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LETTERS

Dynamics of Mid-Palaeocene North Atlantic rifting linked with European intra-plate deformations

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The process of continental break-up provides a large-scale experiment that can be used to test causal relations between plate tectonics and the dynamics of the Earth's deep mantle[1,2]. Detailed diagnostic information on the timing and dynamics of such events, which are not resolved by plate kinematic reconstructions, can be obtained from the response of the interior of adjacent continental plates to stress changes generated by plate boundary processes. Here we demonstrate a causal relationship between North Atlantic continental rifting at ∼62 Myr ago and an abrupt change of the intra-plate deformation style in the adjacent European continent. The rifting involved a left-lateral displacement between the North American-Greenland plate and Eurasia, which initiated the observed pause in the relative convergence of Europe and Africa[3]. The associated stress change in the European continent was significant and explains the sudden termination of a ∼20-Myr-long contractional intra-plate deformation within Europe[4], during the late Cretaceous period to the earliest Palaeocene epoch, which was replaced by low-amplitude intra-plate stress-relaxation features[5]. The pre-rupture tectonic stress was large enough to have been responsible for precipitating continental break-up, so there is no need to invoke a thermal mantle plume as a driving mechanism. The model explains the simultaneous timing of several diverse geological events, and shows how the intra-continental stratigraphic record can reveal the timing and dynamics of stress changes, which cannot be resolved by reconstructions based only on plate kinematics.

Intra-plate basin inversion structures in Europe (Fig. 1) formed initially by transverse shortening and erosion of the central parts of Palaeozoic and Mesozoic era sediment-filled rifts and troughs in response to compressional pulses during the Late Cretaceous, particularly the Campanian and Maastrichtian ages[4]. The shortening produced an internal lithospheric load, as uplifted and eroded lighter sediments were replaced by more compacted sediments and crystalline crust[5]. The presence of these loads and their longevity are corroborated by positive Bouguer gravity signatures[6] along the inversion zones and by the occurrence of flexurally controlled asymmetric primary marginal troughs flanking most of the European inversion structures[5]. The depths and widths of the flexural troughs reflect the magnitudes of the loads and the apparent elastic thickness of the lithosphere, which is of the order of 5–10 km in the basin settings of the European inversion structures[5].

According to the thin elastic plate model (a widely adopted proxy for the effects of low-stress loading of more complex lithospheric rheologies), such flexures provide sensitive barometers of changes in the in-plane tectonic stress[7]. Compression perpendicular to the strike of the structure deepens the flexure, while extension shallows it, and such effects can be preserved by the sedimentary record. Thus, a sudden release of in-plane compression has been invoked to explain the change of deformation style in the evolution of European inversion structures in the mid-Palaeocene (beginning in the Late Danian age, ∼62 Myr ago) from one of compressional shortening to one of

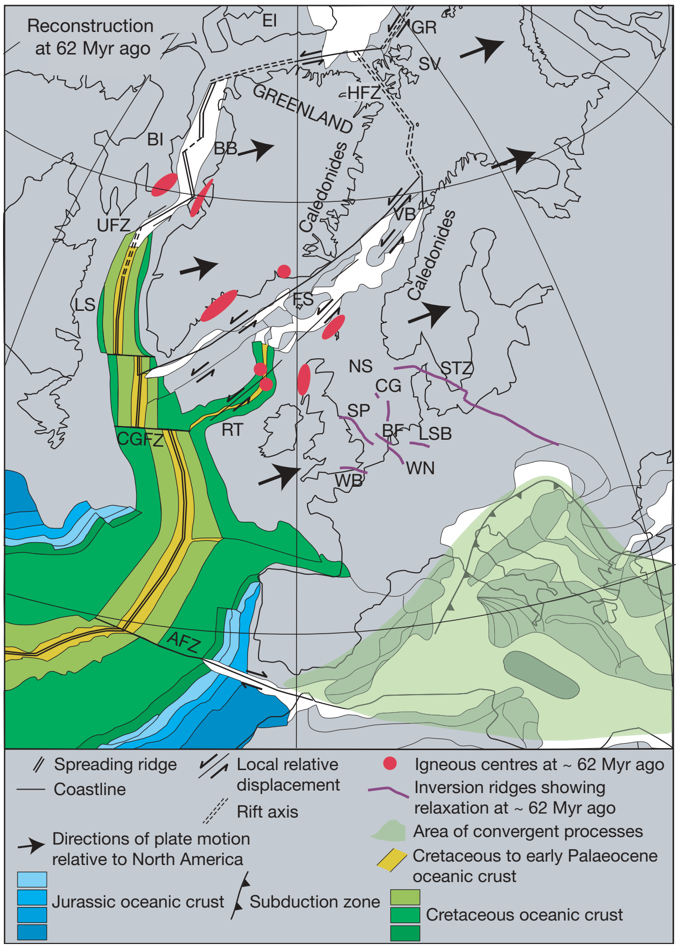

Figure 1 | Regional geological reconstruction[27] at ∼62 Myr with present-day coast lines. For modelling purposes, the complex zone of north–south convergence inferred between Europe and Africa is taken to be a single discrete plate boundary. AFZ, Azores fracture zone; BB, Baffin Bay; BF, Broad Fourteens basin; BI, Baffin Island; CG, Central graben; CGFZ, Charlie–Gibbs fracture zone; EI, Ellesmere Island; FS, Faeroe–Shetland trough; GR, future Gakkel rift; HFZ, Hornsund fault zone; LS, Labrador Sea; LSB, Lower Saxony basin; NS, North Sea basin; VB, Vøring basin; RT, Rockall trough; SP, Sole Pit High; SV, Svalbard; UFZ, Ungava fault zone; WB, Weald–Boulonnais area; WN, West Netherlands basin.

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non-ruptural doming of a wider area[5]. This plate-wide stress change has also emerged from regional microtectonic fault studies[8], but is most accurately dated in the flexural trough along the Sorgenfrei–Tornquist Zone (STZ) of the eastern North Sea area, where the Palaeocene stratigraphy is known in detail (Figs 1, 2). The early Danian deposits (nannoplankton Palaeogene NP1–early NP4; see Fig. 2) record a deepening in the direction of the inversion axis, indicating that compressional shortening was still occurring at this time. The late Danian and Selandian (middle NP4–NP7) depositional centre (depocentre), however, occurs in a more distal position that is consistent with an upward flexural doming of the central inversion ridge at the onset of the Late Danian, and an associated flexural downwarp, creating a secondary marginal trough[5]. The amplitude of the flexure is of the order of 10^2m.

Similar but less stringent timing constraints can be derived from other European inversion zones. The Weald–Boulonnais area, for example, is flanked by Palaeocene depocentres. The northernmost depocentre, which was initially in a continental setting that prevented sedimentation before flooding, occurred slightly before the Selandian–Thanetian boundary (~58.5 Myr ago)[5]. The onset of flexural relaxation of inversion structures in the Netherlands is constrained to be during the Middle Palaeocene (early Selandian, ~61 Myr ago), marked by the occurrence of reworked late Cretaceous nannofossils in Middle Palaeocene deposits, derived from erosion of the late Cretaceous inversion ridges[5].

Neither a drop in eustatic sea level at ~62 Myr ago nor differential compaction effects can explain the plate-wide synchronicity of the mid-Palaeocene shifts in depocentres. In the STZ, for example, the lower to middle Danian deposits (NP1–early NP4, Fig. 2) are thin or missing where the (post-62 Myr ago, middle NP4–NP6) secondary marginal trough is thickest. Furthermore, the Danian sediments are entirely autochthonous and biogenic, without any indication of reworking, which would be expected if a sea level drop had been involved.

Thus, a fundamental change in the intra-plate stress field of Europe at ~62 Myr ago is an appropriate and convincing explanation for the intra-continental sedimentary record[5] and the regional history of fault patterns[8]. This change reduced the compressional component perpendicular to the strike of the inversion structures. Here, we analyse how this change might be related to the following two stress-generating, plate-tectonic events affecting the Arctic, the North Atlantic and the European and African continents.

(1) The impingement of a major thermal mantle plume on the base of the North Atlantic lithosphere. At ~62 Myr ago, there was an almost simultaneous outbreak of volcanism on Baffin Island[9], East and West Greenland[10], in the Hebridean igneous province of northwest Scotland and environs[11] and in the Rockall trough[12]. This magmatic episode predated the eruption of the voluminous flood basalts at ~56 Myr ago[10] along the North Atlantic spreading ridge. The synchronicity of volcanism over a large area has typically been taken to mark the rapid spreading of the plume head at the base of the lithosphere. Such an event would cause isostatic uplift and a change in in-plane stress that would affect the flexural equilibrium of the surrounding lithosphere.

(2) Cessation of north–south convergence between Africa and Europe. Plate kinematic reconstructions strongly suggest that the north–south convergence of Africa and Europe ceased for a period of ~10 Myr during the Palaeocene[3]. The dynamic meaning of this convergence break is not known. It may represent a change in the mode of Alpine collision from the subduction of the intervening ocean (Tethys) exerting compression on Europe, to the subduction being replaced by increasing compression in the continental plates[13,14].

We quantified the effects of the two mid-Palaeocene stress-changing tectonic events on the flexural state of the European lithosphere by calculating stress propagation on an elastic spherical shell and using the flexure equations of an elastic plate. The effects of a mantle plume are simulated by using the gradient of its contribution to lithospheric potential energy as body force in the stress equilibrium equations. The generalized effect of Africa pushing on the Eurasian lithosphere is obtained by displacing northern Africa

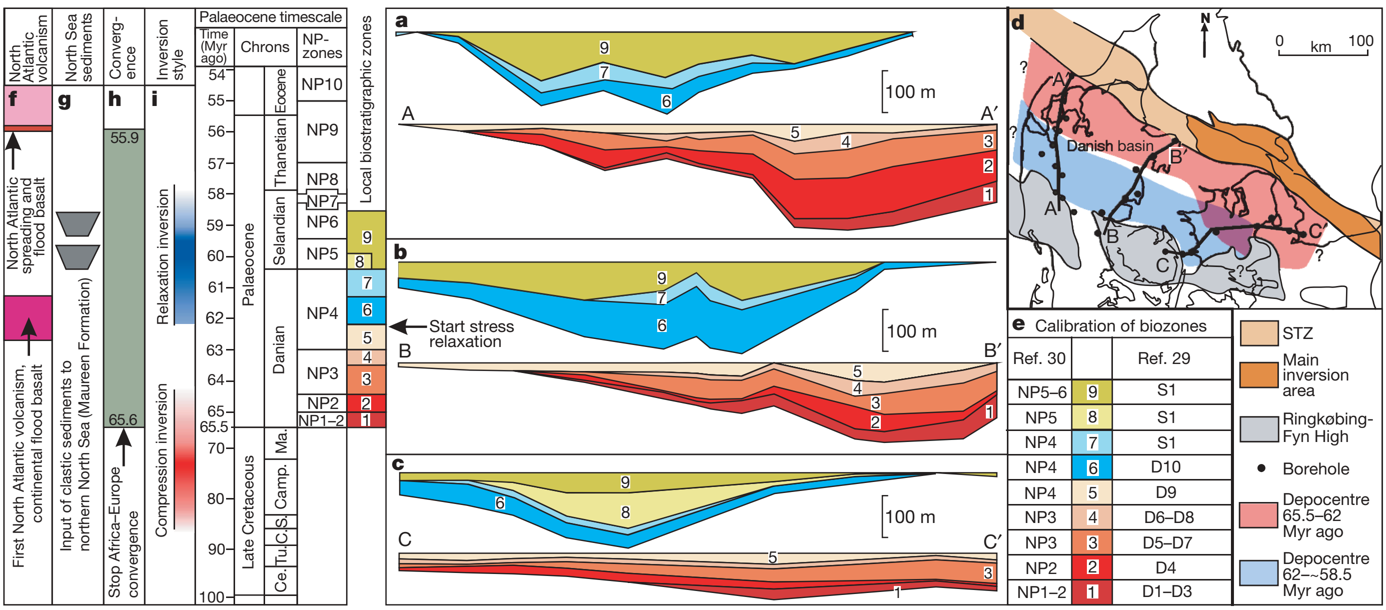

Figure 2 | Correlation of Palaeocene[28] geological events. **a–c**, Sections across the marginal trough of the STZ showing the distribution of lower and middle Palaeocene (Danian, Selandian) deposits subdivided into nine calcareous nannoplankton (biostratigraphic) zones, each plotted using two datum levels. An abrupt shift in the depocentre occurred at ~62 Myr ago (between nannoplankton zones 5 and 6), reflecting a change from compressional to relaxational inversion style. **d**, Location of sections in **a–c** and the shift in depocentre during the Palaeocene. ?, no borehole control. **e**, Correlation between the nannoplankton zonation scheme used in this paper and the local North Sea zonation scheme[29], and the global NP-zonation scheme defined by Martini[30]. **f**, Onset of North Atlantic volcanism and ridge spreading between Greenland and Norway. **g**, Input of clastic sediments into the northern North Sea (Maureen Formation) coinciding with the Danian–Selandian boundary. **h**, Temporary stop in convergence between Africa and Europe bracketed by datings of 65.6 Myr and 55.9 Myr ago[3]. **i**, Timing and shift in intra-plate (inversion) style in the STZ and other inverted basins in the North Sea Basin. Ce., Cenomanian; Tu., Turonian; C., Coniacian; S., Santonian; Camp., Campanian; Ma, Maastrichtian.

towards the north, while keeping the equatorial region to the south a free boundary (see Supplementary Information). Other in-plane lithospheric stress systems also modify the deflections (Fig. 3a), but do not change rapidly at ~62 Myr ago (and therefore do not contribute to changing the flexural equilibrium) and are not considered further. These include ridge push from the central Atlantic Ocean, ridge push from the incipient accretionary plate boundary in the Labrador Sea[15], stresses from the topography of old mountain ranges like the Caledonides, and other density-related lithospheric loads.

We found that even a large mantle plume (80 km thick at the centre with a gaussian half-width of 1,000 km, producing 1,400 m of surface uplift at the centre) at the base of the Greenland and North Atlantic lithosphere produces only minimal stress effects in the European plate. The far-field compression from the plume (about -0.75×10^{12} N m^{-1}) is aligned with the strike of the structures and has only negligible flexural effect, while a small extension (about 0.75×10^{12} N m^{-1}) perpendicular to their strike causes a minor (of the order of 10^1 m) flexural uplift (Fig. 3b). We conclude from this that a plume is not likely to be responsible for producing the well-constrained changes of style of the European inversion structures in the mid-Palaeocene.

The north–south convergence of Europe and Africa in the Late Cretaceous and early Palaeocene in our model contributes a north–south oriented compressional stress component, which depresses (deepens) the European inversion structures (Fig. 3c) because the stress is large and because the structures are favourably oriented. This is in keeping with the style of development of these structures at this time[4]. The magnitude of compression was adjusted to $3\text{–}4 \times 10^{12}$ N m^{-1}, comparable to a ridge push. This could be the main driving mechanism for Africa, which, apart from in the north, was surrounded by spreading ridges at this time. If the suspension of convergence were associated with a further increase in compression[13,14], the flexural deepening would be enhanced according to our model, conflicting with the observed domal flexural uplift of the inversion zones[5]. In contrast, the observed basin inversion style[5] and stress change[8] requires that the convergence break be associated with a relaxation of the convergence-induced stress state in Europe (that is, of the Eurasian plate).

We suggest that this stress relaxation occurred through left-lateral displacements along a fracture system through the North Atlantic and along the (future) Gakkel ridge of the Arctic Ocean, and was eventually involved in, and relaxed by, Arctic Eurasian tectonic processes on the Siberian continental margin[16]. The magnitude of left-lateral displacements on the fracture system is determined by continent-scale relaxation of the elastic strain state of Eurasia and the North American–Greenland plate, which was created and maintained during the Late Cretaceous and earliest Palaeocene Atlantic opening and Africa–Eurasia interactions. This further implies initiation of mid-Palaeocene (~62 Myr ago) separation between Greenland and Eurasia by extension on the Hornsund fault zone and its south-eastern prolongation (Fig. 1). This is documented by early Palaeocene (Danian) basin initiation in Svalbard[17,18] and the occurrence of strongly stretched continental crust along the western margin of Svalbard[19]. The changing geometry along this transfer rift set the scene for the strikingly different structural developments during the latest Palaeocene-earliest Eocene transition to dextral strike slip[18,19], with the onset of spreading in the North Atlantic and the Arctic Ocean.

The timing of the Africa–Europe convergence break to between 65.6 Myr and 55.9 Myr ago is based on sparse ocean magnetic anomaly age data and interpolation of Euler poles of a finite precision[3]. This timing is poorly constrained compared to the ~300,000-year resolution of the continental stratigraphic record at this time (Fig. 2). We therefore suggest that the occurrence of the stratigraphically dated relaxation flexures at ~62 Myr ago marks the onset of the punctuation in relative convergence, which then acquires a dynamic interpretation in terms of the 'escape' of Eurasia from the impinging African continent.

Evidence of mid-Palaeocene left-lateral displacements on fault systems along the proto-North Atlantic exists. Left-lateral displacement on a fracture reaching from the Vøring basin offshore of northern Norway and passing through the Faeroe–Shetland basin and the Rockall trough to terminate in the Charlie–Gibbs fracture zone of the Atlantic Ocean (Fig. 1) has been inferred for the latest Danian–Selandian times[20]. This fracture pathway tracks the trend of the Palaeozoic and Mesozoic rift system that developed during the region's protracted post-Caledonian rifting history. Left-lateral faulting activity with displacements in the 1–2 km range in the north-eastern Vøring basin began in latest Maastrichtian/earliest Palaeocene times and intensified before the onset of ocean spreading at ~56 Myr (refs 21 and 22). Rifting in the Faeroe-Shetland basin, possibly with a strike-slip component, occurred in the early Palaeocene and terminated at ~59.5 Myr before the onset of a brief compressional phase at ~56 Myr (ref. 23), possibly related to the onset of North Atlantic spreading. Furthermore, northeast–southwest extension in the Hebridean igneous province has been inferred from the orientation of dykes in the area[24]. The timing of rifting in the Rockall trough is at present equivocal because of a lack

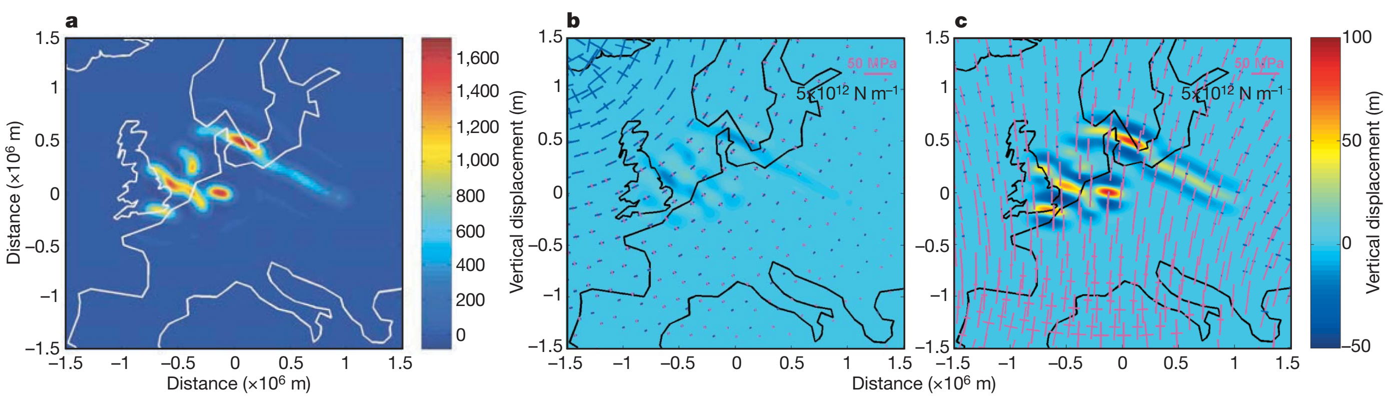

Figure 3 | Model results. Colour bars show vertical displacement. The right colour bar is shared by **b** and **c**. **a**, Vertical displacement of the flexural surface caused by the load of inversion ridges. The deflections host the primary marginal troughs and the inversion ridges (not shown) in their axes. **b**, Flexural effect of swell push from a proto-Icelandic plume. Plume stress could have caused a small flexural uplift because of a small component of extension perpendicular to the strike of the structures. **c**, Flexural over-deepening caused by convergent interaction of Africa and Europe. Flexural uplift of the same magnitude occurred when stresses relaxed because of left-lateral relative motion of North America–Greenland and Europe starting at ~62 Myr ago. Crosses in **b** and **c** represent principal stress directions and magnitudes taken from the spherical stress model (Supplementary Information) and projected onto a flat map for flexural calculations. Purple represents compression (scale bar) and blue represents extension. The flexural elastic plate thickness is 7 km.

of well control and poor seismic resolution below basalts, but it is believed to be mainly of Late Cretaceous age.

In this context, the acceleration of extension and sea floor spreading in Labrador Sea and Baffin Bay at ~62 Myr ago[15], and the associated anti-clockwise, rigid, rotation of Greenland away from Canada, are large-scale expressions of the left-lateral release between Eurasia and the North American–Greenland craton. That this dominates over any dextral displacement of the Greenland block relative to Europe implied by opening in the Labrador Sea–Baffin Bay spreading system suggests that the latter was induced by the European escape rather than driving it. We take the unusual density of pseudotachylyte breccias (dated at 62.9 ± 4.5 Myr ago) along normal and strike-slip faults in East Greenland to indicate the rapidity of this tectonic event[25].

Our model brings a number of diverse geological observations into a unifying framework, including North Atlantic rupture and African–European convergence. The occurrence of mid-Palaeocene stress relaxation in the European continent is well documented by the observation of macrotectonic relaxation flexures[5] and from microtectonic fault analysis[8]. Stress relaxation was simultaneous with the first outbreaks of North Atlantic volcanism ~62 Myr ago. This, together with structural evidence from the North Atlantic and the Svalbard area, and the temporary cessation of African–Eurasian convergence, have led us to conclude that the stress relaxation marked the onset of a plate-scale left-lateral translation between the North American–Greenland and Eurasian plates, which relieved continent-scale elastic strain. This implies the existence of a significant pre-rupture in-plane stress, which could have been responsible for the onset of left-lateral rupture without a causative convective event in the mantle[2]. Continental rupture driven solely by plume uplift would have produced a poloidal[1] (extension/subduction) lithospheric velocity field rather than the toroidal (transform/spin) field inferred here. This further suggests that rapid rifting in the area of the North Atlantic Caledonide suture might have triggered the observed continental-style volcanism[26] starting ~62 Myr ago, thus precluding the requirement of a rapidly spreading plume head under the North Atlantic lithosphere to explain the simultaneous widespread outbreaks of volcanism.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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