Cenozoic exhumation of the southern British Isles

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ABSTRACT

Rocks that crop out across southern Britain were exhumed from depths of as much as 2.5 km during Cenozoic time. This has been widely attributed to Paleocene regional uplift resulting from igneous underplating related to the Iceland mantle plume. Our compilation of paleothermal and compaction data reveals spatial and temporal patterns of exhumation showing little correspondence with the postulated influence of underplating, instead being dominated by kilometer-scale variations across Cenozoic compressional structures, which in several basins are demonstrably of Neogene age. We propose that crustal compression, due to plate boundary forces transmitted into the plate interior, was the major cause of Cenozoic uplift in southern Britain, witnessing a high strength crust in western Europe.

Keywords: British Isles, exhumation, compressional deformation, underplating, plate boundary forces.

INTRODUCTION

The southern British Isles provide perhaps the world's best natural laboratory in which to study the causes of intraplate exhumation because of the preserved Mesozoic–Cenozoic geological record, plate tectonic setting between Atlantic Ocean opening and Alpine collision, and the abundance of data provided by the exploration of petroliferous basins. Cenozoic exhumation controls the geological outcrop pattern, physiography, and the distribution of hydrocarbon resources of the British Isles. In a number of studies, exhumation has been attributed to igneous underplating of the lower crust related to the Iceland mantle plume during the Paleocene (Brodie and White, 1994; Jones et al., 2002), while an alternative view favors shortening of the crust due to plate boundary forces (e.g., Alpine collision) transmitted into the plate interior (Ziegler et al., 1995). Through the analysis and interpretation of the distribution and chronology of Cenozoic exhumation in the southern British Isles, we argue that the tectonic forces responsible for the profound exhumation that shaped the southern British Isles are dominantly compressional rather than resulting from igneous activity. Compressional forces originated from the opening Atlantic Ocean and colliding Alps and have been transmitted in excess of 1000 km into the plate's interior to uplift the British Isles.

Crustal compression and resultant shortening have been dismissed as a cause of Cenozoic uplift and exhumation (Brodie and White, 1994; Jones et al., 2002), despite the long-recognized presence of compressional structures in the southern British Isles and their more recent widespread recognition on the northeast Atlantic margin (Stoker et al., 2005). In order to compare the distribution of exhumation with that of recognized compressional structures, we have compiled 329 estimates of Cenozoic exhumation in the southern British Isles determined using apatite fission-track analysis (AFTA), vitrinite reflectance (VR), and sedimentary rock compaction methods (Fig. 1; GSA Data Repository Fig. DR1 and Tables DR1 and DR2[1]).

DISTRIBUTION AND CHRONOLOGY OF CENOZOIC EXHUMATION

There are major differences between the map of exhumation presented herein and previous maps of Cenozoic exhumation presented in support of the underplating hypothesis (i.e., the Jones et al. [2002] inset maps in Fig. 1). First, there is major short-wavelength variation in exhumation across the southern British Isles: ~1 km variation over ~10 km distance (Fig. 1). It has not been possible to contour exhumation values, other than in some areas of detailed coverage, because there are insufficient data to describe the short-wavelength spatial variation in exhumation. Second, our map indicates significant exhumation in areas beyond the postulated influence of underplating such as the South West Approaches and southern North Sea (Fig. 1). Our data also reveal Early Cretaceous, Paleogene, and Neogene exhumation events, each of varying significance, in different parts of the southern British Isles. This multiple-phase exhumation history is inconsistent with a first-order control related to Paleocene plume-related underplating.

We next discuss the distribution and chronology of exhumation in three areas of the southern British Isles for which detailed data are available (Figs. 2–4). Sedimentary rock porosity decreases (hence sonic velocity increases) with burial, and this decrease is largely irreversible with subsequent exhumation (Hillis, 1995). A detailed picture of exhumation across the Wessex-Weald Basin can thus be obtained from the sonic velocity of the Jurassic Oxford Clay Formation where it is intersected in boreholes in the region, by reference to an undisturbed compaction trend with depth (Fig. 2). Exhumation in the Wessex-Weald Basin is localized over major structures, most notably the Weald anticline and the Portland-Wight disturbance (Fig. 2). Stratigraphic evidence in the Isle of Wight suggests that exhumation may have commenced in mid-late Eocene, with older Eocene and Paleocene rocks eroded (Gale et al., 1999), but the culmination of exhumation is generally considered to be Neogene (House, 1989) (Fig. 2). These results contrast with those of Jones et al. (2002), whose map of their maximum estimate of exhumation shows no variation over the Wessex-Weald Basin (Fig. 1). Jones et al.'s (2002) map of their minimum estimate of exhumation shows a local high, but displaced from the crest of the Weald anticline, and no high over the Portland-Wight disturbance (Fig. 1).

The southern North Sea is largely beyond the region of postulated underplating-related uplift (Fig. 1). Anomalously high sonic velocities within the Upper Cretaceous Danian Chalk Group enable detailed mapping of Cenozoic exhumation around the Sole Pit high and adjacent areas (Japsen, 2000). The structural control

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[1] GSA Data Repository item 2008093, Figure DR1 and Tables DR1 and DR2, exhumation estimates: localities, methods and results, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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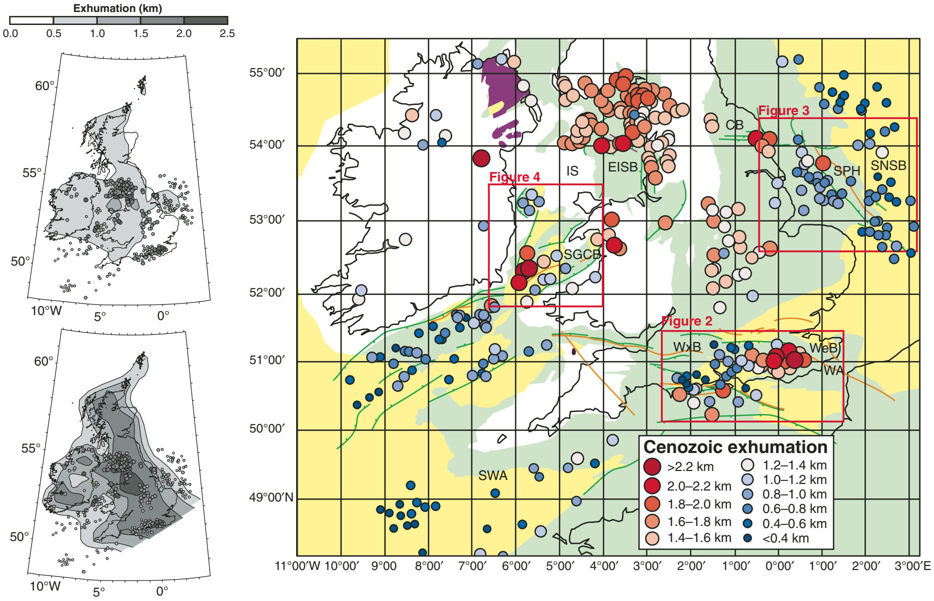

Figure 1. Cenozoic exhumation across southern British Isles. This map shows short-wavelength (~10 km) variations in exhumation and exhumation maxima that coincide with Cenozoic compressional structures (e.g., Weald anticline and Sole Pit high). Shaded areas show sub-Quaternary surface outcrop of Cenozoic (yellow), Mesozoic (light green), Paleozoic and older (white), and Paleogene igneous rocks (purple). Major Cenozoic-aged structures are shown in orange, Mesozoic-aged structures in green. CB—Cleveland Basin; EISB—East Irish Sea Basin; IS—Irish Sea; SGCB—St. George's Channel Basin; SNSB—southern North Sea Basin; SPH—Sole Pit high; SWA—South West Approaches; WA—Weald anticline; WeB—Weald Basin; WxB—Wessex Basin. Gray-scale maps show exhumation estimates from this study superimposed on minimum and maximum estimates of Cenozoic exhumation of Jones et al. (2002). These maps show a regional, long-wavelength pattern of exhumation that is not consistent with the results presented herein.

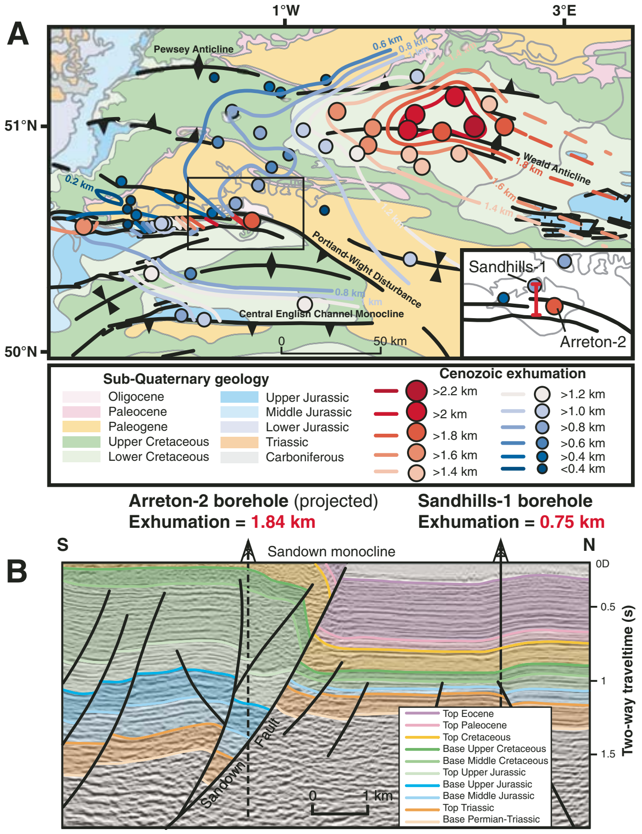

Figure 2. A: Sub-Quaternary geological map of Wessex-Weald Basin with estimates of Cenozoic exhumation. Exhumation is highest (>2 km) along axis of Weald anticline, while exhumation in English Channel is controlled by major compressional structures, e.g., Portland-Wight disturbance. B: Seismic line through Sandown Structure, Isle of Wight (Chadwick and Evans, 2005). This structure is part of the Portland-Wight disturbance and comprises the Sandown fault, overlain by near-vertical northern limb of the Sandown monocline. Lack of stratigraphic thinning on crest of fold by middle Cretaceous–Oligocene strata suggests that compressional deformation and exhumation largely postdate the preserved stratigraphy (i.e., Miocene or younger in age). Majority of the exhumation at Arreton-1 is clearly related to compressional folding and fault reversal, but ~0.75 km of exhumation at Sandhills-1 where the preserved section is largely undisturbed suggests regional component of post-Oligocene exhumation.

on the pattern of exhumation exerted by the northern part of the Sole Pit high and the inverted Cleveland Basin is clear (Fig. 3). Exhumation reaches ~1.5 km on the margins of the Sole Pit high. The Chalk Group is eroded from the crest of the Sole Pit high and the maximum exhumation on its crest (~1.8 km) is estimated from AFTA and VR data from sub–Chalk Group units (Fig. 3). Exhumation has a complex chronology in this area. Compressional structures of Late Cretaceous and Neogene age can be recognized on seismic reflection data (Van Hoorn, 1987) (Fig. 3). Japsen (2000) argued that a component of the structural configuration and exhumation of the Sole Pit high is of mid-Cretaceous age, based on Triassic shale sonic velocities that indicate maximum burial prior to exhumation preceding Chalk Group deposition, but our exhumation estimates are based on Chalk Group sonic velocities and thus only describe the Cenozoic component of exhumation. AFTA data also reveal a Paleocene exhumation phase marked by gentle angular discordance on seismic data (Green, 1989). The age and lack of structural control on the Paleocene event would be consistent with underplating as a cause. However, the overall distribution of exhumation in the southern North Sea is consistent with the major compressional structure of the area (Fig. 3), and causes other than crustal compression may account for, at most, a component of the observed exhumation.

The St. George's Channel Basin and Cardigan Bay Basin are particularly significant for two reasons. First, they are located near the postulated focus of underplating-related exhumation and should therefore provide evidence of substantial Paleocene exhumation. Second, more than 1 km of Paleogene–Neogene sediments are preserved in these basins (Fig. 4), hence the effects of Neogene exhumation can be isolated from those of earlier events. AFTA and VR data from the St. George's Channel Basin indicate as much as 1.5 km of Neogene exhumation across these basins, the highest values being observed over major compressional structures and along the uplifted basin margins (Fig. 4). The Oligocene–lower Miocene sequence preserved at Mochras is overcompacted, demonstrating ~1.5 km of post–early Miocene exhumation (Holford et al., 2005a). AFTA data from the Mochras borehole provide no evidence for substantial Paleocene cooling such as would be observed if exhumation was controlled by Paleocene underplating, and indicate that Early Cretaceous and Neogene cooling dominated at this location (Holford et al., 2005a). The Eocene–Oligocene sequence of the St. George's Channel Basin dips significantly, almost parallel to the underlying Mesozoic, and is truncated by an angular sub-Quaternary unconformity, demonstrating significant Miocene deformation and exhumation (Fig. 4).

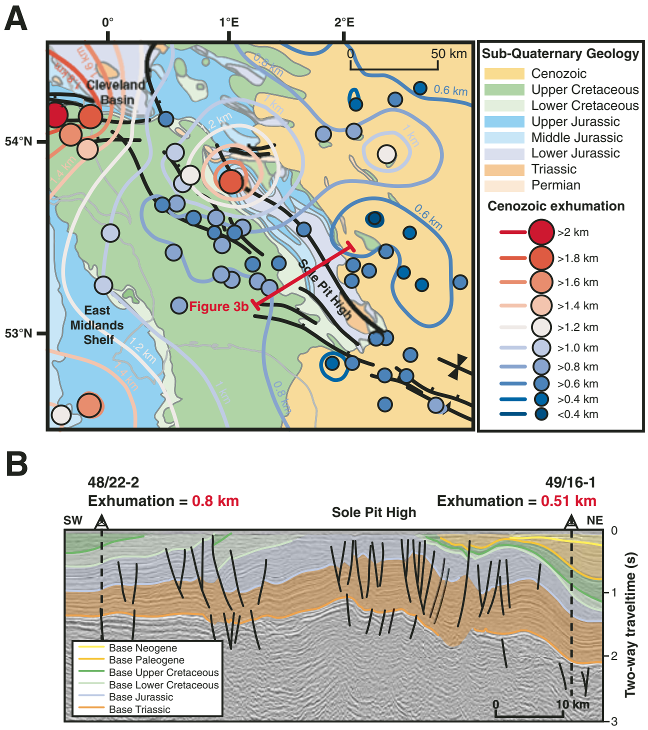

Figure 3. A: Sub-Quaternary geological map of southern North Sea Basin with estimates of Cenozoic exhumation. Exhumation values show maxima over Sole Pit high (SPH) and inverted Cleveland Basin, which are the major compressional structures in area. Similar values of exhumation recorded by Chalk Group sonic velocities either side of SPH suggest additional component of regional Cenozoic exhumation. B: Seismic line through SPH (Van Hoorn, 1987). Exhumation values increase toward crest of the high. Angular unconformity between Paleogene and Neogene apparent at northeast end of section witnesses Neogene compressional deformation.

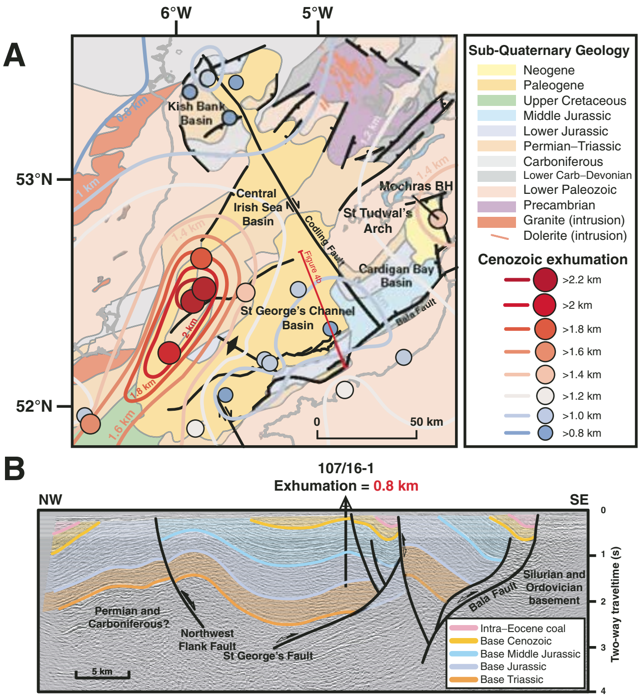

Figure 4. A: Sub-Quaternary geological map of southern Irish Sea with estimates of Cenozoic exhumation (post–70 Ma). Highest exhumation values in the St. George's Channel Basin (SGCB) and Cardigan Bay Basin (CBB) (≤1.5 km) are found near basin margins, where basin-bounding faults were reactivated in compression during the Cenozoic. Higher exhumation values along axis of central Irish Sea Basin (> 2 km) are due to this basin undergoing two phases of exhumation, beginning between 70 and 55 Ma and post–25 Ma, respectively. BH—borehole. B: Seismic line through SGCB. Main depocenter has been folded against basin-bounding Northwest Flank fault and Bala fault, which were reactivated in compression during Cenozoic. Tilting and truncation of intra-Eocene coal marker record Neogene phase of compressional deformation. Line-length restoration of uppermost Lower Jurassic marker across St. Tudwal's Arch indicates ~15 km shortening across ~100 km.

The East Irish Sea Basin and northern England have been proposed as the focus of Paleocene underplating-related exhumation. The absence of sequences younger than Early Jurassic in the East Irish Sea Basin precludes stratigraphic constraints on the age of exhumation. We contend, on the basis of constraints from AFTA and regional geology, that the major angular sub-Quaternary unconformity in the East Irish Sea Basin represents a composite surface recording Early Cretaceous, Paleocene, and Neogene exhumation and that the amount of Paleocene exhumation recorded by this unconformity has been overstated. AFTA data from the south and west of the East Irish Sea Basin show that the main timing of exhumation in these areas was Early Cretaceous (Holford et al., 2005b). AFTA data from the East Irish Sea Basin also record major Paleocene (65–60 Ma) cooling, but AFTA and VR paleotemperature profiles in the north of the basin reveal evidence for significantly elevated Paleocene geothermal gradients (Holford et al., 2005b) (50–60 °C km^{-1} cf. present-day value of ~35 °C km^{-1}). This implies that some of the cooling previously ascribed to Paleocene exhumation in fact records a reduction in heat flow. Several locations around the wider Irish Sea region provide little evidence for substantial Paleocene cooling and exhumation, such as the St. George's Channel Basin, where the main Cenozoic exhumation episode is of Neogene age (Holford et al., 2005a).

DISCUSSION

Magnitude of Shortening

Homogeneous lithospheric shortening of ~25% is required to produce ~0.6 km of tectonic uplift, which may be amplified by the unloading effects of erosion to result in ~2.5 km of exhumation (Brodie and White, 1994). Brodie and White (1994) argued that the amount of shortening required to account for the observed magnitude of Cenozoic exhumation in the southern British Isles is much greater than that observed. Shortening of the required magnitude is observed in parts of the southern British Isles (Fig. 4). Furthermore, measurement of shortening on compressional structures in exhumed sedimentary basins generally underestimates shortening. The reverse reactivation of formerly normal faults means that net reverse-fault displacement along a reactivated fault in an inverted basin decreases downward (Turner and Williams, 2004). In basins with muddy fill (e.g., St. George's Channel Basin, Wessex-Weald Basin), much of the shortening may be accommodated by difficult to measure pure shear, distributed strain rather than by reactivation of discrete faults. Noncoaxial inversion, where axes of minimum and maximum horizontal stress do not coincide during respective episodes of extension and inversion, results in three-dimensional strains with shortening accommodated on a network of oblique-slip faults on which plane strain, line-length restoration methods cannot be used (Turner and Williams, 2004).

Extent of Cenozoic Compressional Structures

Cenozoic compressional structures such as those described above are widespread in the southern British Isles. Recently there has been growing recognition of Cenozoic compressional structures farther north. Seismic stratigraphic mapping of the northeast Atlantic margin has revealed abundant Cenozoic compressional structures (Stoker et al., 2005). The scale of these structures is significant (amplitudes <4 km, axial lengths <200 km). There is also evidence for significant late Cenozoic reverse faulting in the Paleozoic basement onshore Ireland, with kinematics consistent with those observed in the offshore Mesozoic–Cenozoic basins (Dewey, 2000). The abundant evidence of Cenozoic compressional structures in the British Isles, northeast Atlantic margin, and Alpine foreland (Ziegler et al., 1995) demonstrates that Cenozoic shortening was a plate-wide phenomenon. Shortening preferentially occurred in Mesozoic-age basins, suggesting that strength variations in the lithosphere inherited from earlier rifting localized strain during lithospheric shortening (Ziegler et al., 1995).

Regional Cenozoic Exhumation Events

Cenozoic exhumation across the southern British Isles is focused on recognized compressional structures, but there also appears to be a regional component of Paleocene exhumation in areas such northern and central England and the southern North Sea (Green, 1989; Hillis, 1995). A contribution to exhumation from plume activity cannot be ruled out in these areas. Alternatively, strain partitioning between the crust and lithospheric mantle (i.e., heterogeneous lithospheric shortening; Hillis, 1995) may account for the regional component of Cenozoic uplift.

A regional component of Neogene exhumation has been reported from various parts of the northeast Atlantic margin (Japsen, 2000; Japsen and Chalmers, 2000). Stratigraphic data from the Atlantic margin provide evidence for the long-wavelength, large-amplitude seaward tilting of the entire margin beginning in the early Pliocene, during which uplift of onshore regions was accompanied by increased offshore subsidence (Praeg et al., 2005). The mechanism behind the regional component of Neogene exhumation is unclear (Japsen and Chalmers, 2000). Strain partitioning between the crust and mantle may account for this, or it may be a dynamic topographic response to convective flow in the upper mantle beneath the Atlantic margin (Praeg et al., 2005).

Upper Crustal Strength

The world stress map (Zoback et al., 1989) demonstrates that the present-day maximum horizontal stress orientation in most continental areas is parallel to the direction of absolute plate motion. Hence the forces driving and resisting plate motion are inferred to be responsible for the intraplate stress field (Zoback et al., 1989). We propose that the intraplate stress field responsible for Cenozoic compression of the southern British Isles was transmitted into the plate interior from plate boundary interactions ~1000 km distant, i.e., Mid Atlantic Ridge spreading and Alpine collision. The transmission of plate boundary stresses into the plate interior requires a high-strength upper crust in western Europe; this is consistent with present-day stress data. Stress measurements to 6 km depth in the KTB borehole in southern Germany indicate high differential stress (>100 MPa), hence high strength in the upper crust, which thus acts as a stress guide (Zoback et al., 1993).

CONCLUSIONS

We conclude that compressional stress transmitted to the plate interior from the plate boundaries has provided the main driving force for multiple periods of exhumation across the southern British Isles throughout the Cenozoic. In particular, our data emphasize the role of Neogene exhumation related to crustal compression. The role of Paleocene exhumation across the region related to the Iceland plume has been overstated. Further work should focus on determining the distribution and chronology of exhumation in other intraplate settings in order to ascertain whether compressional stress transmitted from the plate boundaries is the key geodynamic force driving the exhumation of sedimentary basins worldwide.

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