

On the Formation of Platinum Group Element–Rich Continental Flood Basalt and the Platinova Reefs of the Skaergaard Intrusion

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Platinum Group Element reefs associated with layered mafic intrusions require a parental magma that contains at least several parts per billion (p.p.b.) Pd or Pt. The extremely high distribution coefficient for PGE between sulphide and magma predicts that PGE-rich magmas can only form if all sulphides are melted out of the mantle. For standard peridotite mantle with 250±50 p.p.m. S (McDonough and Sun, 1995), the mantle sulphides are exhausted only if the mean degree of mantle melting (F) exceeds 20%. Komatiite is of course the type example of a Pd-rich magma (8–21 p.p.b., Fig. 1) formed by high F : well above 20% (Keays, 1995). Mid-ocean ridge basalt (MORB) mostly form by moderately high F (8–20%; Klein and Langmuir, 1987), but rarely contains more than 1 p.p.b. Pd (Fig. 1); this is ascribed either to retention in mantle sulphides or to subsequent sulphide saturation during basalt differentiation (Barnes et al., 1987).

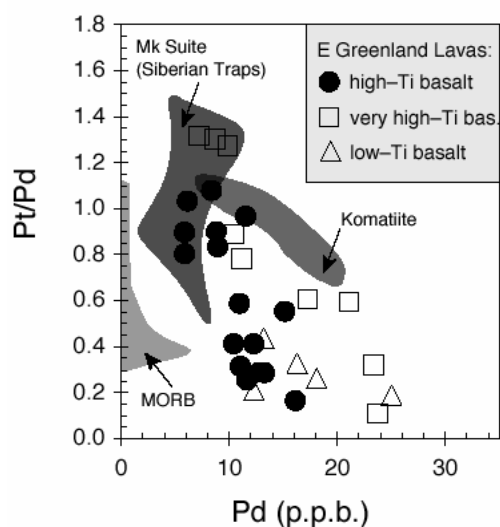


Figure 1. Pd and Pt composition of the Paleogene East Greenland flood basalt province (Momme et al., 2002), recent MORB and old komatiite (Rehkämper et al., 1999), and PGE-rich flood basalts of the Permo-Triassic Siberian traps (Mokulayevsky Suite; Brüggmann et al., 1993).

For continental flood basalts, the constraints on mantle melting conditions are conflicting. On the one hand, the presence of prominent PGE reefs of continental mafic intrusions such as Noril'sk, Bushveld, Stillwater, and Skaergaard associated with flood basalts implies PGE-rich parental magmas. This would suggest high F . On the other hand, the lithophile trace element composition, in particular the rare-earth elements (REE), indicate that most continental flood basalts formed by moderate F in the range from 5 to 15% (Fram and Leshner, 1993). Although most continental flood basalts are inferred to originate from hot mantle plumes, the reason F remains moderate is that the top portion of the melting regime is truncated by thick non-melting lithosphere – this is referred to as the 'lid'–effect (Ellam, 1992). In this contribution we explore the effects of the lithospheric lid on the PGE and REE composition of continental flood basalt with particular emphasis on the Paleogene East Greenland Igneous Province, following Momme et al. (in press, in review), and the Platinova Pd–Au reef of the Skaergaard intrusion (Andersen et al., 1998).

PGE of the East Greenland Continental Flood Basalt Province

This Paleogene flood basalt province formed during continental rifting immediately before the opening of the Northeast Atlantic. The major element and REE composition show the 6 km thick lava pile of the Blosseville Kyst is composed mainly of high-Ti basalt [mg#, = molar Mg/(Mg+Fe) range from 60 to 43] and with subordinate and intercalated low-Ti and very-high-Ti basalt, all largely unaffected by crustal contamination (Tegner et al., 1998). All three magma suites are PGE-rich with Pd ranging from 3 to 25 p.p.b., but we will focus only on the dominant high-Ti suite that contains 6 to 16 p.p.b. Pd (Fig. 1). The concentration of Pd increase with decreasing mg# (Fig. 2), demonstrating that Pd was

excluded during igneous differentiation. This can only be obtained if the magma was undersaturated with respect to S and thus did not reach the point where sulphide droplets are exsolved (Momme et al., 2002). In summary the East Greenland flood basalts contain moderate amounts of PGE between that of komatiite and MORB (Fig. 1) and did not exsolve sulphide.

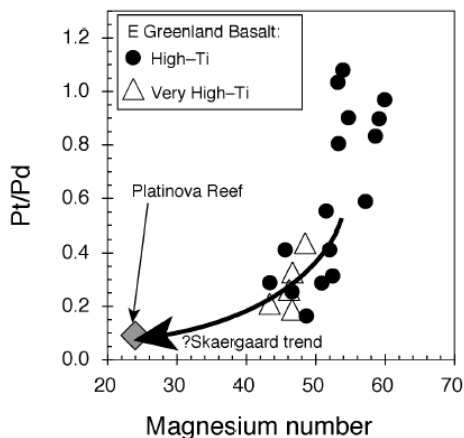


Figure 2. Variation in Pd and Pt with mg# [molar Mg/(Mg+Fe)] for high-Ti and very high-Ti basalt lavas of the East Greenland flood basalt province. Also shown is the typical Pd/Pt of the Platinova Pd-Au reef of the coeval Skaergaard intrusion.

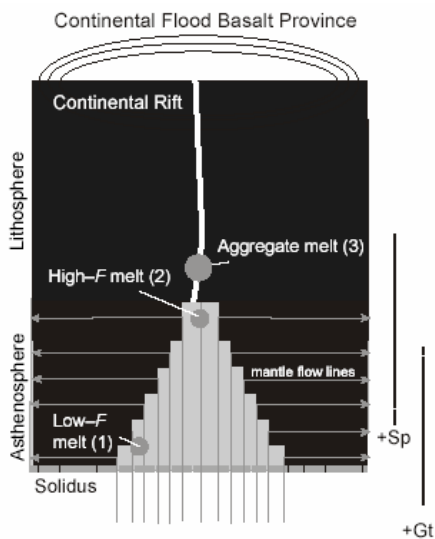


Figure 3. Schematic cross-section showing the melting regime of a corner-flow model (Langmuir et al., 1992) for upwelling mantle plume beneath a continental rift. The mantle solidus is intersected at ~120 km depth and the top of the melting column is at ~60 km depth (Tegner et al., 1998). Predicted melts labelled 1, 2 and 3 are: 1) low-F, high La/Sm_N, low PGE content, and S-saturated; 2) high-F, low La/Sm_N, high PGE content, and S-undersaturated; 3) aggregate melt, intermediate F, PGE content, and La/Sm_N.

Mantle Melting Model

Forward modelling of the REE composition suggests the high-Ti basalts from Greenland formed by mean degrees of melting (F) ranging from 5 to 9%, of mantle depleted slightly (0.5%) relative to Primitive Mantle (Tegner et al., 1998). In this model it was assumed that the melting regime is triangular and governed by upwelling and corner flow as suggested for melting beneath mid-ocean ridges (Langmuir et al., 1992). As depicted in Fig. 3, the mantle starts melting when its solidus is crossed and mantle parcels undergo progressive melting as they ascend. In a forward model, this is approximated by melting mantle parcels at the pressure of the solidus intersection by one percent, extract the magma, recalculate the residual mantle composition and mineralogy, and so forth with pressure of steps decreasing by 1 kbar for each computation. If this is the way the mantle melts, the mantle parcels that reach the top of the melting regime undergo a large degree of melting whereas mantle parcels at the side of the triangle only melts by a few percent before they flow to the side and out of the melting zone (Fig. 3). If melt at any given time is pooled from the entire melt zone it will be a mixture of low and high degree melts. Clearly, the low-degree melts stem from mantle in which sulphides retain the PGE inventory and they will be S-saturated and contain little or no PGE, and will have high concentrations of incompatible lithophile trace elements such as REE. On the other hand, the higher degree melts from the top of the melting column eventually will reach the point at which the sulphides are dissolved and the magmas become PGE-rich. The geometric relations predict that F is half of the maximum degree of melting reached for the topmost mantle parcel of the triangle. Rehkämper et al. (1999) was the first to propose that such a melting model may explain the formation of ocean-island basalts with moderate PGE as the result moderate F .

The results of our forward modelling of the PGE composition of basalt formed during continental breakup is summarised in Fig. 4 and indicate that if the mantle contains 200 S and the magma can dissolve 1000 p.p.m. S, then magmas with 10 p.p.b. Pd may be produced for F larger than 10%. In summary, forward modelling of REE suggests that the high-Ti East Greenland flood basalts may form for F ranging from 5 to 9% and forward modelling of PGE suggests the same basalts may form only for F above 10% for reasonable mantle compositions. The F estimated from REE modelling obviously depends more on assumptions about source composition than that of

PGE modelling. Hence, the major element, the REE, and the PGE composition of the high-Ti flood basalts may all be explained by approximately 10% mantle melting.

The 'Lid'-Effect Drives Magma to S-Undersaturation

The pooled melts of the above model is a mixture of S-undersaturated (high-degree melts) and S-saturated basalts (low-degree melts) and it is not clear whether this mixed product is over- or undersaturated at the depth of the source. In any case, it appears unlikely that the S-undersaturated nature of the East Greenland flood basalts may be so strong without additional effects that drive the magma to S-undersaturation. In fact, there are two mechanisms that may increase the amount of S that may be dissolved in basalt, that is FeO content and pressure. Poulson and Ohmoto (1990) showed that the S-capacity of a magma increases with its FeO content. Because the high-Ti basalts differentiate towards iron enrichment (Brooks et al., 1991) it appears that the S-capacity of the magma may increase solely as a consequence of differentiation. Further, the REE's indicate garnet is present in the source. Hence the lid-effect predicts that the mean pressure of melting, P , is elevated. The FeO content of magma increase with P during melting and thus suggest that continental flood basalts have high S-capacity relative to MORB. Finally, but perhaps most important, Mavrogenes and O'Neill (1999) showed that magmas at high pressure can dissolve less S than the same magma at low pressure. For the reasons outlined above, we believe the high P of melting followed by adiabatic ascent of the magma may be very important in driving continental flood basalts to S-undersaturation.

Formation of the Platinova Reef, Skaergaard intrusion

The Platinova Reef consists of several orthomagmatic palladium- and gold-rich magnetite-gabbro layers at the top of the Middle Zone (Andersen et al., 1998). In terms of igneous differentiation, the host pyroxene and plagioclase composition indicates the reef formed from an evolved magma with mg# close to 23. Compared to PGE reefs of the Bushveld and Stillwater complexes, the Platinova Reef is not only unusual in that the magma was evolved, but also in that it is a Pd reef with Pt/Pd below 0.1. A surprising feature of the Greenland high-Ti basalts is that the Pt content, which ranges from 2 to 11 p.p.b., decreases slightly with fractionation, indicating Pt is incorporated into the fractionating gabbro assemblage (D^{bulk} is 2–3), perhaps as tiny

Platinum-Group Minerals hosted by olivine (Momme et al., 2002). Hence Pd is fractionated from Pt and Pt/Pd decreases with differentiation (Fig. 2). In the same way as the Pt/Pd of the high-Ti basalts decrease with mg# ranging from 60 to 43, we speculate that the low Pt/Pd of Platinova Reef (mg# ~25) may result from prolonged fractionation where Pt is included into and Pd excluded from the cumulates. This is illustrated as the Skaergaard trend in Fig. 2.

Implications for the Siberian Trap Magmatism

The Noril'sk mafic intrusions are associated with the Siberian Traps flood basalts and the parental magmas must have contained considerable amounts of PGE. Almost all the flood basalts of the region are depleted in PGE, saturated in S, and show isotopic evidence for the assimilation of S-rich sediments (Brügmann et al., 1993). However, in the top section of the volcanic pile there are lavas that contain significant amounts of PGE (Brügmann et al., 1993) and may not be S-saturated.

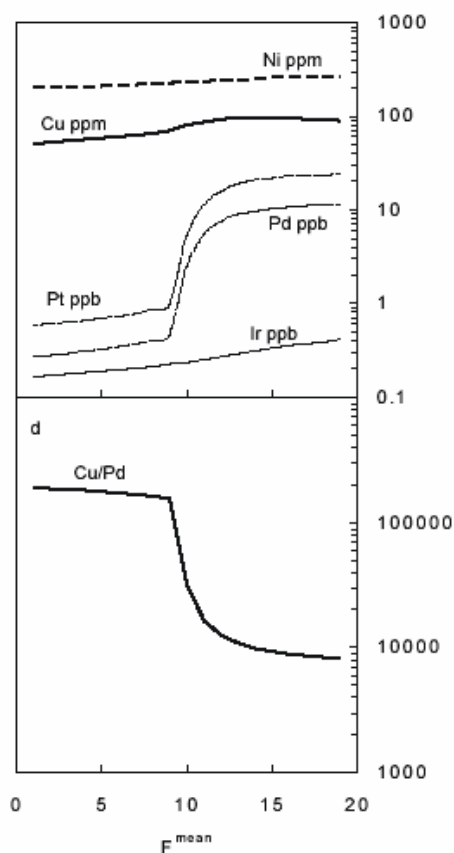


Figure 4. Modelled Ni, Cu, Pt, Pd and Ir composition with mean degree of mantle melting (F). Model calculations assume corner-flow melting regime as shown in Fig. 3, the mantle contains 200 S, and the magma can dissolve 1000 p.p.m. S (Momme et al., in review).

In the Mokulaevsky Suite, the concentration of PGE is similar to the high-Ti basalts of East Greenland (Fig. 1) whereas the REE patterns are steeper. The differences in REE may reflect a more enriched source for the Siberian flood basalts. We speculate that the primary mantle-derived versions of the Siberian Traps flood basalts was very similar to those of the East Greenland high-Ti basalts and that they could have formed at comparable mantle melting conditions. If so, the main difference between the two provinces lie in the crustal processes indicating abundant assimilation in the Siberian case and very little crustal contamination in the East Greenland basalts. However, we speculate whether mantle plume melting beneath a thick lithospheric 'lid' could also account for the composition of these occurrences.

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