Paleogene time scale miscalibration: Evidence from the dating of the North Atlantic igneous province: Comments and Replies

COMMENT

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Jolley et al. (2002) presented two very interesting points: (1) the late Paleocene thermal maximum (LPTM) has an age between 57.5 and 60.54 Ma (vs. 54.98 Ma in the current time scale of Cande and Kent [1995] and Berggren et al. [1995]), and thus the current time scale is too young by up to 5 m.y. for the late Paleocene, and (2) the LPTM correlates with and was most likely caused by the early phase of widespread North Atlantic volcanism. Both points are of broad interest in geosciences because the geological time scale is probably the most important standard in geosciences, and a better understanding of the LPTM is urgently needed as the global CO_2 level appears to have increased at a comparable rate during the LPTM to the present day, and thus the LPTM may offer excellent clues on the current global greenhouse warming. It is therefore important to examine the two points and understand some remaining problems.

Jolley et al. (2002) inferred the age for the LPTM based on: (1) ‘‘A high-precision U-Pb age on zircon separates from the Loch Ba ring dike in the Mull central complex (58.7 ± 0.1 Ma; M. Hamilton, 2001, personal commum.)’’ (p. 8); (2) ‘‘Lower Series lavas from ODP 642E on the Vøring Plateau yielded an Ar-Ar plateau age of 57.9 ± 1.0 Ma (Sinton et al., 1998)’’ (p. 8); (3) ‘‘A nephelinite lava in a series that overlies sediments containing a Staffa-type palynoflora and an influx of *Apectodimium augustum* in northeastern Greenland yielded a plateau date of 58.7 ± 1.4 Ma’’ (p. 8); (4) ‘‘Equivalent lavas’’ in Kangerlugssuaq are cut by sills yielding isochron dates of ca. 55–56 Ma (p. 8 and 9); and (5) ‘‘A single-crystal Ar-Ar date derived from the Skye Loch Ainort granite (58.58 ± 0.13 Ma; L. Chambers, 2001, personal commun.)’’ (p. 9). However, it is not clear what precise relationship is between those igneous rocks and the LPTM because Jolley et al. (2002) did not present the data. It appears that the igneous rocks and the sediments with the LPTM identified were not from the same section but their relationship was inferred based on uncertain bio- and/or lithostratigraphic correlations over long distances. Furthermore, some of those dates were based on unpublished data conveyed by personal communication and some were considered unreliable by the persons who analyzed the samples. For example, Sinton et al. (1998) generated four plateau ages for the same sample from ODP 642E and interpreted a crystallization age of 55–56 Ma, whereas Jolley et al. (2002) picked the oldest plateau age. The age in item (3) above is apparently unreliable as Jolley et al. (2002) mentioned that ‘‘the small spread in the data caused high errors on the isochron diagram and an intercept date of 60 ± 12 Ma’’ (p. 8).

Jolley et al. (2002) accepted the 54.5 Ma date for −17 ash (Berggren et al., 1995) as accurate and cited recent published data as support. It has been well established at Deep Sea Drilling Project (DSDP) Site 550 that −17 ash is within magnetic C24r, with an apparent position two-thirds of the way down in C24r, although its real position could not be determined due to a significant hiatus below −17 ash in C24r (Berggren et al., 1995). It is also well established that the LPTM is older than −17 ash but some distance above the base of C24r (Berggren et al., 1995). Cyclostratigraphy at Ocean Drilling Program (ODP) Sites 690 and 1051 (Rohl et al., 2000; Norris and Rohl, 1999) suggests that the LPTM is ~1.0 m.y. younger than the base of C24r. Assuming that the real position of −17 ash (ca. 54.5 Ma) is about half or even one-third of the way down in C24r, an age of 57.5–60.5 Ma for the LPTM as proposed by Jolley et al. (2002) would require the duration of C24r (2.6 m.y. in the current time scale) to be at least 8–14 or 6–10.5 m.y., respectively. All these are excessive requirements for significant increase in the duration of C24r and corresponding decrease for the interval between C25n and C29r. This lacks supporting evidence and appears to be theoretically impossible, especially when C29r is taken as no older than 66 Ma.

A better age estimate for the LPTM can be made by first constructing a geomagnetic polarity time scale for the early Paleogene with an age calibration of 52.8 Ma at C24n.1r(0.0) (see discussion in Wei, 1995) and another at 65.5 Ma (Cretaceous-Tertiary [K-T] dates listed in Berggren et al. [1995] normalized to the same international standard: MMhb-I at 520.4 Ma) at the K-T boundary, i.e., C29r(0.3). A linear interpolation between these two age calibration points results in the ages for the following normal polarity intervals: C24n.2n, 52.911–52.962 Ma; C24n.3n, 53.083–53.597 Ma; C25n, 56.355–56.847 Ma; C26n, 57.996–58.343 Ma; C27n, 61.235–61.580 Ma; C28n, 62.778–63.924 Ma; C29n, 64.279–65.098 Ma. Assuming that the LPTM is ~1.0 m.y. above the top of C25n (Norris and Rohl, 1999; Rohl et al., 2000), an age of ca. 55.4 Ma can be assigned to the LPTM.

The above shows that Jolley et al.’s age estimate of 57.5–60.5 Ma for the LPTM is not substantiated and it requires unreasonably long duration of C24r and thus unreasonably large variability in seafloor spreading rates; Jolley et al.’s proposed age is considered highly unlikely. Thus, their proposed correlation and causal relationship between the LPTM and the early phase of the widespread North Atlantic volcanism (the Continental Succession) should be revised. An estimated age of ca. 55.4 Ma for the LPTM links the event to the larger, second phase of the widespread North Atlantic volcanism (the Oceanic Succession), when the North American plate separated from the European plate and unrestricted basalt magmatism occurred both at the zone of plate separation and landward of the ocean-continent transition on the European side (Sinton et al., 1998).

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COMMENT

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Jolley et al. (2002) have proposed that the date of the Paleocene-Eocene thermal maximum is ca. 60 Ma, at least 5 m.y. older than currently estimated and, as a result, argue that the Paleogene time scale of Berggren et al. (1995) is grossly miscalibrated. The implications of this proposal are implausible, and we attribute the discrepancy in age noted by Jolley et al. (2002) to miscorrelation of the Staffa-type palynofloras and ambiguous isotopic dates from the North Atlantic igneous province.

In agreement with Berggren et al. (1995) and Cande and Kent (1995), Jolley et al. accept ages of 65 Ma for the Cretaceous-Paleogene boundary and 54.5 Ma for the -17 ash in late Chron C24r, and an $\sim$1 m.y. duration between the Chron C25n/C24r magnetic reversal and the Paleocene-Eocene thermal maximum in early Chron C24r (Norris and Röhl, 1999). Accordingly, at least 5 m.y. would have elapsed between the Paleocene-Eocene thermal maximum and deposition of the -17 ash. Considering that the span between the -17 ash and the Chron C24r/n magnetic reversal is estimated at $\sim$1.1 m.y. (Cande and Kent, 1995), the duration of Chron C24r must be at least 7.6 m.y. This differs spectacularly from the 2.556 m.y. estimated duration in Cande and Kent (1995) and Berggren et al. (1995), itself consistent within 20% with virtually all earlier time scale estimates (see Mead, 1996). Equally troubling is the fact that the Paleocene Epoch would be reduced to 3.5 m.y. (Jolley et al.'s Fig. 3), an aberration that would imply extreme and sudden global variations in rates of seafloor spreading.

Two conditions must be fulfilled for the conclusions of Jolley et al. (2002) to be valid: (1) the radioisotopic ages on the North Atlantic igneous province lavas must be reliable; and (2) the biostratigraphic and magnetostratigraphic correlations must be correct.

On the Island of Mull, the Ardtun Leaf Beds, which yield the Staffa-type palynoflora, lie near the base of the $\sim$1000-m-thick Plateau Lava Group (Bell and Jolley, 1997). Ar spectra and isochron data for the Mull lavas (as well as for much of the North Atlantic igneous province) show disturbed release patterns indicative of excess Ar that make these ages of questionable quality. A $^{40}Ar/^{39}Ar$ date of 58.48 $\pm$ 0.18 Ma on sanidine from the Loch Ba Ring dyke that crosscuts the Plateau Lava, in conjunction with the U/Pb dates of 58.91 $\pm$ 0.07 Ma and 60.53 $\pm$ 0.07 Ma on the Cuillin Complex and the Rum layered igneous complex, respectively, (Hamilton et al., 1998), appear to be reliable and consistent with the lava dates (Chambers and Pringle, 2001). Based on these data, we agree with Jolley et al. (2002) that the underlying Ardtun Leaf Beds must be older than 58.50 Ma, and possibly older than 60 Ma.

Jolley et al. (2002) assume that the Ardtun Leaf Beds, which have been assigned ages as disparate as Maestrichtian and Miocene (Jolley, 1997), are of Paleocene-Eocene thermal maximum age, and can be assigned to a $<$0.2 m.y. interval of Chron C24r. We see no compelling evidence for this correlation. The Ardtun Leaf Beds are only associated with a low-diversity ''thermophyllic assemblage'' consisting of long-ranging, moderately to poorly preserved spores and pollens (Jolley, 1997). As shown by Jolley et al. (2002, their Fig. 2, right column), this assemblage spans the late Paleocene and early Eocene and is not restricted to any particular narrow stratigraphic interval in the North Sea–Faroe–Shetland Basin. In fact, there is no stratigraphic evidence to place the Staffa-type palynofloras anywhere other than within Chron C26r, as indicated by radioisotopic data (Chambers and Pringle, 2001). Jolley et al. (2002) incorrectly place them within Chron 24r using tenuous correlations to biostratigraphically well dated marine units.

For the Lower Plateau lava series in northeast Greenland, Jolley et al.'s (2002) nephelinite lava date of 58.7 $\pm$ 1.4 Ma associated with *Apectodinium augustum*–bearing sediments containing the Staffa-type palynofloras is likewise inconclusive. Nepheline has a notorious reputation for containing excess argon resulting in ages older than expected based on ages of other mineral phases. Isochron data for this nephelinite lava (Upton et al., 1995) gave an isochron age of 60 $\pm$ 12 Ma with a $^{40}Ar/^{36}Ar$ intercept of 284 $\pm$ 200, making this analysis difficult to evaluate for the presence of excess argon. Since the incremental heating spectrum was not published, it is not known whether or not a plateau release pattern was obtained.

In Ocean Drilling Program Hole 642E on the Vøring Plateau, *Apectodinium augustum*–rich sediments with Staffa-type palynoflora are interbedded with the lower series lavas (Boulter and Manum, 1989). Jolley et al. (2002) selectively use a $^{40}Ar/^{39}Ar$ plateau age of 57.9 $\pm$ 1.0 Ma on the lower lava series attributed to work by Sinton et al. (1998). However, Sinton et al. (1998) actually prefer their isochron age of 55.6 $\pm$ 2.0 Ma for the plagioclase from this sample, noting that the incremental-heating release pattern was u-shaped and indicative of excess argon ($^{40}Ar/^{36}Ar$ intercept of 335). The mean of the two lowest ages of the release pattern is 56 $\pm$ 0.7 Ma, whereas age interpretations of the accompanying glass range from 53.9 to 56.2 Ma. Overall, Sinton et al. (1998) conclude that ''the analyses do not give a precise age of eruption of the tuff but indicate an age of $\sim$55 Ma.''

We view Jolley et al.'s (2002) claim that a miscalibration by up to 5 m.y. of currently adopted Paleogene time scales to be without foundation, a result of selective use and misinterpretation of geochronologic data and undue reliance on imprecise and unsubstantiated palynologic evidence.

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REPLY

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The North Atlantic igneous province is providing a rapidly expanding geological data set as a result of hydrocarbon exploration in the province. This focus of research means that several peer-reviewed publications have appeared recently. New isotopic dates within these publications are wholly supportive of our integration of the bio- and sequence stratigraphy. To recap, we identified that there were two intervals around the Paleocene-Eocene boundary, one characterized by late Paleocene to early Eocene Sequence T40, which yielded isotopic ages between 60.5 Ma and 57.5 Ma, and a younger interval characterized by sequences T45 and T50, which yielded isotopic ages of 57.0 Ma to 53.5 Ma. New and internally consistent Ar-Ar data from Mull and east Greenland confirms our assignment (Chambers and Pringle, 2001; Table 1).

Aubry et al. and Wei note the variable quality of Ar-Ar data from east Greenland samples, but we described these dates as having ''variable precision'' and provided sufficient detail to enable readers to determine the quality of the ages. They were intended to demonstrate only that the available dates were consistent with our hypothesis. The recent publication of isotopic data has confirmed our model (see Table 1) with dates that show a remarkable consistency across the North Atlantic igneous province.

Our correlation of lava fields in east Greenland, the Faroe Islands and well sections of the Faroe–Shetland Basin based on the Staffa flora has independent corroboration from isotopic dates and lava geochemical correlation (Larsen et al., 1999; Table 1). It is clear from our paper, and we amplify here, that the Staffa-type flora is restricted in its stratigraphical extent, occurring in lower Chron 24r sediments. Indeed, it exhibits the same stratigraphical range as the well-documented worldwide range occurrence and flood abundance of the dinocyst *Apectodinium* (Crouch et al., 2001).

TABLE 1. ISOTOPIC DATES DERIVED FROM SEQUENCE T40 LAVAS AND ASSOCIATED INTRUSIVES SINCE THE PUBLICATION OF JOLLEY ET AL. (2002)

Location	Age (Ma)	Method	Reference
Faroe Islands			
Lower Formation Lava	56.5 ± 1.3	K/Ar	Riisager et al., 2002
	57.1 ± 1.7	Ar/Ar	Riisager et al., 2002
	57.1 ± 1.6	K/Ar	Riisager et al., 2002
	57.1 ± 2.5	K/Ar	Riisager et al., 2002
Lower Formation Lava, Lopra	60 ± 2.1 to 63.1 ± 1.8	Ar/Ar	Waagstein et al., 2002
Skye			
Loch Ainort Granite	58.58 ± 0.13	Ar/Ar	Chambers and Pringle, 2001
Main Lava Series	59.83 ± 0.12	Ar/Ar	Chambers and Pringle, 2001
Mull			
Dikes	58.12 ± 0.13	Ar/Ar	Chambers and Pringle, 2001
Loch Ba Ring Dike	58.48 ± 0.18	Ar/Ar	Chambers and Pringle, 2001
Central Group Lavas	59.05 ± 0.27	Ar/Ar	Chambers and Pringle, 2001
Plateau Group Lava	58.66 ± 0.25	Ar/Ar	Chambers and Fitton, 2000
Staffa Group Lava	60.56 ± 0.29	Ar/Ar	Chambers and Pringle, 2001
East Greenland			
Milne Land Formation	54.93 ± 1.56	Ar/Ar	Hansen et al., 2002
Milne Land Formation	56.36 ± 1.7	Ar/Ar	Hansen et al., 2002
Milne Land Formation	56.93 ± 2.4	Ar/Ar	Hansen et al., 2002
Urbjurget Formation	59.58 ± 1.68	Ar/Ar	Hansen et al., 2002
Urbjurget Formation	61.19 ± 1.46	Ar/Ar	Hansen et al., 2002

Within the lava fields, chronostratigraphy of flow unit thick normal polarity events has been undertaken by direct reference to the Berggren et al. (1995) time scale (Chambers and Pringle, 2001; Riisager et al., 2002). Because of the time scale disparity and the absence of any other stratigraphical control, this has resulted in differing assignment of chrons and cryptochrons in what are lava fields of the same age. The Staffa flora and the worldwide *Apectodinium* influx event within these lava fields argues for attribution to C24r, but this is the crux of the problem since C24r implies an age of 56 Ma or younger by the standard time scale (Crouch et al., 2001).

Wei suggests that the age of the boundary interval and the late Paleocene thermal maximum can be improved by using interpolation between his 52.8 Ma tie point and the base of the Cenozoic (Wei 1995, and herein). We consider that the longer period of interpolation between data points lowers the resolution of interpolated ages. Conversely, using more direct age estimates that are available and observed near the target allows more precise dates using fewer assumptions. We have no difficulty in accepting the 52.8 Ma = C24n.1r tie point suggested by Wei (1995, and herein). Our paper accepted the 54 Ma ages for the −17 and +19 ash series given by Berggren et al. (1995), and we have no need to comment on the validity of even younger ages. We too have attempted linear interpolations using the array of new isotopic dates presented in our paper, but these cannot satisfactorily explain the range of ages recorded, unless it is recognized that the disparity is nonlinear.

Our sequence framework to dating relationship has now been tested by publication of new isotopic dates and remains consistent. We have never claimed that a date of 60.5 Ma can be attributed to the late Paleocene thermal maximum, contrary to the statement by Aubry et al. Then, as now, we point out that the late Paleocene thermal maximum occurs at the base of an interval that yields dates ranging from 60.5 to 57.5 Ma.

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COMMENT

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The stratigraphy of upper Paleocene and lower Eocene sediments in the North Sea region is highly complex, biostratigraphical correlations are difficult, and the fact that the Epoch boundaries were defined in this region has caused many problems. Jolley et al. (2002) argue that recent estimates of the numerical age of events occurring close to the Paleocene-Eocene boundary are incorrect, because sediments ''between and equivalent to the oldest lavas contain an influx of a diagnostic pollen flora, an influx of the dinocyst *Apectodinium*, a benthic foraminiferal extinction, nannofossil zone NP9, and a carbon isotope excursion associated with the late Paleocene thermal maximum'' (p. 7). The problems are in the words ''equivalent to.'' Events in marine sections (influx of the dinocyst *Apectodinium*, benthic foraminiferal extinction, nannofossil zone NP 9, carbon isotope excursion) have not been recorded in sediments between the subaerial, dated lava flows. A pollen assemblage indicative of very warm climate occurs between the lava flows and must be correlated to marine sections in order to argue that pollen and other events were coeval. The authors' case thus rests, as they state, on numerical dating of lavas as well as biostratigraphical correlations. The results of these correlations, as summarized in their Figure 2, are demonstrably incorrect. The benthic foraminiferal extinction event and the strong decrease in carbon isotope values (CIE) plot within normal magnetochron C25n, in the Upnor Formation in the London Basin, and the lower boundary of the *Apectodinium* acme occurs later than both the benthic foraminiferal extinction event and CIE (in Denmark, this datum plots even above the peak low values of the CIE). It has, however, been documented in many terrestrial and marine sections that the benthic foraminiferal extinction event, CIE, and acme in *Apectodinium* spp. occur in reversed magnetochron C24r, as the authors say in the text. The CIE occurs in the Reading, not Upnor, Formation (Thiry et al., 1998), and the start of the *Apectodinium* acme is coeval with the start of the CIE (Crouch et al., 2001). These inconsistencies show that the correlations made by Jolley et al. cannot all be correct and may have arisen because the authors do not consider the possibility that there may have been more than one unusually warm event (or hyperthermal) in the late Paleocene–early Eocene (Thomas et al., 2000), two of which have been tentatively dated ca. 58 and 60.5 Ma (Thomas and Zachos, 2000). There is thus a strong possibility that the occurrence of a warm event (hyperthermal) cannot be used for unequivocal age correlation in the late Paleocene and early Eocene.

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COMMENT

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On the basis of palynomorph assemblages and radiometric ages, Jolley et al. (2002) proposed that the basaltic volcanism in the North Atlantic igneous province started in the Paleocene at 60 Ma, considering the Cretaceous-Tertiary (K-T) boundary at 65 Ma. They took into account that the Staffa Group of Mull, Inner Hebrides, represents the earliest lavas of the province. The literature referred to in this paper indicates that Jolley et al. (2002) have arrived at these conclusions based on selected references without critiquing previous palynomorph literature, which would have placed the onset of the igneous activity in this province well into the Late Cretaceous.

British basalts became known as ''Tertiary basalts'' in the 19th century on the erroneous age determination of the Ardtun Leaf Beds (Gardner, 1887) and at the time when the Eocene was the oldest Epoch in the Tertiary Period (Lyell, 1833, p. 61). Since then the ages of the British basalts have gained elasticity, snapping back into the Tertiary depending on the prevailing understanding about the age of the K-T boundary, which has fluctuated from 60 to 70 Ma. Radiometric ages from various localities of Mull span from 26 to 81 Ma (Miller and Brown, 1965), but ages falling in the Cretaceous were corrected to Tertiary age due to the lack of fossil evidence supporting an older age (Miller and Brown, 1963). Jolley et al. (2002) have also referred to a deviant date of 60 ± 12 Ma and blamed it on the ''small spread in data.''

The occurrence of several interbasaltic lignites in the Staffa Group indicates that the igneous activity causing lava flows in this area was

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intermittent with quiescent periods during which floras were established. Simpson (1937, 1961) described rich pollen assemblages from two separate interbasaltic lignites of Mull. In the addendum to Simpson's (1961) posthumous publication, J.B. Simpson concluded a Miocene or lower Pliocene age of the flora, which led to the belief that the basalts are of Tertiary age. Martin (1968) re-examined Simpson's slides and recognized Late Cretaceous *Aquilapollenites* pollen in the slides. I (Srivastava, 1975) documented a rich Late Cretaceous *Aquilapollenites* assemblage from the Mull lignite that was collected from Simpson's (1961) localities in Mull. I determined that the pollen assemblage from the Mull lignite correlates with the early Maastrichtian assemblage of the lower to middle Edmonton Group (Srivastava, 1970), spanning from 69.5 to 65.2 Ma. In this context, the radiometric age of 70 Ma for the Blackstones Bank igneous center in western Scotland (Durant et al., 1976) has relevance in considering the initiation of the British lava flows.

The extinction of *Aquilapollenites* flora synchronized with the last occurrence of dinosaur bone, iridium spike, and radiometric age of 64.3 ± 0.7 Ma at the K-T boundary in Canada (Srivastava, 1994a). Simpson's (1961) pollen assemblage from the Ardnamurchan lignite appears to be of Paleocene age because it did not yield *Aquilapollenites* flora and conforms with European Early Tertiary pollen assemblages. The oldest radiometric age of 61.4 Ma from the area (Mitchell and Reen, 1973) supports such an age for the Ardnamurchan lignite.

Dinoflagellate cyst data in Morton et al. (1988) indicating a Danian age in the Faeroe-Shetland area was dismissed in that paper as it did not fit the concept of the Paleocene igneous activity in the area. Danian dinocysts being the youngest component should have been considered a relevant part of the assemblage. Jolley et al. (2002) should have taken that data into account also when discussing Faeroe-Shetland sediments.

Consideration of the onset of basaltic volcanism in the North Atlantic is irrelevant without taking into account the evidence of igneous activity in Rockall Plateau and Greenland as well. Palynomorph documentations are rare but *Aquilapollenites* records from central north Greenland (Croxton, 1980; Batten, 1982) indicate the extent and timing of the east North Atlantic igneous activity at the boundary of the boreal Cretaceous *Aquilapollenites* and Normapolles phytogeoprovinces (Srivastava, 1994b). On the basis of palynological data from the interbasaltic lignites of Mull, the igneous activity in the North Atlantic started well within the Late Cretaceous and not in the Paleocene as claimed by Jolley et al. (2002).

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REPLY

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Credence is given to forty-year-old leaf macrofossil age determinations for the Mull intrabasaltic floras by Aubry et al. (herein), and to the Maastrichtian age assignations by Srivastava (herein). We have no difficulty in dismissing both these age assignations. Recent isotopic dates by Chambers and Pringle (2001) preclude these ages; none are older than the 65 Ma Cretaceous-Paleogene boundary or younger than the early Eocene. Furthermore, the dating of the palynoflora of the Staffa Group of Mull by Srivastava as Maastrichtian is based on misconceptions of the local sedimentary facies and occurrence range of a single genus of pollen grain, *Aquilapollenites*. This taxon is recorded by Srivastava (1975), and by Simpson (1961), in only two localities on Mull. These are positioned against the bounding fault of the main Staffa Group depositional graben and are preserved in alluvial fan sediments derived from a nearby fault. These sediments contain reworked chalk-coated flints derived from the Cretaceous chalk that once mantled the area and now are preserved under the lava field (Bailey et al., 1924). In over twenty Mull Staffa Group localities examined by us, the genus *Aquilapollenites* occurs only in association with reworked Cretaceous lithoclasts in the alluvial fan sediments, and is seen with other reworked Cretaceous restricted pollen taxa (*Pseudointegricorpus* species) and marine dinocysts (*Dinogymnium*, *Cliestosphaeridium* species). It is clear that this component of the assemblage is reworked from older Cretaceous rocks exposed on the upthrown side of the graben. Records of *Aquilapollenites* have also been made from a horizon at the T40-T45 sequence boundary in the Faroe–Shetland Basin (Naylor et al., 1999), where they occur at the base of an erosive sequence within a well-defined stratigraphical framework of Paleogene dinocysts, pollen, and foraminifera. Utilization of a single taxon to determine the age of an entire sequence is outmoded and inappropriate; accordingly, we dismiss the claims of Srivastava.

Some misunderstandings have influenced the response of Thomas. The latest Paleocene to earliest Eocene interval in the North Sea and Faroe–Shetland Basins suffered from restricted water mass circulation. The positioning of the benthic extinction event at some meters below the late Paleocene thermal maximum is acknowledged to be stratigraphically depressed in relation to Atlantic and Pacific records, but this is undoubtedly due to the increasingly anoxic benthic conditions and the relative expansion of this part of the section caused by turbidite-dominated sedimentary systems. We have also examined the section studied by Thiry et al. (1998) and recognize that the Upnor-Reading Formation boundary is diachronous; the basal Reading Formation passes laterally into the uppermost Upnor Formation to the east. Diachronism of sedimentary facies is to be expected in an estuarine environment (Ellison, 1983). The decrease in carbon isotope values therefore represents a time plane that occurs in both formations. In Denmark the first appearance of the Staffa flora and *Apectodinium* acme is at the base of the T40 section preserved. It would indeed be difficult to record the first appearance of this taxon in an interval represented by an unconformity.

Increasingly negative carbon isotope values are seen immediately prior to the late Paleocene thermal maximum, not only in our example presented from the North Sea, but also in Austria (Crouch et al., 2001), in Spain (Lu et al., 1996), and the Bighorn Basin, Wyoming (Koch et al., 1992). The minimum value recorded in the North Sea section by Beerling and Jolley (1998) occurs at the influx of *Apectodinium* species, clearly the global late Paleocene thermal maximum event identified by other authors. In her comment, Thomas aims to demonstrate the existence of multiple isotope excursion events. While we do not dismiss such a possibility, we have found no evidence for a further excursion in Paleogene pollen records from the North Atlantic igneous province basins. Our record of pollen and spore assemblage composition and diversity shows agreement with the climatic types established in northern Spain by Winkler and Gawenda (1999) and leaf macrofossils–derived mean annual temperatures from the Bighorn Basin (Wing et al., 1999). These data contain no convincing evidence for a further thermal excursion in addition to the late Paleocene thermal maximum.

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