Regional intraplate exhumation episodes related to plate-boundary deformation

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ABSTRACT

The sedimentary basins of the British Isles, which are surrounded by plate boundaries that have been variously active from Mesozoic to Cenozoic times, provide a natural laboratory for studying the influence of plate-boundary forces on intraplate vertical motions. A synthesis of apatite fission-track analysis (AFTA) data from the Irish Sea basin system and adjacent regions of the western British Isles reveals a series of cooling episodes from the Cretaceous to the Cenozoic (between 120 and 115 Ma, 65 and 55 Ma, 40 and 25 Ma, and 20 and 15 Ma, respectively). Each episode is of regional extent (~10^6 km^2) and represents a major period of exhumation involving removal of up to 1 km or more of section. These exhumation episodes can be correlated with major tectonic unconformities recognized within the sedimentary succession of the NW European Atlantic margin, but across the western British Isles, the substantially higher exhumation means that little corresponding stratigraphic evidence for these events has been preserved. These exhumation episodes correlate closely with key deformation events at adjacent plate boundaries, suggesting a causative link despite the large distances (up to 1500 km) separating the closest plate boundaries from the zones of exhumation at the time of each episode. Similar kilometer-scale erosional events are revealed by thermochronological studies in other intraplate regions around the world adjacent to passive continental margins, e.g., SE Australia, South Africa, Brazil, stressing the widespread occurrence of such episodes. The low-angle unconformities that result from these regional episodes of kilometer-scale burial and subsequent exhumation are often incorrectly interpreted as representing periods of nondeposition and tectonic stability. Our results indicate that many regions conventionally interpreted as areas of long-term stability have undergone kilometer-scale regional exhumation, and that plate-boundary deformation exerts the primary control on such episodes.

INTRODUCTION

The plate tectonic paradigm has proven extremely successful at accounting for vertical crustal motions (i.e., subsidence and uplift) as well as many other geological, geophysical, and geomorphological observations along active plate boundaries on Earth (both constructive and destructive) in terms of horizontal movements of the lithospheric plates. There has been considerably less success in explaining many observations (for example, creation of topography and seismic activity) across continental interiors located at great distances (i.e., hundreds to thousands of kilometers) away from active plate boundaries (Allen and Allen, 2005). The continental interiors of the lithospheric plates have been traditionally thought of as regions of long-term (i.e., 10^7–10^9 a) stability that have been largely unaffected by deformation and have experienced minimal anomalous vertical tectonic motions (e.g., Şengör, 1999).

Another environment that is commonly associated with long-term tectonic quiescence is the so-called "passive" extensional margin, which mostly consists of deep- to shallow-water shelves that fringe uplifted continental hinterlands, typified by the margins bordering the North Atlantic Ocean (Praeg et al., 2005). Research into the tectonic evolution of passive continental margins has been heavily skewed toward their early development, when continental plates rift and separate to form new oceanic basins (White and McKenzie, 1989; White et al., 2003). The term "passive" originates from the general acceptance that, subsequent to their formation, these continental margins experience no significant deformation, only exponentially decreasing subsidence as the crust and mantle cool down during the "postrift" stage of their tectonic evolution, enabling the accumulation of thick marine sedimentary successions (Sleep, 1971). However, recent tectonostratigraphic analyses of the thick (~2.2–2.7 km; Ceramicola et al., 2005) Cenozoic sedimentary succession preserved along the NW European Atlantic passive margin have shown that this simple model of long-term tectonic stability does not apply to this particular margin. These investigations have identified a number of significant unconformities that are synchronous over ~2500 km of this margin from Rockall (offshore Ireland) to Lofoten (northern Norway) and are of tectonic origin (Praeg et al., 2005; Stoker et al., 2005a, 2005b, 2005c).

We first focus our attention on the history of vertical tectonic motions immediately inboard of the Atlantic margin, and then we present a new synthesis of exhumation-related cooling episodes recorded by existing apatite fission-track analysis (AFTA) data from the British Isles. The reader is referred to the following publications for details of the thermochronologic data used in this study (Bray et al., 1998; Thomson et al., 1999; Green et al., 1999, 2000, 2001a, 2001b; Argent et al., 2002; Green, 2005; Holford et al., 2005a; Holford, 2006; Jolivet, 2007). We show that an area encompassing ~10^6 km^2 experienced multiple episodes of kilometer-scale exhumation during Cenozoic times. Exhumation episodes defined by AFTA data from across the British Isles during the early, middle, and late Cenozoic correlate closely in time with the unconformities identified from seismic and stratigraphic information along the Atlantic margin, which are dated as tightly as possible (i.e., 1–5 Ma) based

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on existing biostratigraphic evidence (Stoker et al., 2005b). However, the effects of exhumation onshore across the British Isles are much more pronounced, to the extent that little or no stratigraphic evidence for the uplift and erosion is now preserved. The synthesis of AFTA data also reveals that parts of the British Isles experienced kilometer-scale exhumation during Early Cretaceous times, coeval with the development of multiple unconformities and hiatuses along the NW European Atlantic margin. The timing of these regional Cretaceous and Cenozoic exhumation episodes correlates closely with key periods of deformation at adjacent plate boundaries, and we thus discuss possible relationships between plate-boundary forces and intraplate vertical motions and exhumation.

TECTONIC FRAMEWORK OF THE IRISH SEA BASIN SYSTEM

The British Isles (Fig. 1) constitute a superb natural laboratory in which to examine the possible effects of plate-boundary deformation on the vertical tectonic motions of intraplate regions because they are surrounded by plate boundaries that have been variously active during Mesozoic-Cenozoic times, with deformation histories that are relatively well understood. The continental margin SW of Britain formed following amagmatic rifting that occurred between the late Hauterivian and late Albian and culminated with the onset of seafloor spreading between the early Aptian and early Albian (de Graciansky et al., 1985). The volcanic continental margin to the NW of Britain experienced a long (~350 Ma) rifting history that climaxed with continental breakup occurring in earliest Eocene times (Doré et al., 1999). The Alpine and Pyrenean mountain belts to the south of the British Isles represent a broad deformation zone that records complex convergence between the African and European plates from Late Cretaceous times onward (e.g., Dewey et al., 1989; Rosenbaum et al., 2002). The widespread Cretaceous-Cenozoic shortening and short-wavelength uplift of sedimentary basins against major basin-bounding faults (basin inversion) in the Alpine foreland due to the transmission of plate-boundary compressional stresses through the upper crust are well documented (e.g., Ziegler et al., 1995).

The occurrence of kilometer-scale uplift and erosion across the British Isles during Cretaceous-Cenozoic times has long been recognized (e.g., George, 1966), but recent attempts to explain these apparently anomalous vertical motions have focused on the role played by the ancestral Iceland mantle plume during the Paleocene-Eocene (Brodie and White,

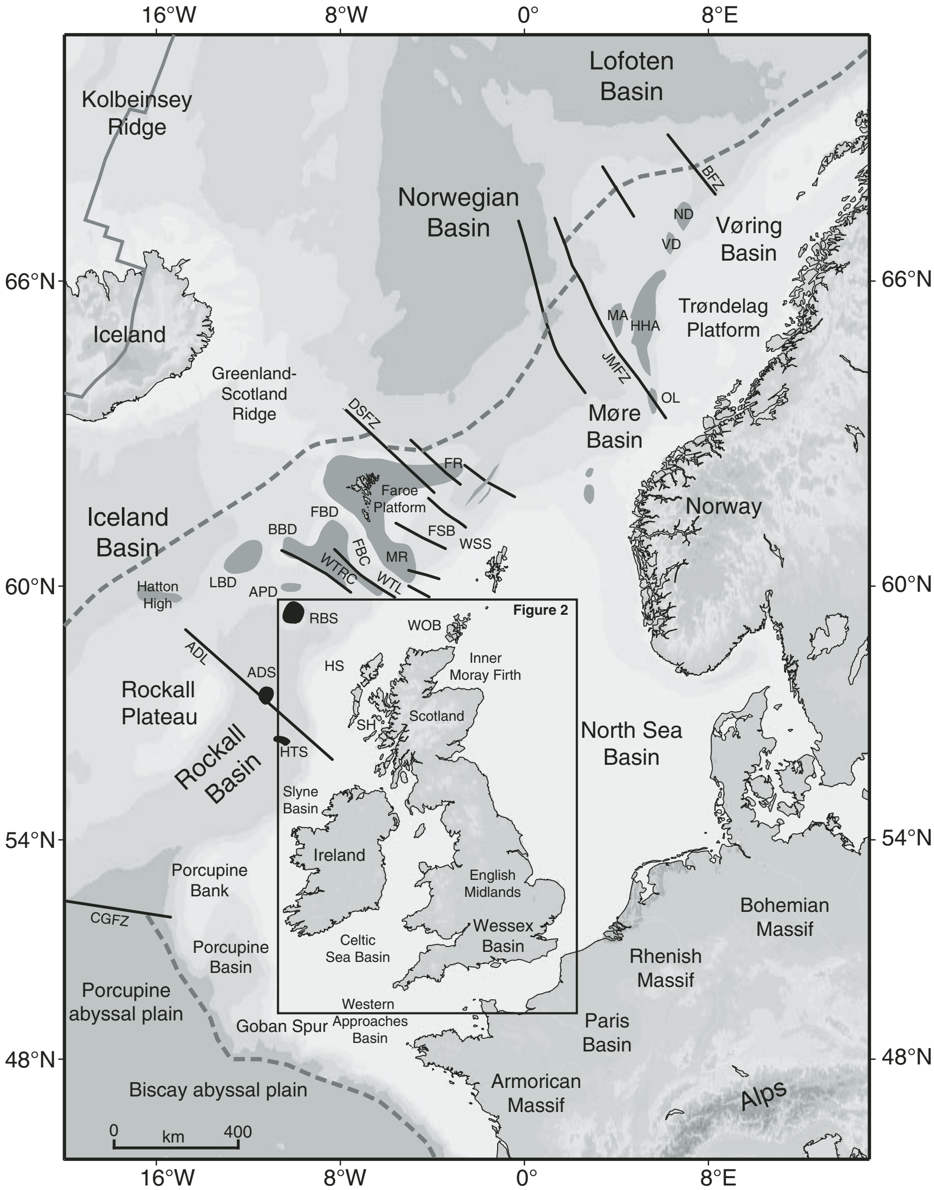


Figure 1. Topographic/bathymetric map and Cenozoic structural elements of the NW European Atlantic margin showing locations discussed in the text. Broken line denotes approximate position of continent-ocean transition, and continuous lines represent fracture zones identified from potential field data. Black shaded areas denote seamounts; gray shaded areas correspond to compressive domes and arches (after Stoker et al., 2005c). Abbreviations: ADL—Anton Dohrn lineament; APD—Aplin Dome; BBD—Bill Bailey's Dome; BFZ—Bivrost fracture zone; CGFZ—Charlie Gibbs fracture zone; DSFZ—Denmark Strait fracture zone; FBC—Faroe Bank Channel; FBD—Faroe Bank Dome; FR—Fugloy Ridge; FSB—Faroe Shetland Basin; HHA—Helland-Hansen Arch; HS—Hebrides shelf; HTS—Hebrides Terrace Seamount; JMFZ—Jan Mayen fracture zone; LBD—Lousy Bank Dome; MA—Modgunn Arch; MR—Munkagrunnur Ridge; ND—Naglfar Dome; OL—Ormen Lange Dome; RBS—Rosemary Bank Seamount; SH—Sea of Hebrides Basin; VD—Vena Dome; WOB—West Orkney Basin; WSS—West Shetland shelf; WTL—Wyville-Thomson Lineament; WTRC—Wyville-Thomson Ridge complex.

1994; Jones et al., 2002). These studies have downplayed the contribution of plate-boundary forces, despite abundant evidence that significant amounts of exhumation (1) were a result of compressional shortening (Hillis et al., 2008a) and (2) occurred during times other than the Paleocene (e.g., Neogene; Japsen, 1997). Paleocene exhumation is often thought to reach a maximum across the basins of the Irish Sea in the western British Isles (e.g., Jones et al., 2002) (Fig. 2), and we focus our attention on this area because it is characterized by the greatest density of fission-track data coverage in the British Isles (Green, 1986; Lewis et al., 1992; Holford et al., 2005b). The Irish Sea basins are made up of a series of linked post-Carboniferous extensional basins located between the Paleozoic basement massifs of northern England, Wales, and Ireland (Tappin et al., 1994; Jackson et al., 1995). The basins and their immediate margins cover a surface area of ~50,000 km^2 and contain a maximum thickness of ~12 km of Permian-Holocene sediments (Tappin et al., 1994). These sedimentary successions contain a number of major unconformities, and, in parts of this region, Triassic and older sediments crop out at the surface or seafloor (Fig. 2), and paleoburial proxies such as sedimentary rock compaction data indicate that these rocks have been buried to depths of >1–2 km (Ware and Turner, 2002).

IDENTIFYING REGIONAL EXHUMATION EPISODES

We have synthesized AFTA data from multiple subsurface and outcrop samples to determine the timing and severity of the regional exhumation episodes that have affected the Irish Sea basin system. Details of the data we have used can be found in the following publications (Bray et al., 1998; Thomson et al., 1999; Green et al., 1999, 2000, 2001a, 2001b; Argent et al., 2002; Green, 2005; Holford et al., 2005a; Holford, 2006; Jolivet, 2007; Hillis et al., 2008a). Our approach in this paper is based on a combination of timing constraints for individual cooling episodes identified in a series of AFTA samples from across the region on the assumption that the data reflect a series of regionally synchronous exhumation episodes. Previous studies that have synthesized regional AFTA data sets in a similar manner (e.g., in northern Australia [Duddy et al., 2004] and Scandinavia [Japsen et al., 2007]) have identified discrete episodes of regionally synchronous cooling that can be correlated with regional unconformities, and therefore interpreted in terms of uplift and erosion, which serves to validate the approach utilized in this paper.

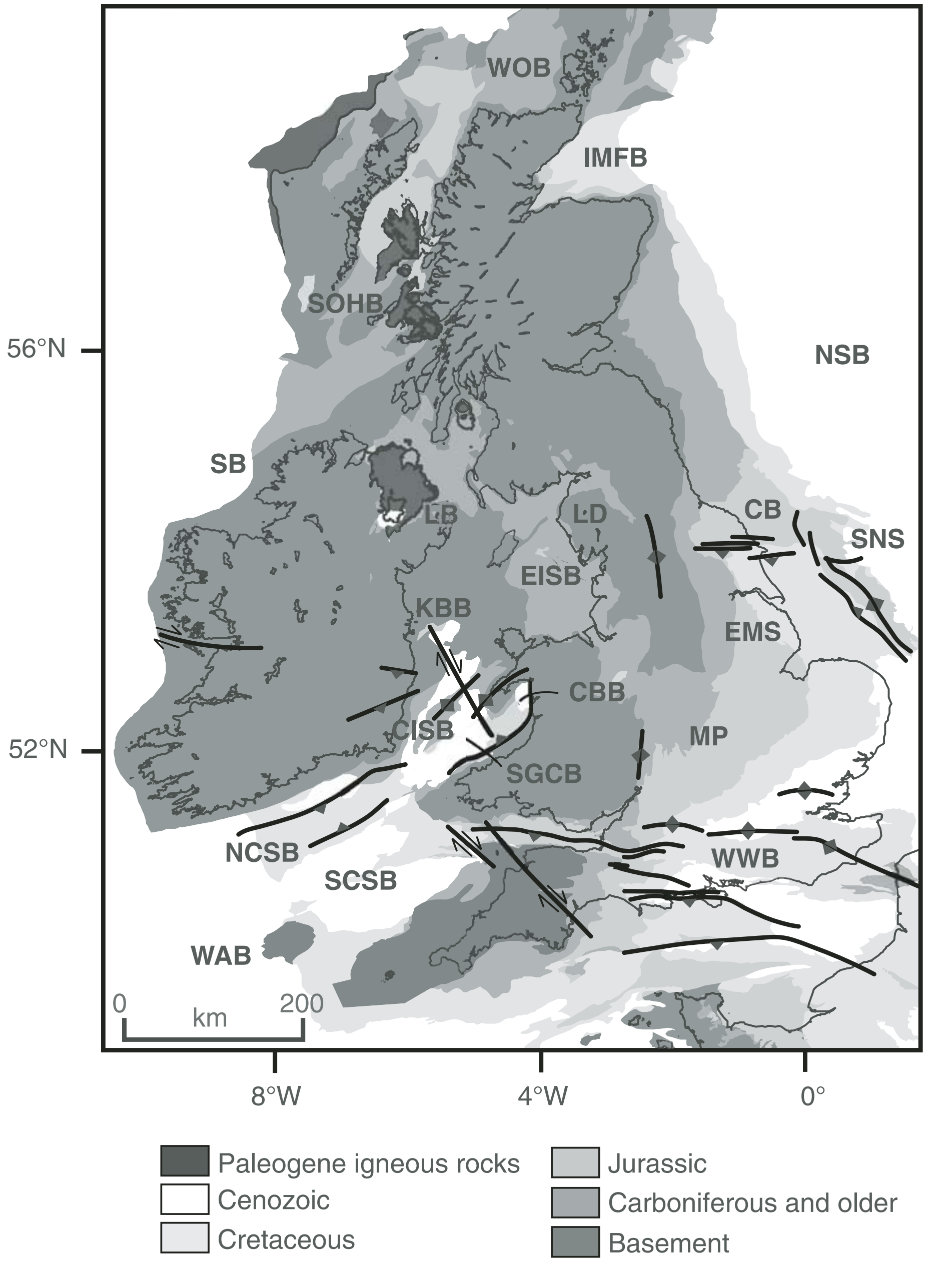


Figure 2. Solid geology and Cenozoic structural elements of the British Isles showing locations discussed in the text. Abbreviations: CB—Cleveland Basin; CBB—Cardigan Bay Basin; CISB—Central Irish Sea Basin; EISB—East Irish Sea Basin; EMS—East Midlands Shelf; IMFB—Inner Moray Firth Basin; KBB—Kish Bank Basin; LB—Larne Basin; LD—Lake District; MP—Midland Platform; NCSB—North Celtic Sea Basin; NSB—North Sea Basin; SB—Slyne Basin; SCSB—South Celtic Sea Basin; SGCB—St. George's Channel Basin; SNS—Southern North Sea Basin; SOHB—Sea of Hebrides Basin; WAB—Western Approaches Basin; WWB—Wessex Weald Basin.

Thermal history constraints for individual samples included in the aforementioned studies were extracted from basic AFTA data parameters (i.e., fission-track age and length distribution) following principles that are outlined in detail elsewhere (e.g., Green et al., 2002, 2004; Holford et al., 2005a). AFTA has the potential to resolve two (rarely three) discrete cooling episodes and provides quantitative constraints on both the peak paleotemperature and timing of cooling from the paleotemperature maxima for each episode in individual samples. We have also used AFTA, along with other paleoburial proxies such as vitrinite reflectance (VR) and sedimentary rock compaction methods (e.g., Corcoran and Doré, 2005) from published studies (references given in the captions of Figs. 3–5) to define paleogeothermal gradients and constrain the magnitude of the section removed during each exhumation episode. We judge compaction-based exhumation estimates to have a resolution of ±200 m, based on previous compaction studies in the British Isles that have demonstrated this level of precision when multiple lithologies are used (Hillis, 1995; Mackay and White, 2006). The resolution of exhumation estimates based on AFTA and VR data is dependent on the range of depths over which samples are available and the value of the paleogeothermal gradient. We consider exhumation estimates utilizing AFTA and VR data from wells and boreholes to have a precision of ±200–500 m (Green et al., 2002). Our assessment of the precision of our estimates is supported by locations at which multiple methods have been used to calculate exhumation, such as at the Mochras borehole, where independent estimates of Cenozoic exhumation from paleotemperature (AFTA and VR) and compaction data show agreement to within less than 200 m (Holford et al., 2005a).

The synthesis of this AFTA database reveals four distinct and previously undefined Cretaceous to Cenozoic cooling episodes during the intervals 120–115 Ma, 65–55 Ma, 40–25 Ma, and 20–15 Ma (Figs. 3–5). Each of these cooling episodes is interpreted to represent a widespread phase of exhumation, thus suggesting that the British Isles have experienced a complex, multistage exhumation chronology. These separate exhumation episodes were then compared with seismic-stratigraphic analyses of contemporaneous sedimentary successions along the NW European Atlantic margin (e.g., Praeg et al., 2005; Stoker et al., 2005a, 2005b, 2005c) to identify the broader patterns of vertical motions across the NW Eurasian plate. The temporal resolution of the regional unconformities that have been identified along the Atlantic margin is as tight as possible given existing biostratigraphic (calcareous nannoplankton) data, with error ranges on the unconformities as small as 1–5 Ma (Stoker et al., 2005a). Furthermore, the age model is underpinned by a regional tectonostratigraphic study extending ~2000 km along the Atlantic margin (Praeg et al., 2005; Stoker et al., 2005a, 2005b, 2005c).

Early Cretaceous (120–115 Ma)

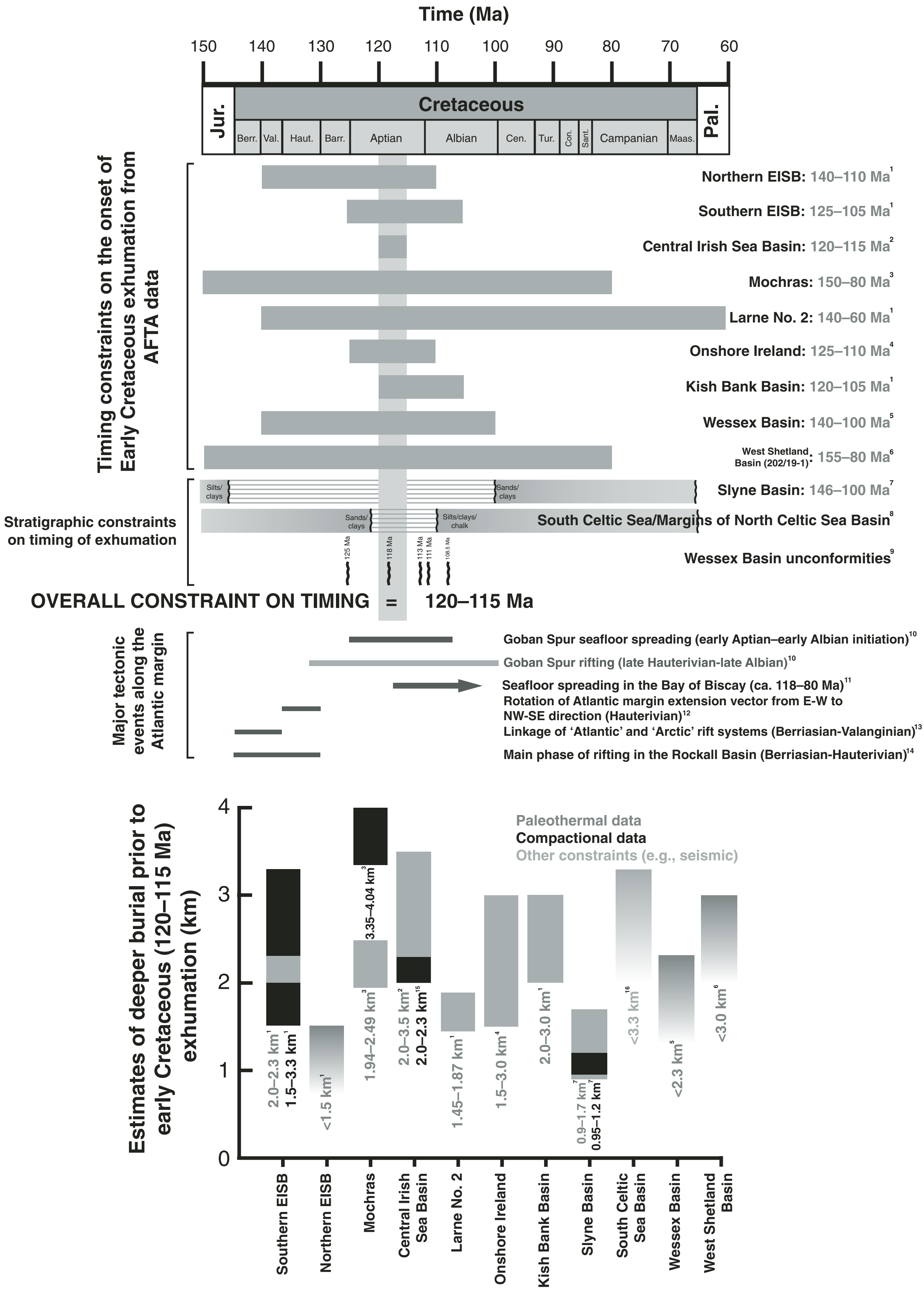
AFTA data suggest that an area covering ~60,000 km^2 focused on the Irish Sea experienced up to 2.5 km of exhumation during the Early Cretaceous (Fig. 3). Precise constraints on the magnitude of this event are provided by results from the Mochras borehole, located onshore NW Wales near the supposed Cenozoic erosional "bull's-eye" of Cope (1994). Early Cretaceous paleotemperatures from Upper Triassic AFTA samples and compaction data from Lower Jurassic shales record similar magnitudes of exhumation around 2.5 km (Holford et al., 2005a). AFTA data from the Central and East Irish Sea Basins indicate comparable exhumation values (~2–3 km) (Green et al., 2001a; Holford et al., 2005b), while data from onshore Ireland also suggest kilometer-scale exhumation at this time (Green et al., 2000). AFTA data from Permian-Triassic sediments in the West Orkney Basin indicate that these rocks were more deeply buried by ~3 km prior to major exhumation that began during the Cretaceous (150–80 Ma) (Green et al., 1999). AFTA data from the SW-NE–trending St. George's Channel and North Celtic Sea Basins do not record Early Cretaceous exhumation, but this does not necessarily mean that these parts of the Irish Sea were not uplifted. Cretaceous sediments are absent from the St. George's Channel Basin, indicating exhumation during the Cretaceous period (Tappin et al., 1994; Williams et al., 2005), while the Lower Cretaceous succession of the North Celtic Sea Basin records a progressive shallowing of facies (Tappin et al., 1994) that is also suggestive of uplift. A compilation of AFTA timing constraints from all parts of the Irish Sea and adjacent regions shows that exhumation-driven cooling began between 120 and 115 Ma, i.e., during the Aptian (Fig. 3).

Early Cenozoic (65–55 Ma)

Following widespread burial beneath thick chalk sequences in Late Cretaceous times, the earliest Cenozoic witnessed major paleogeographic changes in NW Europe and the transition from shelf seas and low-relief landmasses to newly emergent highlands (Doré et al., 2002) accompanied by major exhumation across parts of the British Isles. Much of the evidence for this exhumation is provided by AFTA data; outcrop and subsurface samples from northern England (Green, 2002), Scotland (Thomson et al., 1999), and the English Midlands (Green et al., 2001b) indicate a maximum of 1.5–2 km of exhumation since the early Cenozoic (Fig. 4). Constraints from AFTA suggest that the early Cenozoic exhumation of the British Isles was highly heterogeneous over both regional and basinal scales. AFTA samples from the East Irish Sea Basin record major early Cenozoic cooling, interpreted in terms of up to 2 km of coeval exhumation (Green et al., 1997; Holford et al., 2005a), but AFTA data from the Mochras borehole some 50 km to the southwest require no substantial early Cenozoic cooling and suggest that a maximum of ~0.8 km exhumation occurred at this location (Holford et al., 2005b). This heterogeneous distribution of exhumation, which is better resolved in this study due to the improved precision of our exhumation estimates and our increased spatial coverage of data (cf. Hillis et al., 2008a), conflicts with previous claims of a more uniform pattern of Paleocene exhumation supposedly reflecting epeirogenic, plume-related early Cenozoic uplift across the British Isles (Rowley and White, 1998; Jones et al., 2002). Further heterogeneity is demonstrated by AFTA data from the Inner Moray Firth Basin, where intrabasinal exhumation varies between 0 and 1.25 km (Argent et al., 2002). Because exhumation is compartmentalized over major faults, and is generally higher over footwall rather than hanging-wall blocks, these short-wavelength spatial variations were attributed by Argent et al. (2002) to the superposition of extensional faulting upon regional uplift.

AFTA timing constraints from the East Irish Sea Basin, Central Irish Sea Basin, and

Figure 3. Constraints on the onset of regional exhumation-related cooling during the Cretaceous in the British Isles from apatite fission-track analysis (AFTA) and stratigraphic data, and constraints on the magnitude of this exhumation from paleothermal, compaction, and other methods. This analysis suggests a regional onset of cooling and exhumation between 120 and 115 Ma, which corresponds with plate-boundary deformation (i.e., continental separation) SW of Britain. References from which constraints were derived for the timing of exhumation from AFTA and stratigraphic data, regional tectonic events, and the magnitude of deeper burial across the British Isles prior to Early Cretaceous exhumation are as follows: (1) Holford (2006); (2) Green et al. (2001a); (3) Holford et al. (2005a); (4) Green et al. (2000); (5) Bray et al. (1998); (6) Green et al. (1999); (7) Corcoran and Mecklenburgh (2005); (8) McMahon and Turner (1998); (9) Ruffell (1992); (10) de Graciansky et al. (1985); (11) Sibuet et al. (2004); (12) Doré et al. (1999); (13) Roberts et al. (1999); (14) Scrutton and Bentley (1988); (15) Williams et al. (2005); and (16) van Hoorn (1987). EISB—East Irish Sea Basin.


Time (Ma)
150 140 130 120 110 100 90 80 70 60
Jur.
Cretaceous
Pal.
Berr. Val. Haut. Barr. Aptian Albian Cen. Tur. Con. Sant. Campanian Maas.
Timing constraints on the onset of Early Cretaceous exhumation from AFTA data
Northern EISB: 140–110 Ma1
Southern EISB: 125–105 Ma1
Central Irish Sea Basin: 120–115 Ma2
Mochras: 150–80 Ma3
Larne No. 2: 140–60 Ma1
Onshore Ireland: 125–110 Ma4
Kish Bank Basin: 120–105 Ma1
Wessex Basin: 140–100 Ma5
West Shetland Basin (202/19-1): 155–80 Ma6
Stratigraphic constraints on timing of exhumation
Silts/clays
Sands/clays
Slyne Basin: 146–100 Ma7
Sands/clays
Silts/clays/chalk
South Celtic Sea/Margins of North Celtic Sea Basin8
125 Ma
118 Ma
113 Ma
111 Ma
108.5 Ma
Wessex Basin unconformities9
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Goban Spur rifting (late Hauterivian-late Albian)10
Seafloor spreading in the Bay of Biscay (ca. 118–80 Ma)11
Rotation of Atlantic margin extension vector from E-W to NW-SE direction (Hauterivian)12
Linkage of 'Atlantic' and 'Arctic' rift systems (Berriasian-Valanginian)13
Main phase of rifting in the Rockall Basin (Berriasian-Hauterivian)14
Estimates of deeper burial prior to early Cretaceous (120–115 Ma) exhumation (km)
0 1 2 3 4
Paleothermal data
Compactional data
Other constraints (e.g., seismic)
2.0–2.3 km1
1.5–3.3 km1
<1.5 km1
3.35–4.04 km3
1.94–2.49 km3
2.0–3.5 km2
2.0–2.3 km15
1.45–1.87 km1
1.5–3.0 km4
2.0–3.0 km1
0.9–1.7 km7
0.95–1.2 km7
<3.3 km16
<2.3 km5
<3.0 km6
Southern EISB
Northern EISB
Mochras
Central Irish Sea Basin
Larne No. 2
Onshore Ireland
Kish Bank Basin
Slyne Basin
South Celtic Sea Basin
Wessex Basin
West Shetland Basin

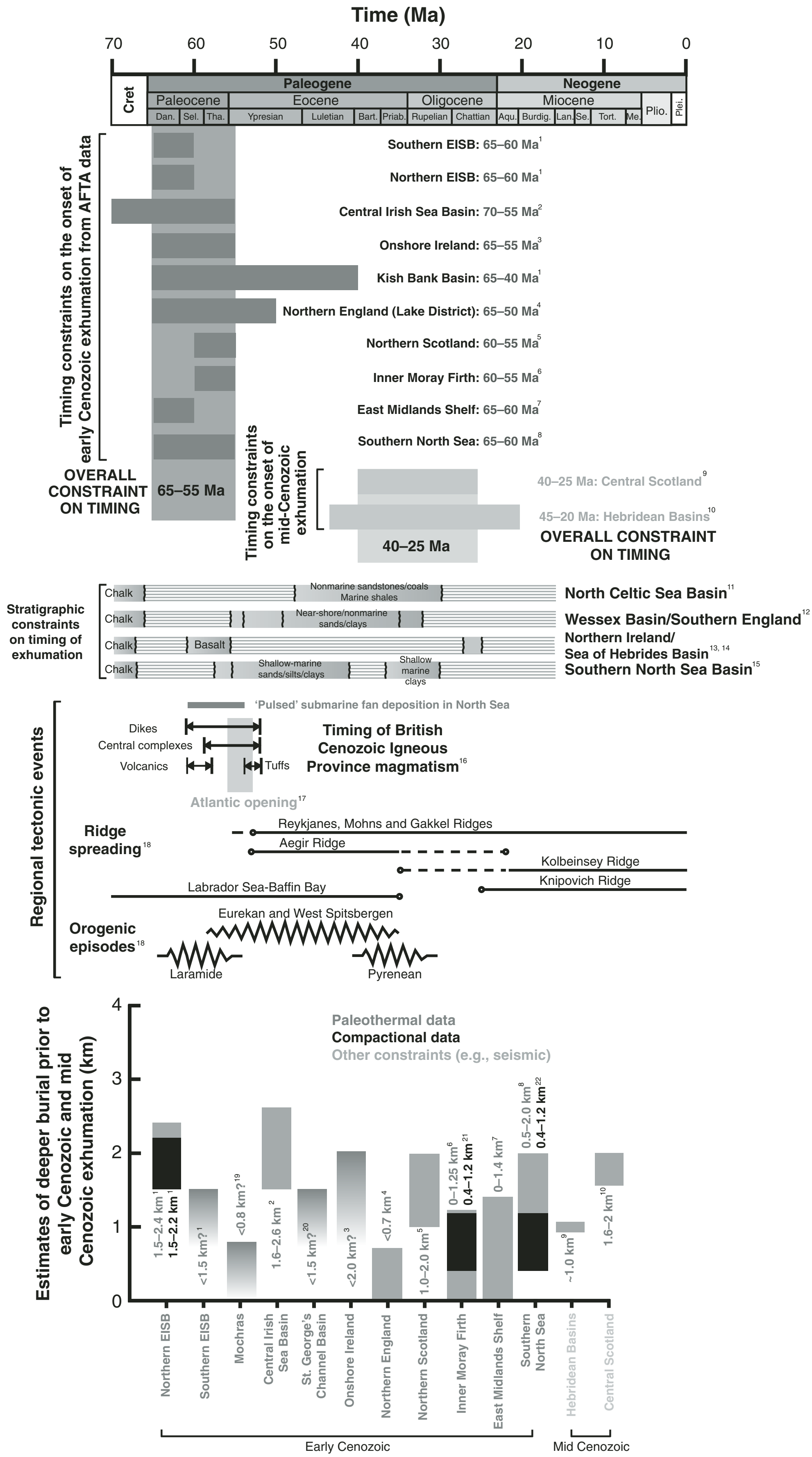


Figure 4. Constraints on the onset of regional exhumation-related cooling during the early to mid-Cenozoic in the British Isles from apatite fission-track analysis (AFTA) and stratigraphic data, and constraints on the magnitude of this exhumation from paleothermal, compaction, and other methods. This analysis shows that regional early to mid-Cenozoic cooling and exhumation began between 65 and 55 Ma, while cooling and exhumation in Scotland and the Hebridean Basins began between 40 and 25 Ma. These exhumation episodes correlate with several periods of plate-boundary deformation, as demonstrated by the compilation of regional tectonic events. References from which constraints were derived for the timing of exhumation from AFTA and stratigraphic data, regional tectonic events, and the magnitude of deeper burial across the British Isles prior to early and mid-Cenozoic exhumation are as follows: (1) Holford (2006); (2) Green et al. (2001a); (3) Green et al. (2000); (4) Green (2002); (5) Thomson et al. (1999); (6) Argent et al. (2002); (7) Green et al. (2001b); (8) Green (2005); (9) Jolivet (2007); (10) Green et al. (1999); (11) Murdoch et al. (1995); (12) Hamblin et al. (1992); (13) Mitchell (2004); (14) Fyfe et al. (1993); (15) Cameron et al. (1992); (16) White and Lovell (1997); (17) Doré et al. (1999); (18) Doré et al. (2008); (19) Holford et al. (2005a); (20) Williams et al. (2005); (21) Hillis et al. (1994); and (22) Japsen (2000). EISB—East Irish Sea Basin.

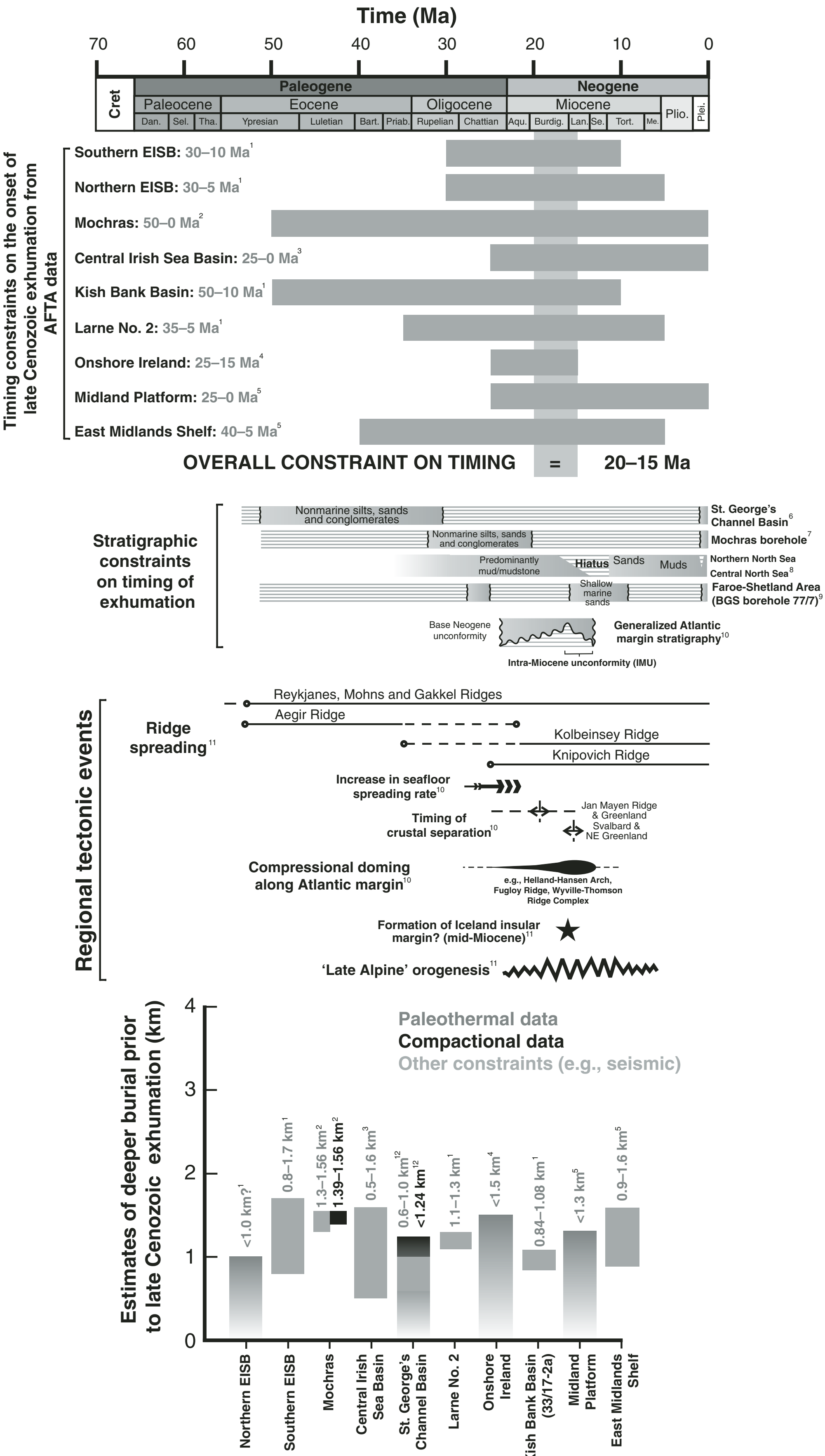


Figure 5. Constraints on the onset of regional exhumation-related cooling during the late Cenozoic in the British Isles from apatite fission-track analysis (AFTA) and stratigraphic data, and constraints on the magnitude of this exhumation from paleothermal, compaction, and other methods. This analysis suggests a regional onset of exhumation-related cooling between 20 and 15 Ma, which corresponds with the timing of compressional deformation along the Atlantic margin, and a number of separate plate-boundary deformation events. References from which constraints were derived for the timing of exhumation from AFTA and stratigraphic data, regional tectonic events, and the magnitude of deeper burial across the British Isles prior to early and mid-Cenozoic exhumation are as follows: (1) Holford (2006); (2) Holford et al. (2005a); (3) Green et al. (2001a); (4) Green et al. (2000); (5) Green et al. (2001b); (6) Tappin et al. (1994); (7) Herbert-Smith (1979); (8) Fyfe et al. (2003); (9) Evans et al. (1997); (10) Stoker et al. (2005c); (11) Doré et al. (2008); and (12) Holford et al. (2008). EISB—East Irish Sea Basin.

onshore Ireland, southwest Wales, and northeast England define a synchronous onset of early Cenozoic exhumation-related cooling in the Irish Sea region between 65 and 60 Ma (Fig. 4), consistent with AFTA results from the English Midlands and southern North Sea (Green et al., 2001b). AFTA data from Scotland suggest a slightly later onset of cooling, between 60 and 55 Ma (Thomson et al., 1999; Argent et al., 2002), although it is as yet unclear whether this represents a real difference in timing or just statistical variation. Overall, AFTA constraints from the British Isles place the onset of early Cenozoic exhumation-related cooling between 65 and 55 Ma (Fig. 4).

Mid-Cenozoic (40–25 Ma)

Around 300 km NE of the East Irish Sea Basin, AFTA data from Triassic and Jurassic rock samples recovered by well 134/5–1 in the Sea of the Hebrides–Little Minch Trough (Fyfe et al., 1993) suggest that ~1 km of post–Early Jurassic overburden was removed from this location during a mid-Cenozoic (45–20 Ma) cooling episode (Green et al., 1999). The compaction and cementation state of Middle Jurassic–age sediments that crop out onshore in the Inner Hebrides region close to the 134/5–1 well suggests maximum burial to depths of ~1 km (Hudson and Andrews, 1987), consistent with the results from AFTA. Mid-Cenozoic cooling is observed in AFTA data from other exploration wells in basins offshore northwest Scotland, such as 202/19–1, located in the West Shetland Basin, where AFTA data indicate that ~1.5 km of overburden were removed at this time (Green et al., 1999). Similarly timed exhumation has been reported from onshore central and western Scotland by Jolivet (2007), who presented apatite fission-track results that suggested 1.6–2 km of regional exhumation beginning between 40 and 25 Ma (Fig. 4). The combination of these timing constraints from onshore and offshore AFTA data thus defines a mid-Cenozoic exhumation episode that affected NW Britain beginning between 40 and 25 Ma.

Late Cenozoic (20–15 Ma)

A growing body of evidence from various types of data is emerging that suggests that a major proportion of the Cenozoic exhumation of the British Isles occurred during the late Cenozoic (Japsen 1997; Holford et al., 2008). Data from the Irish Sea region are particularly significant, because the Cardigan Bay and St. George's Channel Basins contain thick sequences of Paleocene to Miocene sediments. This indicates that the Irish Sea basins experienced renewed burial following early Cenozoic exhumation, and analysis of the preserved Cenozoic rocks thus permits the effects of late Cenozoic exhumation to be separated out from the effects of earlier events. AFTA, VR, and compaction data show that the Paleocene-Miocene sedimentary successions in these basins have been more deeply buried by ~1–1.5 km of overburden that was removed during the Neogene (Holford et al., 2008). Estimates of the removed section for individual wells in these basins based on independent paleothermal, compaction, and seismic methods show agreement to within ~200 m, as demonstrated by Holford et al. (2008). Exhumation patterns show close correspondence with major compressional structures, indicating that exhumation was driven by compressional shortening. Palynological data indicate that Lower Miocene sediments (ca. 20 Ma) preserved at Mochras have been more deeply buried by 1.26–1.59 km, which constrains the timing of exhumation as middle Miocene or younger (Holford et al., 2005a). AFTA data from many parts of the Irish Sea where Cenozoic sediments are not preserved show evidence for major late Cenozoic cooling. AFTA data from Triassic rocks in the East Irish Sea Basin (30–10 Ma) and the Central Irish Sea Basin (25–0 Ma) record similar timing and amounts (~1 km) of late Cenozoic exhumation (Fig. 5). A wide survey of AFTA data from across onshore Ireland reveals a major phase of exhumation-driven cooling beginning between 25 and 15 Ma (Green et al., 2000). A compilation of the timing constraints from all Irish Sea AFTA results, combined with the stratigraphic constraints provided by the Mochras borehole, constrains the onset of Neogene cooling and exhumation to between 20 and 15 Ma, i.e., during the Miocene (Fig. 5).

CORRELATION WITH REGIONAL UNCONFORMITIES ALONG THE ATLANTIC MARGIN

Early Cretaceous (120–115 Ma)

It is difficult to assess the extent of Early Cretaceous exhumation along the Atlantic shelf because the sediments that may record evidence of such an event are mostly buried beneath several kilometers of Late Cretaceous–Cenozoic rocks (Ceramicola et al., 2005). However, thermochronological data from several basins along the margin reveal evidence for major Early Cretaceous exhumation. VR data from Jurassic sediments, supported by Jurassic, Cretaceous, and Cenozoic shale compaction data from the Slyne Basin, offshore NE Ireland, record 1.7 km of exhumation beginning between the Valanginian and Albian (ca. 146–100 Ma) (Corcoran and Mecklenburgh, 2005), and AFTA data from Permian-Triassic sediments from the West Orkney Basin indicate that these rocks were more deeply buried by ~3 km prior to major exhumation that began during the Cretaceous (150–80 Ma) (Green et al., 1999). The timing of the cooling identified from the Irish Sea (120–115 Ma) is thus consistent with the exhumation reported from both the Slyne and West Orkney Basins (Fig. 3).

There is widespread stratigraphic evidence for Early Cretaceous uplift around the British Isles. Ruffell (1992) identified six major unconformities in the Lower Cretaceous succession of the Wessex Basin, southern England, including five during the Aptian-Albian interval. McMahon and Turner (1998) used a combination of seismic and stratigraphic data from the Wessex, Celtic Sea, and Western Approaches Basins to document two distinct unconformities of Berriasian and Aptian age within the Lower Cretaceous succession of southern Britain. The North Celtic Sea Basin contains an almost complete sequence of Cretaceous sediments, but rocks of late Aptian–early Albian age are absent from all parts but the basin center (McMahon and Turner, 1998). There are numerous unconformities and stratigraphic breaks within sediments of Oxfordian-Albian age within the North Sea Basin (Kyrkjebø et al., 2004). On the Atlantic margin, Valanginian–lower Aptian sediments are largely absent from commercial wells on the eastern flank of the Rockall Basin (Smith, 2009), whereas multiple Early Cretaceous unconformities are recorded in numerous wells from the Faroe-Shetland region (Stoker, 2009a)

Early Cenozoic (60–50 Ma)

In several of the basins along the Atlantic margin, there is a conspicuous regional early Cenozoic unconformity of intra-Paleocene age, termed the Base Paleogene unconformity (Praeg et al., 2005). This unconformity has been described from the northern North Sea–Vøring Basin segment of the Atlantic margin (Martinsen et al., 1999), and the Rockall and Porcupine Basins (McDonnell and Shannon, 2001) (Fig. 6), and thus it covers a length of ~2000 km. It is characterized by Late Cretaceous–Paleocene chalk or earliest Cenozoic basalts overlain by margin-long, basinward-prograding shelf-slope wedges of Paleocene-Eocene age (McInroy et al., 2006; Stoker and Varming, 2009; Stoker, 2009b). The early Cenozoic timing of these events is contemporaneous with the exhumation of parts of the British Isles as recorded by AFTA data (65–55 Ma) (Fig. 7), and these areas are thus likely to have acted as

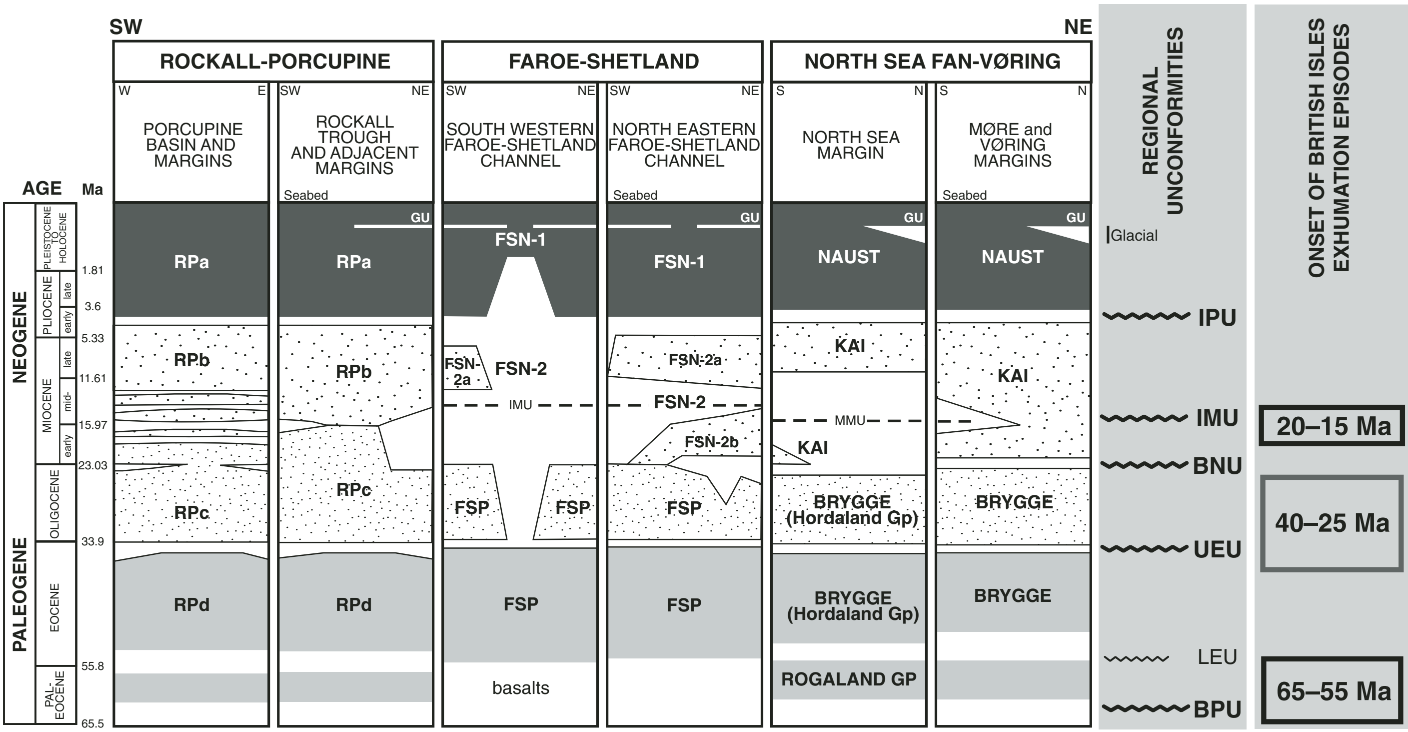


Figure 6. Cenozoic stratigraphic framework for the NW European Atlantic margin, showing regionally significant unconformities based on correlation of stratigraphic megasequences defined within the indicated study areas (after Praeg et al., 2005). This stratigraphic framework is compared with the estimates, from this study, of the onset of Cenozoic cooling episodes constrained by apatite fission-track analysis (AFTA) data from across the British Isles. The onset of the early Cenozoic (65–55 Ma), mid-Cenozoic (40–25 Ma), and late Cenozoic (20–15 Ma) cooling episodes correlates with the Base Paleogene (BPU), Upper Eocene (UEU), and Intra-Miocene (IMU) unconformities, respectively. LEU—Lower Eocene unconformity.

sediment sources for the shelf-slope wedges that prograded along the Atlantic margin during the Paleogene (Praeg et al., 2005). Progradation continued episodically throughout the Eocene, reflecting a pervasive instability along the margin in this interval (McInroy et al., 2006; Stoker and Varming, 2009; Stoker, 2009b).

Mid-Cenozoic (35–25 Ma)

The lower Paleogene megasequence of the Atlantic margin is bounded by the regional Upper Eocene unconformity, which is traceable from the Rockall and Porcupine Basins (McDonnell and Shannon, 2001; Stoker et al., 2001) through to the northern North Sea–Vøring margin (Martinsen et al., 1999). Biostratigraphic data constrain the age of the Upper Eocene unconformity to late Eocene to early Oligocene (34 ± 3 Ma) (Fig. 6) (McDonnell and Shannon, 2001; Stoker et al., 2001). In the Atlantic margin basins adjacent to the Irish Sea–Hebridean Basin system (Porcupine and Rockall), the Upper Eocene unconformity truncates the Eocene prograding wedges that overlie the Base Paleogene unconformity, and it is onlapped by Oligocene contourites (Stoker, 1997; McDonnell and Shannon, 2001). The Upper Eocene unconformity thus marks a major change in sedimentation along the Atlantic margin, which has been interpreted as a consequence of major deepening following accelerated, kilometer-scale subsidence along the Atlantic margin (Ceramicola et al., 2005; Praeg et al., 2005). Eocene strata were rotated by up to 4° during this deepening, which was largely complete by the end of the Oligocene, at around 25 Ma (Vanneste et al., 1995).

Praeg et al. (2005) ascribed this sequence of events during mid-Cenozoic times to the epeirogenic sagging of the Atlantic margin, but the temporal correlation with the 40–25 Ma cooling and exhumation episode across the Hebridean basins and onshore Scotland as recorded by AFTA data suggests that at a larger scale, the Upper Eocene unconformity and subsequent sedimentary response may represent another phase of widespread tilting along the margin, similar to that which occurred during early Cenozoic times (Fig. 7). This contention is supported by the sedimentary record in the eastern North Sea Basin. Coeval uplift of southern Scandinavia is indicated by the progradation of early Oligocene clastic sedimentary wedges away from the south Swedish dome into the eastern North Sea (Faleide et al., 2002), and an earliest Oligocene (ca. 33–30 Ma) hiatus onshore Denmark and around southern Norway that corresponds to a major sequence boundary in the North Sea Basin (Michelsen et al., 1998). Japsen et al. (2007) proposed that these earliest Oligocene events represent the onset of Scandinavian uplift.

Late Cenozoic–Early Neogene (24–11 Ma)

There are two widespread unconformities within the early Neogene deep-water contourite succession of the Atlantic Margin, the origins of which have been ascribed to regional compressional deformation (Stoker et al., 2005c). The base of the Neogene is marked by pronounced angular unconformities (collectively termed Base Neogene unconformity [BNU]) separating Miocene or uppermost Oligocene from older Paleogene strata in the North Sea Fan–Vøring Basin, Faroe-Shetland and northern Rockall areas (Fig. 6) (Stoker et al., 2005a, 2005c),

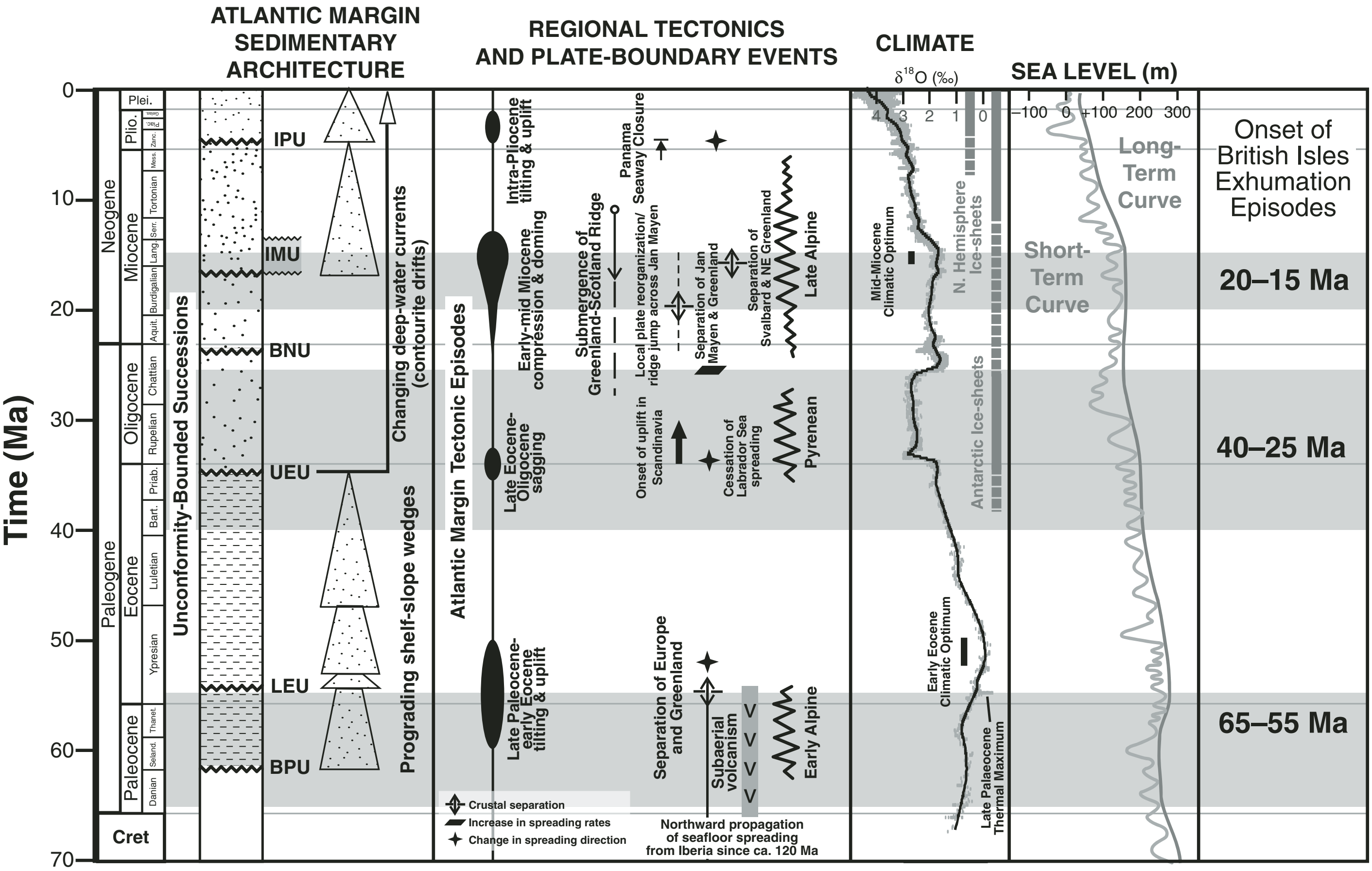


Figure 7. Cenozoic event stratigraphy diagram for the NW European Atlantic margin. Changes in sedimentary architecture (after Praeg et al., 2005) are compared with regional tectonic events (after Praeg et al., 2005; Stoker et al., 2005a, 2005b, 2005c), the global deep-sea oxygen record from Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) records, used as a proxy for Cenozoic climate (after Zachos et al., 2001), Cenozoic eustatic sea-level curves (short term and long term; after Haq and Al-Qahtani, 2005), and the onset of cooling/exhumation episodes identified from apatite fission-track analysis (AFTA) across the British Isles (this study). The Cenozoic exhumation episodes can each be correlated with significant unconformities along the Atlantic margin, and they are also synchronous with tectonic movements along the Atlantic margin and major periods of deformation at proximal plate boundaries. Note the coincidence between the timing of the early and late Cenozoic exhumation episodes, the Base Paleogene unconformity (BPU) and intra-Miocene surface unconformity (IMU), and the initiation of prograding shelf-slope wedges along the Atlantic margin. UEU—Upper Eocene unconformity; LEU—Lower Eocene unconformity; IPU—Intra Pliocene Unconformity; BNU—Base Neogene unconformity.

although in the central and southern Rockall and Porcupine Basins, the base of the Neogene is marked by a mainly conformable seismic reflector (McDonnell and Shannon, 2001), which is recognized in wells as an early Miocene hiatus (Stoker et al., 2005c). This is further confirmed from the West Shetland Shelf, where British Geological Survey (BGS) borehole 77/7 proved upper Oligocene paralic to brackish marine sediments to be unconformably overlain by Lower-Middle Miocene shallow-marine sandstones, a hiatus covering the interval between ca. 26 and 16 Ma (Evans et al., 1997; Stoker, 1999). A comparable hiatus is also recorded from BGS boreholes and commercial wells on the Hebridean margin (Stoker, 2009b). The Base Neogene unconformity may correlate temporally with the top Oligocene sequence boundary in the eastern North Sea Basin (Michelsen et al., 1998), which accords with a latest Oligocene (ca. 27–24 Ma) hiatus recorded in the sedimentary record onshore Denmark (Japsen et al., 2007). AFTA data from Mesozoic sediments encountered by offshore exploration wells in the Norwegian-Danish Basin suggest deeper burial of the preserved stratigraphy by up to 1.1 km of additional section prior to exhumation beginning between 30 and 20 Ma, which Japsen et al. (2007) associated with a ca. 27–24 Ma hiatus onshore Denmark, and the Base Neogene unconformity described from the Atlantic margin by Stoker et al. (2005a, 2005c).

Higher within the Neogene succession of the Atlantic margin, there is a prominent intra-Miocene surface (Fig. 6), which corresponds to angular unconformities and correlative conformities that have been identified in both the deep-water basins and on basin margins through seismic-stratigraphic analyses (Stoker et al., 2005a, 2005b). The angularity of the unconformities is enhanced where it is developed above the major compressional domes and anticlines (amplitudes ≤4 km, axial lengths ≤200 km) that populate the north Rockall–Faroes–mid-Norwegian segment of the Atlantic margin

(Fig. 1) (Stoker et al., 2005c). Along the Norwegian continental shelf, the intra-Miocene surface corresponds to an ~7 Ma hiatus of late mid- to early late Miocene age in basin-margin wells (Eidvin et al., 2000). A comparable hiatus is recorded in BGS boreholes from the Hebrides Shelf (Stoker, 2009b). A similarly timed, pervasive mid-Miocene unconformity and hiatus covering the 19–13 Ma interval is also present throughout the North Sea Basin (Faleide et al., 2002; Fyfe et al., 2003), which otherwise experienced continuous Cenozoic burial (White and Latin, 1993). In the southern Rockall and Porcupine Basins, the intra-Miocene surface corresponds to the distinctive, variably unconformable ca. 16–15 Ma C20 reflector (Stoker et al., 2001).

Stoker et al. (2005c) suggested that both the Base Neogene unconformity and intra-Miocene surface represent regional flexures that bracket a prolonged period of compressional deformation along the Atlantic margin. The culmination of this compressional episode is dated by the folding and tilting of Lower to lower Middle Miocene strata on the flanks of major inversion anticlines such as the Helland-Hansen Arch, Fugloy Ridge, and Wyville-Thomson Ridge (Fig. 1), which suggests that the main phase of compression occurred between 16 and 11 Ma (Stoker et al., 2005c). An important oceanographic consequence of the Miocene compressional deformation of the Atlantic margin was the creation of the 800–1200-m-deep Faroe Bank Channel, which represented the first true deep-water connection between the Atlantic Ocean and the Nordic Seas. Exposure and erosion of the Hebrides Shelf are indicated by the incorporation of reworked Lower Miocene fauna within Middle-Upper Miocene slope deposits, whereas discrete lowstand wedges of mid- to late Miocene age on the West Shetland slope imply subaerial erosion of the adjacent shelf (Stoker, 1999; Stoker et al., 2005b).

The timing of the regional mid-Miocene compressional deformation of the Atlantic margin corresponds closely with the exhumation episode that resulted in the removal of ~1 km of overburden in the Irish Sea basin system beginning between 20 and 15 Ma (Fig. 7). Similarly timed compression and exhumation have been reported from the southern North Sea and southern England (Hillis et al., 2008a) and many other locations throughout western and central Europe (Ziegler et al., 1995; Dèzes et al., 2004). These observations signify that a considerable proportion of the NW Eurasian plate underwent simultaneous compression and exhumation during the mid-Miocene. The magnitude of this exhumation is best constrained in the Irish Sea basin system (Fig. 5), but published estimates from the Atlantic margin correspond well with those from the Irish Sea and adjacent areas. AFTA data from well 6610/7–1 on the mid-Norwegian shelf record ~1 km of Miocene exhumation (beginning between 21 and 10 Ma) on the low angle Eocene-Pliocene unconformity at that location (Green et al., 2007). AFTA and VR data from the 204/19–1 well located on the Westray Ridge in the Faroe-Shetland Basin indicate that between 0.63 and 0.9 km of Eocene to mid-Miocene strata were eroded prior to late Miocene sedimentation (Parnell et al., 2005).

We note that a widespread intra–early Pliocene (4 ± 0.5 Ma) unconformity is documented from seismic-stratigraphic studies along the length of the Atlantic margin (Stoker et al., 2005a, 2005b) (Figs. 6 and 7). The intra–early Pliocene unconformity is overlain by prograding shelf-slope wedges of clastic sediment up to 1.5 km thick that attests to the long-wavelength, large-amplitude seaward tilting of the entire Atlantic margin (Praeg et al., 2005; Stoker et al., 2005a, 2005b). The volume of sediment deposited offshore and the direction of transport of the prograding wedges indicate considerable exhumation of hinterland sources in the Scandinavia and the British Isles (Stoker et al., 2005a, 2005b), where at least 1 km of late Neogene exhumation has been reported from chalk compaction studies (Japsen, 1997; Japsen et al., 2007). The Pliocene-Pleistocene exhumation episode therefore almost certainly affected the British Isles over a similar area to the Miocene exhumation episode. However, we do not document Pliocene-Pleistocene exhumation from our AFTA database. This is due to the fact that the majority of the samples that comprise this database were exhumed to depths at which thermal histories cannot be resolved by AFTA (i.e., temperatures less than 50–60 °C) during earlier exhumation episodes.

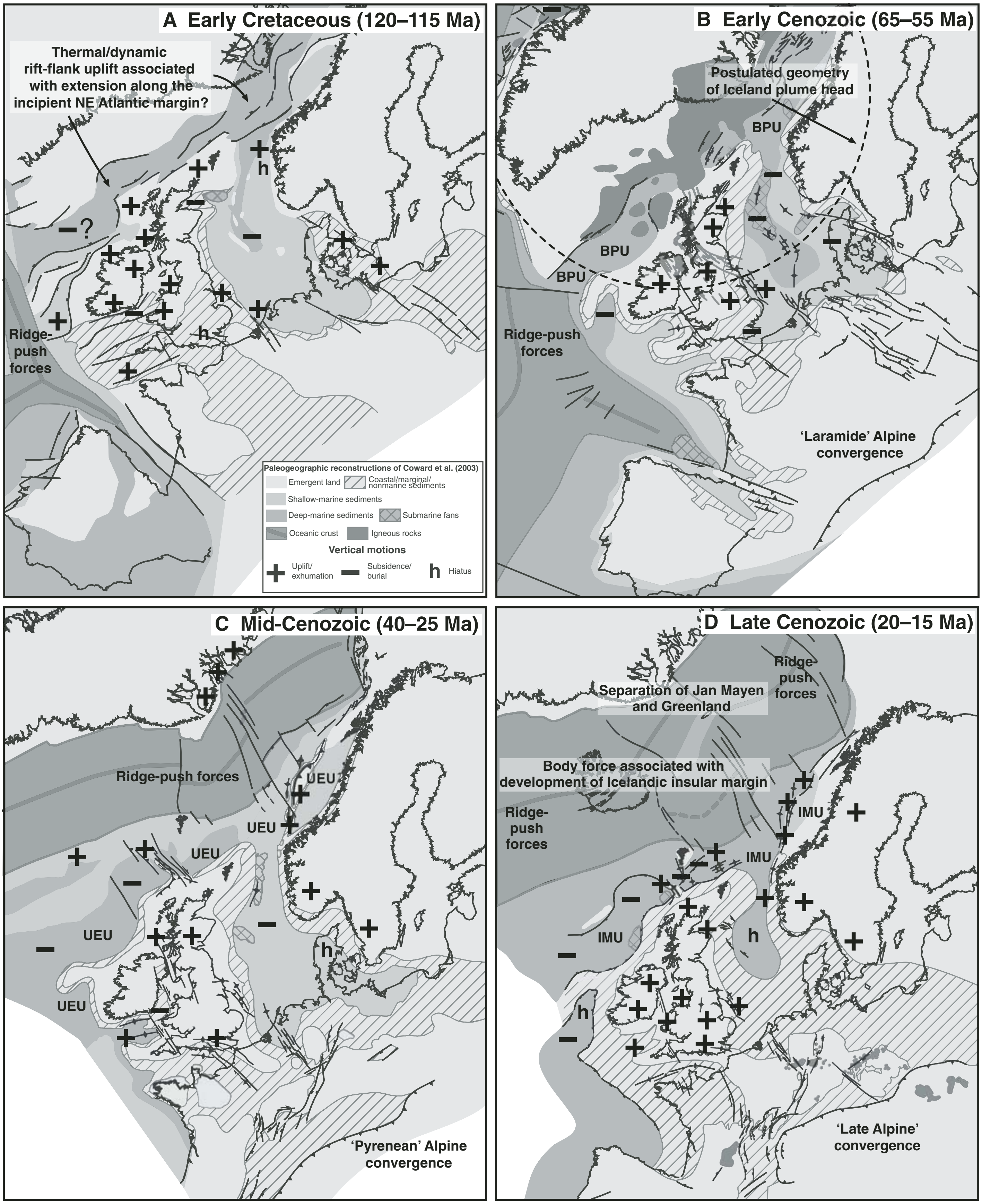
LINKING REGIONAL EXHUMATION EPISODES WITH EVENTS AT PLATE BOUNDARIES

The regional synthesis of AFTA data from the British Isles presented here has resulted in definition of four distinct Cretaceous-Cenozoic cooling episodes focused on the Irish Sea basin system beginning in the intervals 120–115 Ma, 65–55 Ma, 40–25 Ma, and 20–15 Ma (Figs. 3–5 and 8). Each of these represents regional (i.e., >10^6 km^2) exhumation involving removal of kilometer-scale thicknesses of section (Fig. 8). These exhumation episodes were separated by intervening periods of burial, therefore indicating that the British Isles have experienced a complex history of post-Paleozoic vertical motions. Furthermore, the Cenozoic cooling episodes can each be correlated with major unconformities of mid-Paleocene, Upper Eocene–Lower Oligocene, and early–mid-Miocene age that have been preserved within the Cenozoic sedimentary succession of the NW European Atlantic margin (Figs. 6 and 7). These unconformities are tectonic in origin and can be traced for distances of >2000 km, from the Porcupine Basin in the southwest to the Vøring Basin in the northwest (Figs. 1 and 6) (Praeg et al., 2005; Stoker et al., 2005a, 2005b). If the cooling and exhumation witnessed in the British Isles are genetically related to the tectonic unconformities along the Atlantic margin, a region of the NW Eurasian plate with an area of at least ~10^7 km^2 experienced recurring phases of exhumation with amplitudes >1 km throughout the Cretaceous–Cenozoic. (The area affected by the mid-Miocene event could possibly have been much greater, as much of the North Sea Basin was uplifted at this time, resulting in a widespread mid-Miocene hiatus.) The amplitude of exhumation associated with these events appears to increase inboard of the margin, such that in the western British Isles, which have been most severely affected by this exhumation, much of the stratigraphic record encompassing the Cretaceous-Cenozoic has been removed. It is only through the application of AFTA and complementary tools for reconstructing rock burial histories that the true distribution and extent of these exhumation episodes can be identified.

The timing of each of the exhumation episodes identified in this study correlates closely with periods of major deformation along the closest plate boundaries, the North Atlantic ridge spreading system (north of ~45°N), and the Alpine collision belt of western and central Europe (Fig. 8), as illustrated in the following discussion.

Early Cretaceous (120–115 Ma)

The timing of this exhumation episode was coeval with continental breakup and the onset of North Atlantic seafloor spreading southwest of Britain (Figs. 3 and 8A). The most proximal oceanic crust to the Irish Sea basins is found along the Goban Spur and Meriadzek structural highs, >500 km to the southwest (Fig. 1). Establishment of the onset of seafloor spreading off the Goban Spur is hindered by a wide zone of magnetically quiet oceanic crust (Bullock and Minshull, 2005). Synrift sediments encountered at Deep Sea Drilling Project (DSDP) Site 549 are of Barremian and probably Aptian age (i.e., 130–125 Ma and possibly younger), while the youngest postrift rocks are of Lower Albian age (112 Ma and younger). de Graciansky et al. (1985) suggested that continental breakup off Goban Spur



A Early Cretaceous (120–115 Ma)
Thermal/dynamic rift-flank uplift associated with extension along the incipient NE Atlantic margin?
Ridge-push forces
Paleogeographic reconstructions of Coward et al. (2003)
Emergent land
Coastal/marginal/nonmarine sediments
Shallow-marine sediments
Deep-marine sediments
Submarine fans
Oceanic crust
Igneous rocks
Vertical motions
Uplift/exhumation
Subsidence/burial
Hiatus
B Early Cenozoic (65–55 Ma)
Postulated geometry of Iceland plume head
BPU
Ridge-push forces
'Laramide' Alpine convergence
C Mid-Cenozoic (40–25 Ma)
Ridge-push forces
UEU
'Pyrenean' Alpine convergence
D Late Cenozoic (20–15 Ma)
Separation of Jan Mayen and Greenland
Ridge-push forces
Body force associated with development of Icelandic insular margin
IMU
'Late Alpine' convergence

Figure 8. Paleogeographic reconstructions of NW Europe (modified from Coward et al., 2003) with superimposed patterns of vertical motions (from this study) during the (A) Early Cretaceous (120–115 Ma); (B) early Cenozoic (65–55 Ma); (C) mid-Cenozoic (40–25 Ma); and (D) late Cenozoic (20–15 Ma). Plus and minus symbols indicate areas undergoing uplift/exhumation or subsidence/burial, respectively, during the indicated time windows. Postulated planform geometry of Iceland mantle plume head during early Cenozoic is modified from White and McKenzie (1989). h—hiatus; BPU—Base Paleogene unconformity; IMU—Intra-Miocene unconformity; UEU—Upper Eocene unconformity. See text for more details.

may have been coeval with the onset of seafloor spreading between Iberia and the Grand Banks in the Bay of Biscay, which led to the separation of Iberia and North America and began at around chron M0 time (ca. 118 Ma; mid-Aptian) (Fig. 8A) (Sibuet et al., 2004).

Early Cenozoic (65–55 Ma)

Early Cenozoic uplift and exhumation of the British Isles and Atlantic Margin have been attributed to mantle plume activity (either permanent uplift caused by igneous underplating or transient uplift caused by plume-related normal stresses acting on the base of the lithosphere; White and Lovell, 1997; Jones et al., 2001) (Fig. 8B). A mantle plume can account for the scale of early Cenozoic exhumation, but it cannot solely account for the heterogeneous distribution of exhumation at this time (e.g., Hillis et al., 2008a). (Note that mantle plume activity cannot account for either the timing or distribution of the Early Cretaceous, mid-Cenozoic, and late Cenozoic exhumation episodes; Fig. 8; e.g., Praeg et al., 2005.)

The early Cenozoic exhumation episode coincided with two important phases of proximal plate-boundary deformation (Figs. 4, 7, and 8B). First, intense continental rifting NW of the British Isles accompanied by massive subaerial volcanism (White and McKenzie, 1989) culminated in the onset of seafloor spreading and separation of Europe from Greenland at earliest Eocene time (ca. 55 Ma) (Doré et al., 1999). Second, in the Paleocene in western, central, and eastern Europe along the Alpine collision front, the Austro-Alpine orogenic wedge collided with the flexural basins and continental terranes of the European foreland (Dèzes et al., 2004). Compressional stresses were transmitted across distances exceeding 1500 km, inducing a broad spectrum of deformation styles, from reactivation and inversion of preexisting faults and basins to the long-wavelength buckling and uplift of the European lithosphere (Ziegler et al., 1995). During the early Cenozoic, the British Isles and Atlantic margin were thus located between two zones of intense plate-boundary deformation, both of which were capable of producing plate-driving forces of sufficient magnitude ($\sim 3 \times 10^{12}$ N m^{-1}) to deform and uplift intraplate lithosphere (Zoback et al., 2002).

Mid-Cenozoic (40–25 Ma)

The mid-Cenozoic exhumation episode recorded by AFTA data from northern Britain (Fig. 4) and the Upper Eocene unconformity of the Atlantic margin (Fig. 6) (and the possible onset of Scandinavian uplift; Japsen et al., 2007) coincided with a major North Atlantic plate reorganization that saw the termination of seafloor spreading in the Labrador Sea and the consequent joining of Greenland with the North American plate (Figs. 7 and 8C) (Doré et al., 1999). The Oligocene-Eocene transition also witnessed continued, major compressional deformation in the Alpine orogen (Dèzes et al., 2004).

Late Cenozoic (20–15 Ma)

Miocene exhumation in the British Isles constrained by AFTA data was part of platewide uplift and pervasive compressional deformation across NW Europe that commenced during the mid-Miocene. Regional changes in plate tectonic motion were coeval with this uplift and deformation (Figs. 7 and 8D). North Atlantic seafloor spreading rates increased in the earliest Miocene (Mosar et al., 2002), and spreading north of Iceland transferred progressively from the Ægir Ridge east of the Jan Mayen microcontinent to the Kolbeinsey Ridge to the west, culminating in the eventual separation of Jan Mayen and Greenland in the late early to mid-Miocene (Figs. 7 and 8D) (Stoker et al., 2005c). Additionally, Doré et al. (2008) have argued that a mid-Miocene major magmatic event led to the formation of the Iceland Plateau (Figs. 5 and 8D) and caused an elevated radial body force (i.e., $\sim 5 \times 10^{12}$ N m^{-1}; Doré et al., 2008) compared to the normal ridge push forces of $\sim 3 \times 10^{12}$ N m^{-1}; e.g., Parsons and Richter, 1980) responsible for the compression of the NW European Atlantic margin. In the Alpine orogen, strong convergence between Africa and Europe occurred between 22 and 9 Ma (Dewey, 2000).

Summary

We have shown that the British Isles experienced repeated cycles of regional, kilometer-scale exhumation and burial during late Mesozoic to Cenozoic time (Fig. 8). The exhumation episodes correlate with major unconformities revealed by seismic mapping of the thick Cenozoic sedimentary sequences preserved along the adjacent Atlantic margin (Praeg et al., 2005; Stoker et al., 2005a), but they can only be identified inboard of the margin through the application of AFTA because the exhumation has largely removed the sedimentary record that would otherwise contain the geological history of this time interval. These episodes correlate closely with key deformation events at proximal plate boundaries, suggesting a close genetic relationship.

DISCUSSION

Global Evidence for Intraplate Exhumation Caused by Plate-Boundary Deformation

The observations presented here imply that plate-boundary forces have produced vertical tectonic motions and kilometer-scale exhumation in the continental interior of NW Europe. In the following section, we provide further evidence that plate-boundary deformation exerts a primary control on tectonic activity in intraplate regions in many parts of the world, causing kilometer-scale exhumation at distances up to several thousand kilometers from the plate boundaries themselves.

One well-documented example is the exhumation of large areas up to several hundred kilometers inboard of the opposing continental margins of southern Africa and SE Brazil, which occurred diachronously from the early to mid-Cretaceous as continental breakup propagated northward (Gallagher and Brown, 1999; Turner et al., 2008). Moore et al. (2008) recently documented close temporal relationships between major unconformities within the Cretaceous-Cenozoic sequences of the Kwa Zulu, Algoa, Gamtoos, Petmos, Bredasdorp, and Orange Basins offshore southern Africa and the ages of kimberlite and other alkaline volcanic pipes onshore southern Africa. Because the ages of the unconformities/episodes of igneous activity coincide with local plate reorganizations (changes in the spreading histories of the southern Atlantic and Indian Oceans), Moore et al. (2008) attributed their origins to intraplate stresses.

Another region of widespread exhumation is the SE Australian margin, where fission-track data from the Otway Basin record up to ~2 km of exhumation beginning at ca. 100 Ma, concomitant with amagmatic continental breakup (Duddy, 1997; Green et al., 2004). Maps of fission-track ages for the Australian continent show young fission-track ages of <150 Ma extending over 500 km inland from the SE margin (Gleadow et al., 2002), again demonstrating the capability of plate-boundary deformation to generate far-field exhumation. Intraplate exhumation episodes demonstrating clear synchronicity with plate-boundary deformation events have also been identified from fission-track studies of the Falkland Islands (Thomson et al., 2002), the Appalachian Basin (Miller and Duddy, 1989), and northern Alaska (O'Sullivan et al., 1995).

These events are not necessarily restricted to continental platforms, denuded former orogens, or zones of extended continental crust, but they can also lead to kilometer-scale exhumation of long-lived shields that form the apparently stable cores of continental interiors. One such example is from the Western Australian Shield. Apatite fission-track data from Archean basement samples (>2.5 Ga) collected from the northern Yilgarn craton yield ages between 200 and 280 Ma, and thermal history modeling of these data reveals evidence for ~3 km of exhumation across the Permian-Cretaceous interval (Weber et al., 2005). The origin of this exhumation is attributed to plate-boundary deformation related to either Gondwanan breakup or the Alice Springs orogeny (Weber et al., 2005). The probable destination for the products of this erosion was the Perth Basin, SW of the Yilgarn craton, which contains up to 15 km of Permian–Lower Cretaceous clastic sediment. However, U-Pb dating of detrital zircons from the Perth Basin fill reveals few or no grains of Archean age (Cawood and Nemchin, 2000), raising the possibility that the eroded material comprised an early Paleozoic sedimentary cover, thus requiring the supposedly stable Yilgarn craton to also have experienced kilometer-scale burial prior to its exhumation (Green et al., 2006). Other cratonic regions where fission-track data indicate kilometer-scale exhumation during Phanerozoic time include the Fennoscandian (Green and Duddy, 2006) and southern Canadian Shields (Lorencak et al., 2004).

Plate-Boundary Forces, Intraplate Stress, and Regional Exhumation

The suggestion that the repeated regional intraplate exhumation of the British Isles throughout the Cretaceous-Cenozoic was controlled by plate-boundary deformation is consistent with observations of present-day stress orientations from continental interiors, which generally show a first-order control by plate-boundary forces (Zoback, 1992; Gölke and Coblentz, 1996; Hillis and Reynolds, 2000). The projection of compressional stresses over distances >1000 km from oceanic ridges or continental collision zones into the interiors of continental plates can account for a broad spectrum of shortening-related intraplate deformation styles, which vary in scale from upper-crustal folding and fault reactivation to whole lithosphere buckling (Ziegler et al., 1995; Bosworth et al., 1999). We suggest that the early and late Cenozoic exhumation episodes identified in the East Irish Sea Basin and adjacent regions in this study were most likely caused by the transmission of compressional stresses into intraplate NW Europe from the Mid-Atlantic Ridge and the Alpine orogen. A modern-day analog for these exhumation episodes may be the West Siberian Basin, which is experiencing active long-wavelength surface uplift, attributed by Allen and Davies (2007) to low degrees of crustal thickening accommodated by discrete folds and faulting at depth, displacements on which die out upward to produce smooth regional surface tilting. The uplift of the West Siberian Basin is interpreted to be a far-field effect of India-Eurasia collision, some ~1500 km north of the limit of major seismicity and mountain building and ~3500 km north of the original collision zone (Allen and Davies, 2007). The Flinders and Mt. Lofty Ranges of Southern Australia represent another zone of active intraplate deformation and uplift due to crustal thickening that is caused by distant plate-boundary deformation, in this case, arising from the collisional plate boundary at New Zealand ~2000 km away (Sandiford, 2003). Hillis et al. (2008b) showed clear consistency between plate-boundary–sourced stress orientations and the orientation of paleostresses inferred from Neogene–Holocene structures along the southern margin of the Australian continent. Quaternary slip rates of reverse-sense faults in the Flinders and Mt. Lofty Ranges are of the order of 20–150 m Ma^{-1} (Sandiford, 2003). Cumulative movements of this amount over time scales of ~10^7 a^{-1} would be sufficient to reproduce the scale of the exhumation episodes we document from NW Europe.

The regional unconformities present along the Atlantic margin, which we suggest here are linked to the Cenozoic cooling and exhumation episodes observed across the British Isles, have also been associated with plate-boundary deformation events, but in a different way, by the workers that documented them (Praeg et al., 2005; Stoker et al., 2005a). Rather than attributing them to crustal thickening caused by plate-boundary stress-field projection, Stoker et al. (2005a) and Praeg et al. (2005) suggested that the plate reorganizations in the North Atlantic oceanic ridge system that accompanied formation of these unconformities induced edge-driven convective flow in the upper mantle (cf. King and Anderson, 1998), which caused dynamic tilting along the Atlantic margin. Such convective flow is predicted to occur where significant variations in lithospheric thickness (e.g., along rifted continental margins; Japsen et al., 2006) impose lateral temperature variations near the top of the mantle, which give rise to convective flow cells with diameters up to 1000 km in the upper mantle. These can, in turn, induce dynamic surface deflections (uplift and subsidence) caused by varying vertical stresses above areas of upwelling and downwelling in the upper mantle (King and Anderson, 1998). Stoker et al. (2005a) and Praeg et al. (2005) proposed that primary asthenospheric upwelling beneath the recently initiated North Atlantic oceanic ridge during the early Cenozoic induced secondary convection beneath the adjacent continental margin, causing dynamic tilting and consequent uplift as recorded by the Atlantic margin Base Paleogene unconformity and the early Cenozoic (65–55 Ma) cooling episode across the British Isles. Subsequent Cenozoic plate reorganizations may have altered patterns of convective flow, either renewing or reducing dynamic support (Praeg et al., 2005; Stoker et al., 2005a). The model proposed by Stoker et al. (2005a) and Praeg et al. (2005) thus provides a direct link among plate-boundary deformation, convective flow in the upper mantle, and regional intraplate uplift and unconformity formation. Alternatively, dynamic uplift independent of plate-boundary deformation has been proposed to explain the late Cenozoic regional uplift of Southern Australia via the passage of the Australian continent over a regional geoid anomaly (Sandiford, 2007), and the anomalously high topography of the southern African plateau due to an upwelling mantle plume (Lithgow-Bertelloni and Silver, 1998).

Significance of Low-Angle Unconformities

A recent seismic-stratigraphic analysis of the Mesozoic-Cenozoic stratigraphy of the Arabian Platform (from NW Saudi Arabia and southern Iraq to Oman and northern Yemen) by George et al. (2005) has revealed a strikingly similar cycle of repeated exhumation-burial episodes, where five major unconformities alone during the Jurassic-Cretaceous interval each record >300 m exhumation over an area >50,000 km^2. These unconformities are typically low-angle (mostly <1°, rarely >5°) (George et al., 2005), similar to those recording the widespread tilting and uplift along the Atlantic margin (Praeg et al., 2005; Stoker et al., 2005a) and the kilometer-scale exhumation of the British Isles. Analogous low-angle regional unconformities have been documented from the continental interiors of North Africa (Boote et al., 1998) and the Russian Platform (Mitrovica et al., 1996). The absence of pronounced high-angle unconformities across these regions has led to an erroneous perception of their long-term (>100 Ma) tectonic stability, and such unconformities have hitherto frequently been interpreted in terms of nondeposition. A key implication of this study is the recognition that such low-angle (e.g., <5°) unconformities may record kilometer-scale exhumation events. Only through the combined application of seismic or field-based mapping and thermochronological tools or other paleoburial proxies (e.g., sedimentary rock compaction data) can the true scale of this exhumation be appreciated.

CONCLUSIONS

(1) A regional synthesis of apatite fission-track analysis (AFTA) data from the British Isles, focusing on the Irish Sea basins where the greatest density of data is available, shows that an area encompassing ~10^6 km^2 experienced multiple periods of kilometer-scale exhumation during Cretaceous-Cenozoic times.

(2) Major cooling and exhumation episodes are identified beginning during the early Cretaceous (120–115 Ma), early Cenozoic (65–55 Ma), mid-Cenozoic (40–25 Ma), and late Cenozoic (20–15 Ma). The Cenozoic exhumation events correlate with the timing of major tectonic unconformities preserved within the Cenozoic sedimentary succession of the adjacent Atlantic margin, but across the British Isles, the exhumation is much more pronounced, such that the corresponding sedimentary record has been almost completely removed.

(3) The timing of each of the exhumation episodes identified in this study correlates strongly with major deformation events at the most proximal plate boundaries (i.e., the Alpine collisional belt and the North Atlantic rift/ridge system). Despite the considerable (up to 1500 km) distances between the British Isles and these plate boundaries, the timing, distribution, and styles of these exhumation episodes can be explained in terms of mechanisms with a consistent plate-boundary origin, such as mantle convection–induced dynamic topography or lithospheric shortening due to transmission of compressional stresses.

(4) Repeated cycles of kilometer-scale intraplate exhumation coeval with plate-boundary deformation at distances >1000 km are also revealed by thermochronologic and tectonostratigraphic studies across the globe. Particularly good examples are provided by fission-track data from SE Brazil, southern Africa, and SE Australia. In accordance with observations from the British Isles, many of these areas also reveal evidence for repeated cycles of burial and exhumation.

(5) Kilometer-scale intraplate exhumation driven by plate-boundary deformation is not restricted to platform areas or zones of extended continental crust, but it can also be demonstrated for long-lived, supposedly stable cratons, like those of Western Australia and Fennoscandia.

(6) These exhumation episodes are commonly recorded by low-angle (i.e., <5°) unconformities. In the absence of the quantitative constraints on exhumation provided by tools like AFTA, many regional intraplate unconformities have previously been interpreted in terms of nondeposition, leading to erroneous views of tectonic stability in regions that may actually have been subject to (possibly multiple episodes of) kilometer-scale exhumation.

Our observations lead us to suggest that plate-boundary deformation and associated forces and processes exert the primary control upon the regional exhumation of intraplate tectonic settings.

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REFERENCES CITED

Allen, M.B., and Davies, C.E., 2007, Unstable Asia: Active deformation of Siberia revealed by drainage shifts: Basin Research, v. 19, p. 379–392, doi: 10.1111/j.1365-2117.2007.00331.x.

Allen, P.A., and Allen, J.R., 2005, Basin Analysis (2nd edition): Oxford, Blackwell, 549 p.

Argent, J.D., Stewart, S.A., Green, P.F., and Underhill, J.R., 2002, Heterogeneous exhumation in the Inner Moray Firth, UK North Sea: Constraints from new AFTA® and seismic data: Geological Society of London Journal, v. 159, p. 715–729.

Boote, D.R.D., Clark-Lowes, D.D., and Traut, M.W., 1998, Palaeozoic petroleum systems of North Africa, *in* McGregor, D.C., Moody, R.T.J., and Clark-Lowes, D.D., eds., Petroleum Geology of North Africa: Geological Society [London] Special Publication 132, p. 7–68.

Bosworth, W., Guiraud, R., and Kessler, L.G., 1999, Late Cretaceous (ca. 84 Ma) compressive deformation of the stable platform of northeast Africa (Egypt): Far-field stress effects of the "Santonian event" and origin of the Syrian arc deformation belt: Geology, v. 27, p. 633–636, doi: 10.1130/0091-7613(1999)027<0633:LCCMCD>2.3.CO;2.

Bray, R., Duddy, I.R., and Green, P.F., 1998, Multiple heating episodes in the Wessex Basin: Implications for geological evolution and hydrocarbon generation, *in* Underhill, J.R., ed., Development, Evolution and Petroleum Geology of the Wessex Basin: Geological Society [London] Special Publication 133, p. 199–213.

Brodie, J., and White, N., 1994, Sedimentary basin inversion caused by igneous underplating: Geology, v. 22, p. 147–150, doi: 10.1130/0091-7613(1994)022<0147:SBICBI>2.3.CO;2.

Bullock, A.D., and Minshull, T.A., 2005, From continental extension to seafloor spreading: Crustal structure of the Goban Spur rifted margin, southwest of the UK: Geophysical Journal International, v. 163, p. 527–546, doi: 10.1111/j.1365-246X.2005.02726.x.

Cameron, T.D.J., Crosby, A., Balson, P.S., Jeffrey, D.H., Lott, G.K., Bulat, J., and Harrison, D.J., 1992, United Kingdom Offshore Regional Report: The Geology of the Southern North Sea: London, Her Majesty's Stationary Office for the British Geological Survey, 152 p.

Cawood, P.A., and Nemchin, A.A., 2000, Provenance record of a rift basin: U/Pb ages of detrital zircons from the Perth Basin, Western Australia: Sedimentary Geology, v. 134, p. 209–234, doi: 10.1016/S0037-0738(00)00044-0.

Ceramicola, S., Stoker, M.S., Praeg, D., Shannon, P.M., De Santis, L., Hoult, R., Hjelstuen, B.O., Laberg, S., and Mathiesen, A., 2005, Anomalous Cenozoic subsidence along the 'passive' continental margin from Ireland to mid-Norway: Marine and Petroleum Geology, v. 22, p. 1045–1067, doi: 10.1016/j.marpetgeo.2005.04.005.

Cope, J.C.W., 1994, A latest Cretaceous hotspot and the southeasterly tilt of Britain: Geological Society of London Journal, v. 159, p. 905–908.

Corcoran, D.V., and Doré, A.G., 2005, A review of techniques for the estimation of magnitude and timing of exhumation in offshore basins: Earth-Science Reviews, v. 72, p. 129–168, doi: 10.1016/j.earscirev.2005.05.003.

Corcoran, D.V., and Mecklenburgh, R., 2005, Exhumation of the Corrib Gas Field, Slyne Basin, offshore Ireland: Petroleum Geoscience, v. 11, p. 239–256, doi: 10.1144/1354-079304-637.

Coward, M.P., Dewey, J.F., Hempton, M., and Holroyd, J., 2003, Tectonic evolution, *in* Evans, D., et al., eds., The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea: London, Geological Society of London, p. 17–33.

de Graciansky, P.C., Poag, C.W., Cunningham, R., Loubere, P., Masson, D.G., Mazzullo, J.M., Montadert, L., Müller, C., Otsuka, K., Reynolds, L.A., Sigal, J., Snyder, S.W., Townsend, H.A., Vaos, S.P., and Waples, D., 1985, The Goban Spur transect: Geological evolution of a sediment-starved passive continent margin: Geological Society of America Bulletin, v. 96, p. 58–76, doi: 10.1130/0016-7606(1985)96<58:TGSTGE>2.0.CO;2.

Dewey, J.F., 2000, Cenozoic tectonics of western Ireland: Proceedings of the Geologist's Association, v. 111, p. 291–306.

Dewey, J.F., Helman, M.L., Turco, E., Hutton, D.H.W., and Knott, S.D., 1989, Kinematics of the western Mediterranean, *in* Coward, M.P., Dietrich, D., and Park, R.G., eds., Alpine Tectonics: Geological Society [London] Special Publication 45, p. 265–283.

Dèzes, P., Schmid, S.M., and Ziegler, P.A., 2004, Evolution of the European Cenozoic rift system: Interaction of the Alpine and Pyrenean orogens with their foreland lithosphere: Tectonophysics, v. 389, p. 1–33, doi: 10.1016/j.tecto.2004.06.011.

Doré, A.G., Lundin, E.R., Jensen, L.N., Birkeland, Ø., Eliassen, P.E., and Filcher, C., 1999, Principal tectonic events in the evolution of the northwest European Atlantic margin, *in* Fleet, A.J., and Boldy, S.A.R., eds., Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference: London, Geological Society of London, p. 41–61.

Doré, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P., and White, N.J., 2002, Exhumation of the North Atlantic margin: Introduction and background, *in* Doré, A.G., et al., eds., Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration: Geological Society [London] Special Publication 196, p. 1–12.

Doré, A.G., Lundin, E.R., Kusznir, N., and Pascal, C., 2008, Potential mechanisms for the genesis of Cenozoic domal structures on the NE Atlantic margin: Pros, cons and some new ideas, *in* Johnson, H., et al., eds., The Nature and Origin of Compression in Passive Margins: Geological Society [London] Special Publication 306, p. 1–26.

Duddy, I.R., 1997, Focusing exploration in the Otway Basin: Understanding timing of source rock maturation: Australian Petroleum Production and Exploration Association Journal, v. 37, p. 178–191.

Duddy, I.R., Green, P.F., Gibson, H.J., and Hegarty, K.A., 2004, Regional palaeo-thermal episodes in northern Australia, *in* Ellis, G.K., et al., eds., Timor Sea Petroleum Geoscience: Proceedings of the Timor Sea Symposium, Darwin, Northern Territory, 19–20 June 2003: Northern Territory Geological Survey Special Publication 1, p. 567–591.

Eidvin, T., Jansen, E., Rundberg, Y., Brekke, H., and Grogan, P., 2000, The upper Cainozoic of the Norwegian continental shelf correlated with the deep sea record of the Norwegian Sea and North Atlantic: Marine and Petroleum Geology, v. 17, p. 579–600, doi: 10.1016/S0264-8172(00)00008-8.

Evans, D., Morton, A.C., Wilson, S., Jolley, D., and Barreiro, B.A., 1997, Palaeoenvironmental significance of marine and terrestrial Tertiary sediments on the NW Scottish Shelf in BGS borehole 77/7: Scottish Journal of Geology, v. 33, p. 31–42.

Faleide, J.I., Kyrkjebø, R., Kjennerud, T., Gabrielsen, R.H., Jordt, H., Fanavoll, S., and Bjerke, M.D., 2002, Tectonic impact on sedimentary processes during Cenozoic evolution of the northern North Sea and surrounding areas, *in* Doré, A.G., et al., eds., Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration: Geological Society [London] Special Publication 196, p. 235–269.

Fyfe, J.A., Long, D., and Evans, D., 1993, United Kingdom Offshore Regional Report: The Geology of the Malin-Hebrides Sea Area: London, Her Majesty's Stationary Office for the British Geological Survey, 91 p.

Fyfe, J.A., Gregersen, U., Jordt, H., Rundberg, Y., Eidvin, T., Evans, D., Stewart, D., Hovland, M., and Andresen, P., 2003, Oligocene to Holocene, *in* Evans, D., et al., eds., The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea: London, Geological Society of London, p. 279–287.

Gallagher, K., and Brown, R., 1999, Denudation and uplift at passive margins: The record on the Atlantic margin of southern Africa: Philosophical Transactions of the Royal Society of London, v. 357, p. 835–859.

George, R.P., De Monteyard, B., Hardy, M.J., Muratov, N.I., Willan, C.G., Grabowski, G.J., Mitchell, J.C., Steinhuaff, D.M., King, K.C., King, J.K., Beeman, C.R., Lopez, J.A., Sempere, J.-C., and Kleist, R.J., 2005, Plate-scale tectonic events inferred from Mesozoic and Cenozoic stratigraphic of the southeastern portion of the Arabian plate, *in* Proceedings of the American Association of Petroleum Geologists International Meeting, 11–14 September, 2005: Paris, France, American Association of Petroleum Geologists.

George, T.N., 1966, Geomorphic evolution in Hebridean Scotland: Scottish Journal of Geology, v. 2, p. 1–34.

Gleadow, A.J.W., Kohn, B.P., Brown, R.W., O'Sullivan, P.B., and Raza, A., 2002, Fission track thermotectonic imaging of the Australian continent: Tectonophysics, v. 349, p. 5–21, doi: 10.1016/S0040-1951(02)00043-4.

Gölke, M., and Coblentz, D., 1996, Origins of the European regional stress field: Tectonophysics, v. 266, p. 11–24, doi: 10.1016/S0040-1951(96)00180-1.

Green, P.F., 1986, On the thermo-tectonic evolution of northern England: Evidence from fission track analysis: Geological Magazine, v. 123, p. 493–506.

Green, P.F., 2002, Early Tertiary palaeo-thermal effects in northern England: Reconciling results from apatite fission track analysis with geological evidence: Tectonophysics, v. 349, p. 131–144, doi: 10.1016/S0040-1951(02)00050-1.

Green, P.F., 2005, Burial and exhumation histories of Carboniferous rocks of the southern North Sea and onshore UK, with particular emphasis on post-Carboniferous events, *in* Collinson, J.D., et al., eds., Carboniferous Hydrocarbon Resources: The Southern North Sea and Surrounding Areas: Yorkshire Geological Society Occasional Publication 7, p. 25–34.

Green, P.F., and Duddy, I.R., 2006, Interpretation of apatite (U-Th)/He ages and fission track ages from cratons: Earth and Planetary Science Letters, v. 244, p. 541–547, doi: 10.1016/j.epsl.2006.02.024.

Green, P.F., Duddy, I.R., and Bray, R.J., 1997, Variation in thermal history styles around the Irish Sea and adjacent areas: Implications for hydrocarbon occurrence and tectonic evolution, *in* Meadows, N.S., et al., eds., Petroleum Geology of the Irish Sea and Adjacent Areas: Geological Society [London] Special Publication 124, p. 73–93.

Green, P.F., Duddy, I.R., Hegarty, K.A., and Bray, R.J., 1999, Early Tertiary heat flow along the UK Atlantic margin and adjacent areas, *in* Fleet, A.J., and Boldy, S.A.R., eds., Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference on the Petroleum Geology of Northwest Europe: London, Geological Society of London, p. 348–357.

Green, P.F., Duddy, I.R., Hegarty, K.A., Bray, R.J., Sevastapulo, G.D., Clayton, G., and Johnston, D., 2000, The post-Carboniferous evolution of Ireland: Evidence from thermal history reconstruction: Proceedings of the Geologist's Association, v. 111, p. 307–320.

Green, P.F., Duddy, I.R., Bray, R.J., Duncan, W.I., and Corcoran, D.V., 2001a, The influence of thermal history on hydrocarbon prospectivity in the central Irish Sea Basin, *in* Shannon, P.M., Haughton, P.D.W., and Corcoran, D.V., eds., The Petroleum Exploration of Ireland's Offshore Basins: Geological Society [London] Special Publication 188, p. 171–188.

Green, P.F., Thomson, K., and Hudson, J.D., 2001b, Recognising tectonic events in undeformed regions: Contrasting results from the Midland Platform and East Midlands Shelf, central England: Geological Society of London Journal, v. 158, p. 59–73.

Green, P.F., Duddy, I.R., and Hegarty, K., 2002, Quantifying exhumation from apatite fission-track analysis and vitrinite reflectance data: Precision, accuracy and latest results from the Atlantic margin of NW Europe, *in* Doré, A.G., et al., eds., Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration: Geological Society [London] Special Publication 196, p. 331–354.

Green, P.F., Crowhurst, P.V., and Duddy, I.R., 2004, Integration of AFTA and (U-Th)/He thermochronology to enhance the resolution and precision of thermal history reconstruction in the Anglesea-1 well, Otway Basin, SE Australia, *in* Boult, P.J., Johns, D.R., and Lang, S.C., eds., Eastern Australian Basins Symposium II: Petroleum Exploration Society of Australia Special Publication, p. 117–131.

Green, P.F., Crowhurst, P.V., Duddy, I.R., Japsen, P., and Holford, S.P., 2006, Conflicting (U-Th)/He and fission track ages in apatite: Enhanced He retention, not anomalous annealing behaviour: Earth and Planetary Science Letters, v. 250, p. 407–427, doi: 10.1016/j.epsl.2006.08.022.

Green, P.F., Duddy, I.R., Japsen, P., and Holford, S.P., 2007, Synchronous regional kilometre-scale exhumation events around the North Atlantic region: The 5th International Conference on Arctic Margins (ICAM V), 3–5 September, 2007; Tromso, Norway, Norges Geologiske Forening and EAGE, NGF Abstracts and Proceedings, no. 2, p. 93–94.

Hamblin, R.J.O., Crosby, A., Balson, P.S., Jones, S.M., Chadwick, R.A., Penn, I.E., and Arthur, M.J., 1992, United Kingdom Offshore Regional Report: The Geology of the English Channel: London, Her Majesty's Stationary Office for the British Geological Survey, 106 p.

Haq, B.U., and Al-Qahtani, A.M., 2005, Phanerozoic cycles of sea-level change on the Arabian Platform: GeoArabia, v. 10, p. 127–160.

Herbert-Smith, M., 1979, The age of the Tertiary deposits of the Llanbedr (Mochras Farm) borehole as determined from palynological studies: Institute of Geological Sciences Report 78/24, p. 15–29.

Hillis, R.R., 1995, Regional Tertiary exhumation in and around the United Kingdom, *in* Buchanan, J.G., and Buchanan, P.G., eds., Basin Inversion: Geological Society [London] Special Publication 88, p. 167–190.

Hillis, R.R., and Reynolds, S.D., 2000, The Australian Stress Map: Geological Society of London Journal, v. 157, p. 915–921.

Hillis, R.R., Thomson, K., and Underhill, J.R., 1994, Quantification of Tertiary erosion in the Inner Moray Firth using sonic velocity data from the Chalk and Kimmeridge Clay: Marine and Petroleum Geology, v. 11, p. 283–293, doi: 10.1016/0264-8172(94)90050-7.

Hillis, R.R., Holford, S.P., Green, P.F., Doré, A.G., Gatliff, R.W., Stoker, M.S., Thomson, K., Turner, J.P., Underhill, J.R., and Williams, G.A., 2008a, Cenozoic exhumation of the southern British Isles: Geology, v. 36, p. 371–374, doi: 10.1130/G24699A.1.

Hillis, R.R., Sandiford, M., Reynolds, S.D., and Quigley, M.C., 2008b, Present-day stresses, seismicity and Neogene-to-Recent tectonics of Australia's 'passive' margins: Intraplate deformation controlled by plate boundary forces, *in* Johnson, H., et al., eds., The Nature and Origin of Compression in Passive Margins: Geological Society [London] Special Publication 306, p. 71–90.

Holford, S.P., 2006, The Mesozoic-Cenozoic Exhumation History of the Irish Sea Basin System [Ph.D. thesis]: Birmingham, University of Birmingham, 448 p.

Holford, S.P., Green, P.F., and Turner, J.P., 2005a, Palaeothermal and compaction studies in the Mochras borehole (NW Wales) reveal Early Cretaceous and Neogene exhumation and argue against regional Palaeogene uplift in the southern Irish Sea: Geological Society of Journal, v. 162, p. 829–840.

Holford, S.P., Turner, J.P., and Green, P.F., 2005b, Reconstructing the Mesozoic-Cenozoic exhumation history of the Irish Sea basin system using apatite fission track analysis and vitrinite reflectance data, *in* Doré, A.G., and Vining, B., eds., Petroleum Geology: Northwest Europe and Global Perspectives: Proceedings of the 6th Conference on the Petroleum Geology of Northwest Europe: London, Geological Society of London, p. 1095–1107.

Holford, S.P., Green, P.F., Turner, J.P., Williams, G.A., Hillis, R.R., Tappin, D.R., and Duddy, I.R., 2008, Evidence for kilometer-scale Neogene exhumation driven by compressional deformation in the Irish Sea basin system, *in* Johnson, H., et al., eds., The Nature and Origin of Compression in Passive Margins: Geological Society [London] Special Publication 306, p. 91–119.

Hudson, J.D., and Andrews, J.E., 1987, The diagenesis of the Great Estuarine Group, Middle Jurassic, Inner Hebrides, Scotland, *in* Marshall, J.D., ed., Diagenesis of Sedimentary Sequences: Geological Society [London] Special Publication 36, p. 259–276.

Jackson, D.I., Jackson, A.A., Evans, D., Wingfield, R.T.R., Barnes, R.P., and Arthur, M.J., 1995, United Kingdom Offshore Regional Report: The Geology of the Irish Sea: London, Her Majesty's Stationary Office for the British Geological Survey, 123 p.

Japsen, P., 1997, Regional Neogene exhumation of Britain and the western North Sea: Geological Society of London Journal, v. 154, p. 239–247.

Japsen, P., 2000, Investigation of multi-phase erosion using reconstructed shale trends based on sonic data, Sole Pit axis, North Sea: Global and Planetary Change, v. 24, p. 189–210, doi: 10.1016/S0921-8181(00)00008-4.

Jaspen, P., Bonow, J.M., Green, P.F., Chalmers, J.A., and Lidmar-Bergström, K., 2006, Elevated, passive continental margins: Long-term highs or Neogene uplifts? New evidence from West Greenland: Earth and Planetary Science Letters, v. 248, p. 330–339, doi: 10.1016/j.epsl.2006.05.036.

Japsen, P., Green, P.F., Henrik Nielsen, L., Rasmussen, E.S., and Bidstrup, T., 2007, Mesozoic-Cenozoic exhumation events in the eastern North Sea Basin: A multidisciplinary study based on palaeothermal, palaeoburial, stratigraphic and seismic data: Basin Research, v. 19, p. 451–490, doi: 10.1111/j.1365-2117.2007.00329.x.

Jolivet, M., 2007, Histoire de la denudation dans le corridor du loch Ness (Écosse): Mouvements verticaux différentiels le long de la Great Glen fault: Comptes Rendus Geoscience, v. 339, p. 121–131, doi: 10.1016/j.crte.2006.12.005.

Jones, S.M., White, N., and Lovell, B., 2001, Cenozoic and Cretaceous transient uplift in the Porcupine Basin and its relationship to a mantle plume, *in* Shannon, P.M., Haughton, P.D.W., and Corcoran, D.V., eds., The Petroleum Exploration of Ireland's Offshore Basins:

Geological Society [London] Special Publication 188, p. 345–360.
Jones, S.M., White, N., Clarke, B.J., Rowley, E., and Gallagher, K., 2002, Present and past influence of the Iceland Plume on sedimentation, *in* Doré, A.G., et al., eds., Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration: Geological Society [London] Special Publication 196, p. 13–25.
King, S.D., and Anderson, D.L., 1998, Edge-driven convection: Earth and Planetary Science Letters, v. 160, p. 289–296, doi: 10.1016/S0012-821X(98)00089-2.
Kyrkjebø, R., Gabrielsen, R.H., and Faleide, J.I., 2004, Unconformities related to the Jurassic-Cretaceous synrift–post-rift transition of the northern North Sea: Geological Society of London Journal, v. 161, p. 1–17.
Lewis, C.L.E., Green, P.F., Carter, A., and Hurford, A.J., 1992, Elevated K/T palaeotemperatures throughout Northwest England: Three kilometres of Tertiary erosion?: Earth and Planetary Science Letters, v. 112, p. 131–145, doi: 10.1016/0012-821X(92)90012-K.
Lithgow-Bertelloni, C., and Silver, P.G., 1998, Dynamic topography, plate driving forces and the African superswell: Nature, v. 395, p. 269–272, doi: 10.1038/26212.
Lorencak, M., Kohn, B.P., Osadetz, K.G., and Gleadow, A.J.W., 2004, Combined apatite fission track and (U-Th)/He thermochronometry in a slowly cooled terrane: Results from a 3440 m deep drill hole in the southern Canadian Shield: Earth and Planetary Science Letters, v. 227, p. 87–104, doi: 10.1016/j.epsl.2004.08.015.
Mackay, L.M., and White, N.J., 2006, Accurate estimates of the spatial pattern of denudation by inversion of stacking velocity data: An example from the British Isles: Geochemistry, Geophysics, Geosystems, v. 7, p. Q10007, doi: 10.1029/2005GC001192.
Martinsen, O.J., Bøen, F., Charnock, M.A., Mangerud, G., and Nøttvedt, A., 1999, Cenozoic development of the Norwegian margin 60–64°: Sequences and sedimentary response to variable basin physiography and tectonic setting, *in* Fleet, A.J., and Boldy, S.A.R., eds., Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference on the Petroleum Geology of Northwest Europe: London, Geological Society of London, p. 293–304.
McDonnell, A., and Shannon, P.M., 2001, Comparative Tertiary stratigraphic evolution of the Porcupine and Rockall Basins, *in* Shannon, P.M., Haughton, P.D.W., and Corcoran, D.V., eds., The Petroleum Exploration of Ireland's Offshore Basins: Geological Society [London] Special Publication 188, p. 323–344.
McInroy, D.B., Hitchen, K., and Stoker, M.S., 2006, Potential Eocene and Oligocene stratigraphic traps of the Rockall Plateau, NE Atlantic margin, *in* Allen, M.R., et al., eds., The Deliberate Search for the Stratigraphic Trap: Geological Society [London] Special Publication 254, p. 247–266.
McMahon, N.A., and Turner, J., 1998, The documentation of a latest Jurassic–earliest Cretaceous uplift throughout southern England and adjacent offshore areas, *in* Underhill, J.R., ed., Development, Evolution and Petroleum Geology of the Wessex Basin: Geological Society [London] Special Publication 133, p. 215–240.
Michelsen, O., Thomsen, E., Danielsen, M., Heilmann-Clausen, C., Jordt, H., and Laursen, G.V., 1998, Cenozoic sequence stratigraphy in the eastern North Sea, *in* de Graciansky, P.-C., et al., eds., Mesozoic and Cenozoic Sequence Stratigraphy of European Basins: Society for Sedimentary Geology Special Publication 60, p. 91–118.
Miller, D.S., and Duddy, I.R., 1989, Early Cretaceous uplift and erosion of the northern Appalachian Basin, New York, based on apatite fission track analysis: Earth and Planetary Science Letters, v. 93, p. 35–49, doi: 10.1016/0012-821X(89)90182-9.
Mitchell, W.I., ed., 2004, The Geology of Northern Ireland: Our Natural Foundation: Belfast, Geological Survey of Northern Ireland, 318 p.
Mitrovica, J.X., Pysklywec, R.N., Beaumont, C., and Rutty, A., 1996, The Devonian to Permian sedimentation of the Russian Platform: An example of subduction-controlled long-wavelength tilting of continents: Journal of Geodynamics, v. 22, p. 79–96, doi: 10.1016/0264-3707(96)00008-7.
Moore, A., Blenkinsop, T., and Cotterill, F.W., 2008, Controls on post-Gondwana alkaline volcanism in southern Africa: Earth and Planetary Science Letters, v. 268, p. 151–164, doi: 10.1016/j.epsl.2008.01.007.
Mosar, J., Lewis, G., and Torsvik, T.H., 2002, North Atlantic sea-floor spreading rates: Implications for the Tertiary development of inversion structures of the Norwegian-Greenland Sea: Geological Society of London Journal, v. 159, p. 503–515.
Murdoch, L.M., Musgrove, F.M., and Perry, J.S., 1995, Tertiary uplift and inversion history in the North Celtic Sea Basin and its influence on source rock maturity, *in* Croker, P.F., and Shannon, P.M., eds., The Petroleum Geology of Ireland's Offshore Basins: Geological Society [London] Special Publication 93, p. 297–319.
O'Sullivan, P.B., Hanks, C.L., Wallace, W.K., and Green, P.F., 1995, Multiple episodes of Cenozoic denudation in the northeastern Brooks Range: Fission-track data from the Okpilak Batholith, Alaska: Canadian Journal of Earth Sciences, v. 32, p. 1106–1118.
Parnell, J., Green, P.F., Watt, G., and Middleton, D., 2005, Thermal history and oil charge on the UK Atlantic margin: Petroleum Geoscience, v. 11, p. 99–112, doi: 10.1144/1354-079304-618.
Parsons, B., and Richter, F.M., 1980, A relation between the driving force and geoid anomaly associated with mid-ocean ridges: Earth and Planetary Science Letters, v. 51, p. 445–450, doi: 10.1016/0012-821X(80)90223-X.
Praeg, D., Stoker, M.S., Shannon, P.M., Ceramicola, S., Hjelstuen, B., Laberg, J.S., and Mathiesen, A., 2005, Episodic Cenozoic tectonism and the development of the NW European 'passive' continental margin: Marine and Petroleum Geology, v. 22, p. 1007–1030, doi: 10.1016/j.marpetgeo.2005.03.014.
Roberts, D.G., Thompson, M., Mitchener, B., Hossack, J., Carmichael, S., and Bjørnseth, H.-M., 1999, Palaeozoic to Tertiary rift and basin dynamics: Mid-Norway to the Bay of Biscay—A context for hydrocarbon prospectivity in the deep water frontier, *in* Fleet, A.J., and Boldy, S.A.R., eds., Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference on the Petroleum Geology of Northwest Europe: London, Geological Society of London, p. 7–40.
Rosenbaum, G., Lister, G.S., and Duboz, C., 2002, Relative motions of Africa, Iberia and Europe during Alpine orogeny: Tectonophysics, v. 359, p. 117–129, doi: 10.1016/S0040-1951(02)00442-0.
Rowley, E., and White, N., 1998, Inverse modelling of extension and denudation in the East Irish Sea and surrounding areas: Earth and Planetary Science Letters, v. 161, p. 57–71, doi: 10.1016/S0012-821X(98)00137-X.
Ruffell, A.H., 1992, Early to mid-Cretaceous tectonics and unconformities of the Wessex Basin (southern England): Geological Society of London Journal, v. 149, p. 443–454.
Sandiford, M., 2003, Neotectonics of southeastern Australia: Linking the Quaternary faulting record with seismicity and in situ stress, *in* Hillis, R.R., and Muller, D., eds., Evolution and Dynamics of the Australian Plate: Geological Society of Australia Special Publication 22, p. 101–113.
Sandiford, M., 2007, The tilting continent: A new constraint on the dynamic topographic field from Australia: Earth and Planetary Science Letters, v. 261, p. 152–163, doi: 10.1016/j.epsl.2007.06.023.
Scrutton, R.A., and Bentley, P.A.D., 1988, Major Cretaceous volcanic province in the southern Rockall Trough: Earth and Planetary Science Letters, v. 91, p. 198–204, doi: 10.1016/0012-821X(88)90161-6.
Şengör, A.M.C., 1999, Continental interiors and cratons: Any relation?: Tectonophysics, v. 305, p. 1–42, doi: 10.1016/S0040-1951(99)00043-8.
Sibuet, J.-C., Srivastava, S.P., and Spakman, W., 2004, Pyrenean orogeny and plate kinematics: Journal of Geophysical Research, v. 109, B08104, doi: 10.1029/2003JB002514.
Sleep, N., 1971, Thermal effects of the formation of Atlantic continental margins by continental breakup: Geophysical Journal of the Royal Astronomical Society, v. 24, p. 325–350.
Smith, K., 2009, Cretaceous, *in* Hitchen, K., ed., United Kingdom Offshore Regional Report: The Geology of the Rockall Basin: London, Her Majesty's Stationary Office for the British Geological Survey (in press).
Stoker, M.S., 1997, Mid- to late Cenozoic sedimentation on the continental margin off NW Britain: Geological Society of London Journal, v. 154, p. 509–515.
Stoker, M.S., 1999, Stratigraphical nomenclature of the UK North West Margin: 3. Mid- to late Cenozoic stratigraphy: London, Her Majesty's Stationary Office for the British Geological Survey, 61 p.
Stoker, M.S., 2009a, Cretaceous, *in* Ritchie, J.D., and Ziska, H., eds., United Kingdom Offshore Regional Report: The Geology of the Faroe-Shetland Basin: London, Her Majesty's Stationary Office for the British Geological Survey (in press).
Stoker, M.S., 2009b, Cenozoic sedimentary rocks, *in* Ritchie, J.D., and Ziska, H., eds., United Kingdom Offshore Regional Report: The Geology of the Faroe-Shetland Basin: London, Her Majesty's Stationary Office for the British Geological Survey (in press).
Stoker, M.S., and Varming, T., 2009, Cenozoic sedimentary rocks, *in* Hitchen, K., ed., United Kingdom Offshore Regional Report: The Geology of the Rockall Basin: London, Her Majesty's Stationary Office for the British Geological Survey (in press).
Stoker, M.S., Van Weering, T.C.E., and Svaerdborg, T., 2001, A mid- to late Cenozoic tectonostratigraphic framework for the Rockall Trough, *in* Shannon, P.M., Haughton, P.D.W., and Corcoran, D.V., eds., The Petroleum Exploration of Ireland's Offshore Basins: Geological Society [London] Special Publication 188, p. 411–438.
Stoker, M.S., Praeg, D., Shannon, P.M., Hjelstuen, B.O., Laberg, J.S., Nielsen, T., Van Weering, T.C.E., Serjup, H.P., and Evans, D., 2005a, Neogene evolution of the Atlantic continental margin of NW Europe (Lofoten Islands to SW Ireland): Anything but passive, *in* Doré, A.G., and Vining, B., eds., Petroleum Geology: Northwest Europe and Global Perspectives: Proceedings of the 6th Conference on the Petroleum Geology of Northwest Europe: London, Geological Society of London, p. 1067–1076.
Stoker, M.S., Praeg, D., Hjelstuen, B.O., Laberg, J.S., Nielsen, T., and Shannon, P.M., 2005b, Neogene stratigraphy and the sedimentary and oceanographic development of the NW European Atlantic margin: Marine and Petroleum Geology, v. 22, p. 977–1005, doi: 10.1016/j.marpetgeo.2004.11.007.
Stoker, M.S., Hoult, R.J., Nielsen, T., Hjelstuen, B.O., Laberg, J.S., Shannon, P.M., Praeg, D., Mathiesen, A., van Weering, T.C.E., and McDonnell, A., 2005c, Sedimentary and oceanographic responses to early Neogene compression on the NW European margin: Marine and Petroleum Geology, v. 22, p. 1031–1044, doi: 10.1016/j.marpetgeo.2005.01.009.
Tappin, D.R., Chadwick, R.A., Jackson, A.A., Wingfield, R.T.R., and Smith, N.J.P., 1994, United Kingdom Offshore Regional Report: The Geology of the Cardigan Bay and the Bristol Channel: London, Her Majesty's Stationary Office for the British Geological Survey, 107 p.
Thomson, K., Underhill, J.R., Green, P.F., Bray, R.J., and Gibson, H.J., 1999, Evidence from apatite fission-track analysis for the post-Devonian burial and exhumation history of the northern Highlands, Scotland: Marine and Petroleum Geology, v. 16, p. 27–39, doi: 10.1016/S0264-8172(98)00064-6.
Thomson, K., Hegarty, K.A., Marshallsea, S.J., and Green, P.F., 2002, Thermal and tectonic evolution of the Falkland Islands: Implications for hydrocarbon exploration in the adjacent offshore region: Marine and Petroleum Geology, v. 19, p. 95–116, doi: 10.1016/S0264-8172(02)00005-3.
Turner, J.P., Green, P.F., Holford, S.P., and Lawrence, S., 2008, Thermal history of the Rio Muni (West Africa)–NE Brazil margins during continental breakup: Earth and Planetary Science Letters, v. 270, p. 354–367, doi: 10.1016/j.epsl.2008.04.002.
van Hoorn, B., 1987, The South Celtic Sea/Bristol Channel Basin: Origin, deformation and inversion history: Tec-

tonophysics, v. 137, p. 309–334, doi: 10.1016/0040-1951(87)90325-8.
Vanneste, K., Henriet, J.-P., Posewang, J., and Theilen, F., 1995, Seismic stratigraphy of the Bill Bailey and Lousy Bank area: Implications for subsidence history, *in* Scrutton, R.A., et al., eds., The Tectonics, Sedimentation and Palaeoceanography of the North Atlantic Region: Geological Society [London] Special Publication 90, p. 125–139.
Ware, P.D., and Turner, J.P., 2002, Sonic velocity analysis of the Tertiary denudation of the Irish Sea Basin, *in* Doré, A.G., et al., eds., Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration: Geological Society [London] Special Publication 196, p. 355–370.
Weber, U.D., Kohn, B.P., Gleadow, A.J.W., and Nelson, D.R., 2005, Low temperature Phanerozoic history of the Northern Yilgarn craton, Western Australia: Tectonophysics, v. 400, p. 127–151, doi: 10.1016/j.tecto.2005.03.008.
White, N., and Latin, D., 1993, Subsidence analyses from the North Sea triple-junction: Geological Society of London Journal, v. 150, p. 473–488.
White, N., and Lovell, B., 1997, Measuring the pulse of a plume with the sedimentary record: Nature, v. 387, p. 888–891, doi: 10.1038/43151.
White, N., Thompson, M., and Barwise, T., 2003, Understanding the thermal evolution of deep-water continental margins: Nature, v. 426, p. 334–343, doi: 10.1038/nature02133.
White, R.S., and McKenzie, D.P., 1989, Magmatism at rift zones: The generation of volcanic continental margins and flood basalts: Journal of Geophysical Research, v. 94, p. 7685–7729, doi: 10.1029/JB094iB06p07685.
Williams, G.A., Turner, J.P., and Holford, S.P., 2005, Inversion and exhumation of the St. George's Channel Basin, offshore Wales, UK: Geological Society of London Journal, v. 162, p. 97–110.
Zachos, J.C., Pagani, M., Sloan, L., Thomas, E., and Billups, K., 2001, Trends, rhythms, and aberrations in global climate 65 Ma to present: Science, v. 292, p. 686–693, doi: 10.1126/science.1059412.
Ziegler, P.A., Cloetingh, S., and van Wees, J.-D., 1995, Dynamics of intra-plate compressional deformation: The Alpine foreland and other examples: Tectonophysics, v. 252, p. 7–59, doi: 10.1016/0040-1951(95)00102-6.
Zoback, M.D., Townend, J., and Grollimund, B., 2002, Steady-state failure and equilibrium and deformation of intraplate lithosphere: International Geology Review, v. 44, p. 383–401, doi: 10.2747/0020-6814.44.5.383.
Zoback, M.L., 1992, First- and second-order patterns of stress in the lithosphere: The World Stress Map Project: Journal of Geophysical Research, v. 97, p. 11,703–11,728, doi: 10.1029/92JB00132.

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