Discussion of

North Atlantic Igneous Province: A review of models for its formation

by

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31st January, 2007, Laurent Geoffroy

Any effort to summarize the available data from the North Atlantic Igneous Province is welcome, and we should thank Meyer et al. (this volume) for their valuable contribution. However, I would like to make the following comments, the first on a minor aspect and the second concerning a much more general point.

A. The South-East Baffin controversy

Meyer et al. (this volume) refer to the argument concerning the existence of an onshore exposed SDR along the W-Greenland margin north of ~70˚N (Chalmers et al., 1999). I do not think that this is a matter of debate anymore. Geoffroy et al. (1998; 2001) were correct in recognizing that the Disko-Svartenhuk W-Greenland coastal area exposes a thick fan-shaped inner prism of syn-tectonic seaward-dipping basalts and tuffs. As such, it essentially forms an upper crustal structure typical of volcanic passive margins worldwide. The recent confirmation of an SDR located on the conjugate margin offshore from Baffin Island fully supports the view that the S-Baffin Bay margins are of volcanic type (Skaarup et al., 2006). However, Chalmers et al. (1999) rightly point out the geodynamic importance of the Ungava transform splay faults in the tectonic structure of the Disko and Nuussuaq areas. The W-Greenland controversy was compounded by a general misunderstanding about the tectonic setting of SDR wedges across volcanic margins. According to Chalmers et al. (1999), if we consider the W-Greenland coastal flexure to be a SDR, this implies a transition to the oceanic crustal domain across the coast line (conflicting with hopes for the petroleum potential of this area). This ignores the fact that, at volcanic margins, the innermost SDR prisms are often continental, as suggested by Roberts et al. (1979) and confirmed in later studies (e.g. Tard et al., 1991). One can truly consider the W-Greenland volcanic margin at the latitude of Ubekendt-Ejland and Svartenhuk (Geoffroy et al., 2001, Plate 3) as representing the most suitable place to study in detail the development of a partly eroded continental inner-SDR and the relationships linking the pre-breakup and breakup-related volcanic formations with pre-existing sedimentary basins. More generally, in discussing this aspect, we might add that there is little point in interpreting offshore geology at margins without a detailed examination of adjacent onshore data. By the same token, offshore observations (when available) are just as crucial for interpreting onland geology.

B. Distribution and timing of the North Atlantic LIP volcanism

The authors proposed that the distribution of LIP-related magmatism in the North-Atlantic (their Figure 1) is somewhat surprising compared to former views, suggesting a much wider geographical extent (see, for example, Fig. 8 in White & McKenzie, 1989). Could they specify the range of data used for this otherwise quite useful compilation? Did they take into account the extensively sill-intruded basins that are fully part of the LIP? This is not merely a point of detail since the authors' diagram appears to confine most of the magmatism to the break-up area, in good agreement with the mantle melting model developed by Van Wijk et al. (2001). This distribution is also discussed in the text, where the authors state that the "Paleocene magmatism is middle or late syn-rift". From this, we can understand that they are referring to previous Cretaceous rifting in the North-Atlantic (their Fig. 2). According to such a presentation of the data, magmatic activity would be a direct and natural consequence of a late-stage stretching of the lithosphere. This would be surprising because, apart from the break-up zones where Eocene SDR are developed, very little extension took place during the emplacement of most of the North-Atlantic Paleocene-related extrusives. These formations are mainly associated with horizontal dilatation due to dike injection, and thus have no relation to tectonic stretching and thinning. In many cases, traps at LIPs can be seen to seal former sedimentary rifts and basins. For example, this is exactly the pattern observed in the Afar area, where the Ethiopian and Yemen traps form thick horizontal piles over wide areas, lying directly on top of the basement or capping the older Mesozoic rifts. I do not think that we can so easily discount such a robust and generalized observation.

Whatever the mantle melting mechanism (and mantle plumes are certainly not the only possible explanation, as the authors rightly state) we still need to explain why a major and sudden pulse of magmatism occurred simultaneously over such a wide area. At the same time, this magmatism is coeval with a stress pattern that is unrelated to the regime acting during pre-magmatic Mesozoic tectonic events (Geoffroy et al., this volume). This type of scenario strongly resembles a major dynamic plate-scale perturbation of a metastable system, i.e. the buoyant mantle located beneath the rigid and heterogeneous lithosphere.

1st February, 2007, Stephen Jones

Post-breakup magmatism: Iceland and the oceanic part of the NAIP. Several authors have pointed out that the geometry of the V-Shaped Ridges might be explained by passive upwelling of a thermal halo surrounding Iceland and containing outward dipping thermal/compositional anomalies, instead of by lateral advection of thermal/compositional anomalies within a plume head (S.M. Jones et al., 2002a; Vogt & Jung, 2005). Previously, the main difficulty in deciding between the lateral and vertical transport models was a lack of seismic images with sufficient vertical resolution to distinguish a slow sub-lithospheric plume head layer about 100 km thick from a slow thermal halo filling the entire upper mantle (S.M. Jones et al., 2002a). The situation is now improving. Pilidou et al. (2005) presented a Rayleigh wave tomography model that resolves a regional sub-lithospheric slow layer whose base lies at a depth of less than 300 km. The balance of the seismic evidence now appears to favour the lateral outflow model.

Lithospheric Delamination. Constraints on the degree of lithospheric delamination and on regional uplift are available for the British Igneous Province (BIP). The top of the melting region that supplied the BIP has been estimated at about 70 km from modelling of rare earth element distributions (Brodie and White, 1995; White and McKenzie, 1995). The BIP was emplaced within the Sea of the Hebrides Trough, which formed by modest rifting (total strain less than 2) in the Jurssasic, and no significant rifting occurred coeval with BIP emplacement (Emeleus and Bell, 2005). Lithospheric thinning to 70 km is not easily attributed to mild Jurassic rifting, making it more likely that some lithospheric erosion was associated with the mantle circulation that lead to BIP emplacement during the Middle Paleocene. Field observations show that uplift of the BIP itself occurred before and during emplacement and some of this uplift could be related to lithospheric erosion. However, uplift histories interpreted from sedimentary basins surrounding the BIP show relatively little regional uplift coeval with BIP emplacement. Instead, most of the regional uplift (up to 1 km) occurred after BIP activity, peaking close to the Paleocene/Eocene boundary and Europe-Greenland breakup time (a summary and references can be found in Maclennan & Jones, 2006, and Saunders et al., 2007). Thus, in the case of the BIP, it is likely that some delamination did occur but it was not directly associated with major uplift outside the province itself.

Fertile mantle. The authors point out that models involving fertile mantle and no thermal anomaly cannot explain pre-breakup uplift. An equally important problem is that such models cannot explain the present day North Atlantic bathymetric swell, which has a diameter of around 2000 km and a central amplitude of 2 km (excluding the contribution of unusually thick crust; Jones et al., 2002b; Conrad et al., 2004). The topographic swell also correlates with a positive free-air gravity anomaly. It has long been recognized that such broad swells with correlated gravity anomalies must be supported by low density material within the mantle (e.g. Anderson et al., 1973). Even the more sceptical workers agree that it is difficult to explain the 2000 km topographic swell without a thermal anomaly of up to about 100ºC (Foulger & Anderson, 2005).

Small-scale and edge-driven convection. The conclusion that small-scale convection by itself cannot explain the NAIP is supported by the regional uplift history. Although the uplifted swell that developed close the Paleocene/Eocene boundary is not well constrained over its entire area, data from the well-explored basins around the British Isles clearly show that uplift of 100 m – 1 km occurred at a distance of 1000 km from the Europe-Greenland breakup zone (Maclennan & Jones, 2006). Such regional uplift is not easily explained by small-scale convection centred on the breakup zone.

Mantle Plume. It is true that mantle plume models applied to the NAIP differ in many details. However, one common proposal is that a large amount of hot mantle was convectively emplaced beneath the entire NAIP during the Middle Paleocene. The hot asthenosphere first generated the British and West Greenland Igneous Provinces, and then remained beneath the area to generate the Europe-Greenland volcanic margins (Larsen & Saunders, 199). This model implies major regional uplift at or before the Middle Paleocene and persisting until the Early Eocene. The well-resolved uplift history surrounding shows that the model cannot be correct because major regional uplift (up to 1–2 km over a diameter comparable to the NAIP) is not observed until the Late Paleocene, after emplacement of both the British and Greenland Provinces (Maclennan & Jones, 2006; Saunders et al., 2007). It is very difficult to explain both the igneous and the sedimentary record of uplift by a single plume head impact.

Whatever model for the NAIP is accepted in future, it must explain both the igneous record and the record of uplift. My view is that it will be very difficult to do so without advection of hot mantle beneath the lithosphere.

6th February, 2007, Romain Meyer, Jolante van Wijk & Laurent Gernigon

We thank Geoffroy and Jones for their constructive comments on our chapter. The comments confirm the conclusion of the review, i.e., "existing datasets and geodynamic concepts are incomplete, which hinders a more conclusive statement on whether or not the mantle plume or alternative models can be accepted or rejected". Comment (B) from Geoffroy concerns the distribution and timing of North Atlantic Igneous Province (NAIP) magmatism, shown in Figure 1. We initially chose a conservative approach while constructing this figure (map of the NAIP with distribution of volcanism), and used only the published, strongly founded data for its compilation. Following an email-discussion with Geoffroy, we decided to modify the map; in some areas, the volcanic rocks are likely more extensive than our initial map suggested. Note that the boundaries for the localities of the Rockall, Faeroes and Baffin magmatism are still uncertain.

In our chapter we have related NAIP magmatism to the timing of the pre-breakup rift phase (Figure 2). By doing so we did, however, not intend to relate all magmatism to the process of rifting, and we agree with Geoffroy that such a relation is far from being well constrained. The origin of such magmatic formations away from the breakup zone (as in the UK-Rockall area) is not discussed in detail in our chapter; we refer to Geoffroy et al. (this volume) for a discussion on and possible explanation for this phenomenon.

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