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Regional Neogene exhumation of Britain and the western North Sea

PETER JAPSEN
Geological Survey of Denmark and Greenland (GEUS), Thoravej 8, DK-2400 Copenhagen NV, Denmark
(e-mail: pj@geus.dk)

Abstract: Tertiary exhumation of Britain and the western North Sea is interpreted to have taken place in two episodes, each with amplitudes of about 1 km: a Palaeogene phase that principally affected the present onshore Britain (west of the present extent of the Late Cretaceous–Danian Chalk Group), and a Neogene phase that affected both onshore areas and the western North Sea. Consequently maximum burial of Mesozoic and older rocks in the present onshore areas generally occurred in the Palaeocene (*c.* 60 Ma). In the western North Sea, the preservation of the Chalk Group today suggests relatively stable conditions prevailed immediately after its deposition rather than substantial Palaeocene exhumation. In this area, maximum burial is interpreted to have occurred in the Neogene. The proposal is consistent with published exhumation estimates based on studies of sediment compaction (offshore) and of fission tracks (onshore). It also does away with unlikely high burial rates which are implied in the latest Cretaceous–earliest Tertiary if removal of overburden from the Chalk is assumed to have occurred in the Palaeocene.

Keywords: Neogene, Palaeogene, Great Britain, North Sea, uplifts.

Britain and the western North Sea were affected by two episodes of exhumation during the Tertiary: One during the Palaeogene and the other during the Neogene (George 1966; Bulat & Stoker 1987; Green 1989; Hall 1991; Lewis *et al.* 1992; Green *et al.* 1993; Stewart & Bailey 1996). It is not clear, however, which areas were affected by each of the two episodes, nor what their magnitudes were. Over wide areas of the UK, Mesozoic and older sediments experienced maximum burial in the Palaeocene (*c.* 60 Ma) (cf. Green *et al.* 1993; Brodie & White 1994). The extent of the area where maximum burial was *c.* 60 Ma ago has not been established and it is uncertain to what extent Palaeogene sediments covered the area. Exhumation signifies removal of rocks at the Earth's surface, returning rocks once buried to crop out at the surface/sea bed. This usage is similar to that of England & Molnar (1990), who highlighted the need to distinguish uplift of rocks (relative to the geoid) from exhumation of rocks (relative to the Earth's surface). The usage differs from England & Molnar, however, in that a geological formation can be considered exhumed (in the strict sense of the word) only when it has been returned to the surface, not when the overburden has been only partially removed (partial unroofing). For a geological object that is not subdivided vertically, e.g. a region, country or basin, 'exhumation' will always apply. In general, the quantity measured in studies of exhumation will be 'removed overburden' or 'unroofing'.

There has been debate about the removal of cover rocks (cf. Hall 1991; Holliday 1993), fuelled by results of apatite fission-track (AFT) studies, mainly from onshore areas. The AFT studies indicate that regional exhumation of the order of kilometres over wide areas of the UK was initiated in the mid-Palaeocene (*c.* 60 Ma) (cf. Green 1986, 1989; Bray *et al.* 1992; Lewis *et al.* 1992). The debate focused on the magnitude of exhumation (Brown 1991; Green 1991; Holliday 1993, 1994; McCulloch 1994; Green *et al.* 1995*a*), whereas the timing of exhumation was not questioned directly. Only 'implausibly rapid early Cenozoic subsidence' was mentioned by Holliday (1993). 'Intuitively unsatisfactory' high burial rates (Hillis 1995*a*) becomes the consequence where a kilometre-thick missing section is interpreted to have been deposited over relatively few million years. Because of such problems, it is important to time the exhumation.

Regional Tertiary exhumation was documented for different parts of the UK continental shelf, primarily from sediment compaction studies (Bulat & Stoker 1987; Hillis 1991, 1995*b*; Hillis *et al.* 1994; Thomson & Hillis 1995). The timing of exhumation in the southern North Sea was suggested to be Neogene by Bulat & Stoker (1987) and Stewart & Bailey (1996). Hillis (1995*a*), however, found a more accurate estimate of the timing within the Tertiary, to be the primary 'enigmatic aspect' of the regional exhumation of the western North Sea.

In this paper, I try to separate the effects of the two exhumation events. This is done mainly by reviewing published exhumation estimates from onshore fission track studies and estimates based on sediment compaction studies from the UK North Sea. In particular I argue that where the Late Cretaceous–Danian Chalk Group is preserved today, maximum burial of the Chalk (and older rocks) and the subsequent unroofing of the Chalk took place in the Neogene.

Exhumation estimates from fission-track analyses, onshore UK

Extensive apatite fission-track studies (Fig. 1) were reported for northern England (Green 1986), the East Midlands Shelf (Green 1989) and northwestern England (Lewis *et al.* 1992). All studies concluded that maximum palaeo-temperatures were attained at or before *c.* 60 Ma (mid-Palaeocene). The palaeogeothermal gradient was interpreted to be close to the present value, and all three studies concluded that the observed heating was due to greater depth of burial than that presently observed. Uplift and erosion of 2–3 km beginning at *c.* 60 Ma across the area were consequently inferred.

Interpretation of fission-track data suggest that exhumation of the UK took place in two phases occurring in the early and mid-late Tertiary. In a review of fission track studies, Green

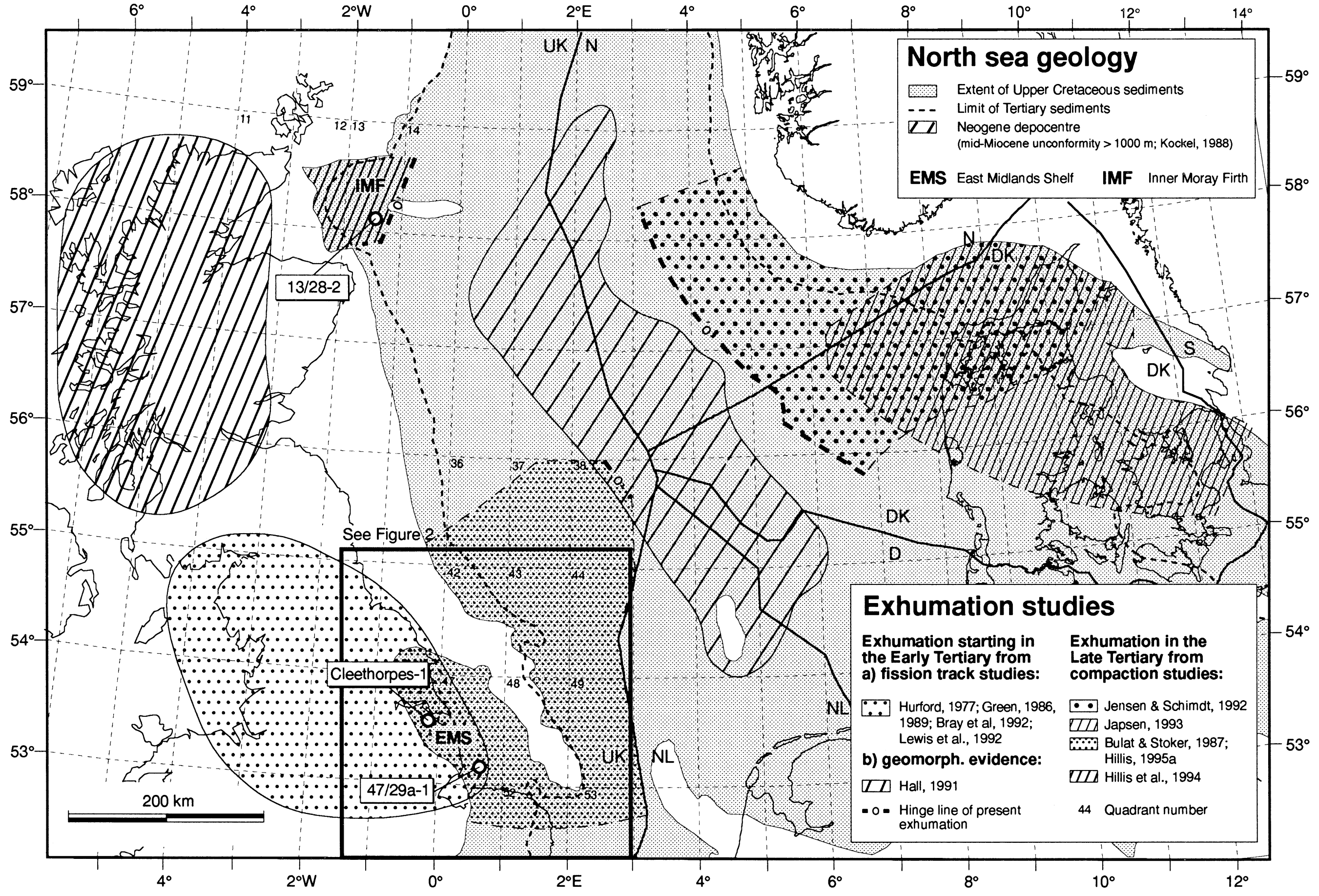

Fig. 1. Exhumation studies in the North Sea region. Removal of overburden from the Chalk occurred along the margins of the North Sea Basin, symmetrical with respect to the Neogene depocentre centrally in the basin. West of the present extent of the Chalk, pronounced exhumation started in the Early Tertiary. Structural outline modified after Ziegler (1990).

et al. (1993) state that the cooling history was protracted throughout the region, and that a series of discrete cooling events throughout the Tertiary might have affected different areas to different degrees. In northwestern England fission track data was found to suggest that uplift occurred in distinct phases in the early and mid-late Tertiary (Lewis *et al.* 1992). On the East Midlands Shelf, the presence of grains with young fission track ages of 20–30 Ma (Green 1989) suggests that a large proportion of the cooling occurred in the last 30 Ma (Green *et al.* 1993).

Fission track results from the Cleethorpes-1 (Green 1989) and the 47/29a-1 (Bray *et al.* 1992) wells on the East Midlands Shelf are of particular interest (Figs 1 and 2). These wells are the only wells in which AFT studies have been done where a section as young as the Late Cretaceous Chalk is preserved. In these wells we can narrow down the time interval during which the now missing section was deposited. However, the 'palaeotemperature estimates derived from AFT analysis in two samples from Cleethorpes-1 that were sampled over large depth ranges were not sufficient to provide useful estimates' (Bray *et al.* 1992). There were only two samples from the Cleethorpes-1 well in the study of Green (1989). Bray *et al.* (1992) thus omitted fission track data for this well from their study. Details of the AFT studies for the 47/29a-1 well, such as distributions of confined track lengths or fission track ages, were not referred by Bray *et al.* (1992). Consequently AFT

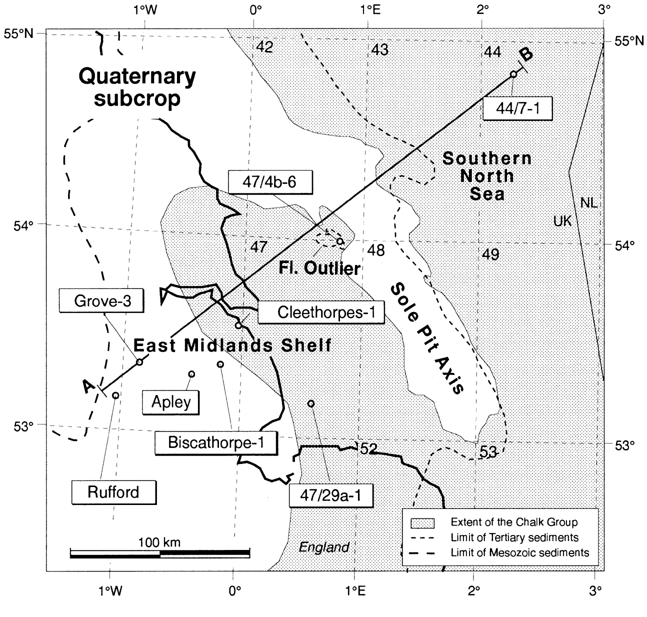

Fig. 2. Quaternary subcrop on the East Midlands Shelf. Detail of Fig. 1 with additions based on Bray *et al.* 1992; Stewart & Bailey (1996). Fl. Outlier: the Tertiary Flamborough Outlier. Cross-sections along AB in Fig. 3.

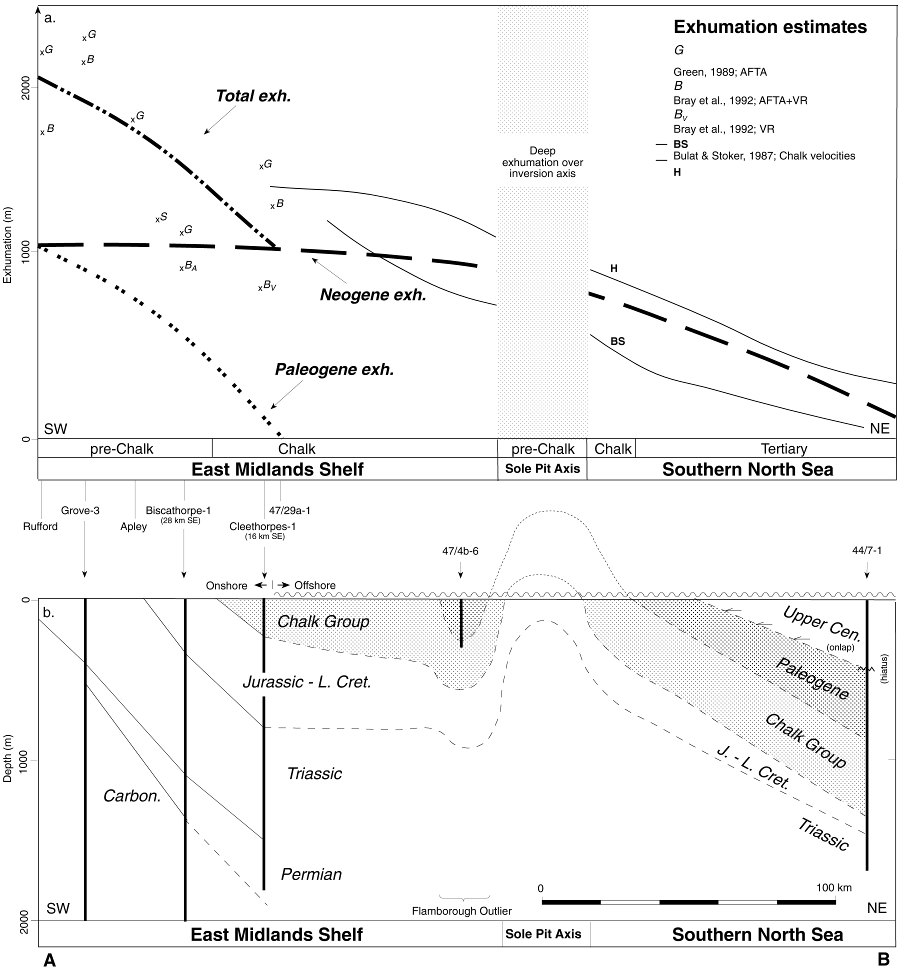

Fig. 3. Cross-sections over the East Midlands Shelf along profile AB in Fig. 2. Note that the increase in Palaeogene exhumation towards SW (**a**) corresponds to the dip of base Mesozoic (**b**). Palaeogene exhumation was small where the Chalk is preserved today.
(**a**) Exhumation along the profile with the interpreted superposition of Palaeogene and Neogene exhumation (solid lines). Exhumation estimates from different studies are projected onto the profile. Pre-Quaternary geology indicated at bottom.
(**b**) Well correlation based on data from PI (Erico) and Green (1989); Bray *et al.* (1992); Hillis (1995*b*); Stewart & Bailey (1996). Depth in m below sea bed/ground level.

data provide no temporal constraints on the burial history where the Chalk Group is present today. There are insufficient data from Cleethorpes-1, and no published data from 47/29a-1.

Exhumation estimates from compaction studies, UK North Sea

Regional exhumation in the UK southern North Sea (Bulat & Stoker 1987; Hillis 1995*b*) and in the Inner Moray Firth (Hillis *et al.* 1994) (Fig. 1) has been inferred from studies of sediment overcompaction as measured by high acoustic velocity relative to a normal velocity–depth trend. Overburden was found to have been removed from the Chalk Group everywhere in the UK southern North Sea (south of 56°N) except in the north-eastern corner of quadrant 38 in the Central Graben area (Bulat & Stoker 1987; Hillis 1995*b*). The amount of overburden removed from Chalk increases with distance from the Central Graben and reaches a maximum values of 1500 m on the East Midlands Shelf (Fig. 3) (Bulat & Stoker 1987; Hillis 1995*b*). In the southern North Sea regional exhumation was found to be of Late Tertiary age based on interpretation of regional seismic and well data (Bulat & Stoker 1987).

Most of the Inner Moray Firth appears to have been exhumed, and estimates of the magnitude of exhumation depend on the methodology and the area covered (McQuillin *et al.* 1982; Roberts *et al.* 1990; Hillis *et al.* 1994; Green *et al.* 1995*b*; Thomson & Hillis 1995). The unroofing of the Chalk Group was found to be up to 700 m in quadrant 13 and up to 1300 m for the Kimmeridge Clay in quadrants 11 to 13 (Hillis *et al.* 1994; Thomson & Hillis 1995). All studies point towards increasing exhumation towards Scotland, reaching almost 1 km where the Chalk is truncated. In the Inner Moray Firth, an unconformity separates the Chalk from Late Palaeocene siliciclastic sediments derived from nearby uplifted areas (Andrews *et al.* 1990). This was interpreted by some workers to suggest that the Chalk was at maximum burial during the Palaeocene (Roberts *et al.* 1990; Hillis *et al.* 1994; Thomson & Hillis 1995). However, McQuillin *et al.* (1982) suggested that exhumation occurred throughout the Cenozoic.

Timing of maximum burial and the effect on burial rates

When a rock started to cool due to reduction of its overburden, may be inferred from the distribution of fission track lengths (Green 1989; Lewis *et al.* 1992), but cannot be deduced directly from studies of sediment compaction. However, temporal constraints may be obtained indirectly from compaction data in two ways. Firstly, comparison of exhumation estimates for different stratigraphic units reveal whether they experienced identical burial histories. The exhumation must postdate the youngest stratigraphic unit affected by the exhumation (Bulat & Stoker 1987). Such a comparison only limits the timing of the unroofing of the Chalk in the western

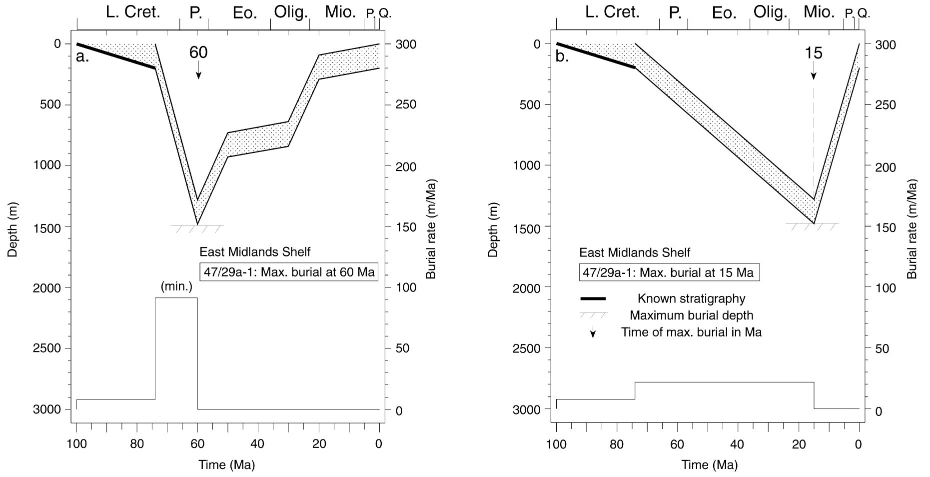

Fig. 4. Burial diagrams for the Chalk Group with and without Paleogene exhumation for well 47/29a-1 (East Midlands Shelf). Note the differences in the derived burial rates. Well data and exhumation estimate from Bray *et al.* (1992). (**a**) Maximum burial at 60 Ma (cf. Green 1989, fig. 9 and Green *et al.* 1993, fig. 4). (**b**) Maximum burial at 15 Ma (cf. Hillis 1995*a*, fig. 5).

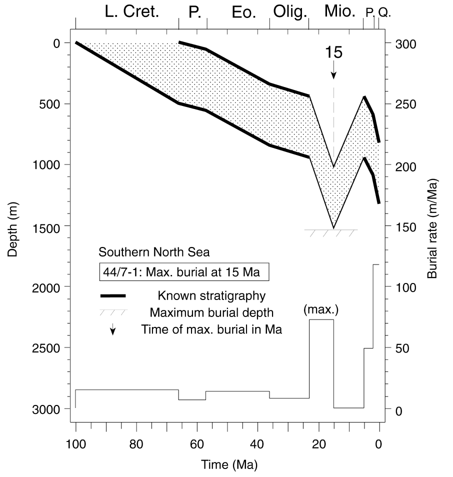

Fig. 5. Burial diagram for the Chalk Group with indication of Neogene exhumation for well 44/7-1 (southern North Sea). Well data from PI (Erico). Exhumation equals mean of estimates from Chalk velocities (Bulat & Stoker 1987; Hillis 1995*b*). Maximum burial at 15 Ma (cf. Hillis 1995*a*, fig. 5).

North Sea to the Cenozoic because it is difficult to resolve the effects on the Tertiary strata (Bulat & Stoker 1987; Hillis *et al.* 1994; Hillis 1995*b*). Secondly, the timing of exhumation can be estimated by constructing burial diagrams based on the preserved stratigraphy and the estimated maximum burial. If a unit, such as the Chalk, previously was deeper buried than it is today, we must identify the major hiati in the overlying strata, during which the missing section could have been deposited and subsequently removed. Burial rates of the deposition of the missing section can be calculated by choosing different hiati, and the different models of burial and exhumation can be tested by comparing their geographical consistency and the resulting burial rates (Figs 4–6).

Burial rates on the East Midlands Shelf

High burial rates in the latest Cretaceous–earliest Tertiary on the East Midlands Shelf were implied by AFT studies of the Cleethorpes-1 well (Green 1989) and the 47/29a-1 well (Bray *et al.* 1992) (Figs 2 and 4). A narrow time interval separates the time of deposition of the preserved Upper Cretaceous rocks and the suggested maximum burial at 60 Ma in well 47/29a-1 (Bray *et al.* 1992). Consequently the inferred burial rate for the missing 1280 m in this well becomes 91 m Ma^{-1} (Table 1). The rate increases if the time interval is narrowed down by estimating the onset of the rapid burial, rather than taking the age of youngest preserved sediments. Burial rates of more than 90 m Ma^{-1} are high for Upper Cretaceous–Lower Tertiary sediments in the southern North Sea. Similar rates during the Palaeocene are only recorded from the Moray Firth, where up to 1000 m were deposited during the 10 Ma of the Palaeocene (Nielsen *et al.* 1986). Palaeocene burial rates are only 14 m Ma^{-1} in the Central Graben area due to reduced sediment supply (Nielsen *et al.* 1986). Southern parts of the North Sea are believed to have been subsiding slowly in the Palaeocene (Cameron *et al.* 1992). Inversion of the Sole Pit Basin took place in two phases during the Turonian–Campanian and the Oligocene (van Hoorn 1987), which pre- and post-date, respectively, the supposed episode of rapid burial. There is thus no independent evidence for a geological event in the southern North Sea that could account for burial rates in excess of 90 m Ma^{-1} during the latest Cretaceous–earliest Tertiary.

A simple model explaining the deposition of the missing 1280 m post-Campanian section in well 47/29a-1 is that maximum burial of the Chalk occurred in the mid- or late Tertiary in the southern North Sea (Bulat & Stoker 1987; Stewart & Bailey 1996). This timing results in a burial rate of only 22 m Ma^{-1} for the deposition of the missing section (Fig. 4b; Table 1).

High burial rates during latest Cretaceous–earliest Tertiary times for the Grove-3 and Biscathorpe-1 wells located more westerly on the East Midlands Shelf (Fig. 2) were suggested by Green (1989, fig. 9). Such high burial rates are, however, not implied by the fission-track dating of maximum burial at *c.* 60 Ma for these wells (Green 1989). The ages of the youngest stratigraphic units are Triassic and Early Cretaceous (Green 1989), and only moderate burial rates (14 and 24 m Ma^{-1}; Table 1) are needed for the deposition of the missing sections.

Burial rates in the Inner Moray Firth

Extremely high Danian burial rates (about 400 m Ma^{-1}) are the consequence of the assumption of Danian maximum burial of the Chalk in the Inner Moray Firth (Fig. 6a; Table 1). The maximum burial of the Chalk in quadrant 13, *c.* 1 km (Hillis *et al.* 1994), equals its present depth plus the estimated overburden removed. If exhumation took place during

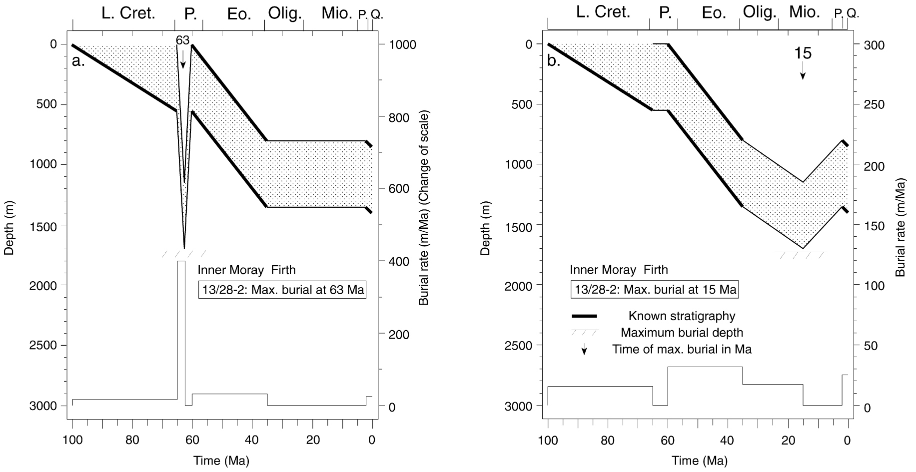

Fig. 6. Burial diagrams for the Chalk Group with and without Paleogene exhumation for well 13/28-2 (Inner Moray Firth). Note the differences in the derived burial rates. Well data from Andrews *et al.* (1990) and PI (Erico), exhumation estimate from Hillis (1994). (**a**) Maximum burial at 60 Ma; note change of scale relative to Figs 4–5 (cf. Hillis *et al.* 1994, fig. 10; Thomson & Hillis 1995, fig. 15). (**b**) Maximum burial at 15 Ma.

Table 1. *Burial rates inferred for the deposition of missing sections*

Well	Exhumation est. + post-exh. burial = missing sect[1] (m)	Youngest pre-exhumation rocks preserved (Ma)	Time of max. burial (Ma)	Time for deposition[2] (maximum) (Ma)	Burial rate[3] (minimum) (m Ma^{-1})	Fig.
47/29a-1 EMS	1240[4] + 0	Campanian[4]: 74[4]	Mid-Palaeocene: 60[4]	14	91	4a
47/29a-1 EMS	1240[4] + 0	Campanian[4]: 74[4]	Mid-Miocene: 15	59	22	4b
Biscath.-1 EMS	2150[5] + 0	Triassic[5]: 210	Mid-Palaeocene: 60[5]	150	14	
Grove-3 EMS	850[5] + 0	Early Cret[5]: 96	Mid-Palaeocene: 60[5]	36	24	
13/28-2 IMF	500[6] + 500[7]	Maastrichtian[6]: 67	Mid-Danian[6]: 63	*c.* 2.5[8]	400	6a
13/28-2 IMF	500[6] + 200[7]	Palaeocene: 54	Mid-Miocene: 15	39	18	6b

Alternative burial rates are based on different timing of maximum burial. Only maximum burial during the late Tertiary results in moderate burial rates for the 47/29a-1 and the 13/28-2 wells. Maximum burial during the early Tertiary is consistent with moderate burial rates for the Biscathorpe-1 and Grove-3 wells. Calculation of decompacted burial curves will tend to reduce inferred burial rates (cf. Hillis 1995*b*). Stratigraphic ages from Haq *et al.* (1987).

[1] Exhumation estimate + post-exhumational burial = missing section (cf. Hillis 1995).

[2] Time interval for deposition of the missing section.

[3] Missing section/time for deposition.

[4] Bray *et al.* (1992).

[5] Green (1989).

[6] Hillis *et al.* (1994).

[7] Burial subsequent to exhumation depends on the suggested timing of exhumation. Post-Danian exhumation means that both Palaeocene and Quaternary sediments (*c.* 500 m) are deposited subsequent to exhumation; post mid-Miocene exhumation means only the Quaternary deposits (max. 200 m; Andrews *et al.* 1990).

[8] According to Thomson & Hillis (1995) maximum burial is related to a mid–late Danian unconformity covering *c.* 5 Ma. Burial may have taken half of this interval.

EMS, East Midlands Shelf; IMF, Inner Moray Firth.

formation of the Danian hiatus, the Chalk must have been buried to a depth of *c.* 1 km by Danian sediments in order for it to have attained its present degree of compaction. The postulated episode of exhumation of the Moray Firth occurred subsequent to this burial. During this period, the Danian sediments must have been removed to accommodate the Late Palaeocene sediments now encountered. The consequence of this hypotethis is that present Late Palaeocene sediments in the Moray Firth were deposited after a yo-yo-like deposition and removal of *c.* 1 km of sediments. Furthermore, this interpretation implies that the Danian uplift phase in took place in less than 5 Ma. This is in contrast to interpretation of AFT data elsewhere in Britain indicating protracted Cenozoic uplift (e.g. Green *et al.* 1993).

The high burial rates implied by assuming that overburden to the Chalk in the Inner Moray Firth was removed in the Danian are not required if exhumation took place during the Neogene (Fig. 6b). The pre-Quaternary hiatus is pronounced in the area where Palaeocene sediments subcrop the Quaternary in quadrant 13 (Andrews *et al.* 1990). If this hiatus marks the deposition and removal of the exhumed cover rocks, the process took place during a long time interval and a moderate burial rate of 18 m Ma^{-1} results.

Model of the burial and exhumation of the East Midlands Shelf and the southern North Sea

I suggest that the burial and exhumation of the East Midlands Shelf and the southern North Sea took place in two episodes of

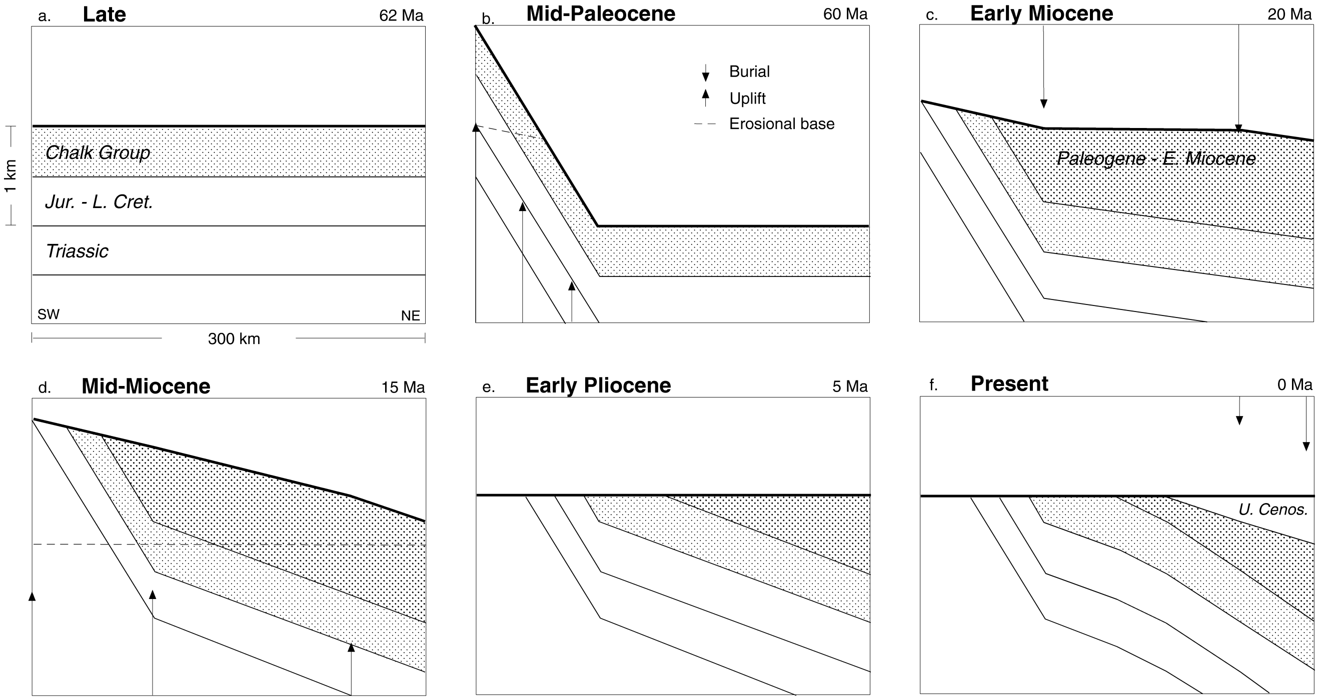

Fig. 7. Interpretation of the Cenozoic evolution of the East Midlands Shelf involving Palaeogene and Neogene exhumation. The profile corresponds to the geological cross section shown in Fig. 3; location is indicated on Fig. 2. The Sole Pit inversion axis is left out for simplicity. (**a**) Late Danian (62 Ma): Chalk and carbonate ooze covered the sea floor of the North Sea Basin. (**b**) Mid-Palaeocene (60 Ma): onset of exhumation. Erosion was small where the Chalk Group is preserved today. (**c**) Early Miocene (20 Ma): peneplanization of the uplifted flanks, and deposition of Palaeocene–Miocene erosional products on the East Midlands Shelf and in the western North Sea Basin. (**d**) Mid-Miocene (15 Ma): onset of regional exhumation. (**e**) Early Pliocene (5 Ma): truncation of the Chalk and the Tertiary sediments. (**f**) Present (0 Ma): rapid burial in the central North Sea.

exhumation (Fig. 7). Palaeogene exhumation affected primarily areas onshore, west of the present extent of the Chalk Group, and Neogene exhumation affected both onshore areas and the western margin of the North Sea Basin (Figs 3a and 8). The basic idea, the superposition of two episodes of Tertiary exhumation of equal amplitude, was suggested by Green (1989). This interpretation implies that a sedimentary cover of about 1 km was removed during the Neogene (Fig. 4), and avoids the high burial rates in the Danian implied by assuming that maximum burial took place at *c.* 60 Ma ago (Green 1989; Green *et al.* 1993).

The model suggests that there was deep Palaeogene erosion to the west of the area (Fig. 7b). The erosional products were redeposited on the East Midlands Shelf and the southern North Sea where the Chalk was deeply buried during the Palaeocene to early Miocene (Fig. 7c). After peneplanization, the entire area was exhumed during the Neogene, probably starting in the mid-Miocene (Fig. 7d, e). A mid-Miocene unconformity (*c.* 15 Ma; cf. Haq *et al.* 1987) is present throughout the central North Sea (Deegan & Scull 1977; Michelsen 1982; van Wihje 1987; Isaksen & Tonstad 1989). This unconformity may indicate the onset of regional exhumation, as it has previously been suggested (Bulat & Stoker 1987; Jensen & Schmidt 1993; Hillis 1995*a*; Jordt *et al.* 1995; Stewart & Bailey 1996). However, towards the coast where the Neogene is missing, the exhumation may have started before the mid-Miocene. The basal Pliocene unconformity in the western North Sea (Cameron *et al.* 1992), evidenced by the absence of Miocene deposits in well 44/7-1, is consistent with Neogene exhumation (Fig. 5). The Neogene exhumation of the southern North Sea thus appear to be related to two unconformities, the mid-Miocene and the basal Pliocene.

Discussion

The amount of Tertiary exhumation all along the present-day western truncation of the Chalk appears to be about 1 km; on the East Midlands Shelf (Fig. 3a), in the southern North Sea (Bulat & Stoker 1987; Hillis 1995*b*) and in the Inner Moray Firth (Hillis *et al.* 1994; Thomson & Hillis 1995). The exact thickness of the removed Chalk overburden may be disputed, but the previously identified areas, where the Chalk is unroofed, appear to be linked (Fig. 8). The increase in exhumation in the western North Sea towards the coast is consistent with the increasing age of the Quaternary subcrop and with the steep easterly dip of base Mesozoic (Figs 1 to 3). This pattern was noted by Brodie & White (1994) and is in accordance with the model suggested in this paper (Fig. 7).

Some studies (Green 1989; Bray *et al.* 1992; Hillis *et al.* 1994; Thomson & Hillis 1995) predict high burial rates immediately prior to the onset of regional exhumation of Britain at *c.* 60 Ma, which seems paradoxical. Only in the period after the onset of regional erosion, are high burial rates to be expected. A number of observations argue against maximum burial of the Chalk having occurred in the mid-Palaeocene (*c.* 60 Ma) in the western North Sea and on the East Midlands Shelf.

(1) The stable geological environment during latest Cretaceous–earliest Palaeocene times inferred from the known geological record near the East Midlands Shelf (Cameron *et al.*

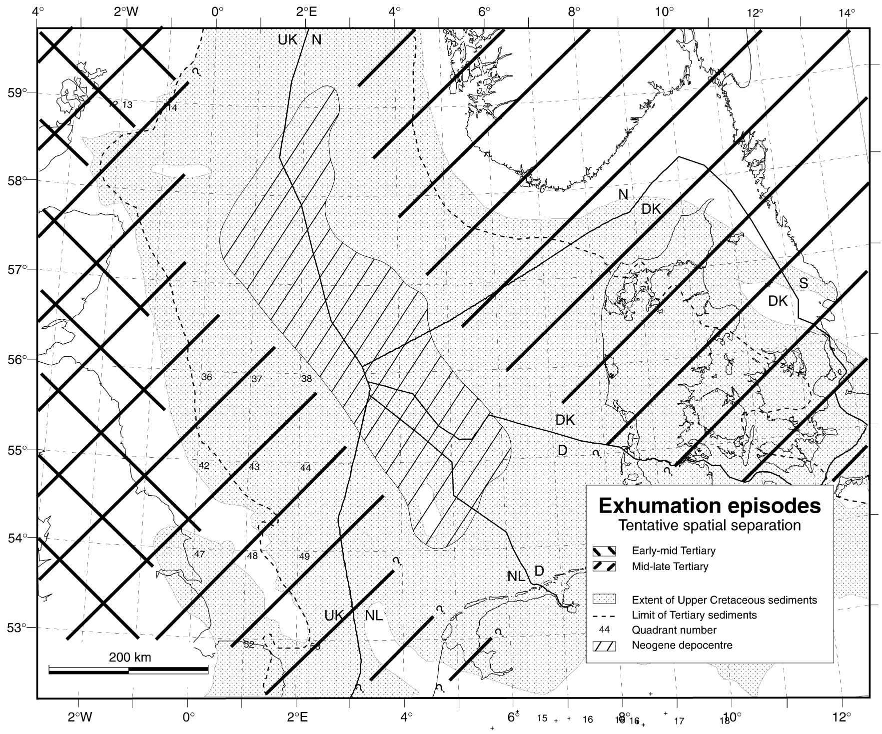

Fig. 8. Tentative spatial separation of Tertiary exhumation episodes in the North Sea region. Early Tertiary exhumation affected primarily the present onshore Britain (west of the present extent of the Chalk Group). Late Tertiary exhumation affected both onshore areas of Britain as wells the western and eastern margins of the North Sea. Extrapolation of results from studies shown in Fig. 1, and the studies of Rohrman *et al.* (1995) and Doré & Jensen (1996).

1992). Maximum burial at *c.* 60 Ma for the Chalk would imply very high burial rates in that period to account for the missing section of about 1 km (Fig. 4).

(2) The discovery of Upper Palaeocene argillaceous deposits believed to be remnants of a more extensive Palaeogene cover on the East Midlands Shelf (Stewart & Bailey 1996). Maximum burial at *c.* 60 Ma would imply exhumation rather than deposition during the Palaeogene (Fig. 3b).

(3) The thick Palaeocene succession in the Moray Firth (Andrews *et al.* 1990) indicates that the Moray Firth was an area of deposition and not of exhumation during that period (Fig. 6). A transient episode of early Palaeogene net uplift that reached the central North Sea from the west (Milton *et al.* 1990) indicates relative sea-level fall, and not maximum burial of the Chalk.

(4) Presence of the Chalk Group today suggests relatively stable conditions immediately after the deposition of the Chalk rather than tectonic activity and extensive Palaeocene exhumation. The removal of the overburden from the Chalk in the western North Sea is more easily explained by exhumation in the late Tertiary (Figs 5 and 6).

Exhumation of the Chalk along its present-day western limit of preservation is more likely to have happened in the Neogene than in the early Palaeogene. Neogene erosion affecting Britain and the western North Sea have been suggested in the past. The regional landscape of Scotland, and that of Britain in general, was interpreted by George (1966) to be Neogene in origin. Hall (1991) suggested that Tertiary erosion of the Scottish Highlands was less than 1 km in many areas and that Palaeogene exhumation exceeded Neogene exhumation. A map of Late Cenozoic uplift of northern England based on the present altitude (550 m) of the base of the Neogene weathering zone was presented by Fraser *et al.* (1990). In the southern North Sea regional exhumation was found to be of Late Tertiary age (Bulat & Stoker 1987; Stewart & Bailey 1996). Furthermore, pronounced mid- and late Tertiary exhumation of wide areas of England was inferred from fission track studies (Green 1989; Lewis *et al.* 1992; Green *et al.* 1993). The thick, shallow marine shelf sandstones of the Mid- to Late Miocene Utsira Formation may also be evidence for Neogene exhumation of northern Britain and the surrounding shelf. This formation is present in the Viking Graben area between 58°N and 62°N and is interpreted to be sourced from the west (Isaksen & Tonstad 1989).

Few attempts have been made to integrate the results from onshore and offshore studies. These comparisons all note the general agreement on the amplitude of exhumation between different studies. Green *et al.* (1993) discussed Early and Late Tertiary exhumation episodes but did not discuss their spatial distribution. Hillis (1995*a*) considered the age of regional exhumation in the southern North Sea to be unclear, but pointed to Palaeocene or Oligocene/Miocene as the two most likely ages. Stewart & Bailey (1996) argued that the high burial rates during the latest Cretaceous–earliest Tertiary estimated from fission tracks studies (Bray *et al.* 1992) were based on wrong geological assumptions, rather than admitting that the high rates based on AFT studies do not conform to the geology. Several factors may have added to the difficulty in identifying the role of Neogene exhumation. Maximum burial of Mesozoic and older rocks onshore UK has been demonstrated clearly by AFT studies to have happened during the Palaeocene, whereas the timing of exhumation offshore, based on compaction studies, was less clearly defined. Furthermore, a questionable indication of early Tertiary maximum burial of the Chalk was given for two wells.

Other areas around the North Atlantic have also suffered exhumation in the Neogene as it has been documented during recent years. Major Neogene or Late Cenozoic exhumation took place along the western margin of the Fennoscandian High from the Barents Sea in the north to Denmark in the south (Jensen *et al.* 1992; Dore & Jensen 1996). On the continental shelf of southern Scandinavia, east of the Viking and Central Grabens, maximum burial of the Mesozoic succession occurred in the Neogene (Fig. 1) (Jensen & Schmidt 1992; Japsen 1993; Michelsen & Nielsen 1993). Neogene exhumation of the mountains of southern Norway, initiated about 30 Ma, was inferred from thermal history modelling of fission tracks in pre-Mesozoic samples (Rohrman *et al.* 1995). The Faeroe–Rockall area suffered Miocene compression, suggested to be associated with sea floor spreading in the North Atlantic (Boldreel & Andersen 1993). Jameson Land, East Greenland, experienced Cenozoic uplift and erosion (Christiansen *et al.* 1992) at a rate that accelerated during Late Cenozoic times (Mathiesen *et al.* 1995). Around the North Atlantic, rapid late Neogene subsidence and sedimentation as well as relative uplift along basin edges was observed by Cloetingh *et al.* (1990). Until now it has been unclear how Britain and its continental shelf fitted into this pattern of North Atlantic late Cenozoic uplift and exhumation.

Conclusion

Timing of exhumation cannot be inferred directly from compaction data, and thus both Palaeogene and Neogene timing have been suggested for the maximum burial of the Mesozoic succession in the western North Sea and on the East Midlands Shelf. Neither do fission track data clearly indicate the timing of exhumation where the Late Cretaceous–Danian Chalk Group is present. If the Chalk was exhumed during the Neogene, a long period is available for deposition of the now-missing, kilometre-thick sedimentary cover. This assumption does away with the need to infer high burial rates for deposition of this cover, implied by the suggestion that maximum burial of the Chalk took place at *c.* 60 Ma (Fig. 4). Presence of the Chalk today suggests relatively stable conditions immediately after the deposition of the Chalk, whereas tectonic activity and extensive Palaeocene exhumation generally would lead to removal of the Chalk.

The model presented in this paper suggests that maximum burial occurred during the Palaeocene in the present onshore areas, whereas it occurred during the Neogene in the western North Sea where the Chalk Group is preserved today. The Neogene exhumation, superimposed on the Palaeogene, affected a wider zone in the North Sea (Fig. 8). The recognition of Neogene exhumation of Britain and its eastern continental shelf places the area in a context of large-scale late Cenozoic tectonic movements.

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