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Transient convective uplift of an ancient buried landscape

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Sedimentary basins in the North Atlantic Ocean preserve a record of intermittent uplift during Cenozoic times[1]. These variations in elevation are thought to result from temperature changes within the underlying Icelandic mantle plume[2]. When parts of the European continental shelf were episodically lifted above sea level, new landscapes were carved by erosion, but these landscapes then subsided and were buried beneath marine sediments[3]. Here, we use three-dimensional seismic data to reconstruct one of these ancient landscapes that formed off the northwest coast of Europe during the Palaeocene–Eocene Thermal Maximum. We identify a drainage network within the landscape and, by modelling the profiles of individual rivers within this network, we reconstruct the history of surface uplift. We show that the landscape was lifted above sea level in a series of three discrete steps of 200–400 m each. After about 1 million years of subaerial exposure, this landscape was reburied. We use the magnitude and duration of uplift to constrain the temperature and velocity of a mantle-plume anomaly that drove landscape formation. We conclude that pulses of hot, chemically depleted, mantle material spread out radially beneath the lithospheric plate at velocities of ~35 cm yr^{-1}.

Despite its importance, the detailed spatial and temporal pattern of convective circulation within the Earth's mantle is poorly understood. One exception is the Icelandic plume, whose present-day structure is known from seismic tomographic studies and from geochemical modelling of basaltic rocks[4–6]. This plume underlies a mid-oceanic ridge, which acts as a linear sampler of the plume's temporal history[1,6]. Recent work shows that short-period (~1 Myr) thermal anomalies generated within the plume conduit spread out radially to distances of ~1,000 km from the plume's centre[7]. These anomalies travel beneath adjacent lithospheric plates and are recorded in sedimentary basins fringing the North Atlantic Ocean[2]. Their stratigraphic and geological expression should contain important information about the size, shape and speed of transient anomalies within convecting plumes.

We describe and analyse a buried landscape that was generated by rapid uplift[3]. This landscape was mapped using a volume of three-dimensional seismic reflection data, which covers ~10,000 km^2 on the northwest continental shelf of Europe. The landscape is buried ~2 km beneath the seabed and formed 57–55 Myr ago at a distance of ~600 km from the centre of the Icelandic plume (Fig. 1). To map this irregular surface, we handpicked in-lines and cross-lines (that is, orthogonal vertical slices) every 150 m and tracked the surface throughout the seismic volume. The resultant resolution is ~30 m. On a typical in-line, the landscape is characterized by a weak, rugose reflection that occurs beneath a package of much stronger reflections (Fig. 2a,b). Later folding of this surface was removed by flattening the volume at the top of the overlying Balder formation. Conversion from two-way travel time to depth was carried out using checkshot surveys from 45 wells that penetrate the seismic volume. The effects of sedimentary compaction were removed using porosity–depth estimates[2].

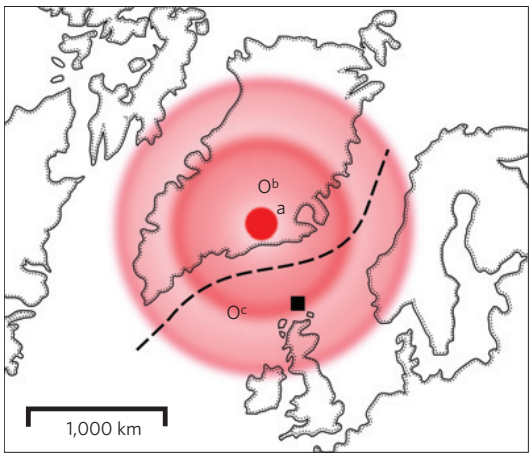

Figure 1 | Icelandic plume. Reconstructed palaeogeography of the North Atlantic Ocean during Late Paleocene times[23]. a, b and c are proposed plume centres of ref. 6, ref. 24 and ref. 1, respectively. Dashed black line, location of continental break-up; black square, region of study shown in Fig. 2; red shading, idealized extent of Icelandic plume, where ripples represent radial spreading of hotter annuli of plume material.

The recovered landscape reveals a pattern of dendritic drainage with steep slopes, typical of regions where poorly consolidated sedimentary rocks undergo rapid erosion (Fig. 2c). To the south and east, topographic highs of ~800 m above the minimum elevation occur. Drainage divides can be traced along their crests. A broad valley with a meandering channel bisects the landscape and terminates in the foreground at a prominent cliff. Above this valley, a network of branching tributaries is observed. Three prominent surfaces occur at ~0.5 km, ~0.8 km, ~0.9 km (that is, green, brown and white shaded surfaces, respectively; Fig. 2c).

This deeply incised landscape is cut into the 58.5–56-Myr-old Lamba formation, which consists of marine deltaic deposits whose flat topset units were deposited at sea level[8]. This formation is largely unreflective and consists of mudstones and siltstones with occasional thin sandy layers. To the south, the landscape progressively oversteps older rocks, notably the ~58.5-Myr-old Kettla Member, a tuffaceous layer located at the base of the

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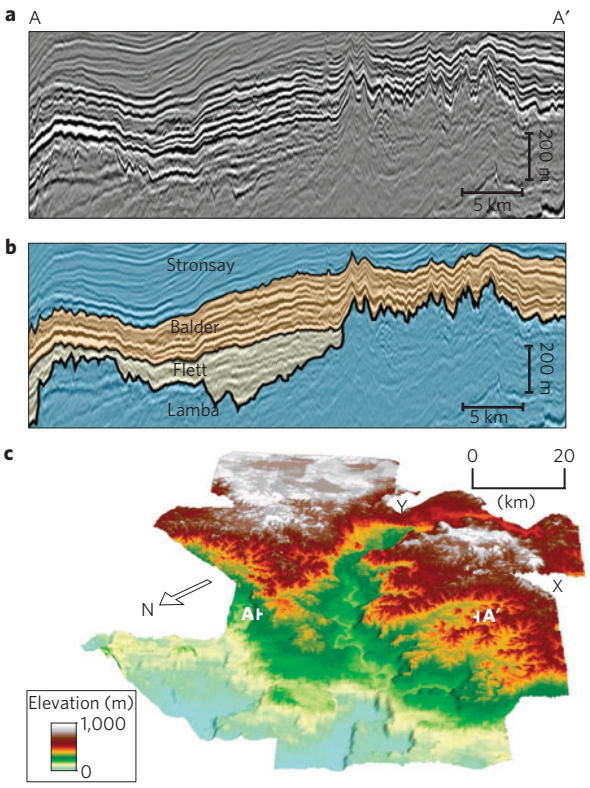

Figure 2 | Seismic imaging of buried landscape. a, Vertical slice through three-dimensional seismic volume. The water depth is ~900 m and the top of the slice is ~700 m beneath the seabed. Black and white bands, reflectivity changes caused by lithological variation. **b**, Geological interpretation. Blue and yellow, marine and terrestrial rocks respectively. Thick line, landscape cut into marine Lamba deposits; thin lines, top of terrestrial Flett and Balder formations. **c**, Perspective view of landscape. Note surfaces at ~0.5 km (green), ~0.8 km (brown) and ~0.9 km (white). A–A′, vertical slice. X and Y, orientation aids (see Fig. 3).

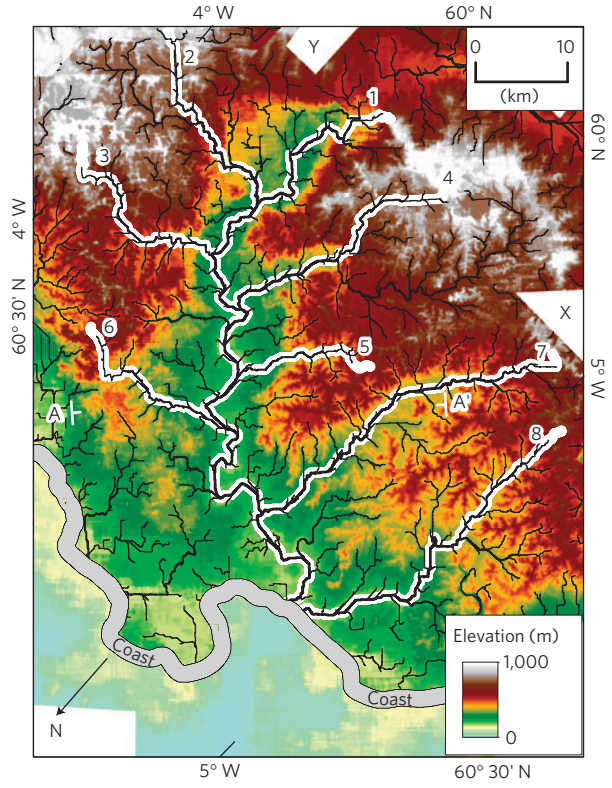

Figure 3 | Topographic map of buried landscape. Numbered black-on-white lines, eight river tributaries traced out by a flow-routing algorithm that reconstructs drainage networks from digital elevation models[11]; grey band, inferred coastline[2]. A–A′, position of vertical slice shown in Fig. 2a; X and Y, orientation aids (Fig. 2c). The line spacing of seismic data is typically 30 m.

Lamba formation. The eroded landscape has been infilled by the 56–54.5 Myr Flett and Balder formations. During the early stages, pollen assemblages and an absence of marine microfauna indicate that terrestrial conditions prevailed. Occasionally, thin mudstones containing dinocysts suggest that short-lived marine transgressions occurred[9]. To the north, the Flett formation lies conformably on the Lamba formation and there is little evidence for drainage incision. This limit of conformable contact is interpreted as the ancient coastline. It coincides with the prominent topographic step and with the basinward extent of Lamba delta lobes[2]. Further south, the Flett formation disappears and the landscape is overlain by mudstones and sandstones of the Balder formation. These rocks contain lignites and oxidized soil horizons, which confirm that the incised surface is terrestrial[9]. The Balder formation is overlain by marine mudstones of the Stronsay group.

These stratigraphic observations show that a buried landscape was generated by transient uplift that lasted 2–3 Myr. Surface envelope mapping indicates that the minimum amount of uplift is 550 m[2], which rules out glacio-eustatic mechanisms[10]. Instead, the landscape could have formed when a thermal anomaly flowed beneath the lithospheric plate. The structure of this thermal anomaly can be determined by analysing the uplift history of the buried landscape. We reconstructed the drainage pattern by calculating flow directions across the landscape[11]. This pattern shows that eight tributaries and their catchments drain the landscape (Fig. 3). Longitudinal profiles (that is, height plotted as a function of upstream distance) reveal that each tributary has a series of knickzones (that is, rapid gradient changes), which match the three prominent surfaces visible in the incised landscape (Fig. 4a). Given the similarity of each profile and the homogeneity of the underlying Lamba formation, it is unlikely that these surfaces and knickzones are lithologically controlled. Instead, the youthfulness of these longitudinal profiles indicates that polyphase uplift was short lived.

We have used these longitudinal profiles to calculate an uplift history[12,13]. The rate of change of elevation along a river profile, $\partial z/\partial t$, is given by

$$\frac{\partial z}{\partial t} = U(t) - \nu A^m \frac{\partial z}{\partial x} + \kappa \frac{\partial^2 z}{\partial x^2} \quad (1)$$

where $U(t)$ is the uplift rate as a function of time only, νA^m is the knickzone velocity, A is the upstream drainage area at any distance x, m is an erosional constant, ν is an advective constant and κ is the diffusivity (Supplementary Information). In ref. 13 it is shown that the most important erosional parameters are m and ν, which trade off negatively against each other. Here, their values are constrained by the duration of landscape exposure, which is ~2.5 Myr. m is usually assumed to be 0.5 and so $\nu = 4.75\,\mathrm{Myr}^{-1}$. This estimate is consistent with rapid erosion rates expected when a landscape is cut into relatively unconsolidated sediments[14–16]. Crucially, different values of m and ν do not significantly alter our results, provided that the knickzone velocity is consistent with the duration of landscape exposure. A is measured directly from the drainage network.

The inverse problem is solved by varying $U(t)$ until the misfit between observed and calculated longitudinal profiles is minimized (Fig. 4). Longitudinal profiles are accurately matched if three discrete phases of uplift are included. These phases have

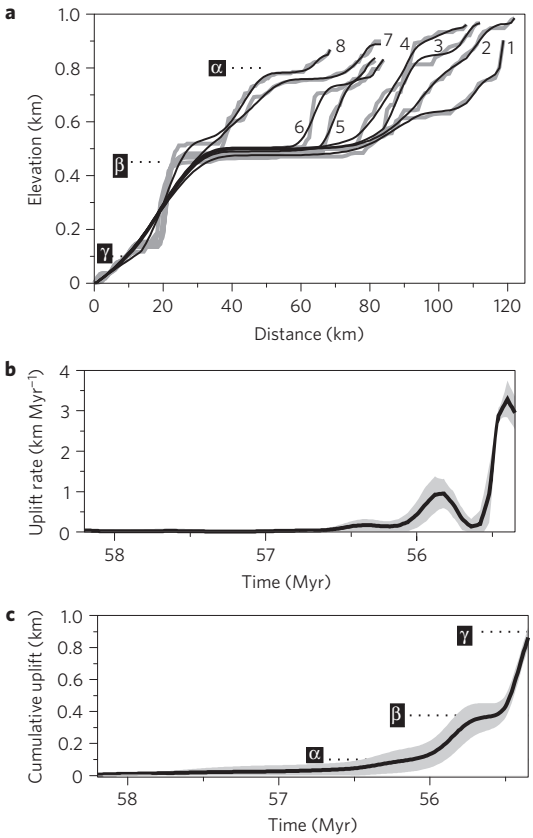

Figure 4 | Uplift histories. a, River profile modelling. Grey numbered lines, observed profiles (Fig. 3); black lines, calculated profiles obtained by varying uplift rate history. Knickzones along river profiles bound low-relief surfaces labelled α, β and γ (Fig. 2c). **b**, Uplift rate history. Black line, uplift rate history calculated from river profiles; grey band, 1σ uncertainty reflecting variation of erosional parameters. **c**, Cumulative uplift history (that is $\int_0^t U\,dt$). Black line, cumulative uplift history; grey band, 1σ uncertainty.

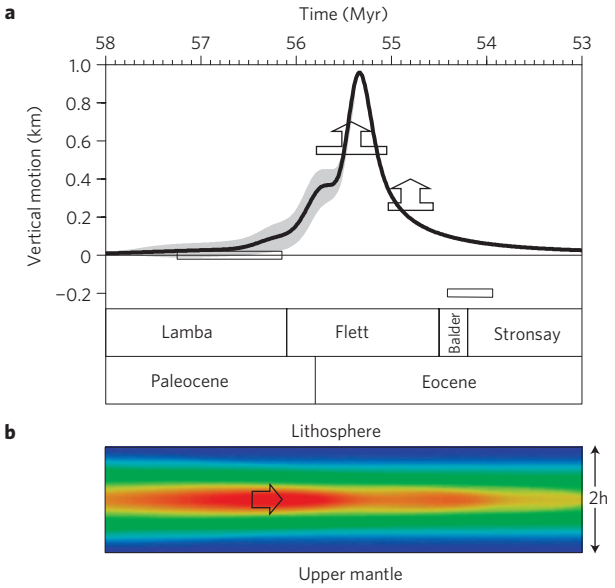

Figure 5 | Model of transient vertical motion. a, Observed and calculated uplift histories. Grey band, uplift history determined from river profiles (Fig. 4); open rectangles with arrows, stratigraphic constraints[2]; solid black line, best-fitting uplift history calculated from complex pulse of hot material[19]. The region subsides by ~200 m between 58 and 53 Myr owing to post-rift subsidence. **b**, Vertical slice through dynamic model of radial flow, where $2h = 200$ km (ref. 25). Viscosity, ν, varies with temperature, T, where $\nu(T) = \nu_0 \exp(B\Delta T)$ with $B = 0.025$. ΔT is the difference between the highest temperature and T. The input is represented as three Gaussian pulses, characterized by height, S, and half-width, δ (Supplementary Information; ref. 19). The time delay between pulses is ~0.4 Myr and their speed is set by the area flux, q (Supplementary Information).

peak uplift rates of 0.5, 1 and 3 mm yr^{-1}, which produce the three elevated surfaces visible in Fig. 2c. The uncertainty envelope for $U(t)$ was calculated by Monte Carlo inversion, whereby 50 inversions were carried out for randomly varying values of m, ν and κ. Total uplift is consistent with previously published estimates[2,17]. Our reconstructed history suggests that uplift peaked at ~55.5 Myr (Fig. 5). Rapid subsidence ensued and the incised landscape was quickly buried.

This complex, transient uplift event can be attributed to the passage of a hot annulus of plume material beneath the lithospheric plate. A similar uplift event is observed 240 km away in the North Sea at 54.5 Myr (ref. 18), which prescribes a radial flow velocity of ~35 cm yr^{-1} beneath the region we have mapped. In a kinematic model of constant flux[19], slugs of hot mantle travel up the plume conduit and then spread out radially by Poiseuille flow. Regional uplift, U, is given by

$$U = \frac{2h\alpha\bar{T}}{1-\alpha T_0} \qquad (2)$$

where $\bar{T}$ is the average temperature anomaly, T_0 is the ambient temperature of the plume, $2h$ is the thickness of the convective layer and α is the thermal expansion coefficient (Supplementary Information).

Our polyphase uplift history suggests that this convective anomaly has a complex internal structure. A simple explanation is that it consists of a series of increasingly hot blobs generated within the conduit of the plume, which flow radially outwards. As the Péclet number is ~4×10^4, radial advection dominates and a tripartite thermal structure will not diffuse away over distances of 600 km (ref. 19). Instead, internal structure is preserved and polyphase uplift is generated. This explanation is corroborated by the present-day structure of V-shaped ridges south of Iceland, where there is evidence for compound, multistranded morphologies that require composite thermal anomalies[7,20]. We use an analytical expression to calculate the temperature structure of the thermal anomaly required to fit the uplift history[19] (Fig. 5a). In this kinematic analysis, the thermal anomaly is made up of three closely spaced hot blobs with average excess temperatures of 15, 60 and 130 °C (see also Supplementary Information). Agreement between theory and observation is good. At 600 km from the plume centre, the ambient plume temperature is ~1,330 °C so the hottest blob has a temperature of ~1,460 °C. This value can be reduced if plume material within the thermal anomaly is compositionally buoyant. Numerical experiments on plume conduits suggest that depleted upper mantle is entrained into plume conduits[21]. As depleted mantle is 0.15 Mg m^{-3} lighter than lower-mantle material, the average temperature of a hot blob can be reduced by ~50°C if up to one-half of the thermal anomaly consists of depleted material. Our kinematic analysis is supported by a fluid dynamical numerical experiment that assumes that hot blobs travel radially outwards in a horizontal layer with depth-dependent viscosity (Fig. 5b). This dynamical simulation shows that composite thermal anomalies maintain their internal structure up to ~600 km from the plume conduit.

In conclusion, we have mapped and analysed a spectacular buried landscape, which contains important clues about otherwise inaccessible details of convective circulation within the Earth's

mantle. Polyphase uplift and subsidence of the landscape show that a composite thermal anomaly flowed horizontally beneath the lithospheric plate. Such anomalies are probably generated by the interaction of discrete solitary waves that flow up plume conduits[22]. Although the existence of solitary waves has been predicted, their passage beneath fringing continental margins as well as our ability to observe their stratigraphic manifestation is both unexpected and significant.

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Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.A.H.

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