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Reply to comment by Hillis *et al.* (2013)

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We agree that there is now convincing evidence which favours the idea that a region encompassing the British Isles is dynamically supported by convective circulation beneath the lithospheric plate. For example, the coincidence of a long wavelength (>800 km) free-air gravity anomaly with anomalously slow velocities beneath the lithospheric plate suggests that regional elevation of Northern Britain is maintained by a tongue of hot asthenosphere protruding away from Iceland (Jones *et al.* 2002a; Arrowsmith *et al.* 2005). These observations are corroborated by the crustal thickness measurements of Davis *et al.* (2012). The Icelandic plume initiated 62 Ma and there is excellent evidence in the Irminger and Icelandic basins that this plume has waxed and waned with different periodicities (Jones *et al.* 2002b; Poore *et al.* 2009). This transient activity has manifest itself in geochemical and earthquake records along the Reykjanes Ridge (Poore *et al.* 2011; Parnell-Turner *et al.* 2013), in the Neogene record of deep-water overflow across the Greenland-Scotland Ridge (Poore *et al.* 2006), and along the fringing continental margins where spectacular buried ephemeral landscapes have been encountered (Shaw-Champion *et al.* 2008; Rudge *et al.* 2008; Hartley *et al.* 2011). Around the British Isles, there is considerable onshore and offshore evidence favouring a history of transient and/or permanent vertical motions which may reflect Palaeogene and Neogene plume activity (White & Lovell 1997; Jones *et al.* 2001; Jones *et al.* 2002a; Al-Kindi *et al.* 2003; Jones & White 2003; Mackay *et al.* 2005). This regional pattern of epeirogeny is locally complicated by faulting and folding, which is often difficult to date with precision.

Hillis *et al.* (2013) have raised two issues which challenge the significance of convectively driven epeirogeny. First, they state that our 'map of Cenozoic denudation is … highly inaccurate'. Secondly, they argue that horizontal shortening alone can account for the pattern of regional denudation. It is important to understand how the denudation map shown in Davis *et al.* (2012) was constructed. First, >3000 sonic velocity, seismic velocity, subsidence and fission track estimates of denudation were assembled. We omitted denudation estimates obtained by inverting vitrinite reflectance data because they have excessive scatter (Rowley & White 1998). Even so, the database is noisy on short wavelengths. Some of this scatter may be geologically meaningful since regional uplift and denudation are undoubtedly moderated by shorter wavelength faulting and folding. Nonetheless, all four methods for estimating denudation rarely agree and individually suffer from significant uncertainties which are unlikely to be smaller than ±500 m. These difficulties encouraged us to calculate mean values of denudation in $0.5^\circ \times 1^\circ$ (i.e. 50 × 50 km) bins. These mean values were then contoured using a minimum curvature interpolating surface with a tension factor of 0.15. Hillis *et al.* (2013) point out that Fig. 10 indicates 0–0.5 km in the Weald basin and on the East Midlands Shelf where they have published spot measurements based on sonic velocity analyses which are >2 km (Hillis *et al.* 2008). Their assertion is incorrect. In the Weald basin, we show a northward embayment which has 0.5–1 km of denudation. On the East Midlands Shelf, several bands have 0.5–1 km of denudation and higher values of 1–1.5 km occur at Flamborough Head.

It is instructive to scrutinize denudation estimates from the Weald basin and from the East Midlands Shelf in more detail. In the Weald basin, Hillis *et al.* (2008) used sonic velocity analyses to argue for denudation values of >2.2 km along the axis of the Weald anticline. They have not quoted uncertainties. In an earlier study, Butler & Pullam (1990) used a combination of stratigraphic reconstructions and interval velocity measurements to propose that up to 1.5 km of Late Cretaceous and Cenozoic strata have locally been removed from the crest of the Weald anticlinorium. Their Fig. 5(b) shows interval velocities which are anomalously fast but subject to considerable scatter. Jones (1999) published a revised stratigraphic reconstruction which implies that up to 1.1–1.4 m are missing from the Central Weald. These different estimates have uncertainties of ±500 m. Inverse modelling of subsidence data from the Weald basin suggests that denudation is 0.1–1 km. It is even less clear when denudation occurred and to what extent regional (i.e. longer wavelength) epeirogeny played a role (Blundell 2002). The consensus is that a series of discrete episodes occurred in Palaeogene, Neogene and Plio-Pleistocene times when extensive peneplains developed. It is important to stress that Fig. 10 only shows average denudation values, which were binned into 50 × 50 km blocks of 0.5–1 km, which accord with the range of published estimates.

On the East Midlands Shelf, denudation estimates have been made by analysing fission track and sonic velocity data (e.g. Green 1989; Hillis 1993). Originally, Lewis *et al.* (1992) argued, based on Green's (1986, 1989) fission track analyses, that up to 3 km of denudation occurred across northern England in Early Cenozoic times. Holliday (1993) suggested that these estimates were excessive because they could not be reconciled with stratigraphic constraints. He argued that 1.2–1.75 km had been eroded from northern England. Green *et al.* (2001) reanalysed the fission track database and concluded that there were two episodes of cooling, at 65–55 Myr and at 25–0 Myr. They indicated that it was not possible to determine the relative proportions of Palaeogene and Neogene denudation. Fission track measurements from four wells on the East Midlands Shelf reveal a west–east gradient in denudation. In our database, we have included denudation estimates from Bray *et al.* (1992), Green *et al.* (2001) and Green (2002) which were corrected, where necessary, using the new assumptions of Green *et al.* (2001). From west to east, these estimates are: (i) Rufford-1 = 1.45 km with a range of 0.91–1.65 km; (ii) Grove-3 = 1.09 km; (iii) Biscathorpe =

460 m and (iv) Cleethorpes-1 = 320 m. Hillis (1993) used sonic velocity analyses to show that the Cleethorpes-1 well was denuded by ∼1.4 km which agreed with Green's (1989) original fission track estimate of 1.3–1.7. Across the East Midlands Shelf, fission track and sonic velocity estimates of denudation are generally higher than those obtained by inverting subsidence data which suggest only 0–1 km (Rowley & White 1998). Thus averaged fission track estimates show that the East Midlands Shelf was denuded by 0.83 ± 0.5 km. At Flamborough Head itself, Hillis *et al.* (2008) proposed that denudation is ∼2 km. Stewart & Bailey (1996) compiled different estimates, which show that ∼1 km of denudation occurred to the south of Flamborough Head. Fig. 10 shows that denudation at Flamborough Head is 1–1.5 km. We agree with Hillis (1993) who stated that 'widely recognized inversion axes are only relatively local culminations of more regional Cenozoic erosion. The base level of apparent erosion in these areas, on which erosion of inversion axes are superimposed, is approximately 1 km'.

Our map of regional denudation, which is based upon a large database of sonic velocity, interval velocity, subsidence and fission track measurements, is consistent with published estimates. Note that long wavelength denudation is greatest in Northern Britain. Nonetheless, Hillis *et al.* (2013) hold great store by minor discrepancies at the crest of the Weald Anticline and at Flamborough Head. We believe that the reason for these discrepancies stems from their reliance upon sonic velocity analyses which form the centrepiece of Hillis *et al.* (2008). This methodology has two important drawbacks. First, an undisturbed compaction trend as a function of depth must be identified against which deviations in sonic velocity measurements are gauged. Secondly, sonic velocity measurements are inherently noisy. Both of these drawbacks give rise to substantial uncertainties in estimates of overburden removal (±1 km). Since Hillis *et al.* (2008) did not quote uncertainties, it is impossible to gauge the reliability of their estimates or to compare them in a meaningful way with independent estimates of denudation. Mackay & White (2006) have described and applied an integrative methodology for estimating denudation from sonic velocity measurements which is more robust than the standard approach used by Hillis *et al.* (2008). Their methodology yields stable results which do not rely upon estimating an undisturbed compaction trend.

The second issue raised by Hillis *et al.* (2013) concerns the relationship between horizontal shortening and regional denudation. They strongly object to our assertion that 'while there is copious field evidence for phases of horizontal shortening during Cenozoic times, the magnitude of shortening is one order of magnitude smaller than required'. This issue was first addressed quantitatively by Brodie & White (1995) who readily acknowledged that horizontal shortening occurred throughout a region encompassing the British Isles. It is straightforward to calculate the amount of regional shortening that is required to produce a given amount of denudation since the NW European Shelf has a very small elastic thickness (Tiley *et al.* 2003). If a reference column of continental lithosphere is shortened uniformly by a factor, *f*, then the amount of regional uplift is given by

$$U = \frac{a\left[(\rho_{\mathrm{m}} - \rho_{\mathrm{c}})\frac{t_c}{a}\left(1 - \frac{\alpha T_1}{2}\frac{t_c}{a}\right) - \frac{\alpha T_1}{2}\rho_{\mathrm{m}}\right]}{\rho_{\mathrm{m}}(1 - \alpha T_1)}(f - 1), \tag{1}$$

Table 1. Symbols and values of parameters used in text are taken from Brodie & White (1995).

Symbol	Parameter	Value
U	Regional uplift	km
D	Regional denudation	km
a	Lithospheric thickness	125 km
t_c	Crustal thickness	30 km
ρ_{w}	Density of water	1 Mg m^{-3}
ρ_{s}	Density of sediment	2.4 Mg m^{-3}
ρ_{c}	Density of crust (at 0°C)	2.8 Mg m^{-3}
ρ_{m}	Density of lithospheric mantle (at 0°C)	3.33 Mg m^{-3}
ρ_{a}	Density of asthenosphere	3.2 Mg m^{-3}
α	Thermal expansion coefficient	3.28×10^{-5} °C^{-1}
T_1	Asthenospheric temperature	1333°C

where values of the different symbols are given in Table 1. For a region encompassing the British Isles, it is reasonable to assume that the thicknesses of crust and lithosphere, which yields zero elevation with respect to the mid-oceanic ridge, are $t_c = 30$ km and $a = 125$ km, respectively. Substitution of the values given in Table 1 yields

$$U = 2.5(f - 1). \tag{2}$$

Since erosion isostatically amplifies regional uplift, the maximum amount of regional denudation is given by

$$D = \left(\frac{\rho_{\mathrm{a}}}{\rho_{\mathrm{a}} - \rho_{\mathrm{s}}}\right)U. \tag{3}$$

If the average density of the sedimentary pile, $\rho_{\mathrm{s}} = 2.4$ Mg m^{-3} then a horizontal shortening, *f*, of 1.15–1.3 is required to achieve a regional denudation of 1.5–3 km. Given that the British Isles is ∼1000 km long, we expect to see evidence for 130–230 km of horizontal shortening over this distance. There are at most ∼7 documented belts of Cenozoic shortening in a region encompassing the British Isles (i.e. Wessex/Weald, South Celtic Sea, St. George's Channel, Sole Pit, East Irish Sea, Moray Firth, Wyville-Thompson/Lui/Westray). Each of these belts is required to have shortened by 19–33 km. Across three of the southernmost structures, Blundell (2002) reported a north–south shortening of ∼4 km over a distance of 200 km. If we assume that small-scale deformation could double this amount of shortening to ∼8 km, then $f =$ 1.02–1.04 which is more than ten times too small. Hillis *et al.* (2013) statement that '15 per cent of shortening is sufficient to generate ∼1.5 km of denudation' is not correct since their percentage calculation entirely depends upon a specified horizontal distance.

Excellent examples of folding and thrust faulting occur from the England Channel to the Faroe-Shetland basin. Nevertheless, conservative estimates of shortening are at least one order of magnitude (i.e. ten times) less than required. Attempts have been made to argue that substantial amounts of shortening are hidden within apparently undeformed sedimentary rocks. For example, Holford *et al.* (2009) suggested that 'cryptic inversion' can occur whereby large thicknesses of apparently undeformed shale take up shortening by a bulk pure shear mechanism. This suggestion is at odds with three important observations. First, widespread development of pressure solution cleavage and bulk pure shear within these shales is not observed either in outcrop or well data. A useful comparison is southeast France where an ancient continental margin has also been denuded by ∼2 km. In this case, denudation is achieved by large-scale tight folding, by growth of arrowhead/harpoon structures, and by pervasive cleavage development. Secondly, in regions of active shortening >90 per cent of deformation is taken up on discrete thrust faults which slip in earthquakes with substantial moment release. Thirdly, and most importantly, if regional uplift and denudation is mainly generated by horizontal shortening, the crust should be thickened by a factor of 1.15–1.3 and crustal thicknesses of 34.5–39 km are expected. There is evidence that ∼35 km thick crust exists beneath the Midland Valley of Scotland and beneath North Wales. However, there is no evidence for thickened crust beneath either the Weald basin or beneath the East Midland Shelf (Davis *et al.* 2013). These structures are rootless and confined to the upper crust (Blundell 2002).

In summary, we maintain that there is a significant shortening deficit which suggests that regional epeirogenic uplift has played a significant, but not necessarily exclusive, role in sculpting the outcrop pattern of the British Isles. Beneath Northern Britain, denudation is greater and circumstantial evidence exists which links episodic phases of uplift to waxing and waning of the Icelandic plume (Jones *et al.* 2001; Jones & White 2003). In Southern Britain, we agree with Blundell's (2002) suggestion that regional epeirogeny has been moderated by short wavelength folding and faulting.

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