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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.

Keywords: Large Igneous Provinces; plumes; plate reconstructions; Pangea; large low shear velocity provinces; core mantle boundary; deep mantle stability

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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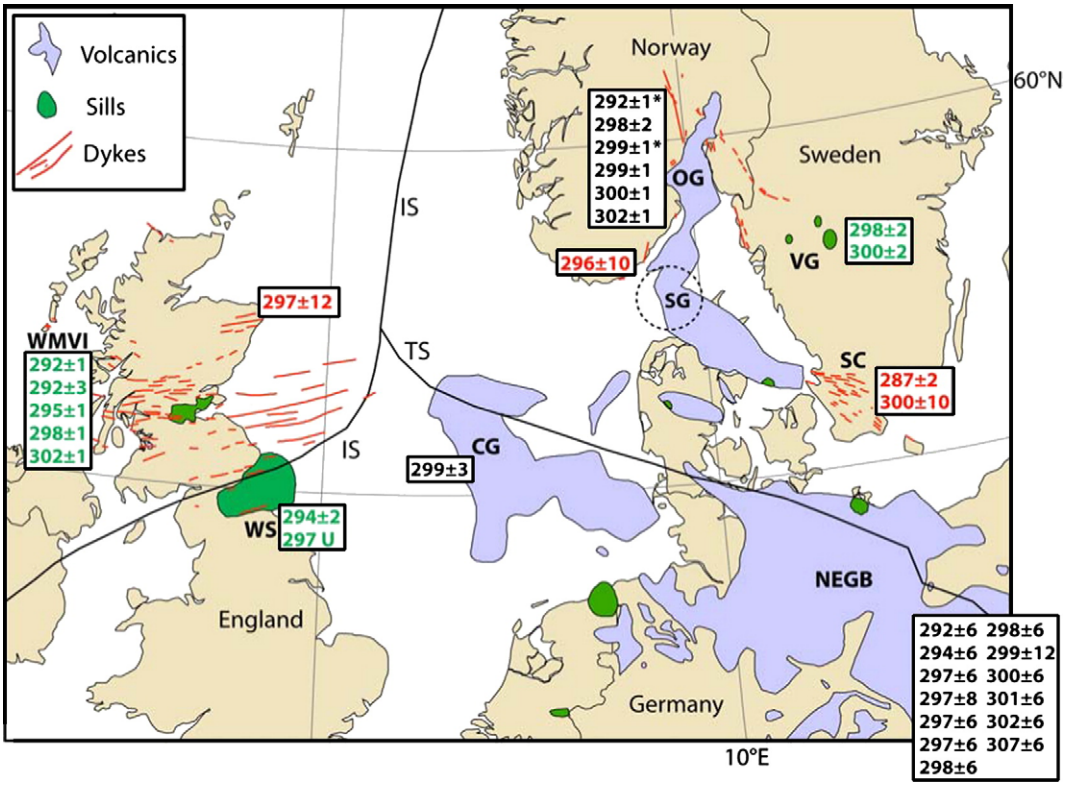

Fig. 1. Map of NW Europe showing the distribution of c. 290–300 Ma volcanics (228.000 km^2), sills (14,000 km^2) and dykes (3353 km in total length). These magmatic products with an estimated volume around 0.5×10^6 km^3 form the SCLIP. Compiled ages (see also age histogram in Fig. 2) are all 'modern' ^{40}Ar–^{39}Ar ages (mostly hornblende, biotite and feldspar ages), thermal ionization mass spectrometry U/Pb zircon and perovskite (OG) and baddelyeite (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 $>0.1\times10^6$ km^2, igneous volumes $>0.1\times10^6$ 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 (?)

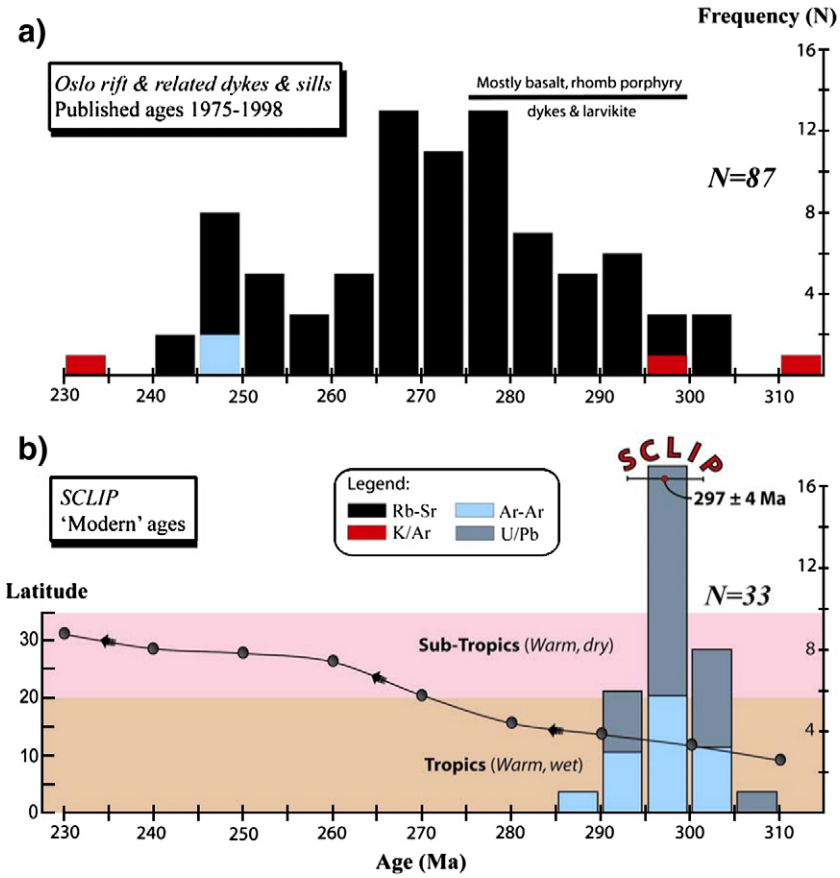

Fig. 2. (a) Frequency distributions of published (1975–1998) isotopic age data from the Oslo rift and presumed related dykes and sills (Torsvik and Eide, 1998). The majority of these isotope ages (82 out of 87) are Rb/Sr ages that often underestimate the true age (see text) (b) 'Modern' age data from NW Europe (Fig. 1; Table 1), including U/Pb ages from the Oslo Graben. Collectively these SCLIP ages average to 297.4±3.9 Ma. 5 My time windows in histograms. The predicted latitude curve for a location near Oslo (60°N, 10°E) is calculated from a global palaeomagnetic apparent polar wander path (Torsvik et al., in press) and shows that Oslo (Baltica/Europe) drifted from low northerly tropical latitudes (Late Carboniferous) and into subtropical latitudes (Late Permian) during Late Paleozoic–Early Mesozoic times.

granitic batholiths and Early Triassic dykes in the northernmost areas (Torsvik et al., 1998), but we do not consider these related to a plume and the SCLIP.

Evidence for normal to only slightly elevated mantle temperature (Neumann 1994) has from time to time been used as argument against a plume origin. LIP generating plumes have risen from the CMB but near surface temperatures need not be elevated because partial melting of mantle rock to generate basalt can dissipate the heat associated with a newly risen plume. Evidence of an elevated plume temperature in rock composition is not to be expected and it is the large volumes (~0.5 mill. km^3; estimated from Breitkreuz and Kennedy, 1999; Neumann et al., 2004) of erupted rock that indicate the short-term proximity of a hot source. Because of (i) huge volume and areal extent of erupted rock, (ii) short interval of eruption and (iii) convergent dyke swarms we here test the idea (Section 4) that the SCLIP was generated by a mantle plume, that we call the Skagerrak plume.

3. Lithospheric controls on the Skagerrak plume eruption site

The causal relation between plumes and rifting has been much discussed (e.g. Courtillot et al., 1999). Some plumes of presumed deep-seated origin, including the Central Atlantic Magmatic Province (CAMP), Karroo, Deccan and Tristan (Fig. 3), erupted into existing rifts (Burke et al., 2003). This can be attributed to "upside-down drainage" by which a plume impinging on the base of the lithosphere generates basaltic magma that travels up-slope to a thin part of the lithosphere (Sleep, 1997, 2006), such as an existing rift, before eruption. The Skagerrak plume eruption site provides another example of the eruption of a plume into a rift, although in this case the rift has not been shown to be significantly older than the time of eruption of igneous rocks of the SCLIP. From the evidence of convergent dykes (Fig. 1) the estimated site where the centre of the Skagerrak plume impinged on the lithosphere lies within a ~150 km diameter circular area around 57.5°N and 9.0°E in the Skagerrak graben (Ernst and Buchan, 1997). The graben is located, as many intra-continental rifts are, close to an older suture zone, in this case the Late Ordovician Thor suture (Cocks and Torsvik, 2005) (Fig. 1). The oldest rocks in the mapped individual rifts of the Skagerrak graben and their extension into the Kattegat are occurrences of Lower Rotliegende (~297 Ma) volcanic rocks and a sill in well penetrations (Heeremans et al., 2004a). We suggest that those are rocks related to the Skagerrak plume and that the establishment of the rift structure may have been as late as the time of the eruption.

Table 1
'Modern' age data from NW Europe (Figs. 1 and 2b)

Locality, country	Rock type	Age±2σ	Method	Mineral	Ref
Larvik, Norway	Lardalite	292±1	U/Pb	Zircon	1
Skien, Norway	Ignimbrite	298±2	U/Pb	Titanite	2
Larvik, Norway	Larvikite	299±1	U/Pb	Zircon	1
Skien, Norway	Lava	299±1	U/Pb	Perovskite	2
Brunlanes, Norway	Lava	300±1	U/Pb	Perovskite	2
Brunlanes, Norway	Lava	302±1	U/Pb	Perovskite	2
Arendal, Norway	Dyke	296±10	$^{40}Ar/^{39}Ar$	Whole rock	3
Central Graben, North Sea	Lava	299±3	$^{40}Ar/^{39}Ar$	Whole rock	7
Mt. Billingen, Sweden	Sill	298±2	$^{40}Ar/^{39}Ar$	Plagioclase	4,3
Mt. Billingen, Sweden	Sill	300±2	$^{40}Ar/^{39}Ar$	Whole rock	4,3
Scania, Sweden	Dyke	287±2	$^{40}Ar/^{39}Ar$	Plagioclase	4,3
Scania, Sweden	Dyke	300±10	$^{40}Ar/^{39}Ar$	Plagioclase	4,3
Peterhead, Scotland	Dyke	297±12	$^{40}Ar/^{39}Ar$	Plagioclase	3
Cathcart, Scotland	Sill	292±1	$^{40}Ar/^{39}Ar$	Biotite	5
Lennoxtown, Scotland	Sill	292±3	$^{40}Ar/^{39}Ar$	Biotite	5
Carskeoch, Scotland	Intrusion	295±1	$^{40}Ar/^{39}Ar$	Hornblende	5
Androssan, Scotland	Sill	298±1	$^{40}Ar/^{39}Ar$	Hornblende	5
Craigen-Avisyard, Scotland	Intrusion	302±1	$^{40}Ar/^{39}Ar$	Biotite	5
Whin Sill, England	Sill	294±2	$^{40}Ar/^{39}Ar$	Plagioclase	4,3
Whin Sill, England	Sill	297	U/Pb	Baddelyeite	6
Petersberg, Germany	Lava	292±6	$^{206}Pb/^{238}U$	Zircon	8
Petersberg, Germany	Lava	294±6	$^{206}Pb/^{238}U$	Zircon	8
Wetting, Germany	Lava	297±6	$^{206}Pb/^{238}U$	Zircon	8
Friedland core, Germany	Lava	297±8	$^{206}Pb/^{238}U$	Zircon	8
Mirow core, Germany	Lava	297±6	$^{206}Pb/^{238}U$	Zircon	8
Kotzen core, Germany	Lava	297±6	$^{206}Pb/^{238}U$	Zircon	8
Penkun core, Germany	Lava	298±6	$^{206}Pb/^{238}U$	Zircon	8
Lobenjun, Germany	Lava	298±6	$^{206}Pb/^{238}U$	Zircon	8
Friedland core, Germany	Lava	299±12	$^{206}Pb/^{238}U$	Zircon	8
Mirow core, Germany	Lava	300±6	$^{206}Pb/^{238}U$	Zircon	8
Landsberg, Germany	Lava	301±6	$^{206}Pb/^{238}U$	Zircon	8
Holzmuhlenthal, Germany	Lava	302±6	$^{206}Pb/^{238}U$	Zircon	8
Schwerz, Germany	Lava	307±6	$^{206}Pb/^{238}U$	Zircon	8

Ref = Reference; (1) Dahlgren et al. (1996), (2) Corfu and Dahlgren (2006), (3) Van der Voo and Torsvik (2004), (4) Timmerman, pers. comm., (5) Monaghan and Pringle (2004), (6) Hamilton, pers. comm., (7) Heeremans et al. (2004a), (8) Breitkreuz and Kennedy (1999).

Not only are intra-continental rifts commonly developed, as the Skagerrak graben is, in proximity to older suture zones but intra-continental rifts are also sometimes reactivated in later tectonic episodes. The Oslo rift has been suggested to overlie and to record reactivation of a Late Precambrian (Vendian) intra-continental rift. The presence of such a rift has been inferred from the proximity to the Oslo graben of the 583±15 Ma Fen alkaline igneous rock and carbonatite complex (Burke, 1978; Meert et al., 1998) and the contemporary Alnö carbonatite (584±7 Ma) in Sweden (Meert et al., 2007). Both are considered related to a Vendian rifting event that immediately preceded the formation of a rifted continental margin to Baltica in latest Precambrian times (Cocks and Torsvik, 2005).

Plume-related basalt may erupt into a rift at a site that occupies a relatively small area, possibly no more than 200 km in diameter, but magma from such small sources has been shown capable of propagating rapidly, presumably within the lithosphere, for more than 1000 km from original plume eruption sites (Marzoli et al., 1999). Propagating magma forms dykes, sills and lavas that erupt into existing and commonly actively extending rifts. CAMP plume magma erupted at ~200 Ma into an active Triassic rift of the east coast of North America and propagated within rifts as far as Canada and Brazil (Marzoli et al., 1999). SCLIP magma appears to have propagated to Scotland (~1000 km) and Northern England forming dykes, sills and lavas that we assign to the SCLIP on the basis of age, dyke trends (Fig. 1) and volume. Those rocks were erupted into the Midland Valley rift that had been active through much of Carboniferous time (Monaghan and Pringle, 2004). SCLIP magma also propagated to the north and south of the Midland Valley in a 500 km wide dyke swarm and into Northern England in the Great Whin sill of County Durham (Fig. 1). To the east of the plume eruption site rocks of the SCLIP have been penetrated in wells in rifts beneath the Kattegat but SCLIP volcanic rock is much more abundant in the sub-surface of the North German and North Sea foreland basins (Heeremans et al., 2004b).

4. Relationship of the Skagerrak LIP eruption site to the deep mantle

Today two large low shear wave velocity (δV_s) regions of the deep mantle, the LLSVPs, are recognized as the most prominent features of all global shear-wave tomographic models. Those well-defined African (Fig. 3) and Pacific LLSVPs are isolated within the faster parts of the deep mantle. Using existing tomographic results Torsvik et al. (2006) found steep horizontal δV_s gradients to be concentrated along the margins of the two LLSVPs at the CMB close to the 1% slow δV_s contour, which forms faster–slower-boundaries (FSB) within the deep mantle.

LIPs at the Earth's surface when reconstructed over the past 200 My to their original eruption sites become concentrated radially above the margins of the African (Fig. 3) and Pacific LLSVPs close to the CMB. This correlation has been established by using paleomagnetic as well as fixed and moving hotspot reference frames. The long-term persistence of the LLSVPs is consistent with independent evidence that they are compositionally distinct and are not just simply hotter than the material making up the rest of the deep mantle (Torsvik et al., 2006 and references therein). The finding that the majority of LIP sources have been generated from sites on the present day LLSVP margins at the CMB requires that within resolution those margins have remained in their present positions with respect to the spin axis for at least 200 My. That led us to consider whether older LIPs and large magmatic events not classified as LIPs in the literature would yield similar results. An obvious LIP to consider was the ~251 Ma Siberian Trap LIP but when that LIP is reconstructed paleomagnetically to its eruption site, it is clear that it was not associated with either the African or the Pacific LLSVP, but at its eruption time rose from a FSB linked to a small isolated low-velocity region at the CMB that borders a prominent slab graveyard volume (Fig. 3).

The establishment of an 'absolute' reference frame (Torsvik et al., in press) for the motion of objects at the Earth's surface is a required critical input to mantle convection simulations oriented

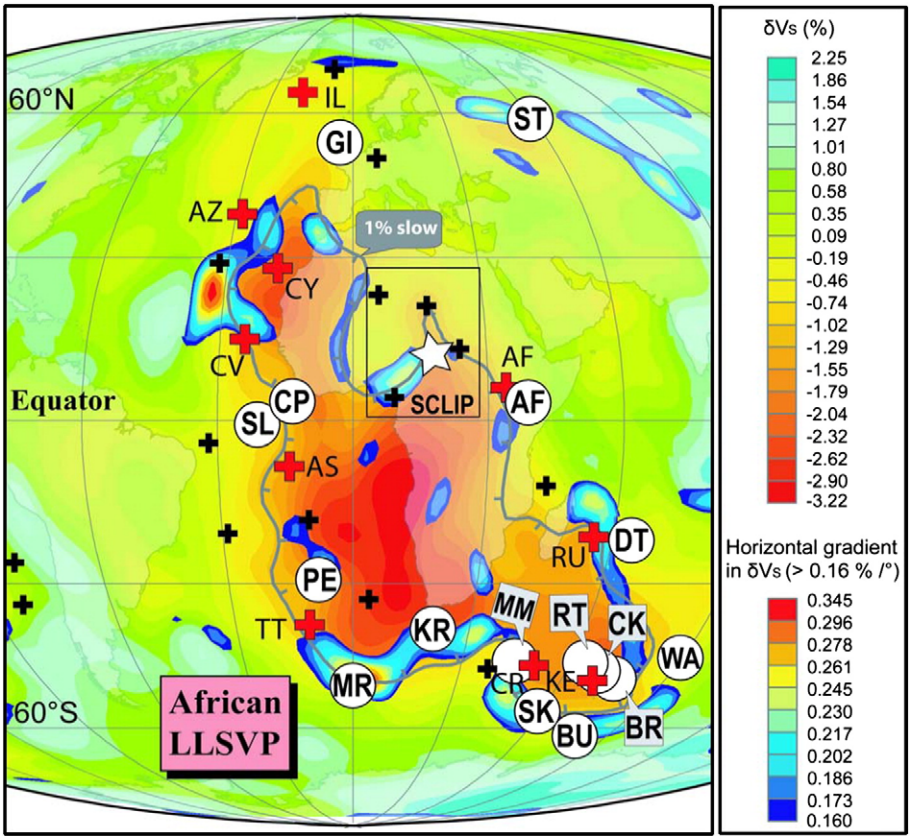

Fig. 3. Reconstructed LIP eruption sites in the Indo-Atlantic realm (annotated circles; extracted from Torsvik et al., 2006) and hotspots (crosses; Steinberger, 2000; Montelli et al., 2006) draped on the SMEAN (Becker and Boschi, 2002) shear wave velocity anomaly (δV_s) model for 2800 km depth. The −1% contour (1% slow) is shown in grey. Horizontal gradients (red-to-blue contours) in shear wave velocity anomaly (%δV_s/°) are indicated where they exceed 0.16%/°. Hotspots argued to have originated from deep plumes (IL, Iceland; AZ, Azores; CY, Canary; TT, Tristian; RU, Reunion; AF, Afar; AS, Ascension; CR, Crozet; CV, Cap Verde; KE, Kerguelen) are shown as enlarged red crosses (Courtillot et al., 2003; Montelli et al., 2004, 2006). Our reconstruction of the Skagerrak-Centered LIP (SCLIP, 11°N, 16°E; open star) shows that it was located near the 1% slow contour and a high gradient, in the vicinity of several active hotspots (Cameroon, Darfur and Tibesti) and some 1500 km from the present Afar hotspot. LIP abbreviations (mean eruption ages in Ma) are: AF, Afar Flood Basalt (31); GI, Greenland/Iceland (54); DT, Deccan Traps (65); SL, Sierra Leone Rise (73); MM, Madagascar/Marion (87); BR, Broken Ridge (95); CK, Central Kerguelen (100); SK, South Kerguelen (114); RT, Rajhmahal Traps (118); MR, Maud Rise (125); PE, Parana-Etendeka (132); BU, Bunbury Basalts (132); KR, Karroo Basalts (182); CP, CAMP (200); ST, Siberian Traps (251); SCLIP, Skagerrak-Centered LIP (297).

towards an improved understanding of the deep mantle. In making a palaeomagnetic reference frame for movement back to 297 Ma so that we could determine whether the Skagerrak plume overlay the margin of an LLSVP at the CMB we used zero longitudinal average motion of Africa as the best possible approximation (Burke and Torsvik, 2004; Torsvik et al., in press) in a Pangea A type configuration (Van der Voo, 1993), i.e. NW Africa located adjacent to the Atlantic margin of North America. The SCLIP eruption site is reconstructed to ~11°N and 16°E (south of Lake Chad, Central Africa). The restored SCLIP eruption site indeed projects radially downward onto the margin of the African LLSVP at the CMB, and near the 1% slow contour in the SMEAN (Becker and Boschi, 2002) tomography model at depth 2800 km (Fig. 4). This result is comparable to findings for practically all LIPs since 200 Ma and for most major hotspots (Steinberger, 2000; Courtillot et al. 2003; Montelli et al., 2004, 2006) argued to have a deep plume origin (Fig. 3). One may argue that these findings are sensitive to the choice of tomography model: Torsvik et al. (2006) examined and compared several global shear-wave tomographic models at the CMB. In Figs. 3–4, the 297 Ma SCLIP reconstruction is draped on SMEAN but for comparison and as a sensitivity test we have also reconstructed SCLIP on two pure D" tomography models. Both models also show that the SCLIP eruption site projects onto the LLSVP margin at the CMB, near the ca. 1% slow contour of Kuo et al. (2000) and the ca. 0.8% slow contour in the Castle et al. (2000) model (Fig. 5). Globally, these contours correspond approximately to the 1% slow contour of SMEAN, because the area with<−1% in the SMEAN and Kuo et al. (2000) models is approximately equal to the area with <−0.8% in the Castle et al. (2000) model. The choice of tomography model is thus not critical to conclusions linking SCLIP to long-term heterogeneities in the deep mantle.

Possible sources of error to which we knew our reconstruction was subject included (i) longitudinal uncertainty (assumption of zero longitudinal average motion of Africa), (ii) relative plate circuits (including our choice of a Pangea A reconstruction), (iii) plume advection, (iv) non-dipole field contributions, and (v) true polar wander (TPW). The overall direction of postulated TPW for the last 130 Ma (Besse and Courtillot, 2002; Torsvik et al., in press) is roughly from the present day location of NE Canada/Greenland (60°W) towards the North Pole. This

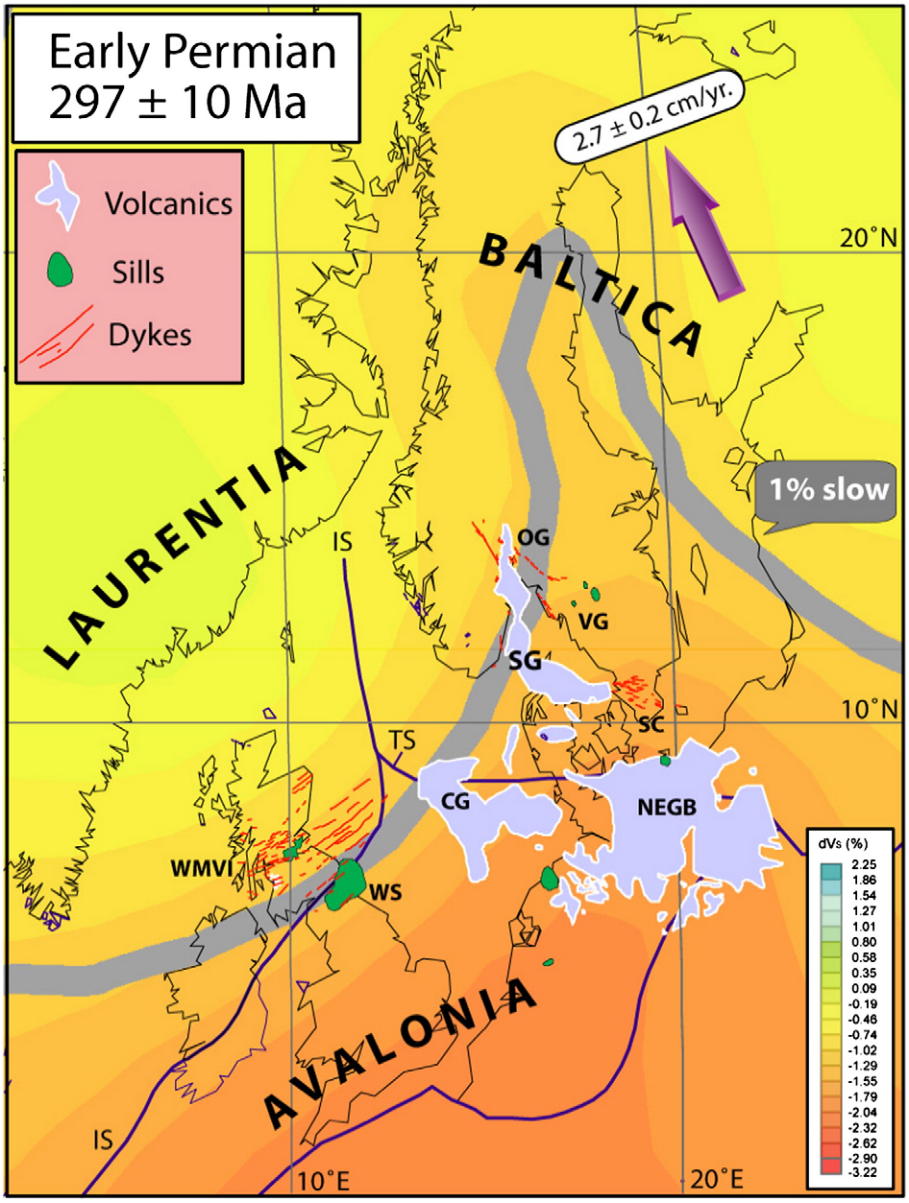

Fig. 4. Expansion/zoom of the box region in Fig. 3 in which we show the distribution of c. 290–300 Ma volcanics, sills and dykes (as Fig. 1). These magmatic products (the SCLIP), along with present coastlines for Scandinavia (Baltica), the British Isles, NW Europe (Avalonia), Greenland (Laurentia) and pre-existing sutures between Laurentia–Baltica (Iapetus) and Baltica–Avalonia (Tornquist/Thor) are all reconstructed to 297 ± 10 Ma using a global running mean (20 Ma window) palaeomagnetic reference frame (Torsvik et al., in press), constructed in South African co-ordinates and restoring all locations to South Africa using appropriate plate circuits in a Pangea A-type configuration. The resulting 'absolute' Euler pole for European elements is latitude = 22.3°N, longitude = 78.4°E, angle = 54.5°, and for Greenland latitude = 36°N, longitude = 76.1°E, angle = 68.8° relative to the spin-axis; at this time Europe was moving NNW with a speed of ca. 2.7 cm/yr. According to our reconstruction SCLIP is estimated to have erupted radially above the 1% slow contour at the CMB.

approximately corresponds, in a reference frame in which the Earth's spin axis is fixed, to a rotation of the African LLSVP around an equatorial location close to its center of mass, very close to the reconstructed SCLIP location (11°N, 16°E). Provided that TPW was in approximately the same or opposite direction before—and this is in fact expected if LLSVPs are associated with highs of the degree-2 non-hydrostatic geoid—the SCLIP will stay close to the LLSVP boundary regardless of TPW, and our result is therefore not sensitive to whether or not there has been TPW.

The reconstructed SCLIP eruption site is based on a global palaeomagnetic apparent polar wander (APW) path. To test the latitude sensitivity we also computed the latitude for the estimated SCLIP centre (57.5°N, 9°E) using only 285–305 Ma European palaeomagnetic poles (Van der Voo and Torsvik, 2004). A European only mean pole (pole latitude/longitude = 41.9°N/167.7°E; 95 percent confidence circle, A95 = 1.9°; number of poles, N = 35) yield a latitude of 11.0 ± 4.8° and thus identical to our global APW path connected through relative plate circuits. Repeating this exercise with only palaeomagnetic data from the Oslo rift and related rocks yield a latitude of 6.9 ± 4.5° (N = 6 poles; 285–305 Ma age range; pole = 37.7°N/167.3°E, A95 = 5.1°), a somewhat lower latitude than our global or purely European mean models but within errors of both.

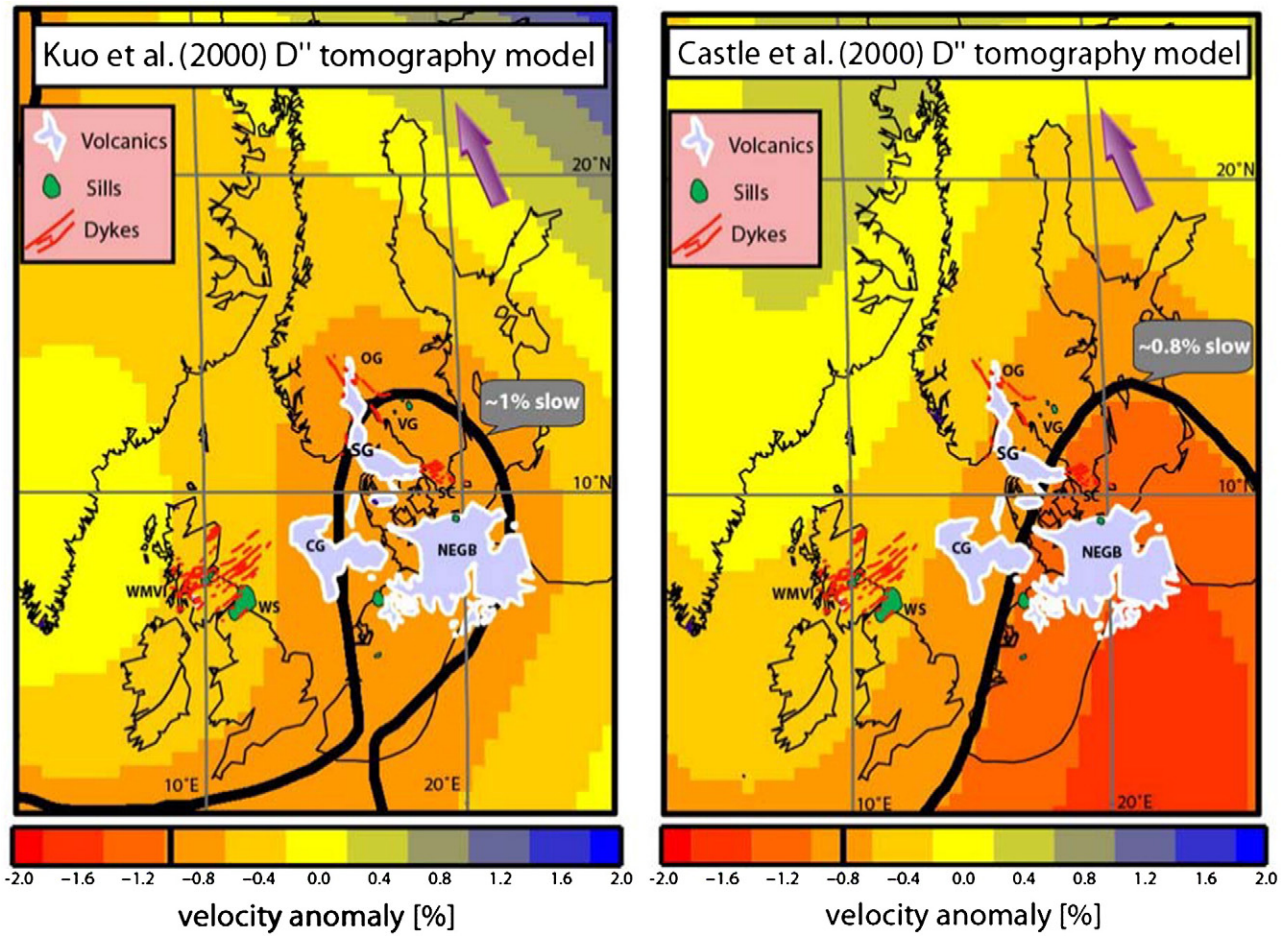

Fig. 5. Similar to Fig. 4 but simplified reconstructions draped on D'' tomography models of Kuo et al. (2000) and Castle et al. (2000). In these models our reconstruction of SCLIP is also estimated to have erupted radially above the African LLSVP margin, and near the ca. 1% (Kuo et al., 2000) and ca. 0.8% (Castle et al., 2000) slow contour at the CMB.

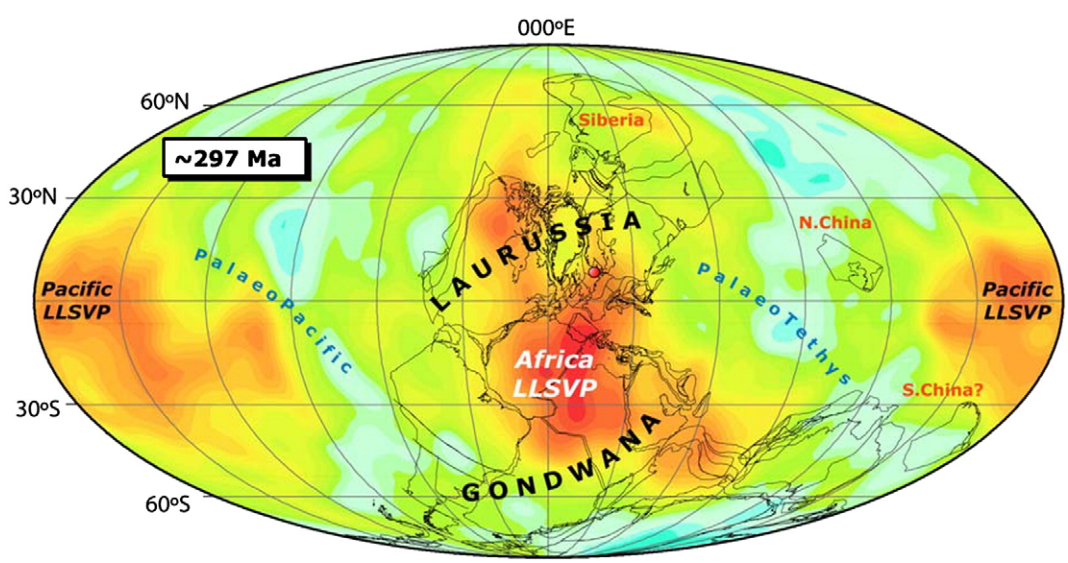

Fig. 6. Early Permian (ca. 297 Ma) Pangea A type reconstruction draped on SMEAN assuming that present-day deep mantle structures, the antipodal Africa (centred beneath Pangea) and Pacific LLSVPs, have existed at least since the Early Permian and have sourced most LIPs erupted at Earths surface. The Gondwana superterrane formed at ca. 550 Ma and included most of South America, Africa, Madagascar, India, Arabia, East Antarctica and Australia. Laurussia formed by the Caledonian (Silurian) collision of Laurentia, Baltica, Avalonia and intervening terranes. Subsequently collided with Gondwana to form Pangea at the end of the Carboniferous. Siberia, North China and South China were not part of Pangea in the early Permian (Torsvik and Cocks, 2004).

Most agree that before the onset of Pangea breakup, the Jurassic Pangea A reconstruction is correct with NW Africa adjacent to NE America (Fig. 6). For Permian times, however, palaeomagnetic poles do not fully agree with a Pangea A fit (e.g. Van der Voo and Torsvik, 2001, 2004) due to substantial continental overlap of Gondwana and Laurussia in the equatorial realm. One possible option to avoid this continental overlap (not favored geologically by the authors) is to modify the Pangea A reconstruction by moving Gondwana eastward (alternatively Laurussia westward) in order to avoid the overlap and later juxtapose them by major lateral shear (as much as 8000 km in some models; i.e. Pangea C) before Jurassic Pangea break-up. If so, this would seriously affect our interpretations, violating the 'zero-Africa' approach, and thus the Pangea A reconstruction in Fig. 6 would be invalid. For many reasons (Van der Voo and Torsvik, 2001, 2004; Torsvik and Cocks, 2004) we consider Pangea A as the only viable reconstruction for the Early Permian (Fig. 6).

Other solutions to the Pangea enigma is to hypothesize sedimentary inclination shallowing or alternatively octupole ($G3 = g^0_3/g^0_1$) field contributions (Van der Voo and Torsvik, 2001; Torsvik and Van der Voo, 2002), and in both cases the Pangea misfit can be explained by a too-far-south position for Laurussia (including the SCLIP) and a too-far northerly position of Gondwana. At around SCLIP eruption time, Torsvik and Van der Voo (2002) hypothesize 10% octupole contributions but since G3 is latitude dependent and most palaeomagnetic sampling sites for Laurussia were at low latitudes, the overall effect is very small, and Laurussia is estimated to be only 1–2° too far south at ca. 300 Ma (see Torsvik and Van der Voo, 2002; their Fig. 9). G3 contributions are thus not critical to conclusions linking SCLIP to heterogeneities in the deep mantle.

5. Conclusions

(1) The SCLIP 297 Ma eruption event in NW Europe covered vast areas, estimated to at least 0.5 million km^2 and thus larger than some other magmatic events characterized as LIPs (e.g. Columbia River and Maud Rise).
(2) Eruption occurred within a relatively short time-span, estimated to ±4 My with existing isotope data but future high-precision U/Pb data may show that the time-span was even shorter.
(3) Based on these characteristics, along with the occurrence of convergent dykes in the Skagerrak graben we conclude that the SCLIP can be characterized as a LIP, and magma propagated more than 1000 km (Scotland) away from its centre (ca. 57.5°N, 9°E)
(4) The restored SCLIP eruption site projects radially downward onto the CMB at the margin of the African LLSVP, and we argue the SCLIP eruption event was triggered by a deep plume from the CMB.
(5) The SCLIP and practically all other LIPs for the last 300 Ma have erupted radially above the African or Pacific LLSVP margin and CMB heterogeneities must therefore have remained the same, at least since shortly after Pangea formation.

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