Cenozoic post-rift sedimentation off northwest Britain: Recording the detritus of episodic uplift on a passive continental margin

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ABSTRACT

The Cenozoic sedimentary basins on the Atlantic margin of northwest Britain contain a remarkable record of tectonically influenced post-breakup sedimentation. We have mapped the distribution and quantified the solid grain volume of four unconformity-bound successions in the region, the Eocene (~6–8 × 10^4 km^3), Oligocene (~2 × 10^4 km^3), Miocene–lower Pliocene (~4–5 × 10^4 km^3) and lower Pliocene–Holocene (~4–5 × 10^4 km^3), complementing previous work on the Paleocene succession. Of the total Cenozoic sediment volume on the Atlantic margin of northwest Britain, ~80% was deposited in Eocene and later time. The relative volumes of the Cenozoic succession do not support previous claims that the Paleocene was the main period of Cenozoic uplift and erosion of sediment source areas. Rather, the Cenozoic sedimentary basins on the Atlantic margin of northwest Britain record the detritus of four major episodes of Cenozoic uplift of the British Isles (Paleocene, Eocene–Oligocene, Miocene, and Pliocene–Pleistocene).

INTRODUCTION

The uplift and deformation of passive continental margins is a matter of wide debate and interest, because passive margins are generally expected to undergo only decaying thermal subsidence during the post-rift stage of their evolution (Praeg et al., 2005). The Cenozoic uplift and deformation of the British Isles and the adjacent Atlantic margin is an example that has been well studied both onshore and offshore using data largely acquired in the search for hydrocarbons. We previously analyzed the exhumation history of the British Isles using apatite fission-track analysis (AFTA) and other quantitative techniques, and concluded that there were several episodes of Cenozoic exhumation (Paleocene, Eocene–Oligocene, and Miocene; Hillis et al., 2008; Holford et al., 2009). We argued that the distribution and chronology of Cenozoic exhumation are not consistent with a dominant control by Paleocene uplift induced by the Iceland plume, as has been proposed (White and Lovell, 1997; Jones et al., 2002), and that episodic intraplate compression, driven by plate boundary forces, was the principal cause of uplift responsible for the observed multiple phases of exhumation (Holford et al., 2009).

The Cenozoic sedimentary rocks in the basins surrounding the British Isles, with particular focus on the Paleocene, have been interpreted as the erosional products of source areas uplifted due to the Iceland plume, and sedimentary patterns have been taken as a potentially sensitive measure of plume activity (White and Lovell, 1997; Jones et al., 2002). Here we present new two-way traveltime (TWTT) thickness maps and estimates of the solid grain sediment volume for four distinct, unconformity-bound, post-breakup Cenozoic sedimentary successions within the Rockall and Faroe-Shetland Basins off northwest Britain: the Eocene, Oligocene, Miocene–lower Pliocene, and lower Pliocene–Holocene (Fig. 1). Of the total Cenozoic sediment volume on the Atlantic margin off northwest Britain, ~80% was deposited in Eocene and later time, hence Paleocene plume-related uplift was not a dominant control on Cenozoic sedimentation in the area. Rather, the ages of the mapped successions correlate closely with recognized episodes of uplift in the British Isles during the Eocene–Oligocene and Miocene (Holford et al., 2009) and also in the Pliocene–Pleistocene (e.g., Maddy, 1997; Watts et al., 2005). In this paper we describe the post-breakup Cenozoic sedimentary successions within the northern Rockall and Faroe-Shetland Basins and discuss their implications for Cenozoic uplift of the British Isles and its continental shelf.

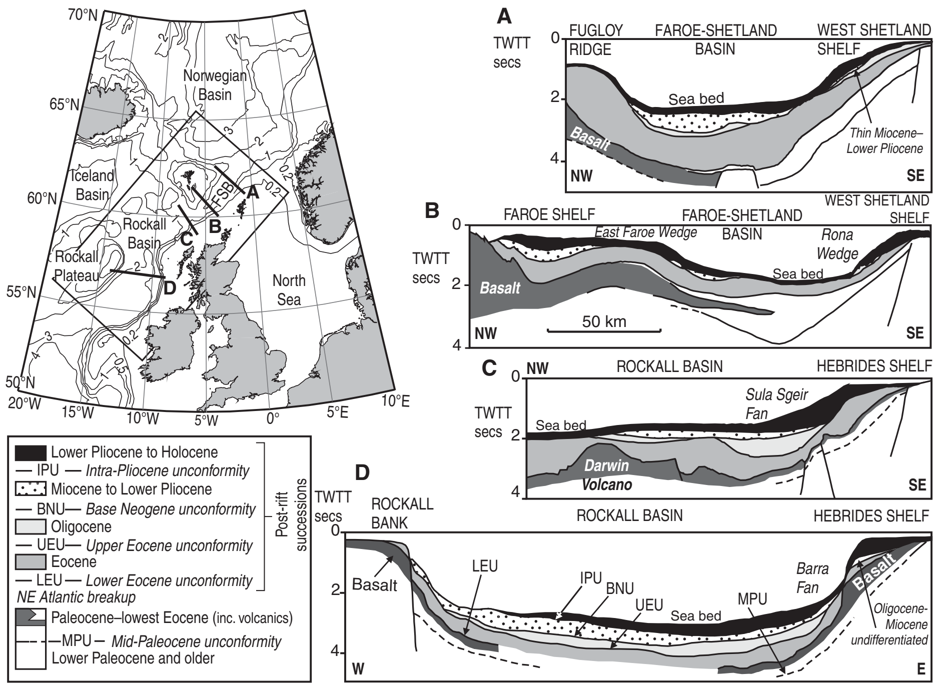

Figure 1. Geoseismic profiles across Atlantic margin of northwest Britain, focusing on Cenozoic post-rift stratigraphic architecture, which is divided into a series of unconformity-bound successions. This stratigraphic architecture has been traced for more than 2500 km along length of northwest European margin, from southwest Ireland to mid-Norway, as part of European Commission–supported STRATAGEM project (Stoker et al., 2005). Inset map shows bathymetry (×1000 m) of northwest European margin, location of profiles across Faroe-Shetland (A–B) and Rockall (C–D) Basins, and limit of map area in Figure 2. Map is defined using Lambert's conformal conic projection with two standard parallels. FSB—Faroe-Shetland Basin.

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CENOZOIC POST-RIFT SEDIMENT DISTRIBUTION OFF NORTHWEST BRITAIN

Our maps are based on four decades of seismic acquisition and borehole drilling by the British Geological Survey as part of its mapping of the UK continental margin, supplemented by additional industry and non-industry data as part of the European Commission–funded STRATAGEM project (further details of data used and mapping methodology are provided in Appendix DR1 in the GSA Data Repository[1]). These data reveal multiple sediment sources to the deep-water basins throughout the Cenozoic, and suggest that sedimentation has not declined in any systematic manner since breakup. This stepwise pattern of sedimentation is incompatible with the notion that the Cenozoic succession is dominated by erosional detritus from sediment source areas uplifted in the Paleocene by the Iceland plume (e.g., Jones et al., 2002).

Sedimentation in both the Rockall and Faroe-Shetland Basins continued in several pulses throughout the Eocene, as reflected by the deposition of a series of progradational shelf-margin to basinal sequences derived from the Hebrides shelf, the West Shetland shelf, the Faroe shelf, and the Rockall Plateau (Andersen et al., 2002; Praeg et al., 2005; McInroy et al., 2006; Fig. 2A). Our maps also show focused intrabasinal sedimentation during the Oligocene, particularly in the northeast Rockall Basin, and in the Faroe-Shetland Basin during the Miocene–early Pliocene (Egerton, 1998; Elliott et al., 2006). This reflects the contemporary response of sedimentation to compressional tectonics during these times (Stoker et al., 2005; Figs. 2B and 2C). Although axially transported deposition from deep-water bottom currents was instigated in the Late Eocene, as reflected in the sedimentary architecture of the Oligocene and younger basinal deposits (Fig. 1), much of this material was derived from contemporary erosion of the adjacent continental margin (Laberg et al., 2005). There was significant (50–100 km) expansion of the shelf margin off northwest Britain and the Faroe Islands in the early Pliocene–Pleistocene interval as sedimentation became focused in a number of discrete prograding sediment wedges (Figs. 1 and 2D). Climate change and glaciation made major contributions to the sediment budget during this interval. However, the onset of prograding wedge development on the northwest British margin was linked to large-amplitude seaward tilting of the margin, which occurred up to 1 m.y. prior to mid-latitude glaciation (Stoker, 2002; Praeg et al., 2005).

We estimated solid grain sediment volumes by converting our TWTT maps into depth maps, using representative end-member velocities for the Cenozoic succession of 1.5 and 2.0 km s^{-1}, and then subtracted the pore-space volume as predicted by a standard porosity-depth relationship (Appendix DR2). Our results indicate that the northern Rockall Basin and the Faroe-Shetland Basin contain volumes of ~57,500–76,800 km^3 for the Eocene succession, ~16,300–22,500 km^3 for the Oligocene succession, ~35,100–48,800 km^3 for the Miocene–lower Pliocene succession, and 37,900–52,100 km^3 for the lower Pliocene–Holocene succession. The volume of Eocene sediment compares well with previous estimates for the Faroe Shetland Basin (~48,000 km^3; Smallwood, 2008), and is larger than the volume of Eocene sediment in the northern North Sea Basin (~51,598 km^3; Liu and Galloway, 1997). It is also larger than the volume of Paleocene sediment in the Faroe-Shetland Basin (~35,000–55,000 km^3; Smallwood, 2005), and is significantly higher than estimates of the Paleocene solid sediment volume in the northern North Sea Basin (i.e., 26,000 km^3; White and Lovell, 1997; 36,301 km^3; Liu and Galloway, 1997). Our analysis indicates a reduction in sediment input to the Rockall and Faroe-Shetland Basins during the Oligocene in comparison to the Eocene, but our volumetric estimate for the Miocene–lower Pliocene succession is comparable to the volumes of Paleocene and Eocene sediment estimated for the Faroe-Shetland Basin by Smallwood (2008). Perhaps the most surprising aspect of our results is the volume of the lower Pliocene–Holocene succession, given the comparatively short time interval (~5 m.y.) this succession represents. Its volume is comparable to the Paleocene succession of the Faroe-Shetland Basin and is considerably larger than the volume of Paleocene sediment in the northern North Sea. Our results thus lend little support to the notion that the acme of Cenozoic sedimentation around the British Isles occurred during the Paleocene, as the Paleocene succession constitutes only ~20% of the total Cenozoic solid grain sediment volume off northwest Britain.

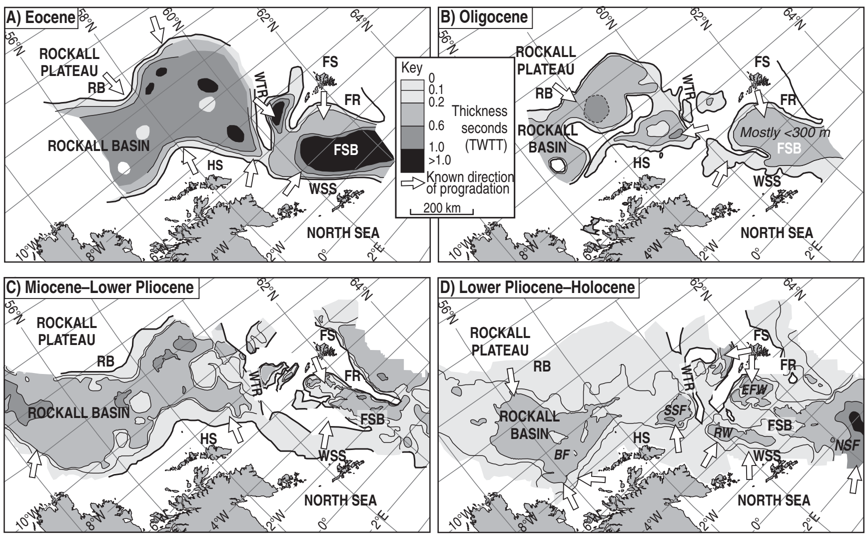

Figure 2. Maps showing sediment thickness, in two-way traveltime (TWTT). A: Eocene. B: Oligocene. C: Miocene–lower Pliocene. D: Lower Pliocene–Holocene. Successions shown with established provenance directions. Map projection as in Figure 1. Abbreviations: BF—Barra Fan; EFW—East Faroe wedge; FR—Fugloy Ridge; FS—Faroe shelf; FSB—Faroe-Shetland Basin; HS—Hebrides shelf; NSF—North Sea Fan; RB—Rockall Bank; RW—Rona wedge; SSF—Sula Sgeir Fan; WSS—West Shetland shelf; WTR—Wyville-Thomson Ridge.

CORRELATION WITH THE UPLIFT HISTORY OF THE BRITISH ISLES AND IMPLICATIONS FOR POST-BREAKUP TECTONIC HISTORY OF THE ATLANTIC MARGIN

Eocene, Oligocene, Miocene–early Pliocene, and early Pliocene–Holocene sediment pulses have been identified in the basins of the Atlantic margin, in addition to the well-documented pulses of Paleocene age that have been described from the North Sea and Faroe-Shetland Basins (e.g., White and Lovell, 1997; Smallwood, 2008). This record of ~60 m.y. of near-continual sediment pulsing implies major uplift and erosion (exhumation) throughout the Cenozoic across likely source areas, such as the British Isles and its continental shelf. Previous

[1]GSA Data Repository item 2010163, mapping methodology (Appendix DR1) and database (Figure DR1), volumetric methodology (Appendix DR2), and results (Table DR1), is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

studies of the Cenozoic sedimentary record of the Atlantic margin have emphasized the role of the syn-breakup Iceland plume as the primary tectonic influence on sedimentation patterns (White and Lovell, 1997; Jones et al., 2002). However, we have shown that significant tectonically driven sedimentation continued throughout the Cenozoic Era. Plume-related underplating is thought to be restricted to the Paleocene (White and Lovell, 1997) and thus may have influenced contemporary sedimentation (contemporary sediments compose ~20% of the total Cenozoic succession), but cannot account for uplift of the source areas of the Eocene, Oligocene, Miocene–early Pliocene, and early Pliocene–Holocene phases of sedimentation. Furthermore, a recent study of the Cenozoic mass flux history of the Iceland plume (Poore et al., 2009) showed that plume flux (and thus dynamic support) peaked in the Early Eocene and subsequently declined throughout most of the Cenozoic, indicating that dynamic support by the Iceland plume is unlikely to have controlled later sedimentation pulses. However, from Miocene time onward, the body forces generated by plume-related geoid undulation around Iceland are likely to have increased horizontal stress levels and contributed to widespread Miocene compression in the continental margins surrounding Iceland (Doré et al., 2008).

A recent synthesis of AFTA data (which can provide constraints on the timing of exhumation-related cooling) from the British Isles has revealed a complex, multistage exhumation history for this area (Holford et al., 2009). This synthesis identified several distinct regional episodes of kilometer-scale exhumation beginning between 65 and 55 Ma (which may correlate with the early Paleogene uplift described above), between 40 and 25 Ma, and between 20 and 15 Ma. The latter is the major episode across much of the southern British Isles and is characterized by deeper burial of Paleogene rocks in the Irish Sea and southern England by ~1.5 km prior to uplift beginning in the Early to Middle Miocene (Hillis et al., 2008; Holford et al., 2009). There is also widespread geomorphological evidence for significant uplift and exhumation of south-central England during the late Pliocene–Pleistocene (Maddy, 1997; Watts et al., 2005) that are not identified by AFTA data (which are insensitive to the thermal histories of samples below ~60 °C). These episodes correlate closely with plate boundary reorganizations during the Cenozoic Era (Fig. 3; Holford et al., 2009), thus implying that plate boundary forces exert a key control on vertical motions across this region. Changes in the nature of plate boundaries due to plate reorganizations lead to fluctuations in the magnitude of intraplate stresses (e.g., Gölke and Coblentz, 1996). Uplift and deformation along the Atlantic margin are

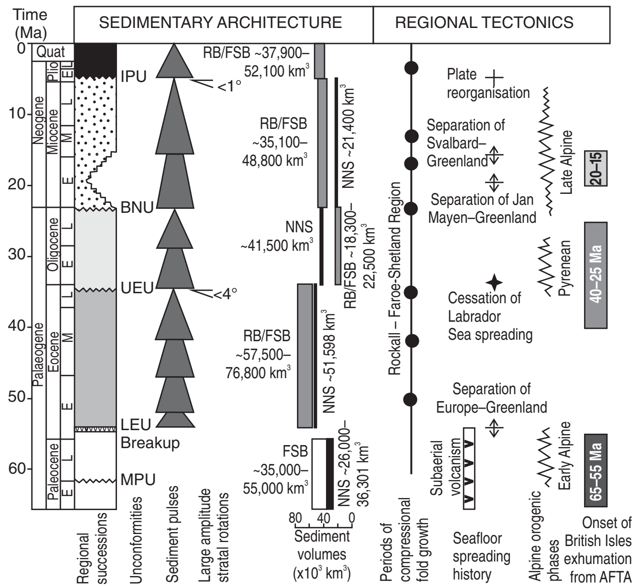

Figure 3. Cenozoic post-rift tectonostratigraphic framework for Atlantic margin off northwest Britain, including sediment volumes (gray bars) calculated in this study for Rockall Basin (RB) and Faroe-Shetland Basin (FSB). Comparative sediment volumes from northern North Sea (NNS, black bars) and Paleocene of FSB (white bars), together with regional tectonic events, are from variety of sources (see text). MPU—mid-Paleocene unconformity; LEU—Lower Eocene unconformity; UEU—Upper Eocene unconformity; BNU—base Neogene unconformity; IPU—intra-Pliocene unconformity. AFTA—apatite fission track analyses.

manifested by numerous compressional growth anticlines (amplitudes ≤4 km; axial traces ≤250 km) and reverse faults that have deformed the Cenozoic succession. In a manner similar to the multiphase uplift and exhumation history of the British Isles, detailed seismic-stratigraphy studies (Andersen et al., 2002; Stoker et al., 2005; Ritchie et al., 2008) have documented an episodic chronology of compressional deformation along the margin (Fig. 3).

The regional impact of these exhumation episodes is demonstrated by their temporal correlation with the unconformities that bound the major Cenozoic sediment sequences along the Atlantic margin (Fig. 3). Of particular note are the large-amplitude stratal rotations that occurred in association with the formation of the Upper Eocene (≤4°) and intra-Pliocene (<1°) unconformities west of Britain and Ireland, indicative of long-wavelength sagging and tilting, which Praeg et al. (2005) attributed to evolving patterns of upper mantle convection. Incremental rotation and landward truncation of the shelf-margin sediment wedges are observed clearly beneath the Hebrides and West Shetland shelves (Fig. 1). The multistage Cenozoic exhumation record of the British Isles displays strong temporal correspondence with the record of Atlantic margin sediment input. The 65–55 Ma episode overlaps with the input of Paleocene clastic sediments into the North Sea and Faroe-Shetland Basins. The 65–55 and 40–25 Ma episodes are coeval with the Eocene and Oligocene progradation of shelf-slope wedges into the Atlantic margin basins, while the Miocene–early Pliocene pulse of sedimentation corresponds closely with the 20–15 Ma exhumation episode constrained by AFTA data. Pliocene–Pleistocene uplift and exhumation are coeval with the latest phase of shelf-margin progradation. By correlating the exhumation episodes and unconformities, we infer that the shelf-to-deepwater Atlantic margin basins may also have been initially affected by regional uplift, which generated both subaerial and submarine unconformities. The submarine unconformities were cut by deep-water erosional processes through bottom currents responding to a change in paleobathymetry and/or circulation regime. Following this, the basins acted primarily as the repositories for material eroded from regions where exhumation was concentrated.

We note that our maps also show significant sediment input into the Atlantic margin basins from sources beyond the British Isles and its adjacent shelf area. The Eocene and Oligocene successions include progradational pulses from the Rockall Plateau (Figs. 1 and 2). Seismic data demonstrate almost continuous Paleocene–Pleistocene sediment input via prograding shelf-slope wedges from the Faroe Platform, where ~46,000 km³ of Paleocene basalt is thought to have been removed from the Eocene onward (Andersen et al., 2002). On the outer continental margin, prograding Eocene deposits have been linked to intra-Eocene tectonic movements on the Rockall Plateau (McInroy et al., 2006). We suggest that this pattern of sedimentation is indicative of a margin-wide response to post-rift differential uplift.

CONCLUSIONS

We conclude that post-rift sedimentation off northwest Britain represents a direct response to episodic passive margin uplift concomitant with plate reorganization. Regional patterns of sedimentation combined with volumetric data, stratal disposition, and AFTA analyses imply three major phases of post-rift uplift (Eocene–Oligocene, Miocene, and Pliocene–Pleistocene time), following which the sedimentary system was repeatedly rejuvenated. These results are incompatible with a post-rift decrease in sedimentation. Instead, the successive tectonic episodes have driven changes in sedimentation patterns, which have in turn found expression from the shelf to the deep-water basins as regionally significant stratigraphic sequences bound by correlative unconformity surfaces. Our preferred model for the tectonic control on post-breakup sedimentation in the Atlantic margin combines short- and long-wavelength compressional uplift of sediment source areas in response to fluctuating intraplate stress fields, the magnitudes and orientations of which are governed by the net torques of all the boundary forces that act on the plate (e.g., Gölke and Coblentz, 1996). Regional phases of tilting and sagging may be related to evolving upper mantle convection patterns, while enhanced body forces resulting from the geoid anomaly around Iceland may be responsible for episodic compression and uplift of the surrounding margins from the Miocene onward (e.g., Doré et al., 2008).

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