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Long term stability in deep mantle structure: Evidence from the ~300 Ma Skagerrak-Centered Large Igneous Province (the SCLIP)

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Abstract

On the basis of large areal extent (~0.5×10^6 km^2), volume, brevity of eruption interval (±4 My) and convergent dyke swarms, the flare-up of igneous activity at 297 Ma in NW Europe marks a typical Large Igneous Province (LIP): The Skagerrak-Centered LIP (SCLIP). LIPs are widely but not universally considered products of deep-seated mantle plumes: We test the idea that a Skagerrak plume rose from the core–mantle-boundary (CMB) by restoring the center of SCLIP eruption, using a new reference frame, to its ~300 Ma position in a Pangea A type reconstruction. That position (~11°N, 16°E, south of Lake Chad in Central Africa) lies vertically above the edge of the African Large Low Shear Velocity Province (LLSVP). It has previously been shown that eruption locations vertically above the edge of one or other of the Earth's two LLSVPs at the CMB characterize nearly all the LIPs erupted since 200 Ma. A deep-sourced SCLIP plume source implies that the edge of the African LLSVP at the CMB has not moved significantly with respect to the spin axis of the Earth during the past 300 My. This is a 30% longer duration for the stability of a deep mantle structure than has been previously demonstrated and suggests that the African LLSVP was at least established by early Permian (Pangea) times.
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1. The Skagerrak-Centered Large Igneous Province

Assembly of Pangea, mainly during late Carboniferous times (Torsvik and Cocks, 2004), was accompanied by intra-continental rift initiation sporadically distributed over about 60% of the supercontinent's area (Burke, 1978). Rifts of this population are well known in NW Europe (Wilson et al., 2004), where at a time close to the Permo–Carboniferous boundary (~300 Ma), as igneous activity in the rifts waned, a flare-up of magmatism occurred. Dyke trends in Scania (Sweden), the Oslo region (SE Norway) and Scotland indicate it to be centred on the Skagerrak (Ernst and Buchan, 1997) (Fig. 1). We estimate this event to have left a record over an area of at least 0.5×10^6 km^2, twice the presently mapped area of volcanics (228.000 km^2), sills (14,000 km^2) and dykes (3353 km in total length) in Fig. 1. That record includes rocks in the Oslo graben, the offshore Skagerrak graben, SW Sweden (Västergötland and Scania), Northern Germany, Scotland, Northern England and the Central North Sea (Heeremans et al., 2004a). Collectively we estimate that these rocks erupted at 297±4 Ma (Figs. 1–2; Section 2) and represent a Large Igneous Province (LIP) for which we suggest the name "Skagerrak-Centered LIP" (SCLIP). Although a globally agreed-upon definition of a LIP does not exist, Coffin and Eldholm's (1994) original definition stressed the importance of areal extent (>0.1×10^6 km^2) of pre-dominantly mafic igneous rocks. In the most recent definition, a LIP is defined as "mainly

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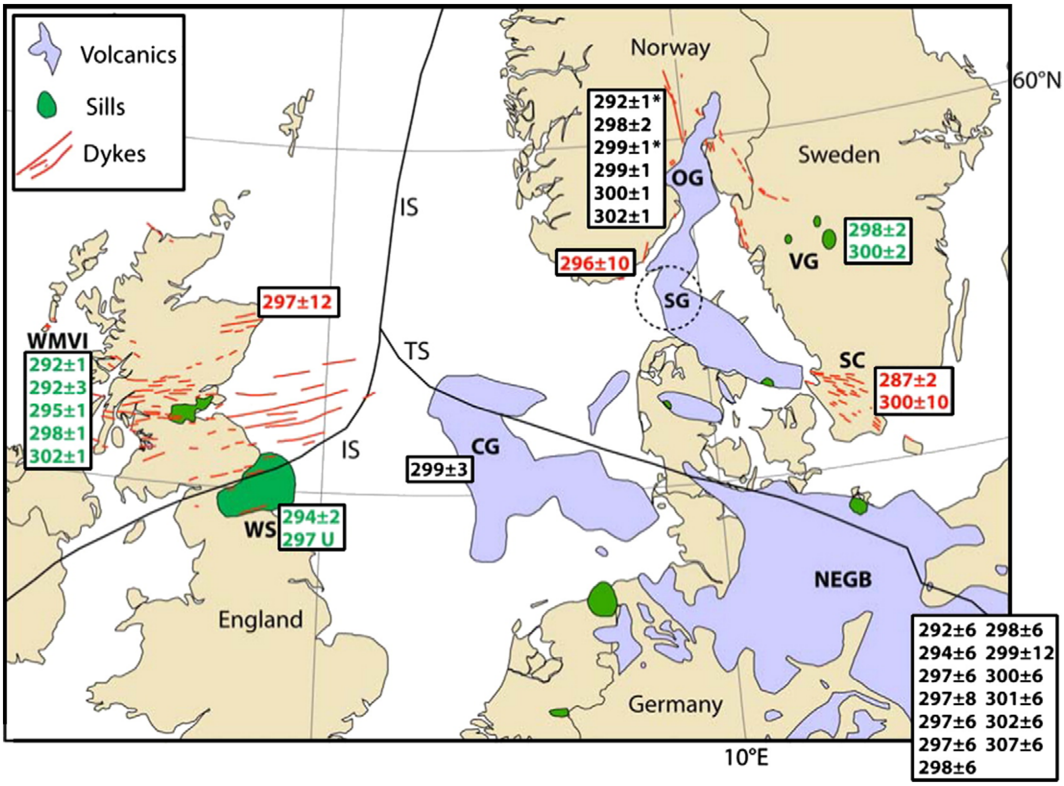

Fig. 1. Map of NW Europe showing the distribution of c. 290–300 Ma volcanics (228.000 km^2), sills (14,000 km^2) and dykes (3353 km in total length). These magmatic products with an estimated volume around 0.5×10^6 km^3 form the SCLIP. Compiled ages (see also age histogram in Fig. 2) are all 'modern' ^{40}Ar–^{39}Ar ages (mostly hornblende, biotite and feldspar ages), thermal ionization mass spectrometry U/Pb zircon and perovskite (OG) and baddeleyite (WS) ages, and high resolution ion microprobe ^{206}Pb/^{238}U zircon ages (NEGB). Ages (Table 1) are shown with 2σ errors. A simple mean age of SCLIP is 297.5 ± 3.8 Ma (1σ, N = 33 ages) or alternatively 297.4 ± 0.2 Ma if ages are weighted by their individual errors. Ages in green are from sills/minor intrusions (Monaghan and Pringle, 2004; Van der Voo and Torsvik, 2004; Hamilton, personal communication 2006), red from dykes (Van der Voo and Torsvik, 2004) and black from volcanics (Breitkreuz and Kennedy, 1999; Heeremans et al., 2004a; Corfu and Dahlgren, 2006) and associated larvikites and lardalites* (Dahlgren et al., 1996). Regions/features discussed in the text include: OG, Oslo graben, SG, Skagerrak graben, VG, Västergötland; SC, Scania; NEGB, North-East German graben; CG, Central graben (North Sea); WMVI, West Midland Valley Intrusions; WS, Whin Sill; IS, Iapetus Suture (mid Silurian); TS, Thor Suture (late Ordovician). Volcanic, sill and dyke outlines follow (Heeremans et al., 2004b).

mafic magmatic province with areal extent $>0.1 \times 10^6$ km^2, igneous volumes $>0.1 \times 10^6$ km^3, and maximum life-spans of ~50 Myrs that are emplaced in an intra-plate setting and characterized by igneous pulses of short duration (1–5 Myrs), during which a large proportion of the total igneous volume has been emplaced" (after Bryan and Ernst, 2008); the SCLIP fulfils these criteria.

2. Was the SCLIP generated by a mantle plume?

It has been shown that at eruption all the LIPs of the past 200 My (except for the Columbia River Basalt LIP) lay over the margins of one or other of the Earth's Large Low Shear Velocity Provinces (LLSVPs, Garnero et al., 2007) at the core–mantle-boundary (CMB) and are for that reason deep mantle plume-derived (Burke and Torsvik, 2004; Davaille et al., 2005; Torsvik et al., 2006), but other criteria have been widely used to distinguish deep plume-derived provinces (see Courtillot et al., 1999; Ernst et al., 2005). These criteria include a link to an age-progressive volcanic track, link to uplift, geochemical signatures (e.g. high ^{3}He/^{4}He values) and the existence of giant dyke swarms. The origin for igneous rocks of the Oslo Graben and related areas of NW Europe is debated (Wilson et al., 2004). The SCLIP clearly lacks an age-progressive volcanic track but other provinces of presumed deep mantle origin (including Karroo) do not have tracks, and in general tracks are rare or poorly developed within continents. The reason for expecting a volcanic track in a plume model are age data from the Oslo Graben and related dykes and sills (mostly Rb/Sr) that suggest long-lived and almost continuous magmatic activity from about 300 to 240 Ma (Fig. 2a). Because palaeomagnetic data imply a change from tropical latitudes (ca. 12°N) in the Early Permian to subtropical latitudes (29°N) by the Early Triassic (Fig. 2b, based on a global compilation in Torsvik et al., in press), a deep plume should have led to an age-progressive track of more than 2000 km in length, i.e. from South France to Oslo. However, 'modern' age data from NW Europe mostly yield SCLIP ages between 290 and 300 Ma (Figs. 1 and 2b; Table 1), averaging to 297.5 ± 3.8 Ma (simple mean age; 1σ error) or 297.4 ± 0.2 Ma (weighted mean age). From the Oslo graben, U/Pb ages (298 ± 3 Ma simple mean age) dating the initial and main rift phases (Stages 2 and 3; Ramberg and Larsen, 1978; Olaussen et al. 1994) cluster between 302 and 298 Ma (Figs. 1 and 2b), and not over an interval of 25–30 My as indicated by Rb/Sr ages (Fig. 2a) that clearly underestimate the true age. Younger magmatism occurred in the Oslo rift, such as Late Permian (?)

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