West Greenland was hot – how else can you make 22,000 km^3 of picrites?

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Introduction

The controversy regarding the temperatures of formation of the Paleocene volcanic succession in West Greenland and Baffin Island has just celebrated its 50 years' anniversary (*Drever & Johnston*, 1957; *Clarke*, 1970; *Hart & Davis*, 1978; *Clarke & O'Hara*, 1979; *Elthon & Ridley*, 1979; *Francis*, 1985; *Larsen & Pedersen*, 2000). Most recently, *Natland* (2008) has called the high temperatures calculated for West Greenland into doubt and also presented an alternative model for the formation of the picrites.

Our contribution consists of two parts. First, we attempt to clarify some features of the West Greenland volcanic succession that have not generally been appreciated or have been misinterpreted. Second, we comment directly on some aspects of Natland's paper.

Facts about West Greenland

Extent and volume

The Paleocene volcanic succession in West Greenland extends from south of Disko to north of Svartenhuk Halvø (Figure 1). It consists of two parts, a lower part consisting dominantly of picrites, and an upper part consisting of basalts (*Clarke & Pedersen*, 1976). The picrites have been formalised as the Vaigat Formation whereas the basalt succession has been named variously in different parts of the region. The volcanic areas can be inscribed within an ellipse with a long (N–S) diameter of 430 km and a short (W–E) diameter of 200 km, giving a total area of 68,000 km^2. There are enough lavas known in the offshore areas and as erosion remnants in the eastern basement areas to be sure that most of this area was once covered with volcanic rocks. The picrites are less extensive than the basalts and occur from central Disko to Svartenhuk Halvø. The areas with picrites can be inscribed within a smaller ellipse with a long (N–S) diameter of 250 km and a short (W–E) diameter of 110 km, giving a total area of 22,000 km^2. The two ellipses are remarkably concentric (Figure 1).

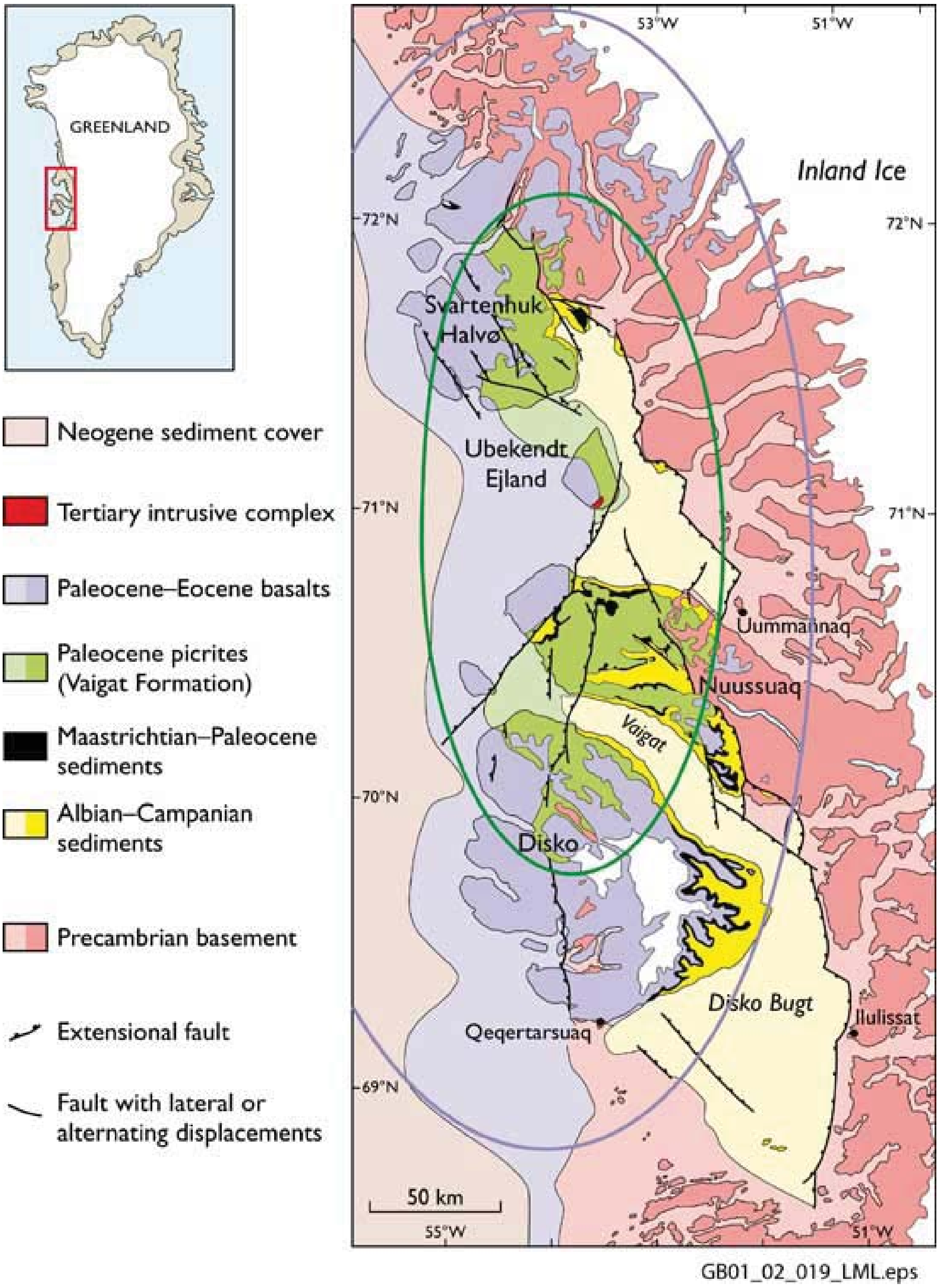

Figure 1. The West Greenland Tertiary volcanic province. The purple ellipse circumscribes the basalt areas and the green ellipse circumscribes the picrite areas (the Vaigat Formation).

Thicknesses given in the following are our data for Disko and Nuussuaq, from *Drever* (1958) and *Larsen* (1977) for Ubekendt Ejland, and from *Larsen & Pulvertaft* (2000) for Svartenhuk Halvø. The thickness of the *basalt succession* varies from maxima of 2,000 m on Disko, 3,000–4,000 m on Ubekendt Ejland, and 2,000 m on Svartenhuk Halvø to considerably less (a few hundred metres) in the eroded areas where only remnants are left. We consider an average thickness of 1,000 m a workable figure for the basalts. The thickness of the *picrite succession* (the Vaigat Formation) increases from the peripheral areas to the central areas of the ellipse in Figure 1. It is about 900 m in central Disko, eastern Nuussuaq and northern Svartenhuk Halvø, 1,000–1,500 m in northern Disko, central Nuussuaq and central Svartenhuk Halvø, 1,500 m in western Nuussuaq (erosion-corrected to 2,500 m), 4–4.5 km in southern Svartenhuk Halvø, and more than 5 km on Ubekendt Ejland. On Ubekendt Ejland, moreover, the lower part of the Vaigat Formation is below sea level. An average thickness is thus uncertain, but we consider that 1,000 m for the whole picrite ellipse in Figure 1 is a very conservative estimate. These thicknesses lead to estimated volumes of 22,000 km^3 of erupted picrites and 68,000 km^3 of erupted basalt. West Greenland is thus not a very large LIP (Large Igneous Province), but about one third of the erupted volume consists of picrites. This does not even take into account that picrites contemporaneous with those in West Greenland were also erupted in the Cape Dyer area on Baffin Island. Similar volumes of picrite are to our knowledge only reported from the Karoo LIP (the Letaba Formation of *Bristow*, 1984). This situation is quite different from other flood basalt successions such as Deccan or Gorgona where picrites occur but only form a very subordinate part of the erupted lavas.

Lithologies in the Vaigat Formation

During the emplacement of the Vaigat Formation some magma batches stalled in high-level magma chambers in the 6–8 km thick sedimentary packet and became contaminated. The contaminated volcanic rocks form some well-defined separate units consisting mainly of siliceous magnesian basalts, Mg-poor picrites and magnesian basaltic andesites but also magnesian andesites, sometimes with graphite or native iron formed by reduction processes due to reaction with organic-rich sediments. Their chemical and isotopic compositions make them easily distinguishable from uncontaminated rocks. Such contaminated rocks constitute 4–5% of the total volume of the Vaigat Formation in the Disko-Nuussuaq area and about the same amount in Svartenhuk Halvø; on Ubekendt Ejland such rocks are either absent or very inconspicuous in the exposed part of the formation. All rocks in the Vaigat Formation that are more evolved than basalt have acquired their composition by contamination processes and not by normal crystal fractionation.

The remaining 95% or more of the Vaigat Formation consist of uncontaminated picrites and basalts. After detailed mapping in Disko and Nuussuaq we now have a complete stratigraphy for that area and coverage of all stratigraphic units with samples and chemical analyses. We can therefore make quantitative statements about the constitution of the Vaigat Formation in that area. Ubekendt Ejland and Svartenhuk Halvø have been mapped earlier (by other teams), and the analytical coverage there is sufficient for general statements but not for the same degree of quantification as on Disko and Nuussuaq.

Uncontaminated rock compositions vary along olivine control lines with large variations in MgO. In Disko and Nuussuaq the total variation is 6.5–30.8 wt% MgO. The rocks (lava flows and pillow breccias) were sampled in profiles and samples were intended to be representative (olivine-rich accumulation zones in lava flows were generally avoided). We found that the amount of basalt (MgO<12 wt%) is subordinate, and the amount of basalt with MgO<8 wt% is very small and confined to a few minor units near the bottom, middle and top of the formation. The calculated volume-weighted average for our analyses of the uncontaminated Vaigat Formation is 16.6 wt% MgO (482 samples). Ubekendt Ejland and Svartenhuk Halvø are also dominated by picritic lithologies and the averages there cannot be much different from that for Disko and Nuussuaq. The Vaigat Formation is thus truly picritic.

Petrography of the picrites

Picrite lavas have phenocrysts of olivine with chromite inclusions and groundmasses of olivine, plagioclase, clinopyroxene, and Fe-Ti oxides. Many picrite lava flows were erupted subaerially and subsequently flowed into the sea or a large lake where they were quenched to pillow breccias. The pillows have well preserved glass rinds, and therefore the mineral assemblage at the stage of quenching is very well known. The pillow rinds consist of fresh yellow glass and up to about one third olivine crystals with chromite inclusions; small euhedral chromites also occur in the glass. The olivines range from equant euhedral crystals to very elongate hopper morphologies which in some cases constitute a significant proportion of the olivine. In some cases tiny plagioclase microlites formed in the melt immediately prior to quenching to glass. Picrites and magnesian basalts with more than 8 wt% MgO do not have either plagioclase or clinopyroxene phenocrysts or microphenocrysts in the glass. The rare plagioclase-phyric basalts do have plagioclase phenocrysts and a few clinopyroxene microphenocrysts in the pillow glasses. We have not observed kink-banded olivines except for rare crystals that are deformed and cracked during flowage of the lava. More descriptions and photographs are given in *Larsen & Pedersen* (2000).

The olivines range in composition from Mg# 77.4 to 93.3 (Fo% 76.6–92.4). The crystals are normally zoned, also the elongate, skeletal hopper crystals, and the crystal rims are in equilibrium with the surrounding glass. The major part of the olivine population has compositions in the interval Fo 84–90 and only a small part of the crystals have Fo 90–92.5; however such Mg-rich compositions are found in most of the microprobed picrite samples. The olivine crystals contain glass inclusions and have high contents of Ca (0.25–0.45 wt% CaO) and Cr (0.03–0.18 wt% Cr_2O_3), indicating beyond doubt that they crystallised from a melt; they are not metamorphic olivines.

Mineral evidence for high temperatures

Chromium in olivine

A plot of Cr_2O_3 *vs.* Fo in olivine is shown in Figure 2. It is very rare to find such high chromium contents in olivine; according to *Li et al.* (1995) the vast majority of olivines from magnesian basaltic magmas contain < 0.02 wt% Cr_2O_3. These authors stated that high Cr_2O_3 (>0.1 wt% Cr_2O_3) in terrestrial olivines is only found in komatiites, olivine inclusions in diamonds, some very high temperature peridotite xenoliths, and olivine in some ultramafic pseudotachylites (*Li et al.*, 1995, p. 126). They concluded that "temperature plays an enormously important part in the stability of Cr^{2+} in olivine at terrestrial oxygen fugacity conditions." *Li et al.* (1995) constructed a diagram of isopleths of Cr in olivine *vs.* temperature which is shown here as Figure 3. The magmas of the Vaigat Formation were not particularly reduced (*Larsen & Pedersen*, 2000) and at high temperatures were close to the FMQ buffer. The high-Mg olivines (with Fo % >90) have Cr_2O_3=0.10–0.18 wt%, corresponding to XCr-in-olivine=0.001–0.0018, and therefore crystallised at temperatures of more than 1740°K, i.e., 1467°C. This temperature is in accordance with our backtrack calculations (*Larsen & Pedersen,* 2000). The olivines with Fo %<90 have lower chromium contents (0.10–0.04 wt% Cr_2O_3) in compositional continuity with the high-Mg olivines; they crystallised at successively lower temperatures down to quenching at 1160–1218°C.

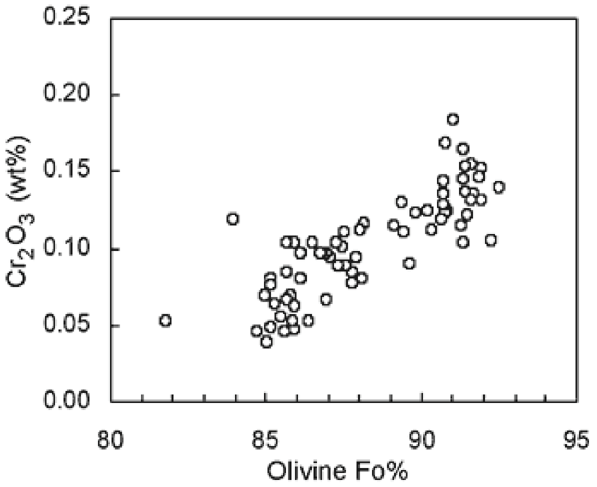

Figure 2. Chromium contents in the olivines from the Vaigat Formation, West Greenland. Data in Larsen & Pedersen (2000), supplementary data.

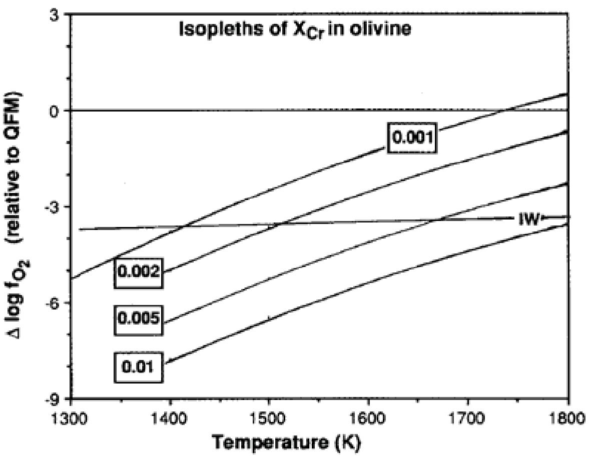

Figure 3. Isopleths of XCr-in-olivine in equilibrium with spinel at zero pressure. The pressure dependence is very small. From Li et al. (1995), reproduced with permission from Oxford University Press.

Spinel compositions

Like the olivines, the spinels crystallised over a range of temperatures, and the high-temperature signal resides in the spinels included in the high-Mg olivines. It is clear from Figure 4 that the spinels in the high-Mg olivines have very high Mg# and high Cr#; they have also low Fe# and Ti contents (see *Larsen & Pedersen*, 2000). These spinels are similar to spinels from the Kambalda komatiites produced experimentally at 1350-1500°C (*Murck & Campbell*, 1986).

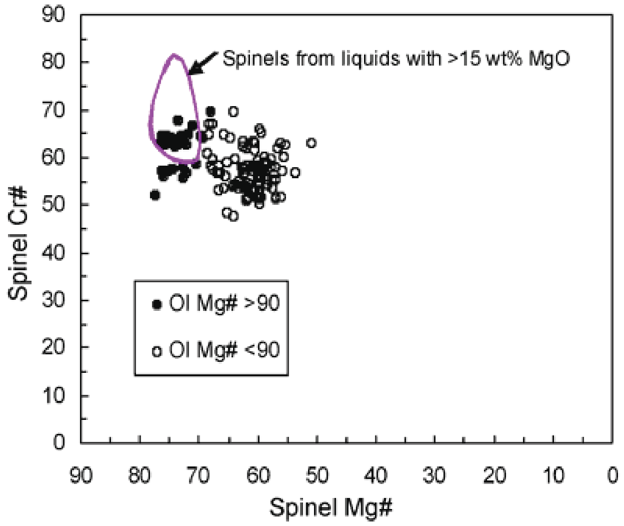

Figure 4. Spinel compositions in the Vaigat Formation, grouped according to Mg# of the enclosing olivine. Xenocrysts are not plotted. Data from Larsen & Pedersen (2000), supplementary data. The purple field of spinels from liquids with >15 wt% MgO is from Natland (2008, Figure 4).

Discussion of the paper by J. H. Natland: Eruptive temperatures of the Paleogene picrites of West Greenland and Baffin Bay

In the following, quotations from *Natland* (2008) are shown in italics and within quotation marks. Our comments are written in normal font.

“Petrological backdrop”

“The stratigraphy also includes silicic lava or tuff (mainly dacite and rhyolite)”.

Comment: As explained above, the most evolved uncontaminated rocks in the Vaigat Formation are basalt with 6.5 wt% MgO. Dacites and rhyolites do not occur. Such rocks do constitute a subordinate part of the uppermost members of the overlying basalts (the Maligât Formation), and they are all strongly crustally contaminated. It is also true of the Maligât Formation that the most evolved uncontaminated rocks are basalts.

“Another surprise……is that ……the picrites have low delta-Nb ….”

Comment: The West Greenland and Baffin Island picrites and basalts are more depleted in the most incompatible elements than Iceland. They are not so depleted in the less-incompatible elements such as Ti. We are not surprised at all because why should these rocks be identical to those formed today in Iceland? The differences are inherent in the mantle in which the melts originated; they have nothing to do with assimilation of rhyolite because the rocks are not crustally contaminated; contamination would immediately show up in the isotopic compositions.

“Is very forsteritic olivine ….a relic of an ancient melting event?”

Comment: The very forsteritic olivines (Fo 90–92.5) crystallised from a melt, as proved by their high contents of Cr, Ca, and glass inclusions (see above). An olivine cumulate from an ancient melt, resident under mantle pressures and temperatures since the Archaean, would not have been able to retain the Cr in the crystal structure but would have exsolved it as chromite dust. Olivine from cumulates in the continental lithosphere can only be part of the Paleocene picrites if the crystals were melted completely, and this would have required an extraordinary amount of heat. We fail to see the necessity of invoking an ancient high-temperature melting event when a Paleocene one can explain all the data.

“Glasses are cotectic liquid compositions with olivine xenocrysts”
“ …none of it [the analyzed glass] is olivine-controlled. …. Glass compositions fall along a low-pressure plagioclase-olivine clinopyroxene cotectic…..”

Comment on the West Greenland glasses: *Larsen & Pedersen* (2000) published analyses of both glass inclusions in olivine and matrix glasses. The glass inclusions are re-equilibrated with the surrounding olivine, and we did not use them for any petrological calculations. On the other hand, the quenched glasses in the pillow rinds (matrix glasses) are abundant and very fresh. The matrix glass in any one sample is quite homogeneous, and in total the glasses have a restricted compositional range, with 6.7–8.8 wt% MgO, 13.5–15.1 w% Al_2O_3, and 12.1–14.6 wt% CaO, i.e., they have a relatively large plagioclase component (Figure 5). The largest relative range is seen in TiO_2 which ranges from 1.35 to 1.93 wt%; this variation is caused by differences in the primary magmas produced over time which is corroborated by differences in the isotopic compositions of the bulk rocks (yet unpublished data, but see *Holm et al.*, 1993). The glass compositions in Figure 5 show no indication of fractionation of either plagioclase or clinopyroxene. It appears both petrographically (see above under petrography of the picrites) and chemically that the melts simply quenched on approach to the two- or three-phase cotectic phase boundary.

In summary: Yes, the matrix glasses are cotectic or near-cotectic liquids. But they are olivine-controlled because the various packets of magma arrived at the cotectic surface by fractionation of olivine from parental liquids that had different contents of TiO_2 (and FeO). Thus, the individual fractionation paths in *Larsen & Pedersen* (2000, Figure 11), also depicted in *Natland* (2008, Figure 2C) form individual, near-parallel lines. What is seen as ‘cotectic trends’ of the glasses in the compositional diagrams are the traces of the cotectic surface in the plots (*O’Hara*, 1968).

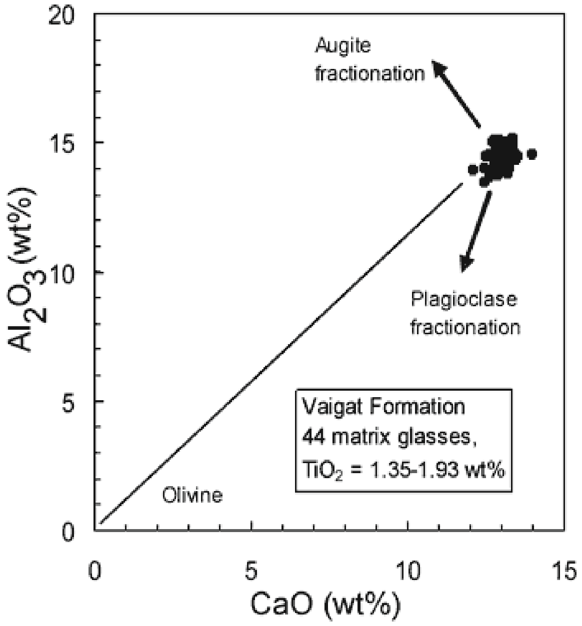

Figure 5. Composition of glass in pillow rinds. Data in Larsen & Pedersen (2000), supplementary data.

"Following the rationale developed for Samoa….."

Comment: This rationale is based on plots of matrix glass compositions in a diagram of Al_2O_3 *vs.* CaO. The Samoa lavas have phenocrysts of clinopyroxene and some of the Samoa glasses duly show depletion in CaO and enrichment in Al_2O_3 caused by fractionation of clinopyroxene (*Natland*, 2008b, Figure 2). Following the rationale developed for Samoa, the very tight cluster of the West Greenland matrix glasses in Figure 5 indicates no fractionation of either plagioclase or clinopyroxene. Thus again, there is no evidence whatsoever, either petrographical or chemical, for fractionation of other phases than olivine and spinel from the matrix glasses. They can safely be used for backtrack calculations of melt compositions by adding olivine back into the glass.

"Melt inclusions"

Comment: The melt inclusions we analysed are clearly out of equilibrium with the surrounding olivine after deposition of olivine on the inclusion walls and re-equilibration of olivine and glass, including loss of both MgO and FeO from the glass to the olivine (*Larsen & Pedersen*, 2000; see also *Gaetani & Watson*, 2000). We agree with Natland that the melt inclusions are difficult or impossible to reconstitute and should not be used for backtrack calculations. We have also not done so; we presented the melt inclusions as analysed and used the well-defined matrix glasses from the pillow rinds for backtrack calculations.

"The crystallization and mixing histories….."

Comment: As we envisaged the picrites in our 2000 paper, the primitive melts were not erupted. The melts precipitated olivine continuously in the conduit systems on their way to the surface and lost heat in the process. The conduit systems were lined with olivine crystals left by previous melt batches, and the passing melts picked some of these olivines up while they left others behind. The *erupted* magmas were slurries of olivine in melts that contained no more than 14 wt% MgO, often less. This concept of slurries is not very different from that of *Natland* (2008). The difference lies in that we consider all the olivine to be cognate (note the compositional continuity of the total olivine trend in Figure 2), and that high-Mg, high-temperature melts did exist at depth but were just not erupted. The high-Mg olivines and spinels bear all the hallmarks of having formed at very high temperatures, and we consider them to provide evidence of the least evolved asthenospheric melts.

Natland (2008) suggests a very different model of picrite formation in which the picrites are mixtures of evolved, cotectic magmas and xenocrystic olivines. He envisages magma chambers in which low-pressure fractionation of olivine, plagioclase and clinopyroxene took place, after which the basaltic melts left their phenocrysts completely behind, moved upwards and into areas with "*stagnant masses of some other magma at depth*", picked up olivine crystals from these stagnant magmas, and from the wall rocks, in amounts up to one third or more of the total volume, and proceeded to erupt on the surface. This model seems extraordinarily complicated. Which magma was sitting around at higher levels than the low-pressure magma chambers? It must have been very magnesian and very voluminous in order to provide enough olivine to make the picrites. A corollary of Natland's theory is that the cotectic basalt magmas with around 8 wt% MgO must on average have picked up 22 wt% (around 30 vol%) olivine (Fo 88) in order for the Vaigat Formation to get an average composition of 16.6 wt% MgO. More than one fourth of the total erupted volume of 22,000 km^3 of picrites must therefore be ascribed to "*some other magma*" and wall rocks. This is contrived.

"Further difficulties with reconstructed melt inclusions"

Comment: We basically agree on the difficulties. However, Natland compares melt inclusions from Greenland and Iceland, and melt inclusions in plagioclase and clinopyroxene are brought into the argument. We therefore reiterate: There are no phenocrysts of plagioclase or clinopyroxene in the picrites in West Greenland. We are well aware that the Icelandic picrites contain plagioclase phenocrysts, and that only stresses the difference between the two; but plagioclase in Icelandic picrites does not imply or necessitate plagioclase in Greenlandic picrites.

"Olivine in picrite might thus have many origins, including some crystals that might be from ancient dunite cumulates….."

Comment: If this is the case in West Greenland, the different populations of olivine picked up must have re-equilibrated heavily in order to no longer form discrete compositional populations. Moreover, the re-equilibration must have stopped just at the moment a continuous compositional suite was formed that looks exactly like one formed by continuous crystallisation of olivine from closely related parental magmas (Figure 2 and *Larsen & Pedersen*, 2000). This is no small requirement as olivines re-equilibrate very easily and complete re-equilibration would be achieved in a few months' time (*Jurewich & Watson*, 1988). Completely re-equilibrated rocks do occur occasionally (*Larsen & Pedersen* (2000) sample 264217), but they are an exception.

The picrites in West Greenland and Baffin Island have very tightly constrained, chondritic to suprachondritic osmium isotopic compositions ($^{187}Os/^{188}Os_{initial}$ = 0.1268–0.1322, *Dale et al.*, 2009) which would not be expected if the rocks contained varying amounts of different populations of olivine of various origins. In contrast, the dunites of Ubekendt Ejland have scattered, mainly distinctly subchondritic osmium isotopic compositions (*Bernstein et al.*, 2006) which effectively rules them out as a significant component in the picrites. Thus, the very high $^{3}He/^{4}He$ in the picrites (up to 50 Ra, *Graham et al.*, 1998; *Starkey et al.*, 2009) cannot originate in dunitic cumulates as suggested by *Natland* (2008).

Again, we reiterate: the high-Mg olivines could not have survived millions of years at mantle temperatures without exsolving their high chromium contents into chromite. Why postulate an ancient high-temperature melting event in preference to a Paleocene event?

The ancient dunite cumulates may be a way of diminishing the problem with the "*some other magma*" invoked earlier. However, the problem of accounting for more than one fourth of the total erupted volume of picrites is not removed.

"could it really be a coincidence that such magnesian olivine just happens to occur in the lithosphere where "plume head" picrite erupts?"

Such magnesian olivine, and dunite, occurs in the lithosphere beneath the whole Precambrian craton of Greenland and is brought to the surface as xenoliths whenever alkaline mafic and ultramafic rocks erupt or intrude (South Greenland: *Emeleus & Andrews*, 1975; Southern West Greenland: *Bizzarro & Stevenson*, 2003; general: *Wittig et al.*, 2008). The olivine in these dunites has low Cr contents, <0.05 wt% Cr_2O_3, including the dunitic olivine from Ubekendt Ejland (*Bernstein et al.*, 2006).

"Spinel"
Figure 3: "Most of this field [spinels from melts with MgO>15%] does not overlap natural spinel from West Greenland and Padloping Island…"

Comment: About seven spinel analyses from West Greenland indeed plot close to or in the ">15% MgO-in-melt" data field (purple) in Figure 3 of *Natland* (2008). These would be the high-Mg spinels in Table 2 of *Larsen & Pedersen* (2000). The full data set is shown here in Figure 4 above, and if these analyses are plotted too, several spinels with

Cr#=62–68 and Mg#=70–77, all from olivines with Fo>90, plot in the field of melts with >15% MgO. The spinels in olivine with Fo<90 were formed from melts with lower MgO at lower temperatures and give the results expected of this.

"Figure 4"

Comment: The temperatures for the matrix glasses calculated in this figure are similar to those calculated by *Larsen & Pedersen* (2000) with the *Ford et al.* (1983) algorithm, i.e., 1160–1218°C. These temperatures represent the final quenching temperatures after flowage of the lavas and extended crystallisation of olivine. Temperatures of eruption would have been higher by some 100°C. However, our main point is this: intratelluric temperatures would have been still higher. As no uncorrupted liquid in equilibrium with the high-Mg spinel is available, it is clear that Figure 4 in *Natland* (2008) can only show the later stages of crystallisation and not the intratelluric high-temperature stages. The high-temperature signal only resides in the high-Mg phases. We used backtrack calculations starting from the matrix glasses and stopping at calculated equilibrium olivines of Fo 92.5 and Fo 92.0 (depending on the rock units). We concluded that the parental melts (the most primitive melts of which we have traces left, i.e., those in equilibrium with olivine Fo 92.5 and 92.0) had MgO contents of 19–21 wt% MgO and temperatures of 1530–1560°C at pressures of 13–16 kbar.

Conclusions

Natland (2008) suggested a model for the origin of the picrites in West Greenland and Baffin Island as mixtures of evolved cotectic basalt magma and more or less accidentally incorporated olivine from various sources including mantle dunites. There is, however, no evidence that the basaltic glasses have fractionated plagioclase and clinopyroxene; on the contrary there is evidence that they have not. Osmium isotopic compositions of the picrites and dunitic mantle xenoliths from the region are widely different.

The high-Mg olivines and spinels show strong evidence of crystallisation at high temperatures. The high-Mg olivines contain 0.10–0.18 wt% Cr_2O_3 which can only be incorporated in the olivine structure at magmatic temperatures of more than about 1450°C.

Natland's model has two corollaries that make it untenable. Firstly, the different olivine populations must have re-equilibrated to a compositionally continuous suite that looks like a suite formed by magmatic fractionation. Secondly, the cotectic basalt magmas must have picked up on average ~30 vol% accidental olivine in order for the picrites to get an average composition of 16.6 wt% MgO. More than one fourth of the total erupted volume of 22,000 km^3 of picrites must therefore be ascribed to some extraneous source and is in reality not accounted for by his model.

The very large volume of picrites in the Paleocene volcanic succession in West Greenland and Baffin Island is unusual and must have formed under conditions rarely fulfilled at other times and places. Very high mantle temperatures are required, and there is also irrefutable evidence of high temperatures in the rocks themselves.

References

- Bernstein, S., Hanghøj, K., Kelemen, P. B. & Brooks, C. K. 2006. Ultra-depleted, shallow cratonic mantle beneath West Greenland: dunitic xenoliths from Ubekendt Ejland. *Contributions to Mineralogy and Petrology* **152**, 335–347.

- Bizzarro, M. & Stevenson, R.K. 2003. Major element composition of the lithospheric mantle under the North Atlantic craton: Evidence from peridotite xenoliths of the Sarfartoq area, southwestern Greenland. *Contributions to Mineralogy and Petrology* **146**, 223–240.
- Bristow, J. W. 1984. Picritic rocks of the North Lebombo and South-East Zimbabwe. *In:* Erlank, A. K. (ed) Petrogenesis of the volcanic rocks of the Karoo Province. *Special Publication, Geological Society of South Africa* **13**, 105–123.
- Clarke, D.B. 1970. Tertiary basalts of the Baffin Bay: possible primary magma from the mantle. *Contributions to Mineralogy and Petrology* **25**, 203-224.
- Clarke, D.B. & O'Hara, M.J. 1979. Nickel and the existence of high-MgO liquids in nature. *Earth and Planetary Science Letters* **44**, 153-158.
- Clarke, D.B. & Pedersen, A.K. 1976. Tertiary volcanic province of West Greenland. In: Escher, A. & Watt, W.S. (eds) *Geology of Greenland*, 364-385. Copenhagen: Geological Survey of Greenland.
- Dale, C.W., Pearson, D.G., Starkey, N.A., Stuart, F.M., Larsen, L.M., Ellam, R.M., Fitton, J.G., Macpherson, C.G. 2009. Osmium isotopes in Baffin Island and West Greenland picrites: Implications for the ^{187}Os/^{188}Os composition of the convecting mantle and the nature of high ^{3}He/^{4}He mantle. *Earth and Planetary Science Letters*, **278**, 267–277.
- Drever, H.I. 1958. Geological results of four expeditions to Ubekendt Ejland, West Greenland. *Arctic* **11**, 199-210.
- Drever, H.I. & Johnston, R. 1957. Crystal growth of forsteritic olivine in magmas and melts. *Transactions of the Royal Society, Edinburgh* **63**, 289-315.
- Elthon, D. & Ridley, W.I. 1979. Comments on: "The partitioning of nickel between olivine and silicate melt" by S. R. Hart and K. E. Davis. *Earth and Planetary Science Letters* **44**, 162-164.
- Emeleus, C.H. & Andrews, J.R. 1975. Mineralogy and petrology of kimberlite dyke and sheet intrusions and included peridotite xenoliths from South-west Greenland. *Physics and Chemistry of the Earth* **9**, 179–197.
- Ford, C.E., Russell, D.G., Craven, J.A. & Fisk, M.R. 1983. Olivine-liquid equilibria: Temperature, pressure and composition dependence of the crystal/liquid cation partition coefficients for Mg, Fe2+, Ca and Mn, *Journal of Petrology*, **24**, 256-265.
- Francis, D. 1985. The Baffin Bay lavas and the value of picrites as analogues of primary magmas. *Contributions to Mineralogy and Petrology* **89**, 144-154.
- Gaetani, G.A. & Watson, E.B. 2000. Open system behavior of olivine-hosted melt inclusions. *Earth and Planetary Science Letters* **183**, 27–41.
- Graham, D.W., Larsen, L.M., Hanan, B.B., Storey, M., Pedersen, A.K. & Lupton, J.E. 1998. Helium isotope composition of the early Iceland mantle plume inferred from the Tertiary picrites of West Greenland. *Earth and Planetary Science Letters* **160**, 241-255.
- Hart, S.R. & Davis, K.E. 1978. Nickel partitioning between olivine and silicate melt. *Earth and Planetary Science Letters* **40**, 203-219.
- Holm, P.M., Gill, R.C.O., Pedersen, A.K., Larsen, J.G., Hald, N., Nielsen, T.F.D. &

Thirlwall, M.F. 1993: The Tertiary picrites of West Greenland: contributions from 'Icelandic' and other sources. *Earth and Planetary Science Letters* **115**, 227-244.

- Jurewich, A.J.G. & Watson, E.B. 1988. Cations in olivine, part 1: Calcium partitioning and calcium-magnesium distribution between olivines and coexisting melts, with petrological applications. *Contributions to Mineralogy and Petrology* **99**, 176–185.
- Larsen, J.G. 1977. Transition from low potassium olivine tholeiites to alkali basalts on Ubekendt Ejland. *Meddelelser om Grønland* **200 (1)**, 42 pp.
- Larsen, J.G. & Pulvertaft, T.C.R. 2000. The structure of the Cretaceous–Palaeogene sedimentary-volcanic area of Svartenhuk Halvø, central West Greenland. *Geology of Greenland Survey Bulletin* **188**, 40 pp.
- Larsen, L.M. & Pedersen, A.K. 2000. Processes in high-Mg high-T magmas: Evidence from olivine, chromite and glass in Paleogene picrites from West Greenland. *Journal of Petrology* **41**, 1071–1098.
- Li, J.-P., O'Neil, H.St C. & Seifert, F. 1995. Subsolidus phase relations in the system MgO-SiO2-Cr-O in equilibrium with metallic Cr, and their significance for the petrochemistry of chromium. *Journal of Petrology* **36**, 107–132.
- Murck, B.W. & Campbell, I.H. 1986. The effects of temperature, oxygen fugacity and melt composition on the behaviour of chromium in basic and ultrabasic melts. *Geochimica et Cosmochimica Acta* **50**, 1871-1887.
- Natland, J.H. 2008. Eruptive temperatures of the Paleogene picrites of West Greenland and Baffin Bay. Paper posted at http://www.mantleplumes.org/Greenland.html
- Natland, J.H. 2008b. Why olivine control arguments cannot be used to infer high temperature at Samoa. Paper posted at http://www.mantleplumes.org/CoolSamoa.html
- O'Hara, M.J. 1968. The bearing of phase equilibria studies in synthetic and natural systems on the origin and evolution of basic and ultrabasic rocks. *Earth-Science Reviews* **4**, 69–133.
- Starkey, N.A., Stuart, F.M., Ellam, R.M., Fitton, J.G., Basu, S. & Larsen, L.M. 2009. Helium isotopes in early Iceland plume picrites: Constraints on the composition of high 3He/4He mantle. *Earth and Planetary Science Letters* **277,** 91–100.
- Wittig, N., Pearson, D.G., Webb, M., Ottley, C.J., Irvine, G.J., Kopylova, M., Jensen, S.M. & Nowell, G.M. 2008. Origin of cratonic lithospheric mantle roots: A geochemical study of peridotites from the North Atlantic craton, West Greenland. *Earth andPlanetary Science Letters* **274**, 24–33.

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