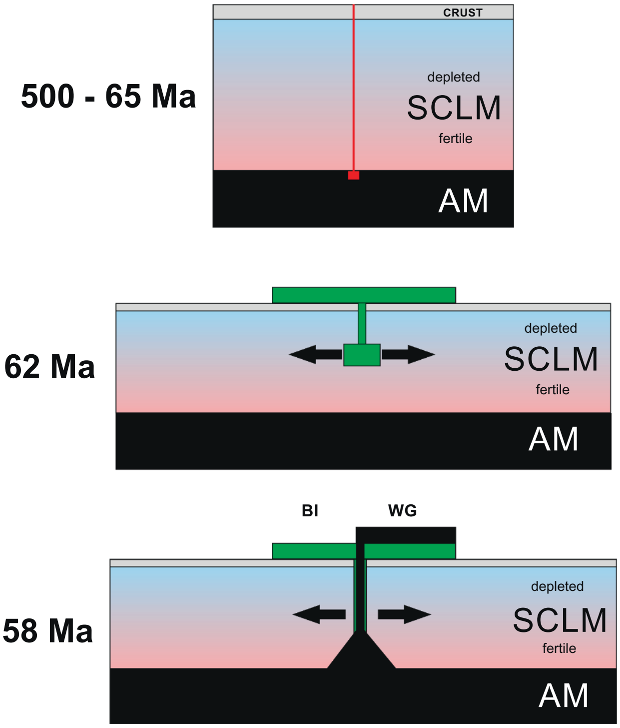
Larsen and Pedersen (2009a) offered an answer to the first question, namely “The change midway in the volcanic succession from picrites to basalts is seen throughout the volcanic province from Disko to Svartenhuk Halvø. The sudden establishment of long-lived magma chambers must be due to a change in the regional plate-tectonic conditions.” We agree, and add that, if the relatively minor change from picrites to flood basalts is attributable to regional plate conditions and restriction of the picrite plumbing pathway, the relatively major change from volcanically inactive to volcanically active conditions at 62 Ma may also be plate-related.

The change from rapidly erupted picrites to flood basalts equilibrated to low pressures in shallow magma chambers occurred after seafloor spreading had been established in Labrador Sea and Baffin Bay, and the Ungava transform fault had formed between the two. If correct, this new plate configuration would effectively decrease the stress between North America and Greenland and cause a change in the relative motion of Greenland. These new plate vectors would change the stress state that had allowed for the creation of the deep extensional stresses that had so readily tapped the picrites. Furthermore, the paucity of picrites and kimberlites world-wide suggests that deep conduits to the SCLM are not common or 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. The flood basalts reached only as far as what is now the offshore Baffin Island part of Davis Strait (MacLean et al., 1978). Alternatively, there was an inherent asymmetry in this E-W spreading system (Chalot-Prat et al., 2017).

5.2. Davis Strait BLIP and NAIP

The Davis Strait picrites have few physical, chemical, or temporal similarities to volcanic sequences in East Greenland, where the early Tertiary volcanic rocks bear a similar positional relationship to the thick Nagssugtoqidian Fold Belt as they do in Davis Strait, or indeed anywhere else in the North Atlantic region. In our view, the picrites of the Davis Strait BLIP are the products of the unique plate tectonic conditions that prevailed in Davis Strait, only, at 62 Ma, and thus there is no reason to seek any parallels in the development of other volcanic rocks in the North Atlantic region (e.g., Storey et al., 2007). If the Davis Strait picrites are exclusively the products of local plate tectonics, the westernmost influence of the hypothetical Iceland plume and its volcanic products (collectively known as NAIP) must be East Greenland; but perhaps there is no plume in Iceland either (Foulger, 2007; Foulger et al., 2005; Kent et al., 2004), in which case all North Atlantic volcanic rocks are the products of plate tectonics.



thick CRUST and SCLM
beginning of lithospheric thinning
minor episodic partial melting of AM
to produce small-volume alkaline
kimberlites, carbonatites, lamprophyres.

thinner CRUST and SCLM
moment of brittle rupture of upper SCLM
one-time rapid decompression causes
partial melting in depleted SCLM
open conduit permits rapid ascent of melt
HD-MORB picrites erupted at surface

change in plate motion
plumbing system becomes clogged
AM ascends into space created by
diverging plates and undergoes normal
adiabatic decompression melting
E-MORB feldspar-phyric flood basalts
erupted at surface

Fig. 11. Summary of the three main phases of magmatism in Labrador Sea – Davis Strait: small-volume alkaline magmatism 500–65 my ago, picrite magmatism 62 my ago; and feldspar-phyric flood basalts 58 my ago. (SCLM - subcontinental lithospheric mantle; AM – asthenospheric mantle).

6. Summary and Conclusions

The eruption of large volumes of picrites in Davis Strait was an unusual and significant magmatic event, strongly restricted in composition, time, and space. In contrast to the many mantle plume models for the origin of these picrites, we conclude that these picrites are entirely the products of plate-tectonic interaction. We base this conclusion on three well-established petrogenetic principles:

1. the picrites have major-element compositions consistent with being primary magmas generated at a pressure of ~4 GPa (depths of ~ 125 km);
2. the picrites are highly depleted, HD-MORBs, and must have a source in an LILE- depleted, somewhat refractory, relatively buoyant, subcontinental lithospheric mantle (SCLM); and
3. the picritic magmas needed an open pathway to ascend rapidly to prevent polybaric fractional crystallization of olivine and preserve their primary magma compositions;

and three well-established tectonic 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; and
3. such enhanced extension may lead to catastrophic fracture, resulting in extensive adiabatic decompression melting, even in an LILE-depleted and somewhat refractory SCLM.

Our finite-element model shows that the intersection of the propagating oceanic rifts with the thickened and multiply sutured Nagssugtoqidian Fold Belt can create the trans-tensional deformation capable of bringing primary magmas rapidly to the surface.

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. Finally, there is little or no connection between Davis Strait volcanism and volcanism in East Greenland and regions farther east, i.e., there is no single plume-related magmatic entity called NAIP.

Acknowledgements

In 1963, J. Tuzo Wilson published his seminal Hawaii hotspot paper as he was undergoing his own personal transformation from believing in an expanding Earth to formulating what shortly thereafter became known as plate tectonics. He also had many other ideas, not least of which was conjecturing that basaltic rocks on southeastern-most 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). Then, in rapid succession, Wilson published “A new Class of Faults and their Bearing on Continental Drift” (Wilson, 1965) and “Did the Atlantic close and then re-open?” (Wilson, 1966). Although he could not have guessed in 1964 that, in along the shores of Davis Strait, he was standing on both a transform fault and another example of closing and re-opening along ancient sutures, we are pleased to provide additional evidence for these brilliant ideas in this paper. In recognition of his enormous contributions, we dedicate this paper to the memory of Tuzo Wilson, the Canadian father of the plate tectonic revolution.

In addition we would like to thank Marie-Claude Williamson and James Natland for their helpful comments on an earlier draft of this paper, Alexander Peace for generously sharing ideas about Davis Strait, Sebastian Tappe for his support and excellent advice, an anonymous reviewer and Tony Doré for their thoughtful reviews of the official manuscript, Carlo Doglioni for editorial handling, and Gillian Foulger for her support and willingness to include this contribution in the North Atlantic Working Group.

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Declarations of interest

None.

Appendix

Definitions and equations

The 3-D model consists of solid elements with applied forces and displacements. Parameters input into the finite-element program include:

Table A1
Finite Element Variables.

	Symbol	Range of Values	Applied to:
Young's Modulus	E	$1e + 10^3$ Pa to $6e + 10^{10}$ Pa	Elements
Density	ρ	2700–3300 kg/m3	
Poisson's Ratio	ν	0.20–0.27	
Displacement	x,y,z	0	Nodes
Force	x,y,z	2900 Pa, 2900 Pa, 0 Pa	

The generalized equation used by the finite-element program LISA (https://lisafea.com/) is:

$$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \sigma_z\\ \tau_{xy}\\ \tau_{yz}\\ \tau_{xz}\end{bmatrix} = \frac{E}{(1+v)(1-2v)}\begin{bmatrix}1-v & v & v & 0 & 0 & 0\\ v & 1-v & v & 0 & 0 & 0\\ v & v & 1-v & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1-2v}{2} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1-2v}{2} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1-2v}{2}\end{bmatrix}\begin{bmatrix}\epsilon_x\\ \epsilon_y\\ \epsilon_z\\ \gamma_{xy}\\ \gamma_{yz}\\ \gamma_{zx}\end{bmatrix}$$

Stress	Rock Properties (Elements)	Strain

$$\begin{bmatrix}\epsilon_x\\ \epsilon_y\\ \epsilon_z\\ \gamma_{xy}\\ \gamma_{yz}\\ \gamma_{zx}\end{bmatrix} = \begin{bmatrix}\frac{\delta u}{\delta x}\\ \frac{\delta v}{\delta y}\\ \frac{\delta w}{\delta z}\\ \frac{\delta u}{\delta y}+\frac{\delta v}{\delta x}\\ \frac{\delta v}{\delta z}+\frac{\delta w}{\delta y}\\ \frac{\delta u}{\delta z}+\frac{\delta w}{\delta x}\end{bmatrix}$$

Strain	Motion of nodes

The node variables input by the user are (Fig. A1a): displacement, force, and degree of freedom (DOF). The element variables input by the user are: Young's Modulus (E), Poisson's Ratio (ν), Density (ρ), and Thermal Expansion Coefficient (however, none of our models used heat). Displacement of the node in the u,v,w space determines the strain (Fig. A1b), and that strain determines the stress for that element and the stress on the next element. Essentially, the program solves for Hooke's Law in three dimensions.

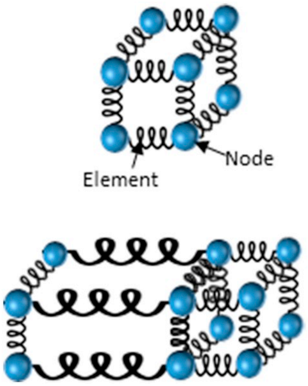

Fig. A1. Finite Elements. (a) Initial configuration, identifying elements and nodes. (b) Subsequent configuration, after displacement of four nodes.

Methods

We assume that the original elastic lithospheric thickness for Nagssugtoqidian mobile belt is between 150 and 250 km (Tesauro et al., 2015, see earlier Fig. 1), with an elastic strength between 10^9 and 10^7 Pa (Tesauro 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 (Fig. 9). The entire model was underlain by asthenosphere, which, in the absence of a viscous element, was modelled as extremely weak with an elastic constant of 10^3 Pa. The applied stress was based on the orientation of the relative motion between a fixed North America and Greenland at 63 Ma, according to Oakey and Chalmers (2012). The magnitude of the stress is relatively small as a result of the short-time scale we are considering but, as the model indicates only relative stresses, the stress magnitude does not have an impact on our output. The overall model has a depth of 200 km with lithosphere thickness varying between ~170 km and ~24 km.

This is a simple model with no variation in density or strength within the lithosphere aside from the suture zones. We have not modelled lithospheric variations in composition, because small-size variations (10s of km) can have profound impacts, and there is not enough information to accurately model all the lithosphere at this scale. Below are the modelling results from changing densities and strengths on a large scale. Note that the relative stress distribution intensity and orientation does not change (scale is the same for all images).

Results of changing variables

Below are several models that show how changing the variables in the model affect the distribution of stresses. The overall effect of the weak suture zones remains the same.

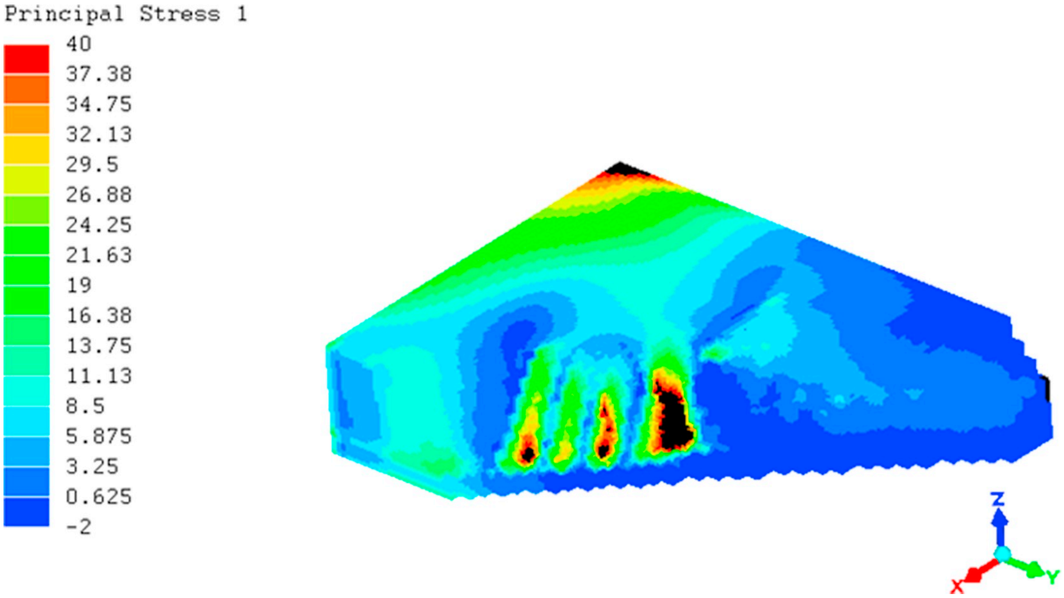

Fig. A2. Relative intensity of extensional stress when the Poisson's ratio for the weaker elements (asthenosphere and sutures) was increased from 0.20 to 0.27.

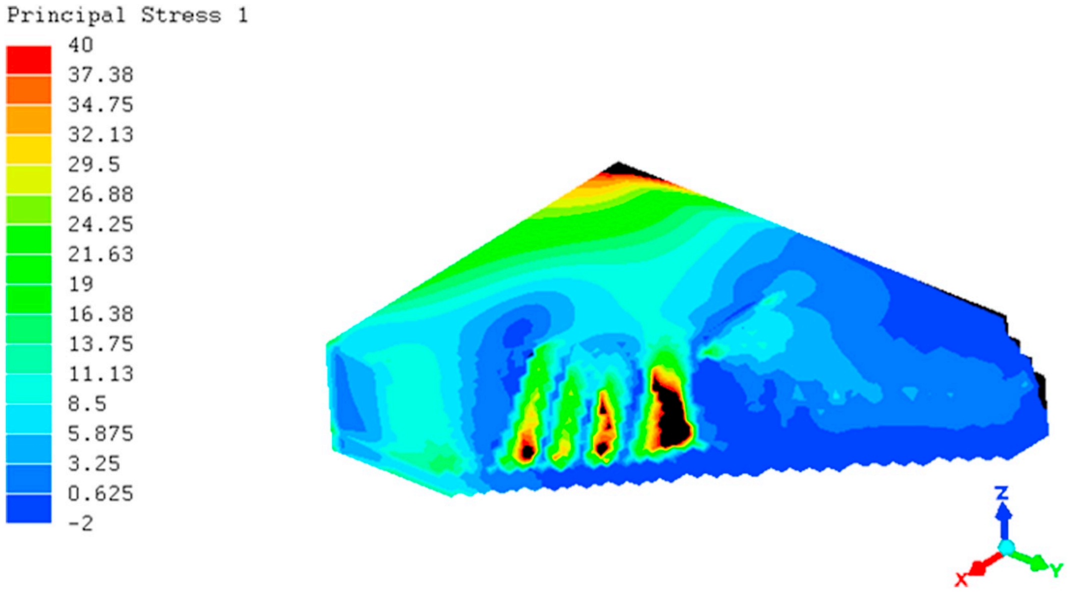

Fig. A3. Relative intensity of extensional stress when the Poisson's ratio was increased from 0.20 to 0.27 for all elements.

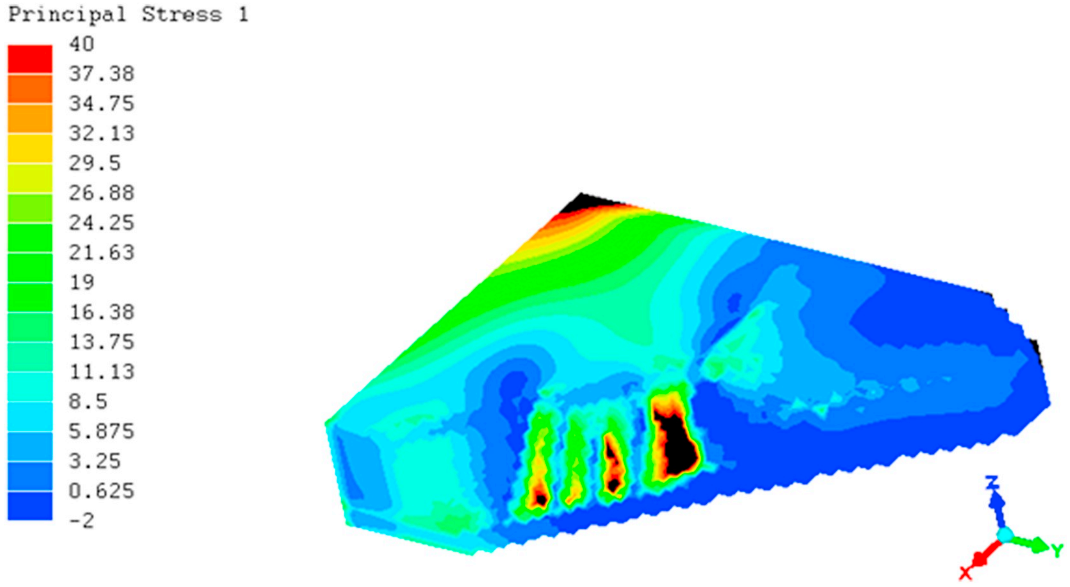

Fig. A4. Relative intensity of extensional stress when a weak layer crustal is added under Davis Strait.

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