Reconstructing the Mesozoic–Cenozoic exhumation history of the Irish Sea basin system using apatite fission track analysis and vitrinite reflectance data

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Abstract: This paper summarizes new and recent apatite fission track analysis and vitrinite reflectance results from across the Irish Sea basin system and its margins, which provide new constraints on the magnitude and timing of post-Palaeozoic exhumation across this area. In particular, these results suggest that this region has experienced a complex, multi-phase exhumation history. Distinct episodes of kilometre-scale exhumation occurred during the early Cretaceous, early Palaeogene and late Palaeogene–Neogene times, with the overall magnitude of exhumation in each episode decreasing over time. Regional early Cretaceous exhumation removed up to 3 km of section from the Irish Sea basins, and appears to be related to incipient Atlantic rifting. Early Palaeogene exhumation attained up to 2 km and was driven by a combination of localized tectonic inversion and regional epeirogenic uplift, although early Palaeogene palaeotemperatures within parts of the Irish Sea basin system are dominated by non-burial-related processes. A final phase of exhumation, related to late Palaeogene–Neogene tectonic inversion, uniformly removed *c*. 1 km of section from this region. Given that these exhumation episodes coincide temporally with important periods of deformation at pre-existing or incipient plate boundaries, events at plate margins are interpreted to have exerted the primary control on the Mesozoic–Cenozoic exhumation of the Irish Sea basin system.

Keywords: exhumation, Irish Sea, AFTA, VR, epeirogeny, inversion tectonics, basin analysis

Exhumation, defined here as the process by which formerly deeply buried rock units are brought to shallower depths following the uplift and erosion of overlying rocks (c.f. Green *et al*. 2002), plays a critical role in both the tectonic evolution and hydrocarbon prospectivity of many extensional basins within intra-plate and passive margin settings (e.g. Doré & Jensen 1996; Doré *et al*. 2002*a*). Much of the current understanding of the mechanisms by which sedimentary basins are exhumed derives from studies of the Mesozoic extensional basins around the British Isles (Ziegler *et al*. 1995; Turner & Williams 2004). Many of these basins were exhumed to varying degrees during the Cretaceous and Cenozoic, primarily in response to (i) intra-plate compression associated with Alpine lithospheric shortening and North Atlantic opening (Ziegler *et al*. 1995; Doré *et al*. 1999) and (ii) epeirogeny attributed to the initiation of the Iceland plume during the Palaeogene (Smallwood & White 2002).

Given that the erosional signatures of major tectonic events are frequently superimposed, it is often difficult to discriminate between the relative importances of these events and, hence, establish the precise causes of exhumation (Turner & Williams 2004). This problem is particularly acute across the Irish Sea basin system of the western UKCS (Fig. 1), where Mesozoic and Cenozoic exhumation following Triassic–Jurassic rifting has resulted in a highly variable stratigraphical record (Tappin *et al*. 1994). This is manifested most strikingly across the East Irish Sea Basin, which has been cited by many workers as the area of maximum post-Palaeozoic exhumation across the British Isles (e.g. Colter 1978; Roberts 1989; Lewis *et al*. 1992; Ware & Turner 2002). Within this basin the youngest preserved sub-Quaternary rocks are generally from the Upper Triassic Mercia Mudstone Group (Jackson *et al*. 1995). In recent years, increasing emphasis has been placed upon the role of plume-related magmatic underplating during the Palaeogene as the primary driving mechanism of exhumation in the Irish Sea (e.g. Brodie & White 1995; Rowley & White 1998). However, studies of the geology of the more southerly Celtic Sea–Bristol Channel basin system and the onshore Wessex Basin of southern England, where the Mesozoic and Cenozoic stratigraphic record is more complete, have identified multiple phases of exhumation, with discrete events during the early Cretaceous (e.g. Kammerling 1979; Van Hoorn 1987), late Cretaceous–early Palaeogene (e.g. Hillis 1992, 1995) and late Palaeogene–Neogene (e.g. Chadwick 1993).

Despite the evidence for multiple episodes of post-Palaeozoic exhumation across parts of the western UK, the comparatively incomplete stratigraphic record has meant that few workers have been able to determine confidently the timing and mechanisms of these episodes within the Irish Sea, since conventional techniques such as backstripping and seismic interpretation, are less useful in exhumed basins. In regions where large periods of geological time are not represented by the preserved stratigraphy, the application of apatite fission track analysis (AFTA®) and vitrinite reflectance (VR) data can provide crucial insights into the nature of events during the unrepresented time intervals (Green *et al*. 2000). These techniques, which provide estimates of the maximum temperature attained by a rock sample at some time in the past, can also be used to assess former burial depths (Green *et al*. 2002). AFTA is especially useful in exhumation studies, because it can also provide an independent estimate of the time at which a rock sample began to cool from maximum palaeotemperatures, which may represent the onset of a period of exhumation (Green *et al*. 1995). Constraining the timing of the exhumation-related cooling is of some importance, as doing so may provide some insight into the underlying causes of the exhumation. For example, if the timing correlates with a phase of significant tectonic activity (e.g. a period of orogenesis or continental break-up) the synchroneity of these events may suggest some kind of genetic relationship.

This paper summarizes recent results from AFTA- and VR-based thermal history studies of the Irish Sea basin system and its margins (which, in this paper, refers to the East Irish Sea Basin (EISB), Central Irish Sea Basin (CISB), Cardigan Bay Basin

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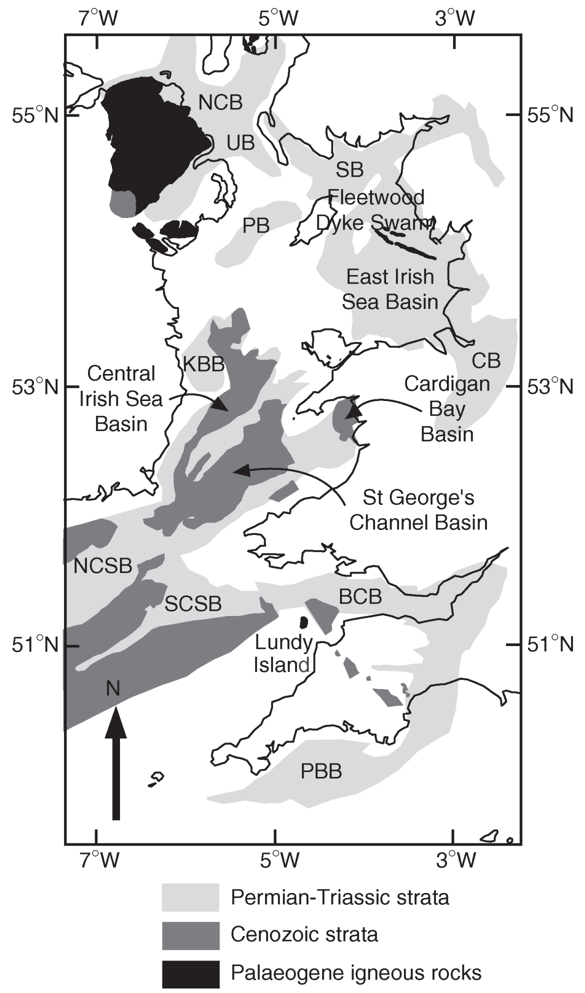

Fig. 1. The extent of preserved Permian–Triassic and Cenozoic sediments across the western UK region. Locations of Palaeogene igneous rocks are also shown. Key: NCB, North Channel Basin; UB, Ulster Basin; SB, Solway Basin; PB, Peel Basin; CB, Cheshire Basin; KBB, Kish Bank Basin; BCB, Bristol Channel Basin; NCSB, North Celtic Sea Basin; SCSB, South Celtic Sea Basin; PBB, Plymouth Bay Basin.

(CBB) and St George's Channel Basin (SGCB)) and presents new data that provide new constraints on the timing and magnitude of Mesozoic and Cenozoic exhumation across the Irish Sea. In particular, these results suggest that the Irish Sea has experienced a complex, multi-phase exhumation history driven by a variety of epeirogenic and non-epeirogenic processes.

Thermal history reconstruction using AFTA and VR data

The fact that temperature increases progressively with depth within the lithosphere means that palaeothermal indicators such as AFTA and VR can be used to assess the former burial depths of rock units (Green *et al*. 2002). Sedimentary units are progressively heated during burial and begin to cool at the initiation of exhumation. AFTA and VR data provide quantitative estimates of the temperatures attained by individual rock samples at a palaeothermal maximum, prior to the onset of cooling (Green *et al*. 1995, 2002). VR data can provide discrete estimates of maximum post-depositional palaeotemperatures, whilst AFTA can provide either upper or lower limits, or a range of values for the maximum palaeotemperature in up to three separate palaeothermal episodes (Bray *et al*. 1992; Green *et al*. 2002). In exhumed basins like those of the Irish Sea, palaeotemperatures derived from AFTA and VR data through a vertical rock section can be used to estimate palaeogeothermal gradients. Moreover, by extrapolation to an assumed palaeosurface temperature, the thickness of section removed during exhumation can be quantified (Green *et al*. 2002). Full methodological descriptions of the analytical and interpretative procedures by which thermal history data are extracted from apatite and vitrinite samples are provided by Green *et al*. (2001, 2002).

The analysis of a series of AFTA and VR samples over a range of depths (e.g. in an exploration well) reveals the variation of maximum palaeotemperature with depth and the form of the 'palaeotemperature profile', characterizing a particular palaeothermal episode, can provide vital information on the likely mechanisms of heating and cooling during that episode (Fig. 2). Heating caused solely by deeper burial should result in an approximately linear palaeotemperature profile, with a similar gradient to the present-day temperature profile. The extrapolation of this profile to an assumed palaeosurface temperature can also provide an estimate of the amount of section removed as a result of exhumation (Fig. 2). In contrast, heating which was primarily a consequence of elevated basal heat flow (possibly also with a component of deeper burial) should produce a more or less linear palaeotemperature profile, with a higher gradient than the present temperature profile. Transient heating as a result of the lateral passage of heated fluids can produce a variety of palaeotemperature profiles (with low, non-linear or even negative gradients) depending primarily on the time-scale of heating (Duddy *et al*. 1994).

Recognition of regional palaeothermal and exhumation episodes

Early Cretaceous

Results from a number of recent AFTA- and VR-based thermal history studies provide convincing evidence for the occurrence of substantial (<3 km) exhumation across the Irish Sea basin system during the early Cretaceous. AFTA and VR data from four exploration wells within the CISB reported by Duncan *et al*. (1998) and Green *et al*. (2001) indicate that the sub-Quaternary units within this basin have been affected by at least three phases of post-Palaeozoic exhumation. Although periods of exhumation-related cooling were identified during the late Cretaceous–early Palaeogene (70–55 Ma) and Neogene (25–0 Ma), AFTA results indicate that these wells cooled from their maximum post-depositional temperatures during an early Cretaceous (120–115 Ma) exhumation episode, with a maximum of *c*. 3 km of additional late Triassic–early Cretaceous section required to explain the observed early Cretaceous palaeotemperatures within this basin.

New AFTA and VR data from EISB exploration wells indicate that parts of this basin also experienced substantial early Cretaceous exhumation, particularly around the southern and western basin margins (Fig. 3). Thermal history interpretation of AFTA and VR data from EISB exploration well 109/5-1, which is located at the western margin of the basin, is presented in Figure 4. Results from AFTA suggest that all samples from the Carboniferous and Triassic penetrated by this well reached their maximum palaeotemperatures prior to early Cretaceous cooling. Figure 4 clearly shows that early Cretaceous palaeotemperatures exceeded those during the Palaeogene over all depths within this well. It is also apparent that the Palaeogene palaeotemperature constraints from AFTA define a non-linear palaeotemperature profile with depth. This suggests that these palaeotemperatures were not reached as a result of purely deeper burial and cannot be used to infer magnitudes of Palaeogene exhumation. VR values from the Carboniferous section vary between *c*. 0.7 and 1.4%R_o, corresponding to maximum palaeotemperatures of 120–160°C. Although these palaeotemperatures are higher than those that can be estimated with AFTA (where total annealing of fission tracks typically occurs between 110°C and 120°C), when

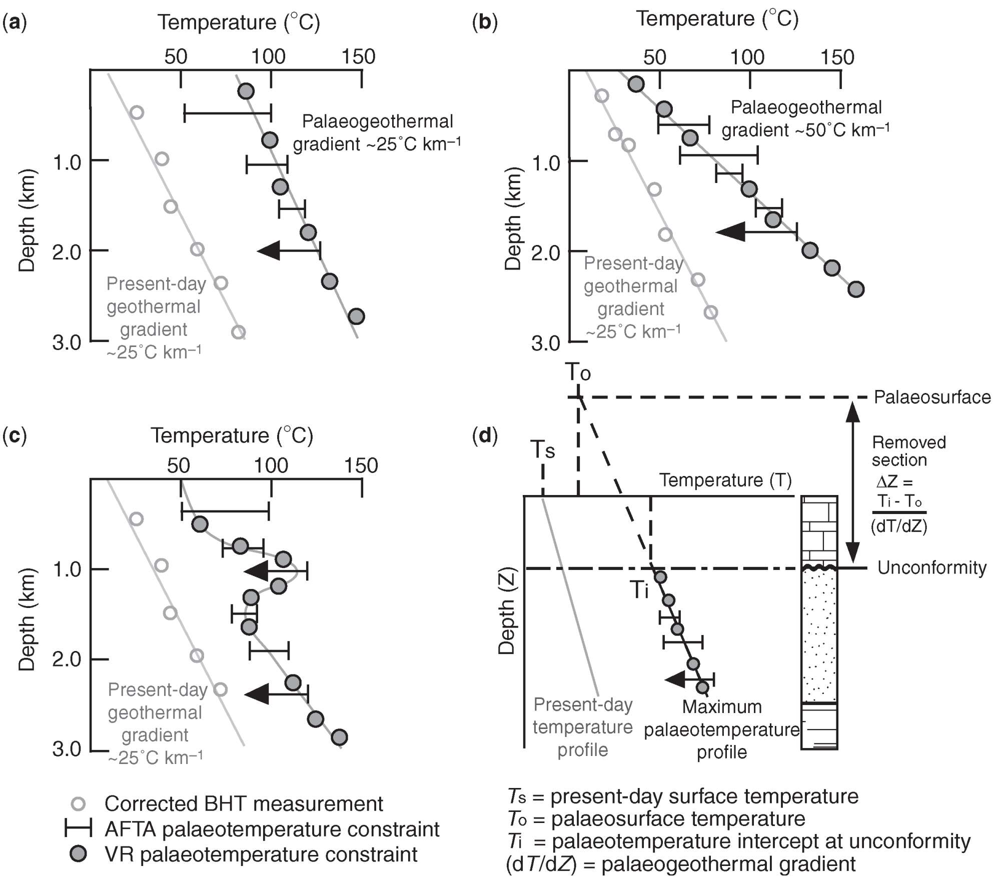

Fig. 2. Schematic examples of palaeotemperature profiles produced by heating related to (**a**) deeper burial, (**b**) elevated basal heat flow and (**c**) heated fluids (**d**) Method by which amounts of exhumation can be estimated by thermal history data, by fitting a linear palaeogeothermal gradient to a series of downhole palaeotemperature constraints and then extrapolating to an assumed palaeosurface temperature (cf. Green *et al.* 2002).

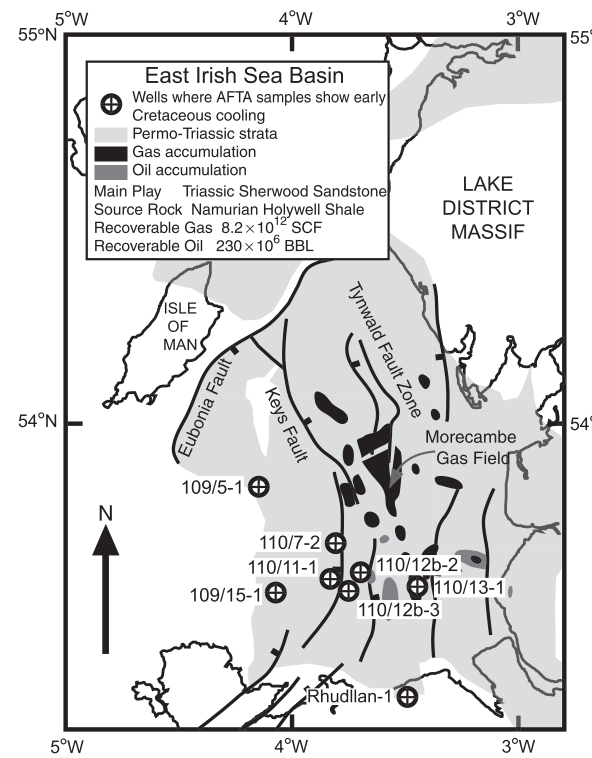

Fig. 3. Map of the East Irish Sea Basin. The locations of wells containing AFTA samples which cooled from their maximum palaeotemperatures during the early Cretaceous are indicated. Diagram modified after Doré *et al.* (2002*b*).

combined with the early Cretaceous palaeotemperatures from AFTA they define an approximately linear palaeotemperature profile. These results indicate that AFTA and VR samples within this well reached their maximum palaeotemperatures as a result of deeper burial, prior to exhumation-related cooling which began during the early Cretaceous. Fitting a linear profile to these data provides an estimate of the early Cretaceous palaeogeothermal gradient for this well; this has a maximum likelihood value of 41.5°C km^{-1}, with an allowed range (within 95% confidence limits) of 28–54.5°C km^{-1}. Extrapolating this profile to an assumed early Cretaceous palaeosurface temperature of 20°C provides a maximum likelihood estimate of 1.85 km of (probably Jurassic) section which was removed during early Cretaceous exhumation (1.15–3.2 km at 95% confidence limits) (Fig. 4).

New AFTA results indicate that <2 km of section was removed from parts of the EISB during the early Cretaceous. This estimate is similar to those provided by Green *et al.* (2001) for the magnitude of early Cretaceous exhumation across the adjacent CISB. As noted previously, AFTA data suggest that the early Cretaceous cooling episode is focused at the western and southern margins of the basin. Towards the northern and eastern parts of the basin the importance of the early Cretaceous palaeothermal episode diminishes, with results from AFTA showing that samples from Triassic units reached their maximum post-depositional palaeotemperatures (which are often >110°C indicating total annealing of apatite samples) prior to early Palaeogene cooling, rather than during the early Cretaceous. One explanation for this observation takes into account the fact that both the AFTA and VR techniques are dominated by maximum temperatures, which means that they cannot provide any information on the thermal

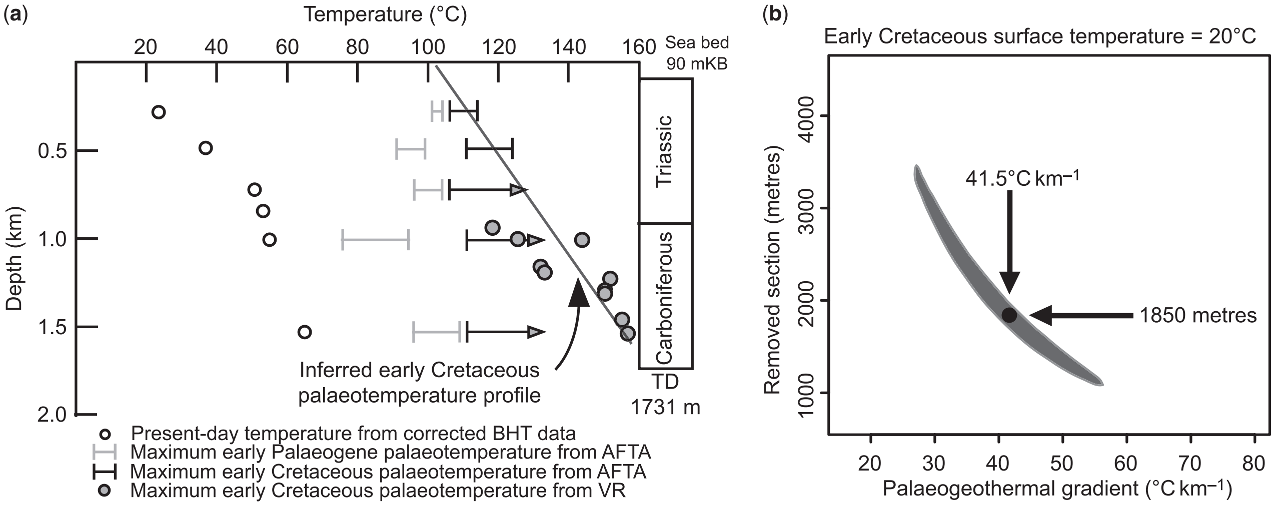

Fig. 4. Thermal history analysis of palaeotemperature data from EISB well 109/5-1. (**a**) Palaeotemperatures derived from AFTA and VR plotted against sample depth (RKB). (**b**) Results of a statistical analysis of the palaeotemperature data. Contoured region defines the allowed range for each parameter within 95% confidence limits. See text for further discussion.

history of a sample prior to a palaeothermal maximum (see Green *et al*. (2002) for further discussion). Therefore, samples within Triassic units across the northern and eastern parts of the EISB which reached their maximum post-depositional palaeotemperatures prior to early Cretaceous cooling (associated with up to 2 km of exhumation) may have been subsequently reheated to higher temperatures prior to another period of cooling which began during the Palaeogene.

Figure 5 shows estimates of the time at which a number of AFTA samples from wells within the EISB (located in Fig. 3) began to cool from their maximum palaeotemperatures as a result of exhumation. The overlap of timing constraints from individual samples enables the definition of a basin-wide cooling episode, which began during the early Cretaceous (between 140 Ma and 110 Ma). This compares well with previous estimates of the timing of early Cretaceous exhumation from AFTA and VR studies within and outwith the Irish Sea basin system (Fig. 5). Combining timing constraints from across the Irish Sea (assuming that all cooling episodes represent the same event) suggests a regional onset of exhumation between 120 Ma and 115 Ma (i.e. during the Aptian). The timing of this exhumation phase coincides with the development of important unconformities across the Wessex Basin during the Aptian (McMahon & Turner 1998), indicating that the effects of the early Cretaceous exhumation episode identified here may not have been restricted to the Irish Sea basin system and its margins.

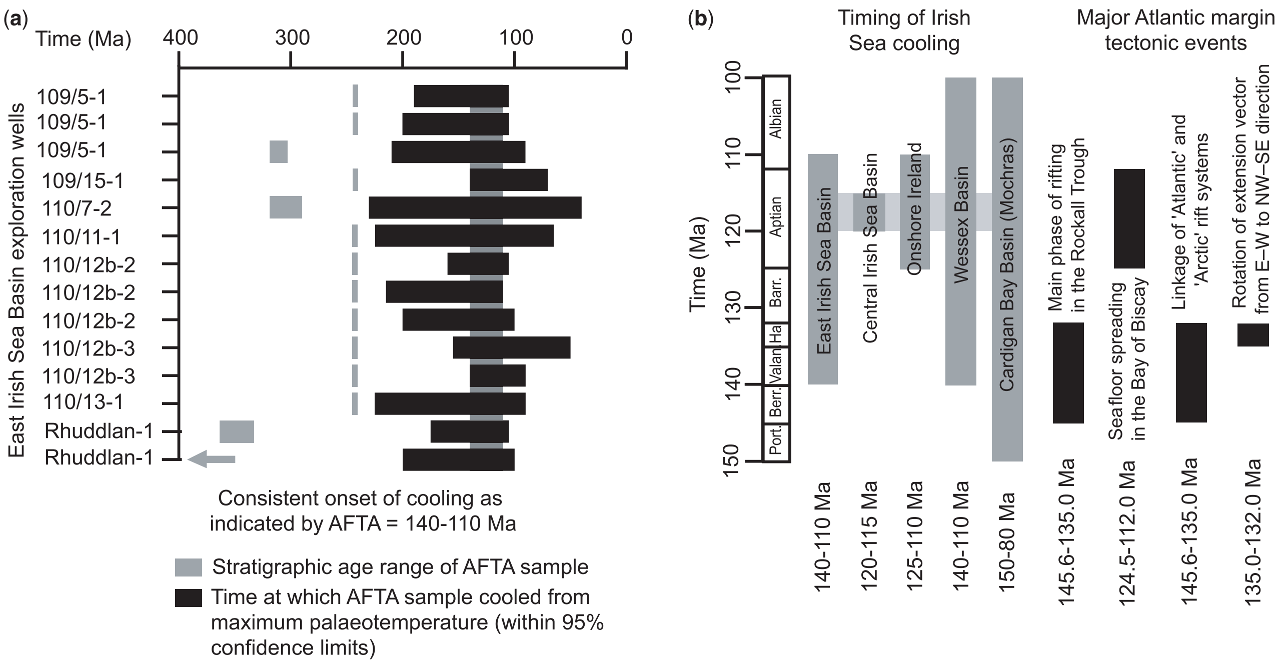

Fig. 5. (**a**) Diagram indicating the time at which selected AFTA samples from eight EISB exploration wells dominated by the early Cretaceous palaeothermal episode began to cool from their maximum palaeotemperatures. Horizontal black bars correspond to estimates of timing within 95% confidence limits, vertical shaded bar represents the time range which is consistent for all samples analysed. This suggests that cooling across the EISB began between 140 Ma and 110 Ma BP. (**b**) Comparison of EISB results with AFTA-derived early Cretaceous cooling estimates from other Irish Sea basins (and the Wessex Basin) and also with the timing of a series of important early Cretaceous tectonic events along the incipient NE Atlantic margin. See text for further discussion.

Early Palaeogene

Although workers have long suspected that the Irish Sea basin system had been affected by an important phase of exhumation during the Palaeogene, primarily on the basis of the absence of post-Triassic sediments from the EISB (e.g. Colter 1978), the magnitude and timing of this event has only recently begun to be directly quantified. The AFTA-based studies of Green (1986) and Lewis *et al*. (1992) demonstrated that samples from the Lake District and EISB that are presently at outcrop or seabed, had reached palaeotemperatures upwards of 100°C prior to cooling during the early Palaeogene (beginning between *c*. 65 Ma and 50 Ma). In the absence of direct constraints on palaeogeothermal gradients prior to cooling, these authors interpreted these elevated palaeotemperatures in terms of deeper burial by around 3 km of Mesozoic sediments which would have been removed during early Palaeogene exhumation (Lewis *et al*. 1992). Since these early studies, increased data availability has enabled considerable improvements in the definition of thermal history styles across this region.

A critical step in extracting information on exhumation magnitudes from AFTA and VR data is to constrain palaeogeothermal gradients at the onset of erosion and, thereby, convert maximum palaeotemperatures prior to cooling into values of erosion. The spatial variation in geothermal gradient prior to early Palaeogene (65–50 Ma) cooling across the EISB is highlighted by Figure 6. Across the north of the basin, AFTA and VR data from wells such as the onshore West Newton-1 define early Palaeogene palaeogeothermal gradients of up to 50°C km^{-1} which are clearly elevated (by up to 50%) with respect to present-day values (30–35°C km^{-1}) (Green *et al*. 1997). Similar values across the northern Lake District were reported by Green (2002), who defined a palaeogeothermal gradient of 61°C km^{-1} prior to early Palaeogene cooling (Green 2002). The early Palaeogene cooling can now be explained in terms of a reduction of heat flow, combined with 0.7–2.0 km of early Palaeogene exhumation. This estimate is clearly lower than that of *c*. 3 km, as proposed by Lewis *et al*. (1992) and is in accordance with AFTA and VR data from the CISB, where late Cretaceous–early Palaeogene palaeotemperatures require up to 2 km of early Palaeogene exhumation (Green *et al*. 2001) and also with stratigraphic constraints which suggest that between 0.7 km and 1.7 km of Mesozoic sediments were removed from the EISB and Lake District as a consequence of early Palaeogene exhumation (Holliday 1993).

In contrast to the northern EISB, early Palaeogene palaeogeothermal gradients from wells towards the southern EISB are either characterized by low values (5–15°C km^{-1}; Fig. 6) or markedly non-linear palaeotemperature profiles (e.g. 109/5-1; Fig. 4). The low palaeogeothermal gradients across the southern EISB prior to early Palaeogene cooling are typified by data from exploration well 110/20-1 (located in Fig. 6). Figure 7 shows a palaeotemperature–depth plot for this well. The palaeotemperature constraints from AFTA samples prior to early Palaeogene cooling define a palaeotemperature profile which has a much lower value (*c*. 13°C km^{-1}) than the present-day geothermal gradient (*c*. 32°C km^{-1}). Green *et al*. (1997) noted that these kinds of palaeotemperature profiles are characteristic of heating related to the circulation of hot fluids (cf. Duddy *et al*. 1994) and implied that the intrusion of the Fleetwood Dyke swarm during the early Palaeogene may have prompted the widespread circulation of heated fluids across the southern parts of the EISB, thereby generating the observed palaeotemperature profiles. Since the elevated palaeotemperatures across the southern EISB appear to be dominated by non-burial-related processes (in this case, heating due to hot fluid flow) it is not possible to estimate the amount of early Palaeogene exhumation using palaeotemperature data from this part of the basin. Largely based upon an extrapolation of results from the northern EISB, Green *et al*. (1997) have estimated that the southern EISB was exhumed by <1.5 km during early Palaeogene times.

Despite the evidence for elevated early Palaeogene palaeotemperatures across the EISB and CISB, in other parts of the Irish Sea basin system, such as the CBB and SGCB, there is little evidence for significant early Palaeogene cooling. AFTA data from the Mochras borehole suggest that the CBB experienced periods of

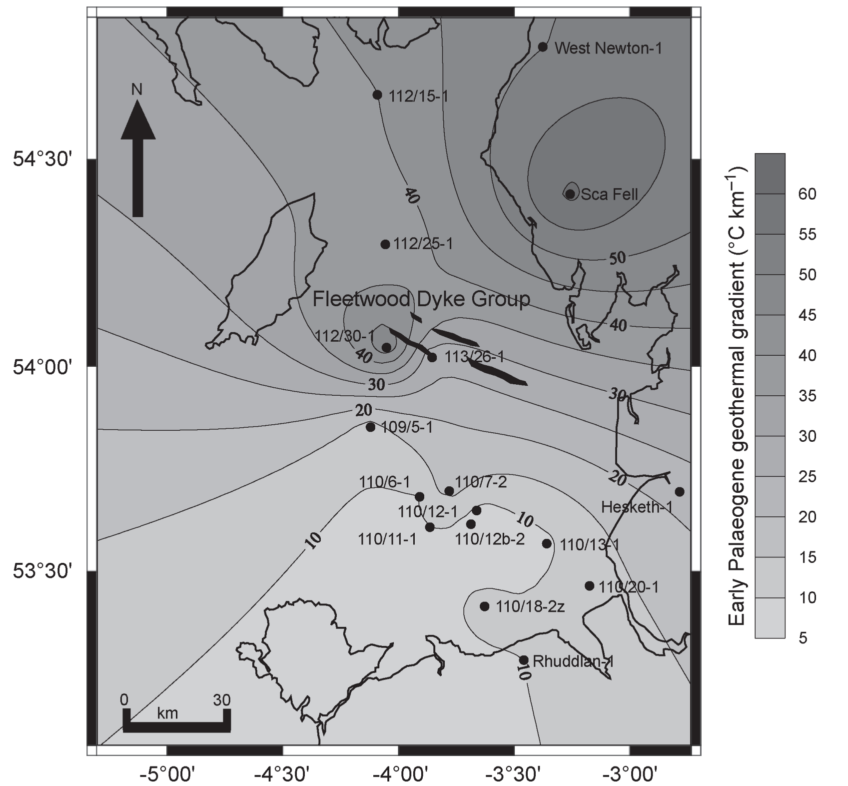

Fig. 6. Thermal structure (i.e. spatial variation in AFTA-defined palaeogeothermal gradients) across the EISB prior to early Palaeogene cooling.

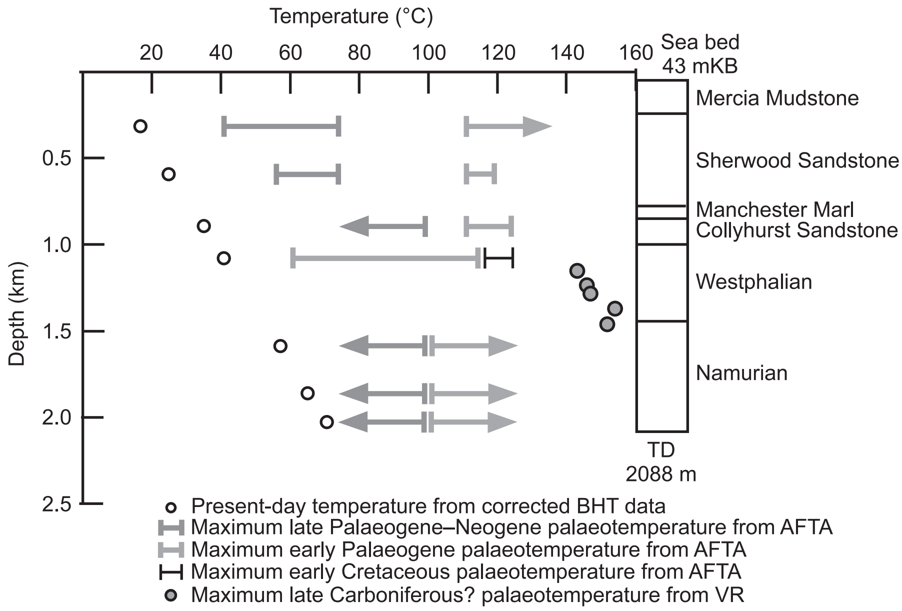

Fig. 7. Palaeotemperature–depth plot for EISB well 110/20-1. Note that the palaeotemperatures required by VR data are higher than both early Palaeogene and early Cretaceous palaeotemperatures at similar depths as indicated by AFTA.

exhumation-related cooling during the Cretaceous (150–80 Ma) and late Palaeogene–Neogene (45–0 Ma), but there is no evidence for elevated palaeotemperatures or cooling during the early Palaeogene (see Fig. 12). Furthermore, AFTA and VR results from the SGCB suggest that samples from Jurassic and Palaeogene units penetrated by exploration wells in this basin cooled from their maximum palaeotemperatures during the late Palaeogene–Neogene, rather than during the early Palaeogene. However, seismic reflection data from the SGCB reveal evidence for major Jurassic/Palaeogene unconformities (e.g. Fig. 8) which Williams *et al.* (2005) attribute to at least 1 km of exhumation during early Palaeogene times. The apparent lack of observable early Palaeogene cooling across the SGCB and CBB is probably associated with the thick sequences of Palaeogene–Neogene sediments that were deposited following early Palaeogene exhumation. Palaeotemperatures reached by samples from the Mesozoic units within these basins prior to exhumation-related cooling during the early Palaeogene, are interpreted to have been overprinted by higher temperatures when these basins experienced re-burial during the late Palaeogene–Neogene. Since both AFTA and VR data are dominated by maximum palaeotemperatures (e.g. Green *et al.* 2002), samples from the SGCB and CBB retain no evidence for exhumation-related cooling during the early Palaeogene.

Late Palaeogene–Neogene

The SCGB and CBB contain some of the thickest sequences of Cenozoic sediments on the western UKCS. The Mochras borehole proved the existence of almost 0.6 km of Middle Oligocene to Lower Miocene sediments within the CBB (Tappin *et al.* 1994), whilst the contiguous SCGB is thought to contain up to 1.5 km of Eocene to Oligocene sediments (Tappin *et al.* 1994). A number of studies have recognized that the Cenozoic successions within these basins were deformed during as a result of tectonic inversion at some point during the Oligocene or Miocene (e.g. Tucker & Arter 1987; Turner 1997). For example, the positive structural culmination of St Tudwal's Arch (Fig. 8a) is thought to have experienced significant tectonic uplift during the Neogene (Ware & Turner 2002). To date, however, few studies have been able to quantify the magnitude of exhumation associated with this period of tectonic inversion (cf. Turner 1997). Here, results from the analysis and interpretation of AFTA and VR data from exploration wells within the SGCB are presented and the magnitude of late Palaeogene–Neogene exhumation indicated by these data is compared to the results of recent AFTA and VR studies across the CISB and EISB.

AFTA and VR results within the SGCB are typified by well 106/24a-2b and palaeotemperature–depth plot for this well is shown in Figure 9. This well is located within the main basin depocentre and seismic reflection data indicate that it penetrates the crest of an inversion-anticline composed of deformed Palaeogene (probably Eocene) sediments (Williams 2002). Figure 9 shows that palaeotemperature estimates from AFTA and VR are in good agreement and, when both are combined, they define an approximately linear gradient. Because the two AFTA samples from this well have only experienced moderate degrees of heating, it is not possible to provide tight constraints on the time of cooling from maximum post-depositional palaeotemperatures (cf. Green *et al.* 2002). However, the fact that VR-derived palaeotemperatures from both the Palaeogene and Jurassic successions show no significant variation across the top Jurassic unconformity suggests that maximum palaeotemperatures over all depths within this well were attained following deposition of the Palaeogene section, prior to exhumation-related cooling. As Figure 9 shows, the palaeotemperature profile is approximately parallel to the present-day geothermal gradient, providing further support for the palaeothermal data recording heating due to deeper burial. Fitting a linear profile to the palaeotemperature constraints from AFTA and VR yields a maximum likelihood estimate of 29°C km^{-1} for the palaeogeothermal gradient during Palaeogene burial (25–33.5°C km^{-1} within 95% confidence limits). Extrapolating this profile to an assumed palaeosurface temperature of 10°C provides a maximum likelihood estimate of 1.1 km of additional Palaeogene–Neogene section removed during exhumation (0.75–1.6 km at 95% confidence limits). Late Palaeogene–Neogene exhumation estimates based upon AFTA and VR data from other SGCB wells range from 0.95 km at 106/24-1, which also penetrates the inverted anticline encountered by 106/24a-2b, to 1.5 km at well 107/16-1, which cuts through a normal fault which has been contractionally reactivated (Fig. 8b).

AFTA- and VR-based estimates of late Palaeogene–Neogene exhumation across the SGCB show good agreement with estimates based on the measurement of anomalous sonic velocities within the Triassic Mercia Mudstone Group (Fig. 10) (results are

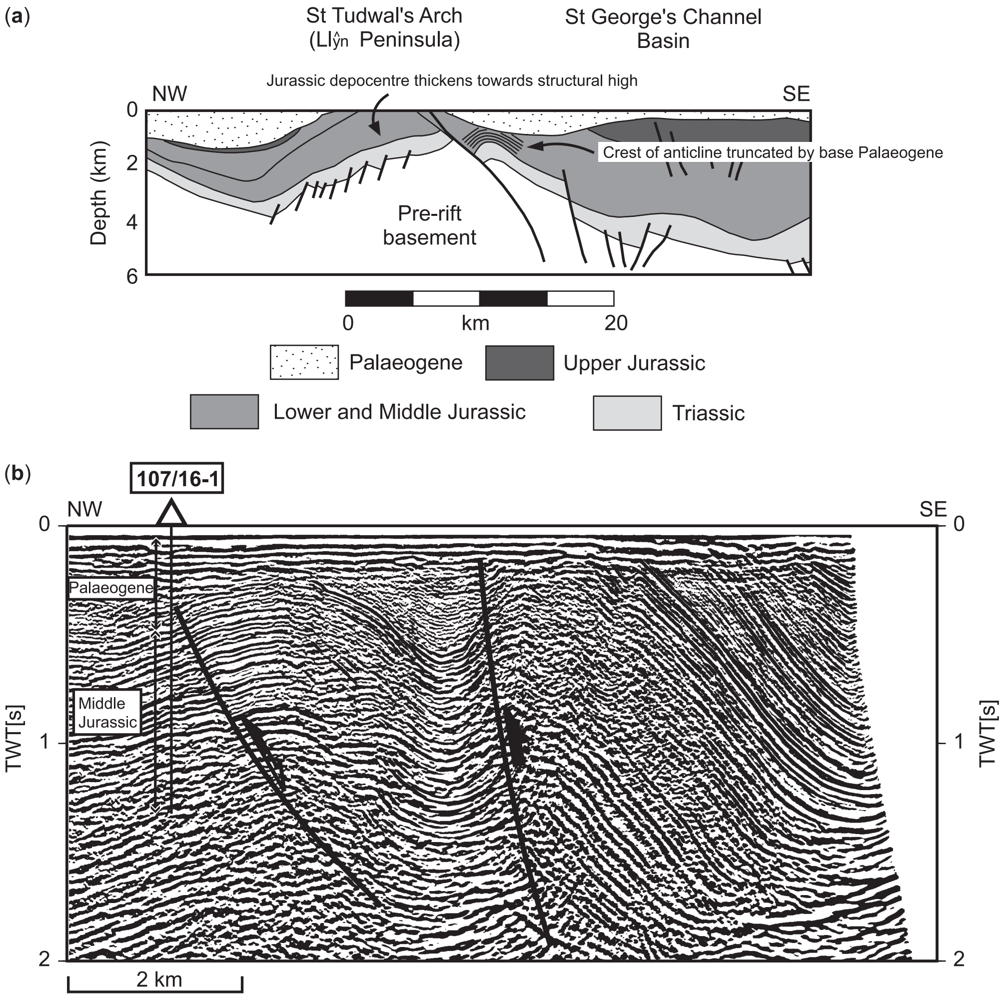

Fig. 8. Examples of inversion structures within the SGCB (locations given in Fig. 10). (**a**) Regional cross-section, across St Tudwal's Arch (the offshore extension of the Llŷn Peninsula) and the SGCB, interpreted seismic data. (**b**) Seismic line through well 107/16-1 located in the NE SGCB. The section is displayed with a significant component of vertical exaggeration to highlight the reactivated fault plane that cuts well 107/16-1. From Williams (2002).

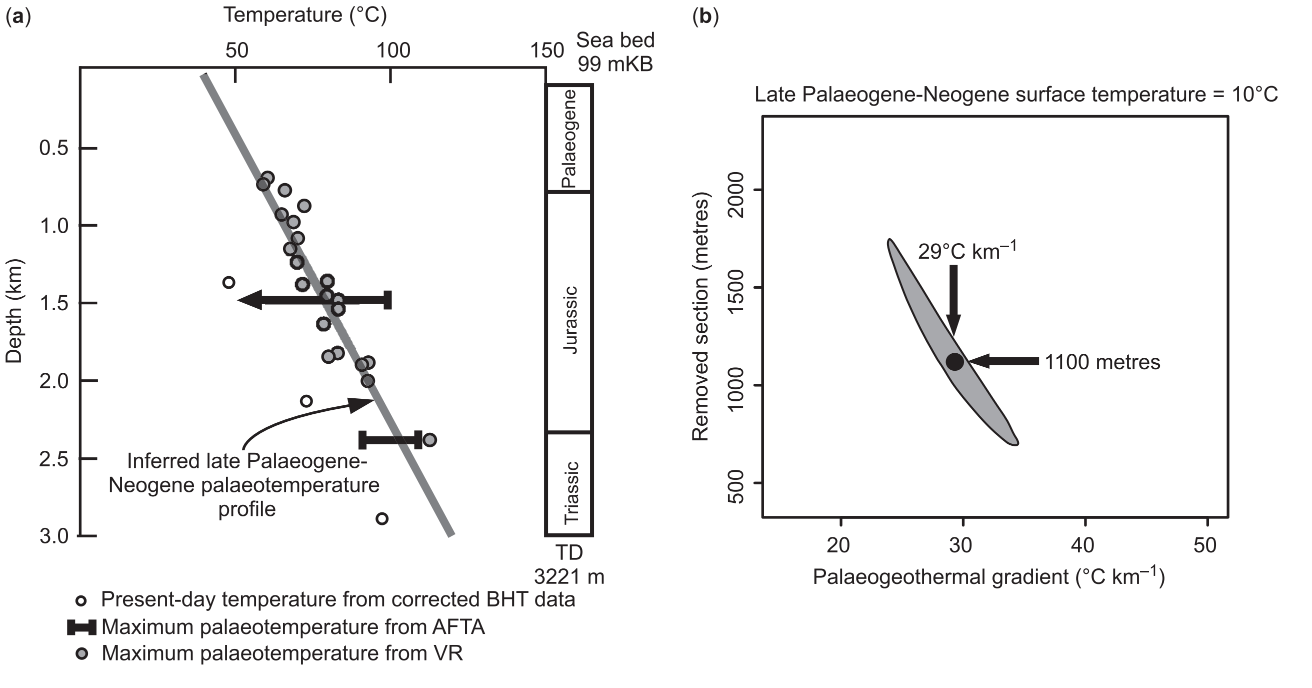

Fig. 9. Palaeotemperature–depth plot for SGCB well 106/24a-2b. (**a**) Palaeotemperatures derived from AFTA and VR plotted against sample depth (RKB). (**b**) Results of a statistical analysis of the palaeotemperature data. Contoured region defines the allowed range for each parameter within 95% confidence limits. See text for further discussion.

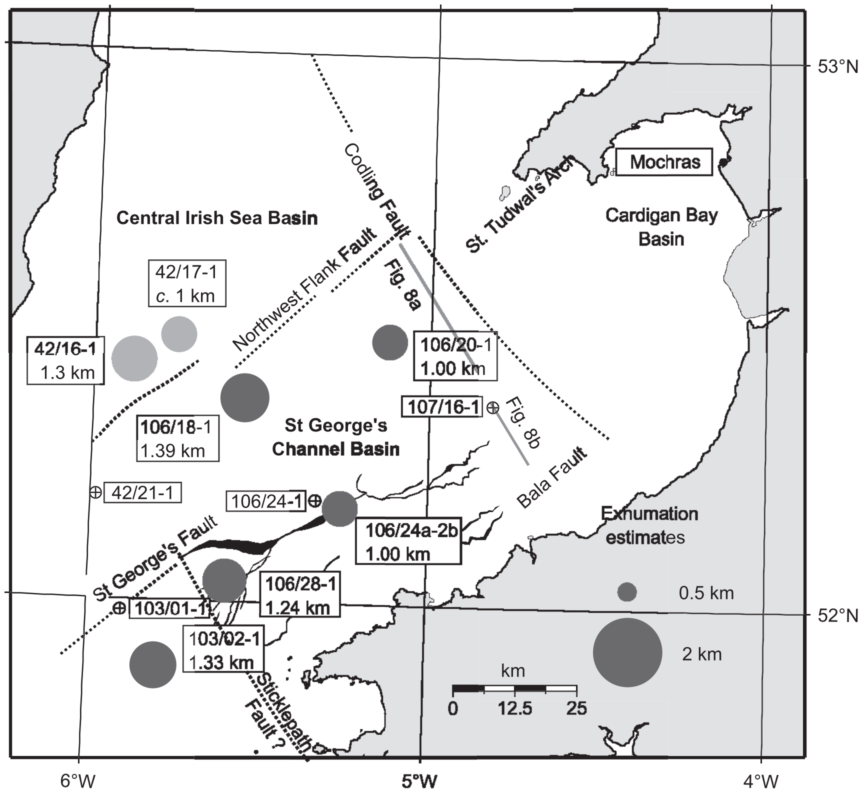

Fig. 10. Map of the SGCB showing main basin-controlling faults and exhumation estimates for SGCB wells based on sonic velocity analyses (reported in Williams *et al.* 2005). Estimates of missing section from sonic velocities are shown adjacent to each well, with the diameter of each circle proportional to the amount of eroded section determined using sonic velocity data. Exhumation estimates for CISB wells 42/16-1 and 42/17-1 based on AFTA data reported in Green *et al.* (2001) are shown by the lighter-coloured circles.

presented by Williams *et al.* (2005), who used a similar approach to that outlined by Hillis (1995)). Sonic velocity data from 106/24a-2b yield an exhumation estimate of 1 km, similar to the maximum likelihood estimate of 1.1 km from AFTA and VR data. Overall, estimates from sonic velocity analyses of SGCB exploration wells range from 1 km to 1.4 km (Fig. 10), which compares well to estimates from thermal history data (ranging from 0.95 km to 1.5 km). Palaeotemperatures from VR data from the Oligocene–Miocene section within the Mochras borehole, indicate that at least 1 km of additional Miocene sediments were deposited within this basin prior to exhumation, which must have occurred at some point during the Neogene. In addition, AFTA data from CISB exploration wells show that the cooling which accompanied *c.* 1 km of exhumation began between 25 Ma and 0 Ma (i.e. during the latest Palaeogene–Neogene) (Fig. 10) (Green *et al.* 2001). In the EISB, where AFTA results tend to be dominated by early Cretaceous and early Palaeogene thermal effects (reflecting the fact that AFTA can usually only resolve two dominant palaeothermal episodes (Green *et al.* 2002)), it is more difficult to quantify the magnitude of late Palaeogene–Neogene exhumation. However, on the basis of results from other parts of the Irish Sea basin system it seems inevitable that this basin was exhumed during the Palaeogene–Neogene, and Ware & Turner (2002) have suggested that short-wavelength variations in exhumation magnitudes within the EISB revealed by sonic velocity analyses record up to 1.2 km of exhumation driven by locally variable late Palaeogene–Neogene tectonic inversion.

Origins of palaeothermal and exhumation episodes

Triassic–early Jurassic

New AFTA data from samples collected from the onshore NW Wales region reveal evidence for a period of Triassic–early Jurassic cooling focused on this region, in which samples began to cool from palaeotemperatures in the region of *c.* 100°C during 230–185 Ma (Fig. 11). The discovery of this palaeothermal episode is interesting because thermal history data from the offshore Irish Sea basins show no evidence for a similarly timed period of cooling (Green *et al.* 1997, 2001). One possible explanation for the observed cooling is related to the subsidence of the adjacent offshore CBB during the Triassic–early Jurassic. The Mochras borehole, located a few kilometres seaward of the Mochras Fault, penetrated a virtually complete sequence of some 1305 m of Liassic rocks, by far the greatest proven thickness known in the British Isles (Hallam 1992) and the combined ages of the Mesozoic sediments penetrated by the Mochras borehole encompasses *c.* 220–180 Ma (Fig. 11) (Tappin *et al.* 1994). Subsidence within the CBB was controlled by normal displacements along the basin-bounding Mochras–Tonfanau–Bala fault system and this hanging-wall subsidence would have been accompanied by co-eval footwall uplift as a flexural-isostatic response to the loads imposed upon the upper crust by normal faulting (Jackson & McKenzie 1983). As the Triassic–early Jurassic sediments of Cardigan Bay appear to have been deposited in fairly shallow-marine environments (depths ≤100 m; Hallam 1992), the uplifted basin margins would have formed a positive feature, exposed above sea-level and, therefore, susceptible to erosion. Although it is not yet possible to provide firm constraints on the amount of section removed during this period of exhumation using the AFTA data alone (which provide only a lower limit on the magnitude of cooling), in some cases, considerable exhumation of footwalls can result following relatively small amounts of extension. Roberts & Yielding (1991) demonstrated that along the Trøndelag Platform, offshore Norway, up to 1.5 km of footwall exhumation resulted from only *c.* 3 km of extension (heave) along the basin-bounding fault.

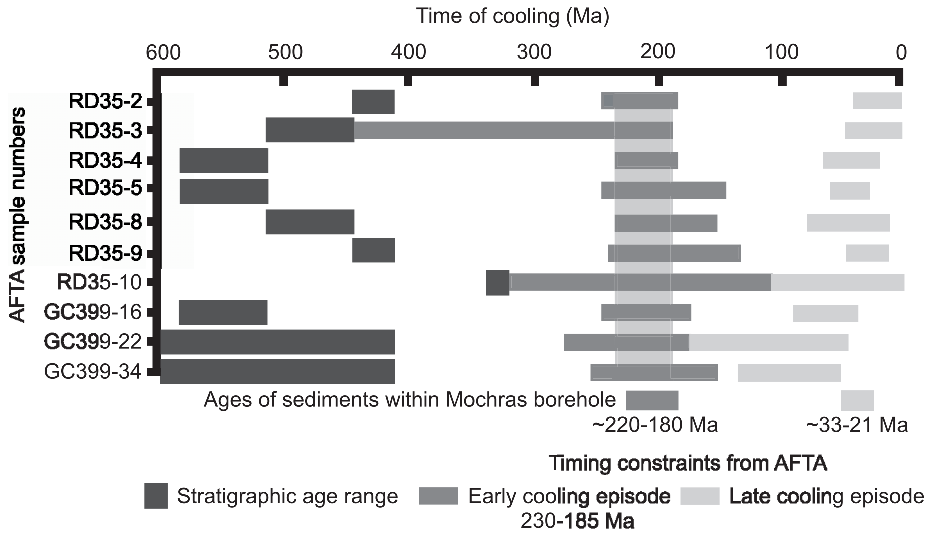

Fig. 11. Timing of cooling episodes for a series of samples from across NW Wales, based upon thermal history interpretation of AFTA data. Ranges shown correspond to 95% confidence limits. Also shown, for comparative purposes, are the ages of sediments within the CBB encountered by the Mochras borehole.

Similar magnitudes of localized exhumation may have occurred across the NW Wales region during the Triassic–early Jurassic in response to normal fault-controlled subsidence in the adjacent CBB. These findings add a further degree of complexity in terms of thermal history styles across this region and highlight the contribution of localized non-epeirogenic processes to the post-Palaeozoic exhumation of the Irish Sea basin system and its margins.

Early Cretaceous

AFTA and VR data indicate that the main phase of post-Palaeozoic exhumation to affect the Irish Sea basin system (at up to 3 km) occurred during early Cretaceous times. New AFTA results from the EISB indicate that exhumation-related cooling within this basin commenced between 140 Ma and 110 Ma, whilst combining timing constraints from across the basin system suggests a regional onset of exhumation between 120 Ma and 115 Ma (i.e. during the Aptian) (Fig. 5). The timing of early Cretaceous cooling across the Irish Sea correlates with a series of important tectonic events which took place along the incipient NE Atlantic margin during the Early Cretaceous (Fig. 5). The main phase of rifting within the Rockall Basin was suggested by Scrutton & Bentley (1988) to have occurred during the Berriasian–Hauterivian (145.6–132.0 Ma), whilst at some time during the Berriasian–Valanginian (145.6–135.0 Ma) the southerly propagating ‘Arctic’ rift (consisting of the Faroe–Shetland–Møre basins) coalesced with the northerly propagating Rockall Basin (the ‘Atlantic’ rift) to form a single, linked rift system (Roberts *et al*. 1999). This important tectonic event was accompanied by the rotation of the least principal horizontal stress direction (i.e. the direction of extension) from E–W to NW–SE during the Hauterivian (135.0 Ma to 132.0 Ma) (Doré *et al*. 1999), which was, in turn, followed by the onset of seafloor spreading between Iberia and the Grand Banks (within the Bay of Biscay) during Aptian times (*c*. 118 Ma) (Johnston *et al*. 2001). These observations demonstrate that the early Cretaceous was a period of intense tectonic activity along the UK and Irish Atlantic margins, and it seems likely that the exhumation of the Irish Sea basin system is related to this activity.

McMahon & Turner (1998) identified two distinct early Cretaceous unconformities to the south of the Irish Sea basins system using seismic and stratigraphic data from the Wessex, Celtic Sea and Western Approaches basins (on- and offshore southern England). The oldest and more significant of these unconformities is Berriasian in age (145.6 Ma to 140.5 Ma), whilst a younger (Aptian; 124.5 Ma to 112.0 Ma) unconformity, apparently associated with lower magnitudes of exhumation is also described. McMahon & Turner (1998) related the Aptian unconformity to exhumation driven by the commencement of seafloor spreading in the proximal Bay of Biscay, whilst the Berriasian unconformity is attributed to regional exhumation centred on the Cornubian Platform. Although the origin or magnitude of exhumation related to the older unconformity cannot be constrained using data from the Irish Sea, it is likely that the Aptian unconformity records the same exhumation episode that affected the Irish Sea basin system. The consistency in timing between the exhumation and the onset of seafloor spreading in the Bay of Biscay suggests a genetic relationship between these events.

Early Palaeogene

The mechanisms by which the British Isles were exhumed during early Palaeogene times have been the subject of considerable debate (e.g. Hillis 1992, 1995; Lewis *et al*. 1992; Brodie & White 1995; White & Lovell 1997; Blundell 2002). The lack of recognized tectonic inversion structures across the Irish Sea region has led many studies to attribute the early Palaeogene exhumation to the activity of the Iceland plume and, specifically, the isostatic response to crustal thickening following magmatic underplating. Brodie & White (1995) proposed that a thick (≤8 km) sheet of basic igneous rock, extending from the recognized early Palaeogene igneous centres of NW Scotland to the granitic Lundy Island, had been emplaced beneath the Irish Sea basin system during the early Palaeogene, resulting in up to 3 km of exhumation. This is despite the fact that, with the exception of Lundy and the Fleetwood Dyke swarm, Palaeogene-age surface magmatism is largely absent from the Irish Sea area (Fig. 1). There is also little support for the existence of substantial lower crustal underplating from deep seismic reflection profiles acquired within this region, which lack the reflectivity patterns associated with magmatic underplating (England & Soper 1997; Chadwick & Pharoah 1998).

Samples from Triassic units within the CISB and parts of the EISB cooled from their maximum palaeotemperatures during the early Cretaceous, which implies that the main phase of post-Palaeozoic exhumation across the Irish Sea basin system occurred during the early Cretaceous rather than during the Palaeogene (e.g. EISB well 109/5-1, Fig. 4; Duncan *et al*. 1998; Green *et al*. 2001). Moreover, early Palaeogene palaeotemperatures within the EISB appear to be dominated by non-burial-related processes (Green *et al.* 1997), making it difficult to establish the magnitude of deeper burial prior to exhumation. This point is highlighted by thermal history results from EISB well 110/20-1 (Fig. 7), where early Palaeogene palaeotemperature constraints from AFTA define a palaeotemperature profile with a low value (*c.* 13°C km^{-1}), which is characteristic of heating by the circulation of hot fluids (cf. Duddy *et al.* 1994). This hypothesis is supported by fluid inclusion data from southern EISB wells, where homogenization temperatures exceeding 110°C measured in quartz, dolomite and ankerite cements within Triassic and Permian sandstones have been related to the migration of heated fluids during the early Palaeogene (Hardman *et al.* 1993). With regard to well 110/20-1, it should also be noted that the palaeotemperatures indicated by VR data from the Carboniferous section are considerably higher (by between 20°C and 40°C) than both the early Palaeogene and early Cretaceous palaeotemperature constraints from AFTA. This difference in temperature suggests that the VR-derived palaeotemperatures from this well record heating during a late Carboniferous palaeothermal episode. Green *et al.* (1997) and Corcoran & Clayton (2001) have previously identified late Carboniferous palaeothermal effects within the Irish Sea basin system and there is a strong likelihood that the majority of VR data from Carboniferous units within the EISB record late Carboniferous palaeotemperatures.

Despite the apparent lack of evidence for early Palaeogene shortening across the Irish Sea basin system (cf. Brodie & White 1995), a number of recent studies have identified potentially important early Palaeogene inversion structures within this area. Seismic reflection data from the SGCB indicate that the early Palaeogene exhumation of this basin was accompanied by the contractional reactivation of the basin-margin faults, including the Bala Fault (Williams 2002). This reactivation occurred in response to NW-directed compression, which is consistent with the kinematics of Alpine convergence (Ziegler *et al.* 1995) and indicates that tectonic inversion was an important process driving the early Palaeogene exhumation of the SGCB (Fig. 8a) (although Williams (2002) could not rule out a component of regional tectonic uplift). The adjacent CISB was also strongly affected by NW-directed compression during the early Palaeogene, which upwarped the central axis of the basin by around 2 km (Izatt *et al.* 2001). AFTA and VR results from the CISB point to *c.* 2 km of early Palaeogene exhumation across the axial parts of this basin (Green *et al.* 2001).

In summary, evidence from AFTA and VR data, combined with the geological observations discussed above, suggests that the early Palaeogene exhumation of the Irish Sea basin system was driven by a combination of localized tectonic inversion and crustal shortening related to Alpine plate convergence (cf. Ziegler *et al.* 1995), with a component of regional uplift which may be associated with plume activity or the initial effects of North Atlantic continental break-up (which was achieved by *c.* 53 Ma) (Doré *et al.* 1999).

Late Palaeogene–Neogene

Results from AFTA and VR, complemented by sonic velocity data, indicate that the Irish Sea basin system experienced *c.* 1 km

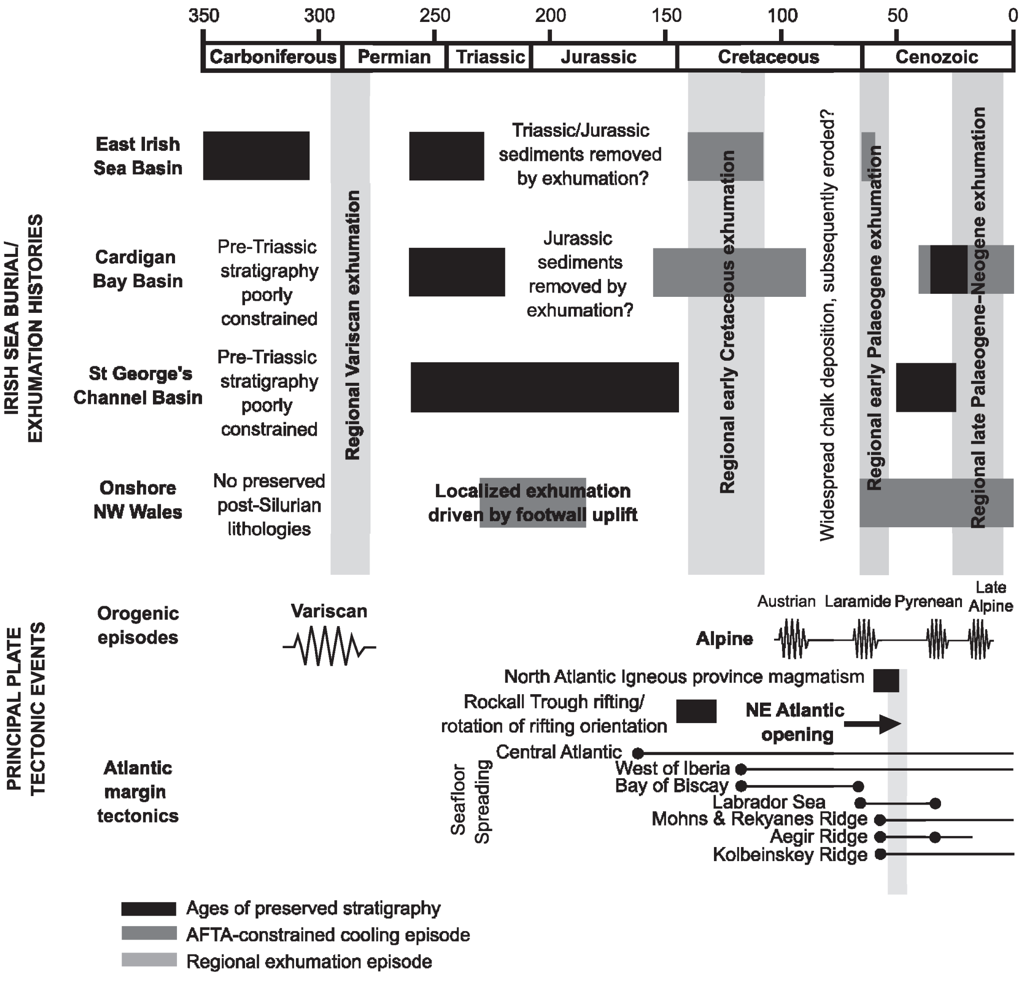

Fig. 12. Post-Devonian geological history of the Irish Sea basin system. Exhumation-related cooling episodes identified by AFTA data are shown, as are the ages of preserved stratigraphic units within the Irish Sea basin system. Note the general temporal consistency between periods of Irish Sea exhumation and the occurrence of major extensional or compressional events at proximal plate margins. Modified from Doré *et al.* (1999).

of exhumation during late Palaeogene–Neogene times. Following early Palaeogene exhumation, thick successions of Eocene–Miocene sediments accumulated in parts of the Irish Sea, most notably in the SGCB, where up to 1.5 km of Cenozoic sediments are preserved (Tappin *et al*. 1994). However, subsequent to deposition, these sequences were subjected to a phase of compressional deformation which led to their uplift and erosion. In the CISB, this compressional deformation is manifested by transpressional reactivation of N–S-trending faults and folding of the base Palaeogene unconformity (Izatt *et al*. 2001), whilst in the SGCB the basin depocentre was folded and extensive contractional fault reactivation occurred (e.g. Fig. 8b; Williams 2002). Furthermore, Ware & Turner (2002) have suggested that a substantial amount of shortening within the SGCB was accommodated by the pure-shear thickening of the *c*. 10 km thick, fine-grained siliciclastic basin fill.

Although some authors have related the late Palaeogene–Neogene (Oligo-Miocene) inversion of the UK Atlantic margin to the either the ‘Pyrenean’ phase of the Alpine orogeny (Roberts 1989) or ridge-push forces (Lundin & Doré 2002), regional fault kinematics indicate that the late Palaeogene–Neogene exhumation of the Irish Sea occurred in response to transpressional deformation caused by dextral shear along major NW-trending strike-slip faults (see Fig. 13) (Turner 1997). The Irish Sea basin system is cross-cut by the Codling and Sticklepath–Lustleigh fault zones, both of which exhibit evidence for dextral displacements during late Palaeogene–Neogene times (Turner 1997). Coward (1994) implied that these faults formed part of a major NW–SE-trending transfer zone during the Oligocene–Miocene, which linked the opening of the North Atlantic with extension within the Rhine–Rhone basin system. It is also possible, however, that some of the inversion structures within the Irish Sea basin system formed during the late Miocene as a result of the ‘Late Alpine’ stage of Alpine foreland deformation, which notably affected the Wessex Basin (Blundell 2002).

Discussion

AFTA and VR data from the Irish Sea basin system indicate that this area has been affected by several phases of widespread exhumation during Mesozoic and Cenozoic times (Fig. 12). The most important of these appears to have occurred during the early Cretaceous, removing up to 3 km of sediments from these basins, although kilometre-scale exhumation occurred during the early Palaeogene and late Palaeogene–Neogene, with the overall magnitude of exhumation associated with these events apparently decreasing over time (cf. Green *et al*. 2002). Although these exhumation episodes appear to have been regional in extent, the underlying driving mechanisms were not necessarily epeirogenic, as tectonic inversion is strongly implicated in both the early

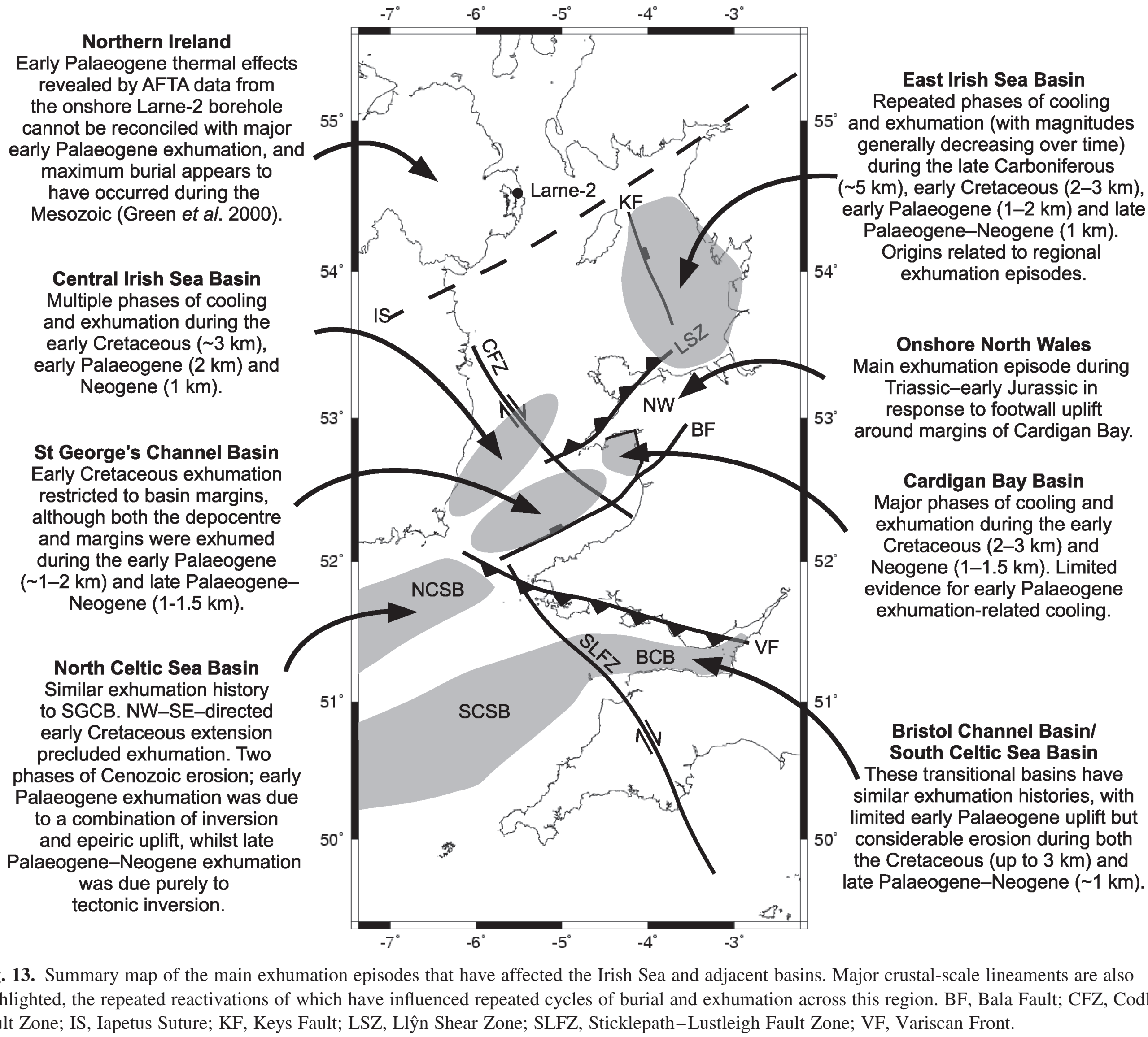

Fig. 13. Summary map of the main exhumation episodes that have affected the Irish Sea and adjacent basins. Major crustal-scale lineaments are also highlighted, the repeated reactivations of which have influenced repeated cycles of burial and exhumation across this region. BF, Bala Fault; CFZ, Codling Fault Zone; IS, Iapetus Suture; KF, Keys Fault; LSZ, Llŷn Shear Zone; SLFZ, Sticklepath–Lustleigh Fault Zone; VF, Variscan Front.

Palaeogene and late Palaeogene–Neogene phases of exhumation. In addition, new AFTA data, which reveal evidence for Triassic–early Jurassic exhumation-related cooling across NW Wales, indicate that localized periods of exhumation may have strongly contributed to the post-Palaeozoic exhumation of the Irish Sea.

Perhaps the most significant aspect of these results is that the regional phases of Irish Sea exhumation broadly coincide with major plate-scale reorganizations (Fig. 12). The fact that collisional events at plate margins can result in the distributed deformation and uplift of areas up to 1600 km away from the actual zone of collision is well documented (Ziegler *et al*. 1995) and the causes of exhumation during the early Palaeogene and late Palaeogene–Neogene appear to be, at least in part related to Alpine plate convergence and Atlantic continental break-up (Fig. 12). Furthermore, the regional phase of exhumation during the early Cretaceous was co-eval with a series of major rifting events which effectively established the template for the development of the North Atlantic Ocean (Fig. 5) (e.g. Doré *et al*. 1999; Roberts *et al*. 1999). The consistency of the temporal correlations between periods of widespread exhumation across the Irish Sea and western UK (Fig. 13) and major extensional or compressional events at incipient or pre-existing plate boundaries, implies that the regional exhumation of intra-plate regions are probably driven by major tectonic events at plate margins (cf. Green *et al*. 2002).

Conclusions

- AFTA and VR results indicate that the Irish Sea basin system has experienced a complex, multi-phase Mesozoic–Cenozoic exhumation history.
- Regional exhumation episodes occurred during the early Cretaceous (<3 km), early Palaeogene (<2 km) and late Palaeogene–Neogene (*c*. 1 km), with the overall magnitude of exhumation associated with each episode decreasing over time.
- The NW Wales region was affected by localized exhumation during the Triassic–early Jurassic, interpreted as a response to footwall uplift around the margins of the co-evally subsiding Cardigan Bay Basin.
- Given that the regional exhumation episodes generally coincide with important periods of deformation at pre-existing or incipient plate boundaries, it is probable that events at plate margins have exerted the primary control on the Mesozoic–Cenozoic exhumation of the Irish Sea basin system.

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