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PALEOGENE GEOCHRONOLOGY: AN INTEGRATED APPROACH

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Abstract. Geochronology is the conceptual division of continuous time as measured (geochronometry) by the progression in an ordinal series of events. This is best achieved by an approach which integrates four independent data sets: magnetostratigraphy, seafloor spreading magnetic lineation patterns, biostratigraphy, and isotopic ages. This integrated approach results in an ordinal framework which can measure time with greater resolution, though perhaps less accuracy, than a radiometric approach alone. A comparative analysis of two recently proposed Paleogene geochronologic time scales is presented.

INTRODUCTION

A geochronologic framework is essential to understanding and estimating rates of geological processes. However, as Blow [1979, p. 1399] observed, "Geochronology is a conceptual division of absolutely continuous past time, related to the geostratigraphical sequence. Geochronology is not to be regarded as merely a scale of absolute dates dependent solely on radiometric dating". Various components are fundamental to a truly integrated time scale (for example, biochronology, radiometric dating, biostratigraphy, magnetostratigraphy). A number of schemes for the Cenozoic incorporating some or all of these components have been developed over the past two decades, spurred to a large degree by the need of the Deep Sea Drilling Project (DSDP) and successors for a

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reliable chronology for estimating rates of sedimentary processes as well as basement/sediment contact ages, among other things.

Berggren et al. [1985a] recently revised Paleogene geochronology utilizing an integrated methodology. Odin and Curry [1985] presented a detailed critique of their paper and, at the same time, raised several questions regarding its validity as a "standard" for Paleogene geochronology. We address their critique here.

The critical comments by Odin and Curry [1985] can be separated into three parts: comparison of the structure of the time scales submitted by Curry and Odin [1982] and by Berggren et al. [1985a], the value of the dates based on good quality glaucony dating, and comments on certain disputable correlations. They also question the temporal resolution and the overall accuracy of the numerical time scale for the Paleogene presented by Berggren et al. [1985a]. We address these comments by first reviewing the role of the geomagnetic polarity sequence in the construction of an integrated numerical geologic time scale; then, by answering the specific points raised concerning "disputable correlations"; and finally by reviewing major problems which we perceive with the methodological approach of Curry and Odin [1982] in the construction of their Paleogene time scale purportedly based solely on isotopic data.

COMPARISON BETWEEN THE CONSTRUCTION OF A GEOMAGNETIC POLARITY TIME SCALE AND THAT OF AN ISOTOPIC TIME SCALE

A Geomagnetic Time Scale

The construction of a geomagnetic polarity time scale is based on the integration of four independent data sets: (1) seafloor spreading magnetic lineation patterns; (2) magnetostratigraphy from sedimentary and igneous rocks; (3) biostratigraphic assemblage correlations; and (4) radiometric, or rather, isotopic, ages. There are precision and resolution limits associated with each of these data sets, but because these data sets are largely independent, these limits may be improved by properly merging the data sets. The first three data sets provide relative sequence information, independent of any isotopic ages, by using conventional stratigraphic techniques [e.g., Miller, 1977; Shaw, 1964]. Standard reference sections are studied and then combined to form a composite sequence that best represents the relative location of features in the data set. Although identification of reference sections is usually discussed with regard to magnetostratigraphic or biostratigraphic studies of vertical (often tilted by later deformation) geologic units, it also applies to horizontal patterns provided by seafloor spreading magnetic lineations.

The combination of standard reference sections into a standard composite sequence represents the primary procedure for converting the three sets of relative sequence information into a form in which they can be compared with each other and with isotopic age data. A standard composite sequence represents our most precise statement of the overall succession (relative spacing) of, in this case, geomagnetic polarities for a defined time interval. Identification of type sections is a crucial first step in establishing a stratigraphic succession that is consistent over a large region or that is of global extent. Standard reference sections are chosen from type sections using, usually, subjective criteria such as the most characteristic, most complete, and/or highest resolution record of a segment of the overall sequence pattern. The "most characteristic" criteria are usually made less subjective by comparing *sequence patterns from different locales* and identifying sections which were formed during periods of relatively constant deposition rates or seafloor spreading rates. It is usually possible to identify part or all of the better local type sections which were formed during a period of constant deposition or spreading rate, assuming a specific amount of data scatter. These are standard correlation techniques with best fit criteria determined by the desired resolution for polarity sequences. A composite standard sequence does not necessarily, if at

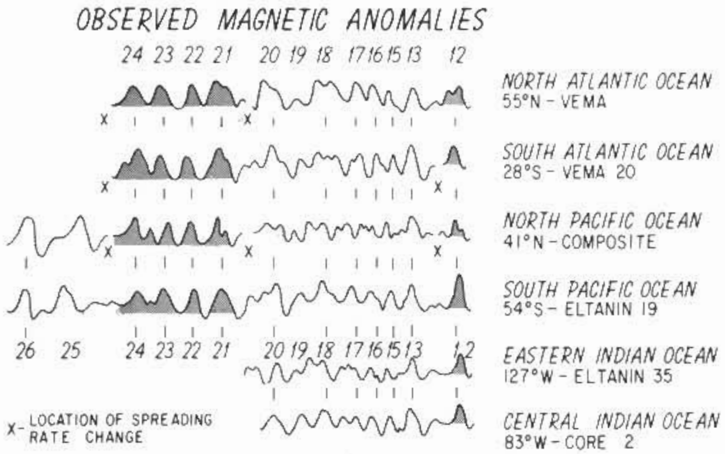

Fig. 1. Magnetic anomalies 12 to 26 on profiles from the North Atlantic (north of Charlie Gibbs Fracture Zone), South Atlantic (south of the equator), North Pacific (off California coast), South Pacific (near Eltanin Fracture Zone), eastern Indian Ocean (north side of Australian-Antarctic Ridge), and central Indian Ocean. Constant spreading rates can be shown for the segments between crosses and these segments have been expanded by a constant amount to match the anomaly spacing on the South Pacific profile.

all, correspond to the entire succession recorded in any given magnetic anomaly profile or magnetostratigraphic section. The reliance on an abstract composite in magnetic polarity correlation is identical with the technique of many other types of stratigraphic correlations which are rooted in type specimens (for example, biostratigraphic zones) or type sections.

On the basis of the study of seafloor spreading magnetic patterns in different ocean basins, Heirtzler et al. [1968] chose the Vema-20 (west flank) magnetic profile in the South Atlantic as their reference section. At that time, it was the longest and most complete record of the seafloor spreading magnetic patterns consistent with the patterns in other ocean basins. Subsequent studies have identified seafloor magnetic anomaly reference sections that span shorter time intervals [e.g., Blakely, 1974; Klitgord et al., 1975; Cande and Kristoffersen, 1977] but which are more complete, have better resolution, and better fit the constant spreading rate assumption than the Vema-20 profile. These anomaly pattern reference sections have been combined into composite sections, producing revised geomagnetic time scales (e.g., LaBrecque et al., 1977; Ness et al., 1980; Lowrie and Alvarez, 1981; Harland et al., 1982; Berggren et al., 1985b]. The primary differences for the Paleogene for all these time scales are the calibration points selected and the techniques used to apply them to the standard reference sections. Lowrie and Alvarez [1981] and Harland et al. [1982] assumed that every calibration point was exact and interpolated the polarity pattern of LaBrecque et al. [1977] between each point. The other three time scales assumed periods of constant spreading between anomaly 5_o and 24_o (23 for LaBrecque et al. [1977]). All five of the above mentioned time scales are based on the Vema-20 profile from Chrons 5_o to 24_o (or 23) and on either the North Pacific profile or Vema-20 profile for 24_o (or 23) to 34. These studies do not assume (or support) constant spreading rates for any ocean basin during the entire Cenozoic. However, it is possible to identify periods of relative constant spreading that lasted for 5 to 20 m.y. [Klitgord et al., 1975; LaBrecque et al., 1977; Klitgord and Schouten, 1986]. Otherwise it would not be possible to make the necessary correlation of the anomalies in such detail (Figure 1) because their identification is based on a characteristic relative spacing.

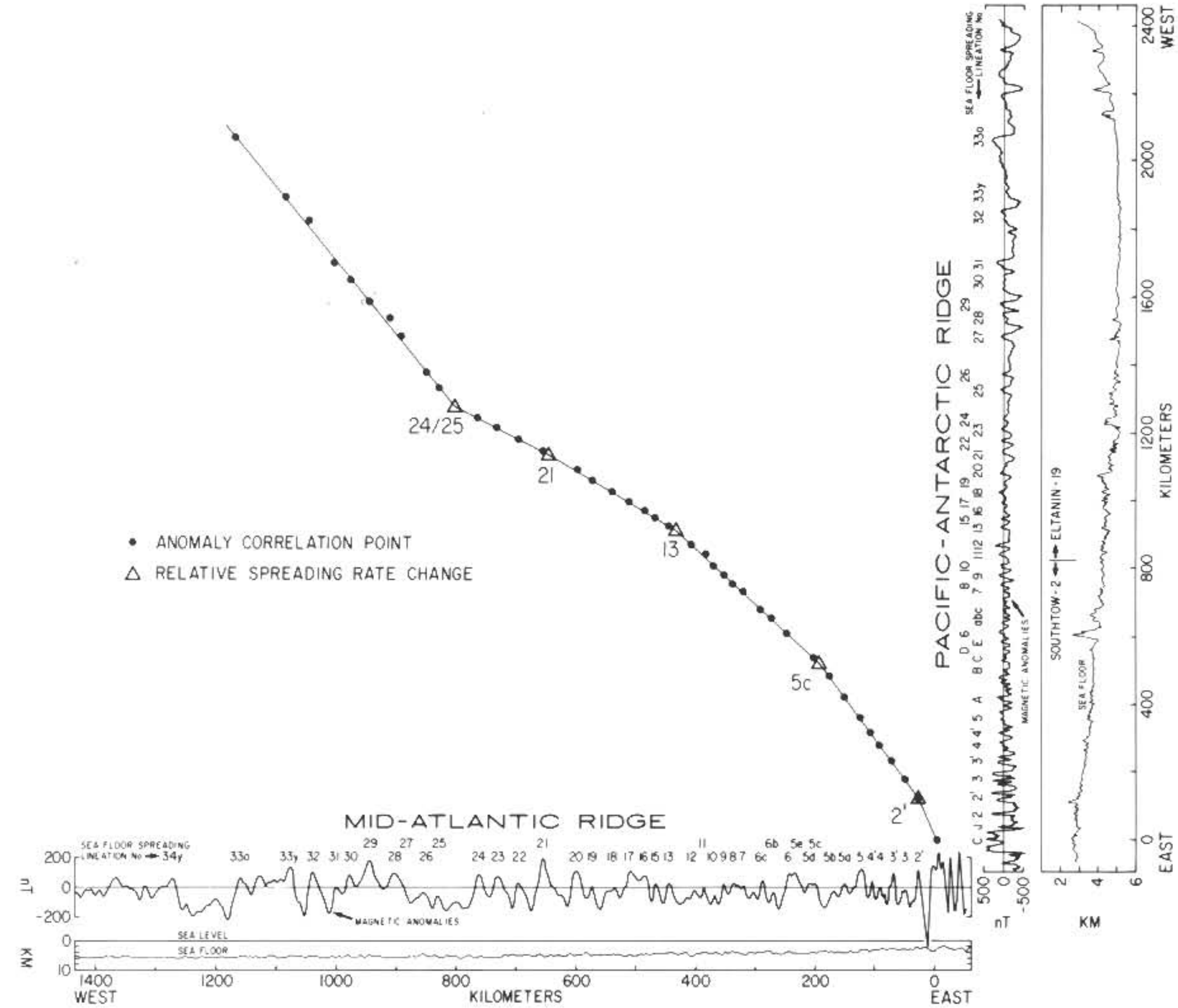

Fig. 2. Magnetic anomalies on *Atlantis* II-93 cruise crossing the western flank of the Mid-Atlantic Ridge plotted against magnetic anomalies from profiles *Eltanin*-19 and *Southtow*-2 on the western flank of the Pacific-Antarctic Ridge in the southeastern Pacific. The graph indicates distance along track to the same magnetic lineation on both mid-ocean ridges. The slope of the lines connecting these points represents the relative spreading rates between the two spreading centers [from Klitgord and Schouten, 1986, Figure 8).

The utility of a comparison of seafloor magnetic anomaly spacings in different ocean basins [Heirtzler et al., 1968] (Figure 2) is that it enables one to identify 5 to 20 m.y. periods of constant spreading rates common to different mid-ocean ridges [Klitgord et al., 1975; LaBrecque et al., 1977; Klitgord and Schouten, 1986]. For example, the comparison of anomaly spacings between the North Atlantic and South Pacific (Figure 2) indicates spreading rate changes at anomalies 2' and 5c and between anomalies 12/13, 20/21, and 24/25. A comparison of Paleogene anomaly spacings between the North Pacific, South Pacific, and South Atlantic [Klitgord, 1986] (Figure 3) indicates spreading rate changes between anomalies 12/13, 16/17, 20/21, 24/25/26, and 31/32. This type of comparison disproves the conclusion of Odin and Curry [1985, p. 1186] that "there is no reason a priori to assume that the rate

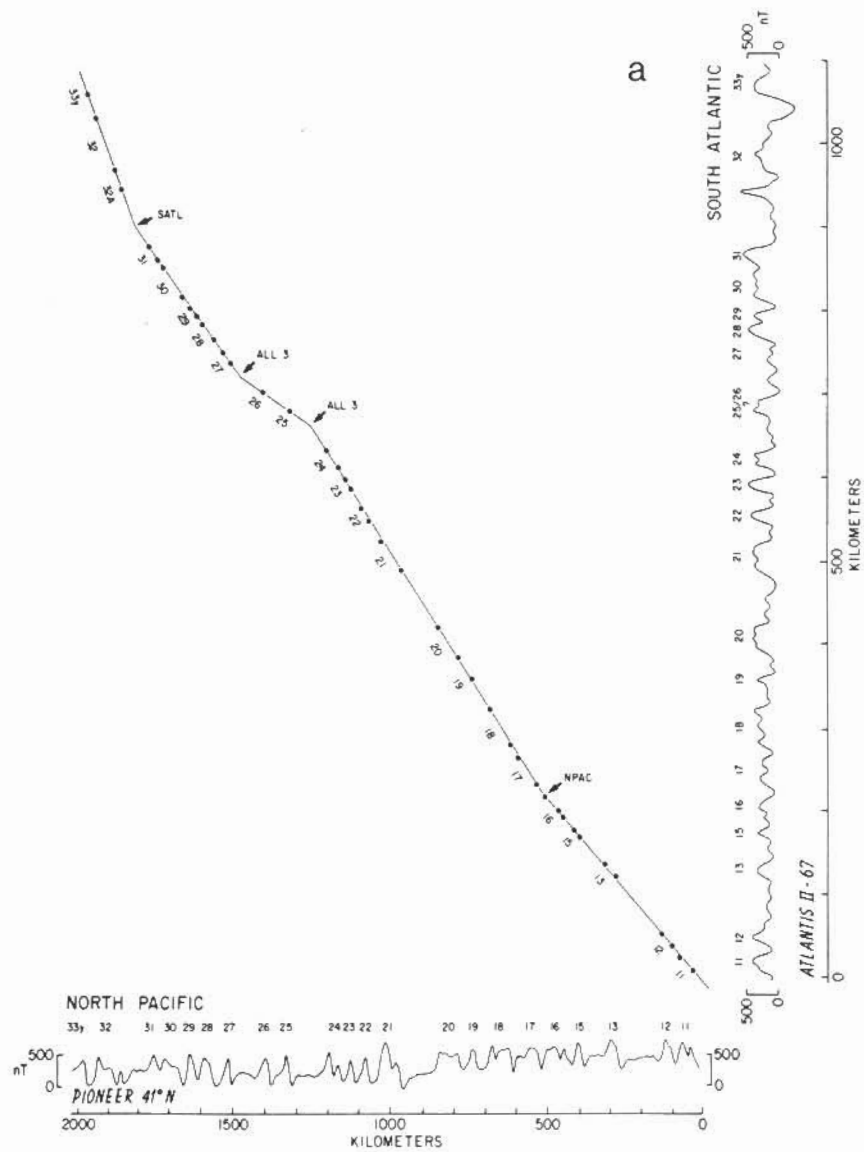

Fig. 3. Comparison of magnetic anomaly patterns from Chron 11 to Chron 33y in the South Atlantic (SATL) (Atlantis II 67 profile), the South Pacific (SPAC) (Eltanin 19 profile), and the North Pacific (NPAC) (41°N composite). Arrows indicate locations of spreading rate changes and label indicates ridge where rate change occurred based on comparison of all these graphs using the technique of Klitgord et al. [1975]. (a) SATL vs NPAC indicates constant spreading rates on these two ridges from Chron 11 to Chron 16 and Chron 17 to Chron 25. (b) SATL vs SPAC indicates constant rates on these two ridges from Chron 12 to Chron 22 and from Chron 22 to Chron 25. (c) NPAC vs SPAC indicates change in rates on one of these two ridges at chrons 12, 17 21, and 25. Note that all these ridges had rate changes at chrons 25 and 26.

of seafloor spreading is constant with time." There is no doubt that seafloor spreading anomaly spacings show some higher-frequency variability within any ocean basin [e.g., Blakely, 1974], but the same problem exists with deposition rates and their influence on magnetostratigraphic or biostratigraphic

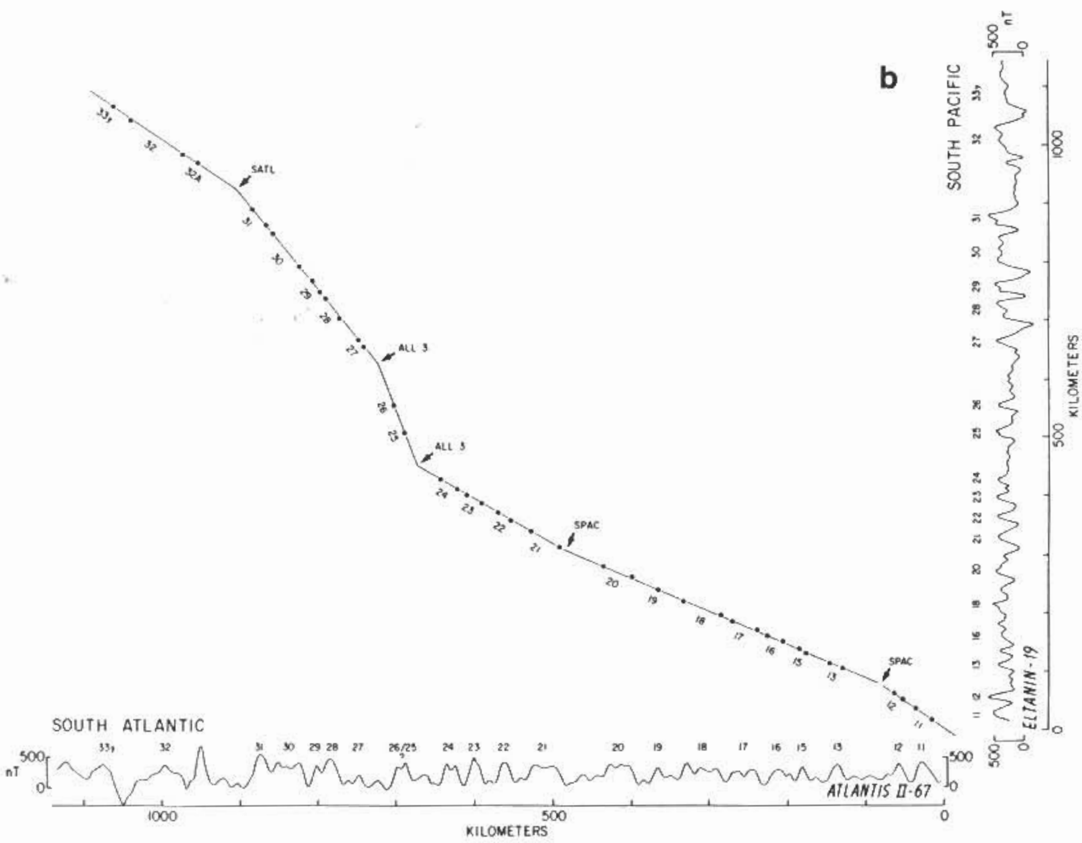

Fig. 3. (continued)

studies. The important conclusion is that significant lengths of seafloor spreading record from different ocean basins can be demonstrated to have formed during periods of relatively constant spreading rates (for example, Figure 3). These sections are then appropriate for consideration as candidates for standard reference sections. Examination of seafloor spreading magnetic anomalies in five ocean basins for chrons 12 to 25 (Figure 1) indicates that anomaly patterns are very consistent for chrons 13 to 20 and 21 to 24. There are small variations between each profile, but that is why it is important to compare the patterns for each segment (for example, 21 to 24) from many locales to determine the most representative pattern.

Careful regional studies are therefore used to eliminate clearly anomalous sections and to select the best representative sections for a given area. Comparisons of representative sections from different areas (for example, Figures 2 and 3) are used to determine segments of the magnetic record that are most consistent for all oceans and give the best resolution of the anomaly pattern for a given time interval. These best representative sections (for example, seafloor spreading anomalies 13 to 21 in the South Atlantic and South Pacific and 17 to 25 in the South Atlantic and North Pacific) are then combined to form a composite section. The overlap in standard reference sections (for example, anomalies 17 to 21) provides a check when creating the composite section.

Calibration of the composite geomagnetic polarity succession to time and the relation of this chronology to the isotopic time scale is the greatest source of disagreement. Clearly, a numerical scale using actual time units is unattainable through magnetostratigraphic (or biostratigraphic) means alone; it must be based ultimately on the application of stratigraphically

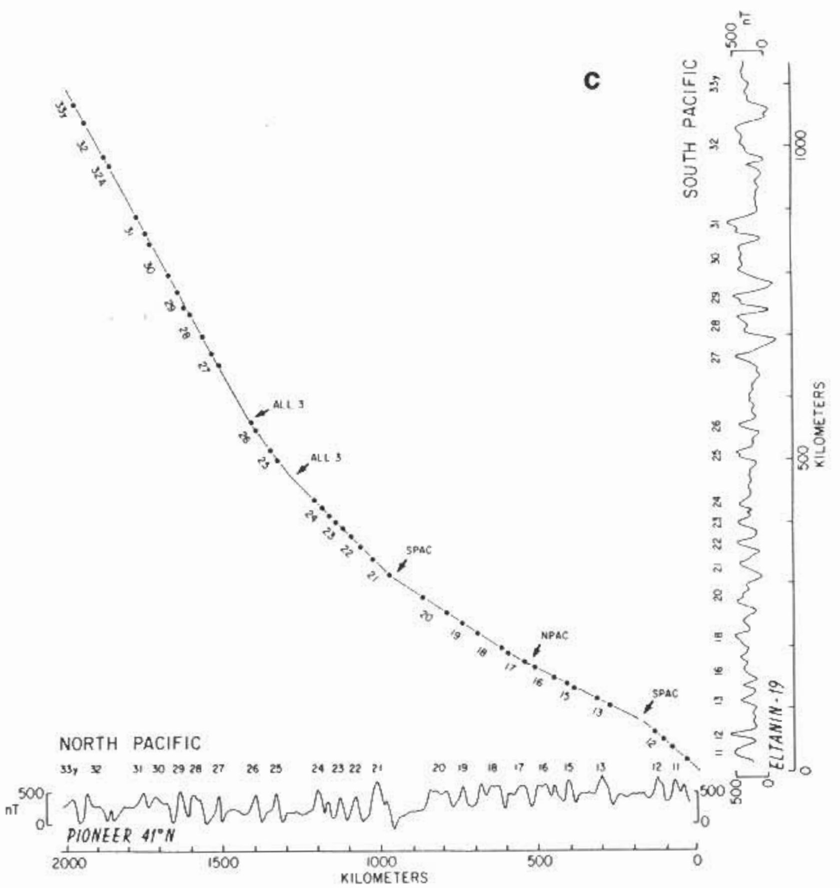

Fig. 3. (continued)

meaningful isotopic ages to the succession of polarity intervals and geological stages. Heirtzler et al. [1968] derived a numerical time scale of geomagnetic polarity by extrapolation of the axial zone spreading rate in the South Atlantic, hence the "constant" spreading rate assumption for the entire Cenozoic and Late Cretaceous that was needed at the time because few other age constraints were available. A major accomplishment since the work of Heirtzler et al. [1968] has been the detailed correlation of the geomagnetic polarity sequence and the classical chronostratigraphic succession, through biostratigraphic dating of sediments overlying the oceanic basement with identified magnetic anomalies, and by first-order correlations between biostratigraphy and magnetostratigraphy as reviewed and discussed by Berggren et al. [1985a]. Thus, numerical age calibration of geomagnetic polarity perforce becomes equivalent to that of the chronostratigraphic sequence, and vice versa. An integrated methodology becomes imperative, one that utilizes the best attributes of seafloor spreading history (complete, high-resolution, standard reference sections), magnetostratigraphy, and biostratigraphy in the application of relevant isotopic ages to derive a high-resolution and internally consistent time scale. Since the geomagnetic time scale of LaBrecque et al. [1977], there has been no need to assume that the South Atlantic seafloor has been created at a constant rate since Late Cretaceous time, although a parsimonious geomagnetic polarity time scale is one that reduces the number and magnitude of apparent changes in relative spreading rate in the global ocean. Constant spreading rates were assumed in the South Atlantic from Chrons 5_o to 24_o and in the North Pacific from 23 to 34. We would observe that the claim by Odin and Curry [1985,

p. 1182] that Berggren et al. [1985a] invoke an "arbitrary change" in spreading at anomaly 24 is incorrect. The comparison of magnetic anomaly patterns between the North Pacific, South Pacific, and South Atlantic (Figures 2 and 3) clearly indicates a distinct disruption in anomaly patterns just before Chron 24 time. Spreading changes were proposed only in places where strong evidence in the plate tectonic regime supported major plate reorganizations and spreading rate/direction changes [e.g., Klitgord and Schouten, 1986, Table 4].

Berggren et al. [1985a] chose to calibrate the geomagnetic polarity sequence using exclusively isotopic ages on volcanic material which can be placed stratigraphically within the reversal pattern. For the Paleogene, three calibration points were explicitly used. However, it was shown that the sequence thus calibrated was consistent with what was regarded as the best age estimates for other chronostratigraphic boundaries within the Paleogene. For example, an assessment of available radiometric data for the Eocene/Oligocene boundary, correlated to Chron C13R, suggests an age of 36 to 37 Ma, compared to 36.6 Ma given by our calibrated sequence. Similarly, an age of 66.5 Ma is indicated for the Cretaceous/Tertiary boundary, virtually identical to the age (66.4 Ma) based on correlation of this level to Chron C29R. An assessment of isotopic ages for the east Greenland basalts suggests an age of 56.5 Ma for the Eocene/Paleocene boundary. This is approximately 1 m.y. younger than the age of 57.8 Ma derived by Berggren et al. [1985a]. However, the stratigraphic correlation network that relates the Blosseville basalts to the Paleocene/Eocene boundary is reinterpreted, which leads to a revised estimate for the Paleocene/Eocene boundary of about 57.0 Ma (see below), very close to the ages reported for the Blosseville basalts. Thus, while Berggren et al. [1985a] explicitly used a minimal number of calibration data (in part to maintain some degree of independence of the calibrated geomagnetic polarity time scale for comparison to the isotopic time scale), we reiterate our contention that the integrated magnetobiostratigraphic time scale we propose is a workable temporal framework which satisfies our best estimates of Late Cretaceous to Recent chronology.

An Isotopic Time Scale

Curry and Odin [1982] (and Odin and Curry [1985]) offer an alternative Paleogene chronology, purportedly based solely on about 70 isotopic ages, predominantly on glauconies. We acknowledge that the chronologies of Curry and Odin [1982] and Berggren et al. [1985a] for the late Paleocene to middle Eocene are markedly divergent, but for the reasons given above, we reject the explanation stated by Odin and Curry [1982, p. 1183] that Berggren et al. [1985] gave "undue reliance on the hypothesis of a constant rate of ocean floor spreading."

The major differences in the Paleogene time scales of Curry and Odin [1982] and Berggren et al. [1985a] have in fact little to do with seafloor spreading and geomagnetic polarity per se; rather the apparent numerical discordances stem from using different age estimates in constructing a Paleogene chronology. For example, Channell [1982] calibrated virtually the same geomagnetic polarity sequence, with magnetostratigraphic correlations similar to those of Berggren et al. [1985a], using the Paleogene chronology of Curry and Odin [1982]. Channell [1982] estimated that the early/middle Eocene boundary and Anomaly 22 are at 45 Ma, about 7 m.y. younger than the estimate of 52 Ma for both the boundary and the anomaly by Berggren et al. [1985a].

Thus, Odin and Curry [1985] apparently misinterpret the role of the geomagnetic polarity sequence in the construction of a numerical time scale: They overstate the importance of magnetostratigraphy in contributing to the determination by Berggren et al. [1985a] of ages for major chronostratigraphic subdivisions of the Paleogene. Yet they underestimate the utility of magnetostratigraphic correlation in resolving small time increments and make what we regard as untenable numerical assignments on the basis of isotopic ages (primarily glaucony) alone.

We would argue that the glaucony ages and the biostratigraphic assignments favored by Odin and Curry [1985] do not provide an internally consistent chronology even in the northwest European Paleogene sequences, let alone for global geochronology. The comparison between isotopic ages and standard reference sections provides a tool for calibrating and evaluating age data on regional and global scales.

Considering the spread of reported glaucony ages, which often range 5 m.y. and more, for nominally coeval levels, we are sceptical that the criteria used by Odin [1982] are sufficient to differentiate amongst the various possible causes for this spread and to discover which are the correct ages, and that such data alone provide the accuracy, let alone precision, to construct a Paleogene time scale. We address the subject of the isotopic data used by Curry and Odin [1982] in their time scale in greater detail in a later section of this paper. We discuss below several of the points raised by Odin and Curry [1985] concerning some of the correlations on which Berggren et al. [1985a] rely.

COMMENTS ON "CERTAIN DISPUTABLE CORRELATIONS"

Four points are to be made regarding these correlations.

1. Odin and Curry [1985, p. 1182] cast doubt on the significance of the isotopic ages from Flagstaff Rim, Wyoming, for Paleogene geochronology. Since these ages "are linked to the chronostratigraphic scale only by the use of a series of magnetic reversals," they are necessarily inferior, according to Odin and Curry [1985]. Recent work on these same sections has shown that the correlation is much stronger than they suggest. The revised Flagstaff Rim magnetostratigraphy [Prothero, 1985] not only corroborates the earlier interpretation of Prothero et al. [1982, 1983] and Berggren et al. [1985a], but also shows that the polarity zones are very consistent in thickness [Prothero, 1985, Figure 7]. Indeed, this lengthy series of magnetic polarity zones spans approximately 10 million years and can be convincingly correlated to the Chron C13 to Chron C9 interval of the standard geomagnetic polarity time scale. In addition, a similar section from Ledge Creek, Wyoming, produces an almost identical polarity pattern. Thus, the terrestrial record from Wyoming produces a consistent pattern of polarity zones, which are directly associated with K-Ar ages on high-temperature minerals. The long reversed zone in the upper part of the Flagstaff Rim section, bracketed by ages of 32.4 and 34.6 Ma, is too long to correspond to any other reversed interval except Chron C12R. Odin and Curry's [1985, p. 1182] criticism of the several alternative correlations that are possible for the "similarly correlated" west Texas sequence is a straw man argument with no bearing on the validity of the Wyoming calibration points; the west Texas sequence is not used by Berggren et al. [1985a] as a calibration point, and no definitive correlation is proposed for Texas because the Texas sequence is much shorter than the Wyoming sequence (2-3 m.y. versus 10 m.y.). Magnetic polarity patterns do provide strong evidence for global correlation when the reversal sequence is long and well developed, and radiometric ages bracket intervals of characteristic polarity duration.

This point is underscored by a recently published study of a marine sediment section from the Olympic Peninsula of Washington [Prothero and Armentrout, 1985]. The Lincoln Creek Formation represents about 2900 m of continuous late Eocene and Oligocene sedimentation and contains a diagnostic fauna of benthic foraminifera and molluscs. The magnetostratigraphic pattern is well developed and can be readily correlated to the geomagnetic polarity time scale. Two successive long zones of reversed polarity appear in the lower Oligocene which clearly correspond to Chrons C12R and C13R. An age of 38.5 ± 1.6 Ma was determined on whole-rock basalt that occurs just below the Narizian/Refugian boundary, which is located in Chron C15R; it strongly suggests that Chron C13R (and therefore the Eocene/Oligocene boundary) is near 37-36 Ma in age [Prothero and Armentrout, 1985].

2. In their criticism of the 49.5 Ma calibration point of Berggren et al. [1985a], Odin and Curry [1985, pp. 1182-1183) evidently do not appreciate

the biostratigraphic correlations employed and just how many radiometric ages constrain this calibration point.

2a. Diachrony of formations in volcaniclastic terrains has no bearing on the biostratigraphic correlation of assemblages within a single stratigraphic section to assemblages in other areas. Intracontinental synchrony of mammalian assemblages is almost universally accepted [see Flynn et al., 1984]. Berggren et al. [1985a] used mammalian assemblages (directly bracketed by four radiometric ages in a single section of Wyoming and bracketed by marine microfossil assemblages in California) to correlate the two magnetostratigraphic sequences in the two field areas.

2b. On the basis of this simple biotemporal correlation, Berggren et al. [1985a] unambiguously identified Chrons C20R and C21N in both sections and correlated the Bridgerian/Uintan North American Land Mammal Age boundary with Chron C20R. They used the four directly bracketing isotopic ages in the Wyoming section to provide a tightly constrained age estimate for the younger boundary of Chron C21N. The statement by Odin and Curry [1985, p. 1182] (see also Odin and Curry [1985, p. 1183]) that Berggren et al.'s [1985a] "preferred magnetic identifications may be incorrect" refers to the latter's presentation of possible alternative correlations of the basal polarity interval in the Wyoming section. However, no ambiguity was expressed by them on the identification of the magnetic polarity interval (Chron C21N) used as a calibration point at 49.5 Ma.

2c. Odin and Curry [1985, p. 1183] state that the 49.5 Ma calibration point is a "single radiometric date" used as the only control on the Berggren et al. [1985a] chronology between 32 and 84 Ma. This statement is incorrect. The 49.5 Ma calibration point was determined by the selection of four high-temperature isotopic ages directly bracketing magnetic polarity Chron C21N and the Bridgerian/Uintan North American Land Mammal Age boundary in a single section. In addition, 16 other isotopic ages on high-temperature minerals from nearby sequences tightly constrain the age of the same chronostratigraphic interval [see Berggren et al., 1985a; Flynn, 1986; Krishtalka et al., 1988]. The 20 K-Ar ages on high-temperature minerals constraining the 49.5 Ma calibration point of Berggren et al. [1985a] represent almost one third of the total number of results used to construct the entire Paleogene chronology of Curry and Odin [1982] (Figure 4). In addition, two other calibration points were used by Berggren et al. [1985a] at 32.4 Ma and 34.6 Ma.

2d. Berggren et al. [1985a, Figure 2, pp. 145-147] provided independent age estimates for the major Paleogene biochronologic boundaries (Eocene/Oligocene, Paleocene/Eocene, and Cretaceous/Paleocene) that yield further constraints (or "control") on the accuracy of the Berggren et al. chronology in the 32 Ma to 84 Ma interval. These points were used as an independent test of the validity of the chronology derived from the calibration points (which all integrate high-temperature isotopic ages, biochronology, and magnetochronology), although they could have been used as calibration points without significantly altering the Berggren et al. chronology (see discussion by Berggren et al. [1985a]). Flynn [1986, Figure 12) provides additional data points which integrate high-temperature isotopic ages and biostratigraphy/magnetostratigraphy. All of these points support the validity of the Paleogene geochronology of Berggren et al. [1985a] rather than that of Curry and Odin [1982] and Odin and Curry [1985].

3. Odin and Curry [1985, pp. 1183-1184) state that "it is, of course, impossible to compare radiometric dates with those deduced from magnetically interpolated time scales unless the rocks dated can be tied to the marine magnetic sequence." They also claim that the magnetozones recorded in the lower Paleogene of the United Kingdom cannot be reliably correlated with the seafloor magnetic anomaly sequences and suggest that the differences observed between ages obtained from glaucony dating and ages inferred from magnetobiostratigraphic correlations for the Paleogene formations of the Hampshire Basin results from misidentification of these magnetozones. Aubry [1983, 1985] pointed out the fact that these

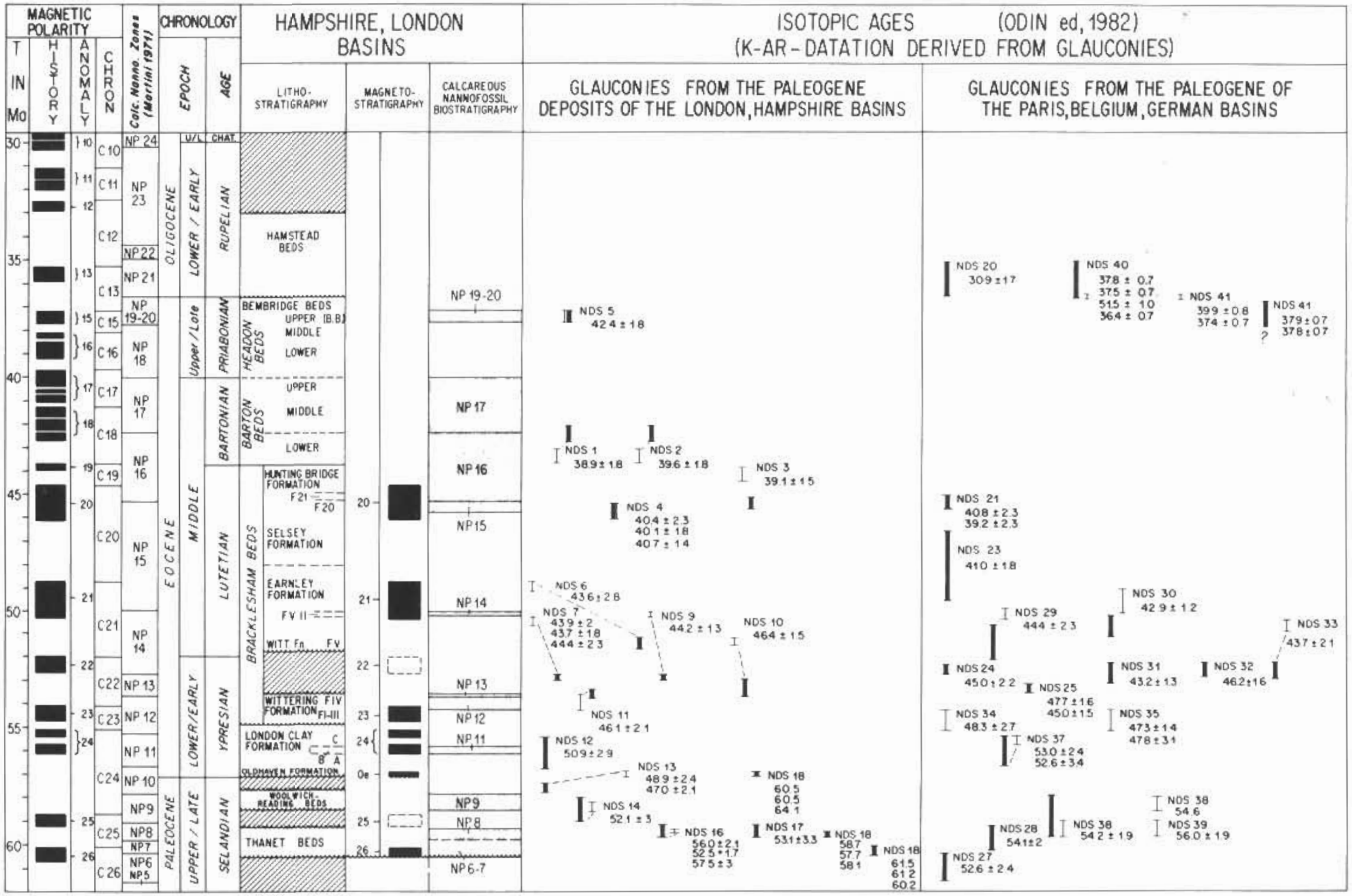

Fig. 4. Stratigraphic repositioning of glaucony samples from the Paleogene of northwestern Europe, analyzed for K-Ar dating, listed in the work of Odin [1982]. Many of these dates are used as calibration points in Curry and Odin's [1982] time scale. The thick lines refer to stratigraphic placement in the work of Odin [1982], and the thin lines to our stratigraphic repositioning. NDS 18 are samples analyzed by Fitch et al. [1978] and regarded by Curry and Odin [1982] as of poor reliability.

magnetozones could be identified independantly of one another based on their direct correlations to calcareous nannofossil biozones identified in the same levels where the magnetozones occur and not simply as a numerical succession of polarity intervals. Thus, comparisons between isotopic ages obtained on land sequences and those estimated from magnetic interpolation scales are entirely valid.

The bathyal sedimentary sections near the village of Gubbio, Italy, serve as informal reference sections for the Late Cretaceous-Paleogene time scale [Lowrie et al., 1982]; the magnetostratigraphic correlation framework established there has been corroborated by studies in the South Atlantic [Poore et al., 1984]. These sections allow correlations between polarity intervals recorded in a sedimentary sequence and seafloor magnetic anomalies and provide first-order correlations between these magnetochrons and first and last occurrences of a number of planktonic foraminifera and calcareous nannofossils. Odin and Curry [1985, p. 1184] indicate that "data from the four sections there . . . are not wholly consistent" but do not discuss these inconsistencies. A more recent study on the Gubbio sections than those cited by Odin and Curry [1985] recognizes that "there is a considerable degree of internal stratigraphic variability" [Monechi and Thierstein, 1985, p. 432] and also shows that whereas a number of biostratigraphic events show this variability, others appear to be constant, always occurring at the same level with respect to the magnetochrons. Also, some of the magnetobiostratigraphic correlations established in the Gubbio sections have been corroborated by similar correlations obtained from deep-sea sections [Poore et al., 1984; Townsend, 1985, Monechi et al., 1985]. To cite only a few biostratigraphic events which are relevant to our discussion, it appears that the first appearance datum (FAD) of Discoaster multiradiatus (within Chron C25N), that of Tribrachiatus orthostylus (within Chron C24R), that of Discoaster lodoensis (within Chron C24A), and that of Nannotetrina fulgens (within Chron C21N) are reliable markers. Odin and Curry [1985, p. 1184] also question the "puzzling variations" of the magnetozones recorded at Gubbio. As the authors do not discuss this question, we suppose that they refer to the fact that at some localities a chron may appear as a single magnetozone, whereas at another one it may be triple, rather than to the relative thicknesses of the correlative magnetozones between the various sections. Chron C26N, for instance, corresponds to a single magnetozone in the Contessa Highway section and was thought to also correspond to a single magnetozone in the Bottaccione section [Lowrie et al., 1982; Napoleone et al., 1983]. However, calcareous nannofossil biostratigraphy has shown that Chron C26N is a double magnetozone in the Bottaccione section and that what was interpreted as Chron C25N corresponds to a younger normal magnetozone in Chron C26N [Monechi and Thierstein, 1985]. An unconformity explains that Chron C25N is missing at Bottaccione. That Chron C26N is double rather than triple in the Bottaccione section may result from this unconformity or rather from the sampling interval of the Bottaccione section not allowing the delineation of a discrete intervening reversed interval. A similar reason can be invoked to explain why Chron C24N appears to be single in the Contessa Highway section and the Bottaccione section, whereas the seafloor record shows it as double. It is unrealistic for us to expect to find complete parallelism between what is recorded by the deep-sea floor and the sedimentary sequence everywhere. Very short polarity intervals may be recorded on the seafloor only where spreading rates were relatively rapid and higher resolution is therefore possible. The difficulty in identifying Chron C26N, which appears as a triple normal magnetozone in some magnetostratigraphic sections but corresponds to a single anomaly, is an example of this problem. Similarly, new evidence from several sources indicates the possible presence of at least two normal polarity intervals within Chron C24R [Backman et al., 1984] which could correlate with small-scale anomalies not recorded in all magnetic anomaly profiles [Pitman and Hayes, 1968; Pitman et al., 1968]. Thus, one cannot expect to find one section where all magnetic polarity zones can be identified, nor one seafloor profile where all the reversals are recorded; hence the construction of composite standard reference "sections" in profiles. Proper identification of magnetozones must be made in the light of a careful magnetobiostratigraphic network, in particular when recorded in hiatus prone sections of epicontinental areas.

The Thanet Magnetozone

The Thanet Formation can be seen in two localities. In the cliffs of Pegwell Bay, its lower part rests unconformably on the Cretaceous chalk. Its upper part is exposed in the sea cliffs which stretch between Herne Bay and Reculver. The Thanet Beds at Pegwell Bay are of normal polarity (corresponding to the Thanet magnetozone) whereas those at Herne Bay are of reversed polarity [Townsend and Hailwood, 1985]. Proper identification of the Thanet magnetozone requires (1) correct biozonal assignment of the Thanet Beds and (2) comparison with sections where magnetochrons have been clearly identified and characterized with biostratigraphic events. We shall discuss these two requirements in order.

Biozonal assignment of the Thanet Beds. Aubry [1983, 1985] assigned the upper part of the Thanet Beds to Zone NP8 (with Heliolithus riedelii and without Discoaster multiradiatus), thus agreeing with earlier assignments [Bramlette and Sullivan, 1961; Hay and Mohler, 1967; Bignot and Lezaud, 1969; Martini, 1971]. She observed that neither the base nor the topmost part of the formation could be assigned to a biostratigraphic zone, both being barren of calcareous nannofossils, but suggested that the Thanet Beds at Pegwell Bay may be correlative with Zone NP7 [Aubry, 1983, p. 90]. Prior to the publication by Aubry [1983], Hamilton [Hamilton and Hojjatzadeh, 1982] reported the presence of D. multiradiatus (whose FAD marks the base of Zone NP9) in the topmost beds of the Reculver silts and that of Heliolithus riedelii at two levels of the Thanet Beds at Pegwell Bay (7.5 m above the Bullhead and in the shell bed at the top of the Pegwell marls).

Although Aubry [1983] conceded that those reports were interesting and not surprising, as preservation of calcareous nannofossils in epicontinental sediments is irregular and somewhat unpredictable, she questioned the report of Discoaster multiradiatus on the basis of the incorrect stratigraphic range given for that species, the absence of illustrations of specimens found (in fact, only a single specimen was observed) in the critical levels (i.e., in the uppermost Reculver silts), and incorrectly identified figures given as D. multiradiatus.

In order to verify Hamilton's finding, Godfrey and Lord [1984] resampled the Thanet Beds for a calcareous nannofossil study. They could not confirm the presence of Discoaster multiradiatus in the uppermost Thanet Beds, nor could they find it in the Thanet Beds at Herne Bay. However, they identified as D. multiradiatus a form found in the upper levels at Pegwell Bay. On the basis of this single specimen assigned to D. multiradiatus, they suggested that the Thanet Formation belongs to Zone NP9. This unwarranted assignment is discussed in Aubry [1986]. Together with W. A. Siesser, M.-P. Aubry (unpublished data, September, 1985) reexamined this specimen with the light microscope: it is clearly not a species of the genus Discoaster but rather an isolated cycle of a species of the genus Heliolithus. We trust that the recent reinvestigation of the calcareous nannofossil content of the Thanet, Reading, and Woolwich beds by W. A. Siesser in clearly establishing the biozonal position of the Thanet Formation will end the disagreement. No Discoaster multiradiatus were found in the Thanet Beds which are assigned, for the most part, to Zone NP8. A relatively well-preserved assemblage with Heliolithus kleinpelli (whose FAD defines the base of Zone NP6) and without H. riedelii was found at Pegwell Bay, suggesting that the lower part of the Thanet Formation belongs to Zones NP6 to NP7 undifferentiated. The lowest Heliolithus riedelii was found at the top of the Pegwell marls indicating Zone NP8. The Woolwich-Reading Bottom Bed at Clarendon Hill (east of Salisbury) yields common D. multiradiatus and belongs to Zone NP9 (W. A. Siesser, written communication, November 1985) [Siesser et al, 1987].

Identification of the Thanet magnetozone. It now appears well established that most of the Thanet Beds belong to Zone NP8 and that their base lies within Zones NP6 to NP7 undifferentiated. Thus the Thanet magnetozone can be directly correlated, mostly with Zones NP6 to NP7; its younger part may correlate with the base of Zone NP8. Evidence for its identification as Chron C26N is presented by Aubry et al. [1986] and for brevity's sake will not be discussed here. We concede that this identification may not appear straightforward, but we shall point out that identification of Chron C26N appears problematic, here as well as elsewhere (see, for instance, discussions by Shackleton et al. [1986]. On the other hand, there are no data justifying identification of the Thanet magnetozone as Chron C25N as proposed by Odin and Curry [1985]. Whereas some biostratigraphic events may vary with respect to magnetic chrons, the FAD of Discoaster multiradiatus has been found to occur within Chron C25N in various land and deep-sea sections [Monechi and Thierstein, 1985; Poore et al., 1984; Shackleton et al., 1984; Steinmetz et al., 1984; Townsend, 1985; Monechi et al., 1985]. In the upper Paleocene of the United Kingdom, D. multiradiatus first occurs in the Woolwich-Reading Beds at least 7 m above the Thanet magnetozone. A magnetozone corresponding to Chron C25N in the United Kingdom would thus be expected to occur in the upper part of the Thanet beds, and possibly in the Woolwich-Reading Beds. We suggest that Chron C25N is missing from the stratigraphic record in the United Kingdom and that its absence indicates the development of a notable hiatus associated with an unconformity developed between the Thanet Beds and the Woolwich-Reading Beds [Aubry, 1985; Aubry et al., 1986].

As a consequence, with regard to the discussion by Odin and Curry [1985, p. 1184], we observe that the isotopic ages of glauconies from Fitch et al. [1978] on the basal and uppermost units of the Thanet Formation correspond well with the estimated ages of Berggren et al. [1985a]. While 58.6±0.6 Ma is perhaps slightly young for the upper Thanet Beds, 60.9±0.9 Ma agrees well with the NP6 to NP7 age of the basal Thanet beds, although we recognize that Odin would reject these ages because of low K content.

The Oldhaven Magnetozone

With regard to the question of identification of the Oldhaven magnetozone [Odin and Curry, 1985, p. 1185, Figure 4), as has been pointed out by Aubry [1983, 1985] and above, each magnetozone in the United Kingdom can be identified independently from one another on the basis of calcareous nannofossil biostratigraphy. As already discussed above, it is not surprising that a normal polarity interval not known from other sections has been recorded. In fact, several short magnetozones are recorded in various sections, but their validity as global events remains questionable until their discovery elsewhere corroborates their probably true global nature. Three normal magnetozones are observed within Chron C24R at DSDP sites 555 and 553 [Backman et al., 1984], and correlation of the Oldhaven magnetozone with one of these short normal polarity intervals is possible (see discussion by Aubry et al. [1986]). As Backman et al. [1984] noted, two small-scale anomalies in the reversed interval between anomalies 24B and 25 are seen in seafloor magnetic profiles from the North Pacific [Pitman et al., 1968] and the Gulf of Alaska [Pitman and Hayes, 1968]. These were also observed by Blakely and Cox [1972], who used signal enhancing ("stacking") techniques to resolve short-term magnetic events in magnetic profiles from the northeast Pacific.

The Earnley magnetozone

Odin and Curry [1985] repeatedly indicate that the magnetozones identified in the English succession have not been satisfactorily identified in terms of marine anomalies, although they do not provide any evidence to the contrary. Revision of the magnetostratigraphic interpretation would be considered if new elements of correlation were brought into discussion by Odin and Curry. Odin and Curry [1985, p. 1186] claim that "the Earnley magnetozone, for example, might be a composite representing 22 and 21 with a hiatus masking the intervening reversal" but do not offer any evidence in support of their statement. Many interpretations are conceivable in science, and that is why hypotheses are constructed. However, the selected interpretation must be the one which is best supported by scientific evidence. There is no evidence that the Earnley magnetozone might be a composite representing Chrons C22N and C21N. There is, however, biostratigraphic evidence which strongly suggests that the Earnley magnetozone corresponds to Chron C21N and the Wittering magnetozone to Chron C23N, and there is field evidence that the absence of Chron C22N results from an unconformity developed between Fisher Beds IV and V in the upper part of the Wittering division of the Bracklesham Beds [Islam, 1983; Aubry,1983, 1985; Aubry et al., 1986] (J. Hardenbol, personal communication, March, 1985; J. Baum, personal communication, October, 1985).

In their Figure 4, Odin and Curry [1985] present an interpretation of the stratigraphic sequence of the United Kingdom in relation to magnetostratigraphy, biostratigraphy, and isotopic ages, after revision of the stratigraphic position of the dated glauconies using Aubry's biostratigraphic ages in the work of Berggren et al. [1985a, appendix 2) (compare with Odin et al. [1978] and Odin [1982]). Odin and Curry indicate that the line drawn between the various data points corresponding to isotopic ages represents the Curry and Odin [1982] time scale. This curve represents, in the first place, a sedimentation rate curve where the thickness of the sedimentary section is plotted on the y axis and the geological ages on the x axis. What we learn from this curve is that there is an inflection at the level of sample 96, i.e., just above the <u>Nummulites planulatus</u> Beds and that sedimentation rates appear to be noticeably lower during the Lutetian time (from samples 96 to 97 in the lower Barton Beds). Considering the imprecision in stratigraphy derived from isotopic ages with an error bar of more than 1 m.y. on each sample (longer duration than most normal polarity chrons), there is no possibility of further interpreting, using isotopic data alone, this point. We consider the inflection as reflecting the unconformity seen between the lower and middle Eocene Beds in the Hampshire Basin [Aubry,1983, 1985]. Overlap of isotopic ages from glauconies which belong to different biostratigraphic levels and appreciably different ages obtained from glauconies from correlative beds obscure the evidence (see Figure 4 and Table 1). Comparison of the numerical values of Odin [1982](same as NDS numbers)with those presented by Odin and Curry [1985, Figure 5] reveals notable discrepancies. We refer here to the numerical ages of Odin [1982]. Sample G96 (same as NDS 11) from Fisher Bed IV (NP12/NP13) (below the unconformity at Whitecliff Bay) yields the same isotopic age (46.1 ± 2.1 Ma) as sample G144 (same as NDS 10) from Fisher Bed 2 (correlative with NP14, above the unconformity (46.4 ± 1.5 Ma), and with lower Fisher Bed VI or upper Fisher Bed V at Whitecliff Bay). For a comparison of the nomenclature of the Fisher Beds' lithostratigraphy the reader is referred to Curry [1965], Aubry [1983] and Townsend and Hailwood [1985]. An age difference of approximately 2.5 m.y. would be expected regardless of whose time scale is used. Sample G437 (same as NDS 6) from Fisher Bed IX (NP15) (late Chron C21N) yields the same isotopic age (43.6 ± 2 Ma) as sample G145 (same as NDS 7) (43.8 ± 1.5 Ma) from Fisher Bed VI (NP14) (early Chron C21N) whereas sample G234 (same as NDS 9) from Fisher Bed 6 (close to NP14/NP15) has an isotopic age (44.2 ± 1.3 Ma) older than sample G145 (same as NDS 7). Samples G144 (same as NDS 10) and G435 (same as NDS 7) from levels stratigraphically close to Fisher Bed 2 and Fisher Bed VI, respectively, yield isotopic ages of 46.4 ± 1.5 Ma and 44.4 ± 2.3 Ma respectively. However, Odin and Curry [1985] do not comment on these discrepancies and in particular, on the similarity in age between sample G96 (same as NDS 11) and sample G144 (same as NDS 10) correlated respectively with Chrons C23N and C21N (their Figure 5, p. 1186). They (p. 1186) remark that

TABLE 1. Comparison of Numerical Values of Some Lower and Middle Eocene Glauconies Presented by Odin [1982] and Odin and Curry [1985, Figure 5]

Sample	Sample	NP Zone	Isotopic age*	Isotopic age+	Age estimate#
G437	NDS 6	15	43.6±2.8 Ma	43.6±2.8 Ma	49 Ma
G145	NDS 7	upper 14	43.9±2.0 Ma	43.8±1.5 Ma	50-51 Ma
G435	NDS 7	upper 14	44.4±2.3 Ma	44.4±2.3 Ma	50-51 Ma
G234	NDS 9	14/15	44.2±1.3 Ma	44.2±2.2 Ma	50 Ma
G144	NDS 10	mid 14	46.4±1.5 Ma	46.4±2.1 Ma	51 Ma
G96	NDS 11	12/13	46.1±2.1 Ma	46.1±1.5 Ma	53.5 Ma

* From Odin [1982]
\+ From Odin and Curry [1985]
\# From Berggren et al. [1985a]

"the dates are, in fact, coherent within the analytical errors quoted, and they can be interpreted as falling into two main groups, at around 47 and 44 Ma, respectively, characterizing units with classical Cuisian (late Ypresian) and Lutetian faunas." While we recognize that given the analytic uncertainties attached to their ages, it is difficult to make an absolute case for one value being older than the other within a 95% confidence limit, we draw attention to the systematic differences in these values. This grouping likely reflects, in fact, the sedimentary discontinuity which occurs in all northwestern Europe at the lower/middle Eocene boundary [Aubry, 1983, 1985]. What has become apparent from the integrated magnetobiostratigraphy of the Paleogene sequences of the United Kingdom is that, contrary to what had long been supposed, this sequence is not continuous, but is interrupted by major breaks in the late Paleocene and early Eocene. It is not surprising that "the whole group of northwestern European dates is concordant with CO82" [Odin and Curry, 1985, p. 1186] since Curry and Odin [1982] (CO82 in the quotation) based their time scale essentially on glaucony dating of the Paleogene of northwestern Europe. The question remains, however, What isotopic ages would be derived from Paleogene formations from other epicontinental basins? We expect that isotopic ages on glaucony alone would not allow firm interregional correlations.

4. A major weakness of isotopic dating compared to magnetostratigraphic correlations is that whereas the latter lead to firm and precise correlations and discrimination between small time increments, isotopic data alone do not serve as elements of correlation. In this view we believe that isotopic dates used solely to determine the ages of stage boundaries in order to construct a time scale do not constitute the elements of a geochronology but merely those of a chronometry. The following two examples show how isotopic dating alone fails to provide decisive elements of correlations.

4a. It is not our purpose to discuss the biostratigraphic assignment of the Bashi Marls. However these, compared to the Thanet Beds, provide a good example of inconsistencies in isotopic dating and how isotopic ages alone may be misleading. Odin and Curry [1985] adopt a NP9 zonal assignment for the Thanet Beds with an isotopic age of 54.8 ± 3.5 Ma. As these authors believe the Thanet magnetozone to be Chron C25N, they date this chron at about 54.8 ± 3.5 Ma. Odin and Curry also seem to prefer a NP9 to NP 10 assignment for the Hatchetigbee (Bashi) Marls following Siesser's [1983] work, although they point out that these marls could belong to Zone NP11 [Berggren et al., 1985a], and thus correlate accordingly with late Chron C25N, C24R, or C24N.

Odin and Curry [1985, p. 1185] proposed a combined age of 51.5 ± 1 Ma for these marls and noted that "the

Hatchetigbee data date either anomaly 25 or anomaly 24 at about 51.5 Ma, depending on whichever of the two biostratigraphic correlations proves to be correct." The question arises then, How can Chron C25N be dated at 51.5 ± 1 Ma in the Gulf Coast area and at 54.8 ± 3.5 Ma in northwestern Europe? This indicates that Odin and Curry recognize that isotopic data do not allow discrimination between younger and older deposits and that an isotopic age of 51.5 Ma cannot be used to favor a younger biozonal assignment to the Bashi Marls than to the Thanet Formation even if we make allowances for analytical uncertainties at the 95% confidence level between these two data sets.

4b. Similarly, we read: "Material of about the same age from France (NP9) and Belgium (NP8, ? + NP7) . . . yields a mean of five dates of 54.3 Ma" [Odin and Curry, 1985, p. 1185]. The material in question is supposed to be the stratigraphic equivalent of the Thanet Beds which are of NP9 age for Odin and Curry, and NP8 for most other observers, except in their lower part. There may be as much as 4 million years (according to Berggren et al. [1985a]) represented between the base of NP7 and the top of NP9: we regard this as rather loosely controlled stratigraphy. It should be pointed out that the Thanet Beds (NP6 to NP7 and NP8) are somewhat older than the Sables de Bracheux (sensu stricto) which, if correlative with the Woolwich-Reading Beds as we believe, are above an unconformity which represents a time span at least equal to the duration of Chron C25N.

METHODOLOGICAL CRITIQUE OF CURRY AND ODIN [1982] AND ODIN AND CURRY [1985]

In this section we turn our attention to general and specific problems which we perceive in the methodological approach used by Curry and Odin [1982] and Odin and Curry [1985] in the construction of their Paleogene time-scale based on isotopic data.

Reliance on glauconies

Odin and Curry [1985, p. 1182] claim that their Paleogene chronology [Curry and Odin, 1982] is founded on a "mixture of glaucony and high temperature dates." Examination of the work of Curry and Odin [1982] indicates that this is only marginally correct.

1. Of the 47 data points used in constructing their time scale [Curry and Odin, 1982, Figure 4], only four were high-temperature points.

2. Of the 17 Paleogene high-temperature analyses listed in Numerical Dating in Stratigraphy (NDS)[Odin, 1982], only four were used in constructing the Paleogene scale of Curry and Odin [1982].

3. Points 1 and 2 strongly conflict with the statement by Odin and Curry [1985, p. 1182] that "it is not correct that CO82 favored glaucony dates; Odin and his collaborators use all published information and give greater weight to high temperature data when these are available."

4. It is interesting that Odin and Curry [1985] choose to illustrate the Cretaceous, rather than the Paleogene, in their Figure 3, to support concordance of high-temperature and glaucony ages. This is really due to the absence of high-temperature data points for Cenozoic (marine) strata. However, this concordancy is illusionary. We have replotted the data from Figure 3 of Odin and Curry [1985] (Figure 5) with some deletions and additions.

The deletions are as follows:

1. NDS 163, marginal material, with large analytical uncertainties is deleted.

2. NDS 104, 105, and 106 [Obradovich and Cobban, 1975] are deleted, as numerous samples from different biostratigraphic levels are lumped together and assigned an average age. The precise biostratigraphic levels of these samples vis-a-vis the type Campanian and Maestrichtian stages are not well constrained.

3. NDS 188 is deleted. This sample has poor biostratigraphic control (post-Bajocian to Bathonian and pre-late Aptian) and a large analytical uncertainty. Note that Odin and Curry [1985] plot this data point with ± 1σ uncertainty.

The additions are as follows:

1. The unpublished ^{40}Ar-^{39}Ar age of 113 ± 1.4 Ma (J. D. Obradovich, unpublished data, 1988) on sanidine from

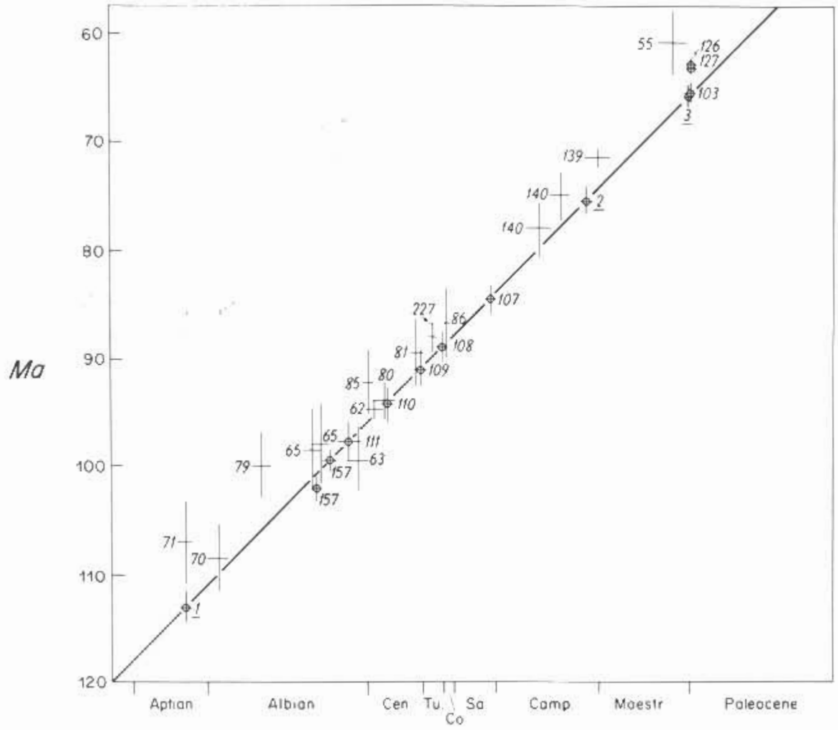

Fig. 5. A replot of Figure 3 of Odin and Curry [1985]. The same symbols are used to indicate the glaucony data (+) and the high temperature data (⌖). The underlined numbers represent additions of unpublished data while the other numbers refer to NDS items [Odin, 1982]. The reasons for the deletions and additions to this figure are discussed in the text.

a bentonite from within the Parahoplites nutfieldensis Zone of the latest Aptian in Northwest Europe is added. This result is in excellent agreement with the $^{40}Ar-^{39}Ar$ stepwise heating results on sanidine from a bentonite published by Jeans et al. [1982]. This latter bentonite is from the same biostratigraphic level within the Upper Aptian Fullers Earth at Surrey, England. For some unknown reason Odin and Curry [1985] ignore this tie point in constructing their Figure 3.

2. The unpublished conventional K-Ar age of 75.5 ± 1.2 Ma ((J. D. Obradovich, unpublished data, 1988) on biotite from a bentonite in the Anonna Formation of Southwest Arkansas is added. This bentonite is from the basal part of the Globotruncanita calcarata Zone [Pessagno, 1969; Hazel and Brouwers, 1982]. The extinction level of G. calcarata marks the Campanian/Maestrichtian boundary.

3. The $^{40}Ar-^{39}Ar$ stepwise heating results on bentonitic sanidine of 66.0 ± 1.1 Ma [Obradovich and Sutter, 1984] are added. This bentonite is above the Cretaceous/Tertiary boundary as recognized by the presence of the Ir anomaly in eastern Montana and Red Deer Valley, Alberta, Canada. The age of 66.0 Ma contrasts markedly with the ages of samples NDS 126 and 127, and the reasons for this discrepancy are discussed by J. D. Obradovich and Sutter (unpublished manuscript, 1988).

4. NDS 55 is added. This sample of Late Maestrichtian age (late Navarro) from the Gulf Coast region of the United States is the only glaucony sample that Odin [1982] thought was reliable because of its high K content (6.02% K).

The salient feature of this time scale for the Cretaceous (Aptian/Albian to the Cretaceous/Tertiary boundary) is that all the results for the high-temperature minerals (except NDS 126 and 127) are from two laboratories (U.S. Geological Survey, Denver and

Reston) that are well intercalibrated. This minimizes the problem of interlaboratory bias.

The replot of Figure 3 of Odin and Curry [1985] (Figure 5) indicates that some glauconies (nine of 16) fit the high-temperature time scale within their large analytical uncertainties. Some glauconies (seven of 16) decidedly do not and are significantly younger than their inferred ages. In the absence of an independent time scale, how does one decide which ages are valid and which are not?

In this regard it is interesting to note the qualifications that Odin [1982, p. 661] adds to some of his NDS glaucony items such as NDS 2, for which he states "39.6 ± 1.8 Ma . . . and bearing in mind the long time for the evolution of the dated glaucony. One should therefore add 1.5 to 2 my (about 1 biozone + duration of genesis) to give a number representative of the limit, situated between 39.3 and 43.4 Ma as extreme values." This qualification then should be applied to any and all suitable glauconies that Odin accepts, although he does not specifically say so. At 40 Ma all analyses automatically are too young by as much as 5% even in the absence of any other geochemical problem.

5. Odin and Curry [1985, p. 1185] state that "The classical late Palaeocene and Eocene sequences of northwest Europe have yielded a large number of glaucony dates, but none as yet on high-temperature chronometers." The "geochronology" of Curry and Odin [1982] is in fact a chronology of northwestern European glaucony horizons (43 of 47 calibration points on Northwestern European glauconies).

Chronostratigraphy

It is unclear how Curry and Odin [1982] and Odin and Curry [1985] determine the precise chronostratigraphic position of many of their calibration samples.

1. In order to construct a standard numerical geochronology it is necessary to integrate isotopic ages into a standard chronostratigraphic sequence. Any composite standard chronostratigraphic sequence is subject to all the same criticisms that Odin and Curry [1985, pp. 1180-1181] apply to constructing composite magnetochronologies. In particular, Curry and Odin [1982, Figure 4] use a plot of standard biochronologic sequence (y axis, NP biozonation) versus isotopic ages to construct their standard Paleogene geochronology. The simple linear relationship between isotopic ages and biochronologic position of the dated horizons of Curry and Odin [1982, Figure 4] will yield a valid geochronology only if the relative durations of the standard biochronologic zones have been determined correctly. However, Curry and Odin [1982] never justified how their standard biochronologic sequence was constructed. It is almost impossible to construct a composite biochronology, with accurate determination of the duration of the NP zone, from the highly variable thicknesses of the hiatus-rich, isolated stratigraphic sequences of the northwest European Basin. For example, Odin and Curry [1985, Figure 4] show a practical illustration in which the durations of the NP zones preserved in the British lower Paleogene sequence vary widely from the durations predicted from the Curry and Odin standard geochronology (variation shown by inflections in the Curry and Odin(1982)'s chronology curve on the plot of chronostratigraphy, y-axis, versus standard numerical chronology).

2. Of the high-temperature calibration data used in Figure 4 of Curry and Odin [1982], one is incorrectly placed stratigraphically (NDS 218; stratigraphic position questioned by Odin [1982, p. 896] because of "conflict with the glaucony dates from the same laboratory"), and two are from zeolitized volcanics in Mediterranean sequences (NDS 49 has poor stratigraphic control, "Lutetian," although it is placed at the NP14/15 zonal boundary by Curry and Odin [1982, Figure 4]. If the biostratigraphy of NDS 218 is correct, the age of sample To [Odin, 1982, p. 896] at the NP21/22 zonal boundary would be 32.6 ± 0.3 Ma on glaucony, not 35.4 Ma [Berggren et al., 1985a]. However, a K-Ar age of 35.4 ± 0.4 Ma on the upper part of Zone NP21 at the top of Chron C13N at Gubbio, Italy [Montanari et al., 1985, p. 596] strongly supports Berggren et

TABLE 2. Comparison between K-AR Ages on two magnetochrons from Gubbio [Montanari et al., 1985] and ages for the same chrons estimated in the Berggren et al.' [1985a] time scale

Sample Level*	Magnetic Chron*	Biostratigraphy*	K-Ar Age*	Age estimate+
5	base Chron C9N	upper NP23-24 (undiffenciated) CP18	28.0±0.3 Ma	29 Ma
4	upper part C12R	G. ampliapertura - C. chipolensis Zone; lower part NP23, bottom CP18	32.0±0.8 Ma	33.4 Ma

* From Montanari et al. [1985]
\+ from Berggren et al. [1985a]

al. [1985a] at this level. Indeed, a comparison of two other K-Ar ages in the Oligocene at Gubbio shows a close similarity with the chronology of Berggren et al. [1985] (Table 2). These K-Ar ages on high-temperature minerals [Montanari et al., 1985] and the magnetobiochronologic age estimates of Berggren, et al. [1985a] stand in marked contrast to the glaucony ages on corresponding levels in northwestern Europe [see Odin, 1982].

3. The chronostratigraphic position of several of the calibration points is interpolated on the basis of lithology or the isotopic ages when stratigraphic control is poor (for example, NDS 35, 38, 39, 49, 90, 218). This is clearly circular reasoning.

4. Many calibration points of Curry and Odin [1982, Figure 4] are shown at different positions within single NP zones. *Such stratigraphic refinement is* difficult even in continuous sequences and seems impossible when determining the position of isolated samples from the isolated sequences (many poorly fossiliferous) present in the different geographic areas of the northwest European Basin.

Problems of Interpretation of Glaucony Ages

To support their northwest European glaucony chronology, Odin and Curry [1985] present two figures (Figures 4 and 5).

Figure 4 purports to show a series of "internally homogenous" ages [Odin and Curry, 1985, p. 1186]. However, the following problems are noted:

1. These ages are not strictly homogeneous; they tend to fall in several clusters showing wide age variability between horizons but small or no decreases with higher stratigraphic position (for example, intervals 109-230, Sables de Cuise: 144, 435-437, 396-397).

2. Inflection points in the Curry and Odin [1982] chronology do not necessarily coincide with trends of age change in the actual data of Odin and Curry [1985, Figure 4].

3. Conflicting data points are arbitrarily excluded by Odin and Curry [1985, p. 1184] (for example, sample 101, "rejected as unreliable and discrepant").

Figure 5 [Odin and Curry, 1985] again shows temporal gaps separating clusters of ages in discrete horizons, possibly indicative of large hiatuses, or closure of the glaucony systems in different areas at similar times during phases of transgression and deposition. In fact, Odin [1982, p. 793] states that "this may illustrate the fact that the apparent age of an evolved glaucony is related to the time of closure, which occurs during deposition of the covering deposits". Odin [1982, pp. 296 and 304] further states that the highly evolved glauconies, which he promotes as the most reliable for dating, "represent

10^5-10^6 years of evolution," and in regard to closure of the chronometer, "in relation to biozonation, this moment is closer to the moment of deposition of faunas in the horizon immediately above the glaucony than to that of the faunas deposited with the glaucony" (emphasis original). Glauconies may well date the time of deposition of overlying rocks rather than the age of the sediments in which they are found. Perhaps this accounts for the generally younger ages of the (northwest European-based) glaucony chronology of Curry and Odin [1982] relative to the high-temperature date-based global chronology of Berggren et al. [1985a]. Great caution must be exercised in interpretation of glaucony ages from the Paleogene of northwest Europe because of the impossibility of determining the timing of closure of the glaucony system and the episodic history of transgression and regression in this epicontinental sequence.

Biased Selectivity of Odin and Curry [1985] and Curry and Odin [1982]

Odin and Curry are highly selective in their choice of calibration points for their geochronology [Curry and Odin, 1982], contrary to their claim [Odin and Curry, 1985, p. 1182] that they "use all published information" Biased selectivity is particularly obvious for two of the examples discussed by Odin and Curry [1985]: the Thanetian (Thanet Formation, pp. 1184-1185) and the Paleocene/Eocene boundary (London Clay, etc., p. 1185).

The Thanetian. A "difference between magnetic and radiometric dates" for the Thanetian exists only "If Odin's conclusions are accepted" regarding "Odin's preferred date on the Thanet Formation" [Odin and Curry, 1985, p. 1185]. There is no clear reason to accept Odin's preferred result, for the following reasons:

1. Odin [1982] regards his age (based on six determinations) of 54.8 ± 3.5 Ma on the uppermost Thanet Formation as a minimum in view of the possible presence of weathering. Regarding these ages Odin [1982, pp. 674-675] further states that "the heterogeneity of the results . . . is not a favorable indicator of the reliability of the apparent ages obtained. . . Samples from the Thanet beds are apparently not favorable for the obtaining of accurate analytical results." (In actual fact, the term "accurate analytical results" should read "accurate geologic results.") The analysis may be accurate and still yield incorrect numbers in terms of dating the actual time of deposition. Geologic accuracy and analytical accuracy need not be synonymous. Yet Curry and Odin [1982] still choose to use these unreliable Thanet results as five of their six chronology calibration ages for the Thanetian. Clearly, the uppermost Thanet Formation may well be older than 55 Ma, as in fact proposed by Berggren et al. [1985a].

2. Glaucony ages from Thanetian strata vary widely, ranging from 52.5 to 64.1 Ma; one horizon (NDS 16) gave three separate ages of 52.5, 56.0, and 57.5 Ma when analyzed by different laboratories at different times.

3. Odin and Curry [1985, p. 1185] cite a set of five ages (NDS 27, 28, 38, 39; mean = 54.3 Ma) from Thanetian strata of France and Belgium that "appears to be of good quality and reliable" to support Odin's "preferred" age for the Thanet Formation. However, there are several significant problems with the "corroborating" ages:

3a. Sample NDS 28 gives "evidence of weathering which may have slightly lowered (by 0-5%) the Ar/K ratio," and the validity of the age is justified by Odin [1982, p. 685] because it "is similar to all those obtained for Thanetian glauconies" (but see points 1 and 2 above).

3b. Sample NDS 38 (two determinations; Sables de Bracheux) "may have been altered by percolating water," and appears to result from "slow deposition and long evolution," and "the precise moment of closure is not established" [Odin, 1982, pp. 694-695].

3c. It is stated of sample NDS 39 (Sables de Bracheux), "Unfortunately these sands are not precisely situated in the pelagic faunal sequence" [Odin, 1982, p. 696].

3d. These five results span a long biochronologic interval (NP6 to NP9 [Odin, 1982]); and the glaucony ages appear to be poorly or inversely correlated with the biochronologic ages listed in the NDS descriptions (Table

TABLE 3. Comparison between biochronologic ages and glaucony ages for Thanetian beds [form Odin, 1982]

Sample	Biostratigraphic Assignment	Age, Ma	Source
NDS 39	(?NP8-NP9)*	56.0±1.9	Sables de Bracheux
NDS 38	NP8-NP9	54.2±1.9	Sables de Bracheux
NDS 38	NP8-NP9	54.6	Sables de Bracheux
NDS 28	NP7-NP8	54.1±2.0	
NDS 27	NP6	52.6±2.4	

* For a discussion of this assignment, please see text.

3). (Parenthetically, one may ask with regard to sample NDS 39 that if this core sample is indeed from the Sables de Bracheux, why the questionable biostratigraphic assignment to ?NP8-9. The Sables de Bracheux are definitely of late NP9 age.)

3e. Odin and Curry [1985] ignore conflicting results from the Sables de Bracheux, discussed by Berggren et al. [1985a].

3f. Odin and Curry [1985] ignore conflicting, apparently reliable, glaucony ages from the U.S. Atlantic Coastal Plain listed by Odin [1982]: NDS 113 correlative with the early or middle Thanetian at 57.5 ± 2.0 Ma and the early Eocene NDS 112 with an age (54.9 ± 1.8) older than many of their "preferred" Thanetian values. Both NDS 112 and 113 are tightly constrained biochronologically (see discussion above).

Early Ypresian and the Paleocene/Eocene boundary. Contrary to Odin and Curry's [1985, p. 1185] assertion that their early Eocene age estimates are "not challenged by any other item pointing to a notably older estimate," we provide the following items and observations:

1. Although Odin and Curry [1985] emphasize the conflict between the Curry and Odin [1982] and Berggren et al. [1985a] chronologies near the Paleocene/Eocene boundary, Odin [1982, p. 715] recognized that the early Eocene calibration points for Curry and Odin [1982] were "generally poorly reliable data obtained in Europe." As can be seen in Figure 4 of Curry and Odin [1982], very few glaucony ages constrain the early Eocene.

2. The single London clay result of 50.9 ± 2.2 Ma (cited as 50.9 ± 2.9 Ma in NDS 12 in the work of Odin [1982, p. 669] is recognized by Odin and Curry [1985] to be on a glaucony of poor quality. Odin [1982, p. 670] further stated that "this apparent age will be considered as *a minimum for the London clay*" (emphasis original). The older age for the Paleocene/Eocene boundary advocated by Berggren et al. [1985a] cannot be considered strongly contradicted by this single, poorly reliable, minimum age estimate.

3. The discussion of Odin and Curry [1985, p. 1185] selectively ignores two contradictory early Eocene glaucony results listed by Odin [1982]. Sample NDS 112 is from the lower Eocene Manasquan Formation of the Atlantic Coastal Plain and "the analytical result" (54.9±1.8 Ma) "may be used as a minimum value for the Paleocene-Eocene boundary" [Odin, 1982, p. 775]. Curry and Odin [1982, p. 623] observe that this age is significantly older than that (mean apparent age of 50.8 Ma) on coeval glauconies of the Bashi Marl in the Gulf Coast as well as lower Eocene glauconies from the middle part of the London Clay (NDS 12; approximately equivalent to Zone NP11; age of 50.9 ± 2.9 Ma [Odin, 1982 p. 669]). On the other hand, the Manasquan age of 54.9 ± 1.8 Ma is comparable to the ages of 53.0 ± 2.4 Ma and 52.6 ± 3.4 Ma obtained on the upper glauconitic part of the Argiles de Varengeville (NDS 37 [Odin, 1982, p. 693]) which is

equivalent to Zone NP11. Despite the fact that all these ages are from levels within the early Eocene (Ypresian), Curry and Odin [1982] place the Paleocene/Eocene boundary (as correlated to the Thanetian/Ilerdian boundary) and middle part of Zone NP9 at 53.1 ± 1 Ma and the base of the Ypresian (as correlated to the NP10/11 boundary) at 51 Ma. It will be seen that the Manasquan age of 54.9 ± 1.8 Ma (Zone P6b) and, to a somewhat lesser degree, the Varengeville ages of 53.0 ± 2.4 Ma and 52.6 ± 3.4 Ma (Zone NP11) are in relatively close agreement with the age estimate made here of 57 Ma for the Paleocene/Eocene boundary (within Zone NP10), and both support an age for the Paleocene/Eocene boundary (equivalent to the base of the Ypresian) older than the 51 ± 1.5 Ma proposed by Curry and Odin [1982] for the Pseudohastigerina datum (with which we would equate the base of the Ypresian). It should be kept in mind that the estimate of 53 ± 1 Ma for the Paleocene/Eocene boundary by Curry and Odin [1982] refers to their correlation of the Thanetian/Ilerdian boundary (middle part of Zone NP9) with the Paleocene/Eocene boundary. Our magnetobiochronologic estimate for this level would be between 58 and 59 Ma.

4. The K-Ar age determinations on the Blosseville Basalt have been discussed in detail by both Odin and Curry [1985] and Berggren et al. [1985]. Although Odin and Curry [1985] conclude that one suite of ages on this unit is consistent with the chronology of Curry and Odin [1982], this conclusion does not negate conflicting, older ages on the same unit.

Odin and Mitchell [1983] have dated six basalt flows from the Scoresby Sund, East Greenland area, and obtained a mean age of 50.0 ± 1.4 Ma. They contend that the mean value is a more realistic expression of the actual age for the extrusion of the basalts and "emphasize that the results presented here from the Scoresby Sund tholeiites, appear easier to interpret than the preceding ages reported by Beckinsale et al" [Odin and Mitchell, 1983, p. 119]. While Odin and Mitchell [1983] do not question the quality of the results obtained by Beckinsale et al. [1970], they believe that their single group of basalt ages at 50.0 ± 1.4 Ma should supersede the perplexing existence of a bimodal distribution in Beckinsale et al.'s [1970] age data (around 46 and 56 Ma). However, if they do not question the quality of the results, they infer that analytically, Beckinsale et al. (1970) measured correctly the quantity of argon and potassium present in the rock. There can only be two explanations then for ages older and younger than 50 Ma. Ages older than 50 Ma would imply the existence of excess radiogenic argon. Yet Odin and Mitchell [1983, p. 117] "conclude, therefore, that inheritance of radiogenic argon is unlikely to have occurred." Given this assessment and the unquestioned analysis of Beckinsale et al. [1970], we can only conclude that the ages grouping around 56 Ma have real meaning regarding the timing of the extrusion of these lavas. Fitch et al. [1978, p. 504] state, "Thus, the most accurate estimate of the true age of the upper part of the main sequence of basalt lavas currently available may be that indicated by the regressive line analysis of the fresher rocks from Kap Brewster, i.e., close to 54.5 ± 1.0 Ma (Fig. 4). This conclusion is considerably strengthened by the results of correlation diagram regression analysis of K-Ar apparent ages quoted by Tarling and Gale [1968] for the basalts of the Faeroe Islands." Utilizing modern decay constants, the age quoted above should be 55.8 ± 1.0 Ma. A different treatment of the Kap Brewster results by Obradovich (in the work of Berggren et al. [1985a, Appendix 1]) leads to an age of 56.5 ± 0.6 Ma.

For ages younger than 50 Ma, the explanation is argon loss due to deuteric alteration of the glassy phase of these basalts. Beckinsale et al. [1970, p. 31] in discussing the results for the Kap Brewster flow state, "Samples from the interior of the flow which is about 30 m thick gave ages down to ca. 46 m.y. and appeared to have suffered argon loss in the same pattern as has been found for the Palisades sill [Ericksen and Kulp, 1961]. In thin sections of the basalt this pattern can be seen to correlate with increasing deuteric alteration and large quantities of brown glass, now partially altered, which probably contains the bulk of the potassium in the rock." This latter point needs to be discussed in greater detail.

When the radiometric ages by Mitchell were first mentioned by Hailwood et al. [1973, p. 47], the material selected was "particularly fresh." Odin and Mitchell [1983, p. 116] later remark that "petrological examination of all of the analyzed specimens in thin section showed them to be very fresh except for partial palagonitization of interstitial glass which originally formed less than 5% of most samples." Later in this same article [Odin and Mitchell, 1983, p. 120] they conclude: "This age may be tentatively be written as $50.0\,^{+3.9}_{-1.4}$ Ma, assuming the possibility of a 5% rejuvenation of the lower basalts." This upper limit of +3.9 Ma is based on the erroneous assumption that the potassium is uniformly distributed throughout the basalt specimen. Dalrymple and Lanphere [1969, p. 182] state, "Similar electron microprobe studies on basalts that contain glass have shown that the interstitial glass contains most of the potassium. For this reason, a careful evaluation of the conditions and composition of the interstitial material is very important for whole-rock dating." If most of the potassium is in the glass and the glass is partially palagonitized, the question arises as to just how much argon has been lost? Saying that the amount of rejuvenation is limited to 5% simply ignores the points made earlier regarding the location of the potassium in the basalt. Electron microprobe analysis of the Blosseville samples would clearly indicate the distribution of the potassium and would either substantiate or disprove the assertion by Odin and Mitchell that only a 5% rejuvenation is realistic.

Despite the limited range of ages reported by Odin and Mitchell vis-a-vis Beckinsale et al. [1970], we contend that the situation now is that we have a complete spectrum of ages from 46 to 56 Ma and only those ages around 56 Ma are unlikely to reflect alteration. We contend that Odin and Mitchell have succeeded in filling the gap between 46 and 56 Ma by their analyses of less altered (but nonetheless altered) samples as compared to those of Beckinsale et al. We now simply have a continuum of ages between 46 and 56 Ma with the ages of 56 Ma representing the best estimate of the time of lava eruption.

One additional point needs to be made concerning the Blosseville Basalt ages. These basalt samples are extremely heterogenous as indicated by the extremely large errors attached to the analyses. Two σ errors (95% confidence limit) range from 4.9 to 9.1% despite triplicate analyses for potassium and duplicate analyses for argon. For a homogeneous sample with 30% radiogenic argon, $\pm 2\sigma$ values of 3% are readily achievable for conventional K-Ar analyses. Perhaps the definitive answer will only come about when a ^{40}Ar–^{39}Ar stepwise heating study is undertaken on these crucial samples.

Despite the contention by Odin and Curry [1985, p. 1185] "that the homogeneity of the newer dates points to their geological reliability," we believe the most rational interpretation of the results is that only those samples whose ages are near 56 Ma have not suffered argon loss. All the rest have to varying degrees.

We agree with Odin and Curry [1985, p. 1185] that "at the worst, . . . there are problems with the K-Ar ages of the Blosseville basalts," but we disagree emphatically that the age of 50.0 ± 1.4 Ma is correct just because it is consistent with the data of Curry and Odin [1982] or Odin and Curry [1985]. We stress that Odin and Curry's preference for the younger Blosseville Basalt ages does not provide sufficient basis for rejecting the older values of Beckinsale et al. [1970] as reassessed by Fitch et al. [1978] and Obradovich (in the work of Berggren et al. [1985a]); revised stratigraphic assignment for the Paleocene/Eocene boundary is now seen to be in even closer agreement with these ages (see below).

Conflicting results on glaucony and K-Ar ages. Odin and Curry [1985] do not adequately justify their selective disregard of conflicting results on glaucony (for example, NDS 55, Danian/Thanetian boundary; NDS 246, middle Eocene) and the K-Ar ages on high-temperature minerals (NDS 42, 43, 50, 52, 58, 103, 120, 126, 138, 154-156; see also discussion above, Berggren et al., [1985a]; Flynn [1986]; Montanari et al. [1985]) in other temporal intervals. Results on whole-rock basalt dates from the northwest United States

TABLE 4. Paired Age Analyses on Lutetian-Bartonian Samples [from Odin, 1982]

NDS	Sample	K-Ar Age, Ma	Rb-Sr Age, Ma	Sample	NDS
1	G97A	38.9±1.8	37.4±0.7	G97A	159
2	G148AB	39.1±1.5	38.7±1.2	G148AB	159
6	G437A	43.6±2.8	42.9±0.7	G437	160
7	G145A	43.9±2.0			
7	G145A	43.7±1.8			
7	G435A	44.4±2.3	42.9±1.3	G435A	160
10	G144AB	46.4±1.5	45.1±0.9	G144AB	160
4	G150A	40.4±2.3	38.4±0.9	G150A	212
4	G150A	40.1±1.8			
4	G396A	40.7±1.4			

[Prothero and Armentrout, 1985] and the biochronologically and magnetochronologically well-constrained pelagic sequences at Gubbio, Italy [Montanari et al., 1985] support the approximately 37 Ma Eocene/Oligocene boundary estimate of Berggren et al. [1985a] rather than the 34 Ma estimate of Curry and Odin [1982].

Calibration points. Of the 47 calibration points used in Figure 4 of Curry and Odin [1982], 14 of the points were stated by Odin [1982](NDS listings) to be minimum estimates; possibly anomalously younger because of alteration, poor mineral closure, or tectonism; or of poor reliability. These points hardly seem appropriate for establishing a standard geochronology.

K-Ar and Rb-Sr ages. Odin and Curry [1985] use both K-Ar and Rb-Sr ages on the same samples as independent calibration points, even when there are conflicts or geochemical anomalies between the two systems. In particular, the following discrepancies are noted:

1. A series of K-Ar and Rb-Sr ages from the Lutetian/Bartonian "Bande Noire" (NDS 84) indicate age discrepancies of up to 10% between the K-Ar and Rb-Sr systems on the same sample.

2. Rb-Sr analyses on two samples from the same horizon (NDS 212) differ by more than 3 m.y. (38.4 ± 0.9 versus 41.4 ± 0.7 Ma).

3. Pairs of analyses from the same samples on the same horizons (Lutetian/Bartonian strata) reveal consistent discrepancies in which Rb-Sr ages are from 0.4 to 1.85 m.y. younger than equivalent K-Ar ages (Table 4).

4. All of these conflicting analyses (NDS 84, 212, 1, 3, 6, 7, 10, 4, 159, 160) are used by Curry and Odin [1982] as calibration points. While we recognize that these different ages may not be statistically significant at the 95% confidence limit, we draw attention merely to the systematic deviation which is observed.

Internal Discordance of the Odin and Curry [1985] and Curry and Odin [1982] Chronologies

Odin and Curry [1985, p. 1182] claim that some of their Paleogene calibration samples "have been dated by as many as three laboratories and the group of ages as a whole forms an internally concordant set" However, many of the points raised above, and below, indicate that the data do not form an internally concordant set.

1. Dating of the same samples/horizons by different laboratories at different times often yielded widely discrepant results (see Odin [1982]; NDS 14, 16, 18, 29, 56, 90). For instance, NDS 16 cited glaucony ages from two horizons in upper Thanetian strata of 56.0 ± 2.1 Ma (K-Ar, Odin, Berne), 52.5 ± 1.7 Ma (K-Ar, Bonhomme, Strasbourg), and 57.5 ± 3.0 Ma (Rb/Sr isochron, Bonhomme et

Table 5. Summary of the Internal Inconsistencies of the Odin and Curry Glaucony Chronologies

Item	Sample	CO82*	OC85+	NDS	NDS Abstracts
1	109	uppermost NP8	NP8	16	NP8; top Thanet Beds
2	432	same horizon	NP8 (above 432)	17	late Thanetian
3	420 (=24)	base NP10	base NP9	14	NP9 (Thanetian/Ypresian boundary)
4	101	upper NP10	NP9 or NP10	13	?base NP10 (base London Clay
5	230	middle NP11	middle NP11	12	?NP11 (lower Ypresian)
6	96	middle to upper NP13	NP12/NP13 boundary	11	base NP 13 (Bracklesham Bed IV)
7	144	same horizon as 6	NP13 or NP14	10	NP13 (Bracklesham beds V-VI)
8	435	lower-middle NP14	NP14	7	NP13/NP14 boundary (Bracklesham Bed IV)
9	145	same horizon as 8	NP14 (above 435)	7	NP13/NP14 boundary (Bracklesham Bed IV
10	234	not shown	NP14	9	base Lutetian (Brackle-(sham Bed VIII)
11	437	middle to upper NP14	NP14 or NP15	6	"NP10" (<u>vel</u> NP14) (Bracklesham Bed IX)
12	396	uppermost NP15	NP15	4	NP15
13	150	NP15/NP16 boundary	NP15/NP16 boundary	4	NP15
14	148	upper NP16	base NP16	3	near NP15/NP16 boundary
15	98	middle to upper NP17	middle to upper NP16	2	top NP16/base NP17
16	97	same horizon as 15	NP16 (above 98)	1	top NP16/base NP17

The biochronology conflicts are as follows: between Curry and Odin [1982] and Odin and Curry [1985], item 3, 6. 14, 15, and 16; between Curry and Odin [1982] and the NDS abstract, items 3, 4, 6, 8, 9, 13, 14, 15, and 16; and between Odin and Curry [1985] and the NDS abstract, 8, 9, 13, 15, and 16.

* Curry and Odin [1982, Figure 4].

\+ Odin and Curry [1985, Figure 4].

al.) for horizon 1, and of 54.6 Ma and 55.0 Ma (K-Ar, Obradovich, Berkeley 1964) and 53.1 ± 3.3 Ma (K-Ar, Odin, Berne) for horizon 2 [see Odin, 1982, p. 673]. Dates cited in NDS 16 were used as calibration points in curry and Odin [1982], even though conflicts of 5 m.y. (10%) exist between ages from both horizons.

2. Berggren et al. [1985a, Table 2] list 19 ages on glaucony from lower-middle Eocene strata in northwestern Europe that illustrate internal discordance in the results from the same biochronologic intervals. As Odin and Curry [1985, p. 1186] find Table 2 of Berggren et al. [1985a] confusing, Odin and Curry [1985, Figure 5] attempt to portray this information graphically (although four ages from Berggren et al. [1985a, Table 2], are arbitrarily omitted, including the conflicting Argiles de Varengeville result discussed above).

3. Discrepancies and internal discordance exist even between different versions of the Curry and Odin [1982] chronology. Many dated samples are placed in different biochronologic positions by Curry and Odin [1982, Figure 4] relative to Odin and Curry [1985, Figure 4], and relative to the positions indicated in the NDS abstracts [Odin, 1982]. Such inconsistencies

raise serious doubts about the validity of the methodology of constructing the Curry and Odin [1982] chronology. Table 5 presents a summary of the internal inconsistencies of the Odin and Curry [1985] and Curry and Odin [1982] glaucony chronologies.

CONCLUDING REMARKS

Geology is a historical philosophy. The reconstruction of the history of the Earth involves integration of data from the area of geostratigraphy (i.e., the physical evidence of geologic data) and geochronology (i.e., the conceptual division of continuous time as measured by the progression in an ordinal series of events). As observed so cogently by Blow [1979] in the quotation at the beginning of this article, geochronology is an integral part of the geostratigraphic sequence and not a scale of numerical dates dependent solely on isotopic dating.

Indeed, as discussed above, and by Berggren et al. [1985a], isotopic dating is an essential component of geochronology, but it is still a long way from providing the precision that biostratigraphy allows, in particular if coupled with magnetostratigraphy in regional or global correlation. Thus, we would object in part to Odin and Curry's [1985, p. 1186] statement that "radiometric dates must provide the major control for numerical geological time-scales: the use of magnetostratigraphic information for this purpose is unacceptable except for interpolations over a short time span. Such scales should consider all available data, should be based on as many tie-points as seem reliable, and should be accompanied by estimates of margins of error." We do agree with Odin and Curry [1985] in that a time scale "should be based on as many tie points as seem reliable." We disagree, however, as to what constitutes reliable data. It is the use of standard reference sections that is a cornerstone to determining reliable data.

Two ordinal scales are widely used today: radiochronology and biochronology. Geomagnetic polarity reversals are nonordinal (iterative) repetitions but have been closely correlated with the radiometric time scale for the past 10 m.y. and with the biochronologic scale for the Cenozoic and the Late Cretaceous. In this way the polarity reversal sequence has assumed a secondary, shadowy ordinality of its own where the paleomagnetic record is so complete that its more distinctive variations can be securely identified.

Magnetostratigraphy (if it contains a diagnostic polarity signature and is coupled with age diagnostic fossil assemblages) and biostratigraphy are, by far, more superior means of correlation than isotopic ages, and the first goal of a time scale is to provide firmly established correlations. The dilemma posed in the title "The Palaeogene time-scale: Radiometric dating versus magnetic approach" [Odin and Curry, 1985], as we view it boils down to a different philosophical approach: a choice between an undiscriminating time scale where all stratigraphic levels and in particular chronostratigraphic boundaries yield an inherent 1 m.y. uncertainty in analytical precision alone and an unknown "geological error", and a time scale which allows discrimination of closely spaced events with a precision of an order of magnitude better than this and which thus provides the precise geochronologic framework necessary for understanding historical geological processes and rates.

Construction of a geologic time scale is an iterative procedure that should incorporate the best attributes of all available data sets. We have identified four major independent data sets (biochronology, isotopic dating, biostratigraphy, and magnetostratigraphy), and each plays an important role in time scale construction. One important outcome of this critique should be the expressed need for a more comprehensive comparison between biostratigraphic and magnetostratigraphic reference sections and the available isotopic age data (with appropriate error limits). As with the identification of type samples and type sections, this should lead to the identification of "type isotopic calibration points."

The chronology of Curry and Odin [1982] was based on approximately 70 selected ages that "were thought to be of sufficient quality for the purposes of time-scale calibration" [Odin and Curry, 1985, p. 1182]. The above discussion emphasizes the many problems with the selection process and the glaucony ages used by Curry and Odin [1982]. Harland [1983, p. 395] expressed similar reservations about the use of glauconies for chronology because of the complexities of genesis of the authigenic glaucony system: "It leaves one wondering how useful may be any glaucony data that have not been fully investigated by Odin himself. The test of this will eventually be found in comparisons between a glaucony time-scale and others based on different minerals and methods." We believe that integration of biochronology and magnetochronology with high-temperature isotopic ages [Berggren et al., 1985a) provides such a comparison. On the basis of the methodological and empirical objections expressed above and in the work of Berggren et al. [1985a], we believe that Odin and Curry have failed to justify the validity of their northwestern European glaucony chronology as a global geochronology, and we view a time scale solely established on isotopically dated chronostratigraphic boundaries more as a geochronometry than as a geochronology.

APPENDIX 1: THE AGE OF THE PALEOCENE/EOCENE BOUNDARY

The secure correlations which can now be established based on mineralogy (ash layers [Knox, 1984]), calcareous nannofossil biostratigraphy [Aubry, 1983, 1986](W. G. Siesser, personal communication, November 1985), magnetostratigraphy [Townsend and Hailwood, 1985], and magnetobiostratigraphy [Aubry et al., 1986] indicate that the Paleocene/Eocene boundary (equivalent to the Woolwich-Reading Beds'/Oldhaven Beds' lithostratigraphic boundary, i.e., base of the Oldhaven Beds) falls within Zone NP10 rather than at the NP9/NP10 zonal boundary where it is generally placed. As a result, its age must be slightly younger than estimated by Berggren et al. [1985a].

Estimation of the age of the Oldhaven Beds is of critical importance for estimating the age of the Paleocene/Eocene boundary which, since Von Koenen's [1885] work, is placed in the London and Hampshire basins between the base of the London Clay and the Woolwich-Reading Beds. The upper Paleocene-lower Eocene deposits of the London and Hampshire basins are the only deposits of this time interval which, in northwestern Europe, yield sufficient elements for correlation with deep-sea deposits. Calcareous nannofossil biozone NP9 has been identified in the Woolwich-Reading Bottom Bed [Hamilton and Hojjatzadeh, 1982; Siesser et al., 1987] (W. G. Siesser, written communication, November 1985). Magnetobiostratigraphic correlations indicate that the position of the Woolwich-Reading Beds is in the upper part of that zone, based on the evidence that Chron C25N is missing in the London and Hampshire basins [Aubry et al., 1986]. Indirect correlations by means of volcanic ash layers [Knox, 1984] corroborate this position and suggest that the NP9/ NP10 zonal boundary occurs within the Woolwich-Reading Beds. Because the Paleocene/Eocene boundary in the deep sea is commonly drawn at the NP9/NP10 zonal boundary, Knox [1984] suggests that it be placed within the Woolwich-Reading Beds, between the marine Bottom Bed and the overlying freshwater to lagoonal sands and clays of the Hampshire and London basins. Aside from the fact that the base of Zone NP10 can rarely be characterized due to the general scarcity of Tribrachiatus bramlettei in oceanic sediments, this suggestion is unfortunate because the Paleocene/Eocene boundary cannot be moved to satisfy a biozonal boundary used elsewhere to approximate it. The Paleocene/Eocene boundary has been defined in northwestern Europe as corresponding to a major lithostratigraphic boundary. Knox's (1984) results merely indicate that the Paleocene/Eocene boundary lies within Zone NP10 and does not correspond to the NP9/NP10 zonal boundary. In the London Basin, the ash sequence of the North Sea subphase 2a [Morton and Knox, 1983] extends from the marine Woolwich Beds up to the Harwich Member of the London Clay, a lateral equivalent of the Oldhaven Beds [Cox et al., 1985]. This ash sequence is equated with the bentonites which occur in the basal

Eocene sediments of the Goban spur area (DSDP 550) [Knox, 1985]. Calcareous nannofossil biostratigraphy allows assignment of these bentonites to the lower half of Zone NP10 and provides evidence that the onset of subphase 2a volcanic activity correlates with the NP9/NP10 zonal boundary [Knox, 1984, 1985]. Since an unconformity is developed between the Woolwich-Reading Beds and the Oldhaven Beds [King, 1981; Knox et al., 1983; Aubry et al., 1986], the base of the Oldhaven Beds, taken as the base of the Eocene, must lie quite high in Zone NP10. As these elements of correlation were not available when Berggren et al.'s [1985a] manuscript was being prepared, the Paleocene/Eocene boundary was approximated with the NP9/NP10 boundary and was estimated at 57.8 Ma. On the new grounds presented above, it is clear that this estimated age is too old and must be revised. We correlate the Paleocene/Eocene boundary with the upper part of Zone NP10 and estimate its age at 57 Ma. We point out, in passing, that the position of the Paleocene/Eocene boundary in Figure 2 of Aubry et al. [1986] was incorrectly drawn (owing to a drafting error) within the Woolwich-Reading Beds, rather than at the base of the overlying Oldhaven Beds.

APPENDIX II: PALEOGENE GEOCHRONOLOGY

The following comments refer to particular points on the Paleogene time scale recently published by Berggren et al. [1985a, b]. In some instances, they require corrections to published figures and these are included here in the form of revised figures (Figures 6 and 7).

1. In the work of Berggren et al. [1985b, Figure 5] and Berggren et al. [1985a, Figure 6], the P18/P19 zonal boundary (defined by the FAD of Dentoglobigerina sellii) is drawn at 34.0 Ma. Inasmuch as there was no (un)published data regarding the FAD of this taxon, the LAD of Pseudohastigerina was chosen.

2. The base of Zone NP10 corresponds to the FAD of Tribrachiatus bramlettei and its top, and that of Zone CP9a to the LAD of Tribrachiatus contortus. In actual fact, T. bramlettei is often rare, and the LAD of Fasciculithus is used to denote the base of Zone NP10 as was the case in the work of Berggren et al. [1985a, b]. The base of Zone CP9 is defined by the FAD of T. contortus. The CP8/CP9 boundary is correlative with a level within Zone NP10. According to the data of Berggren et al. [1985b] Zone NP10 spans the interval from 57.6 Ma to 56.8 Ma, and Zone CP9a spans from 56.8 Ma to 56.3 Ma. The temporal values of Zones NP10 and CP9a were incorrectly drawn in the work of Berggren et al. [1985b, Figures 3 and 4] and Berggren et al. [1985a] [Figures 3, 5]. They are corrected here in Figures 6 and 7.

3. The base of Zone P7 (The Morozovella formosa Zone) is defined by the FAD of M. aragonensis; that of Zone P8 (M. aragonensis Zone) is the FAD of Acarinina pentacamerata. In the work of Berggren et al. [1985b, Figures 3 and 4) and Berggren et al. [1985a, Figures 3 and 5] the base of Zone P7 was inadvertently drawn at the FAD of Morozovella formosa (56.1 Ma, base anomaly 24 correlative). The base of Zone P8 was drawn at the FAD of M. aragonensis at 55.2 Ma and the top of anomaly 24 correlative. The base of Zone P7 is redrawn here (Figures 6 and 7) at the FAD of M. aragonensis at 55.2 Ma. Lacking a direct magnetobiostratigraphic correlation for the FAD of Acarinina pentacamerata, we have drawn the P7/P8 boundary (arbitrarily) at 54.0 Ma, approximately midway between the boundaries of Zones P6/P7 and P8/P9.

A corollary of these corrections and of the discussion presented above regarding the revised age estimates of the Paleocene/Eocene boundary is an upward (younger) repositioning of the chronostratigraphic units associated with the boundary interval. The Paleocene/Eocene boundary, as modified, is correlative with a level within Zone P6b, the middle of Zone NP10, and the uppermost part of the Apectodinium hyperacanthum Zone.

4. The top of the Truncorotaloides rohri Zone was originally defined as the LAD of the nominate taxon [Bolli, 1957; 1966] and this usage was followed by Berggren [1969] in erecting his Zone P14, by Berggren and Van Couvering [1974], and by Blow [1969] for his Zone P14 (Truncorotaloides rohri-Globigerinita howei Partial-range Zone). Blow [1979] subsequently emended

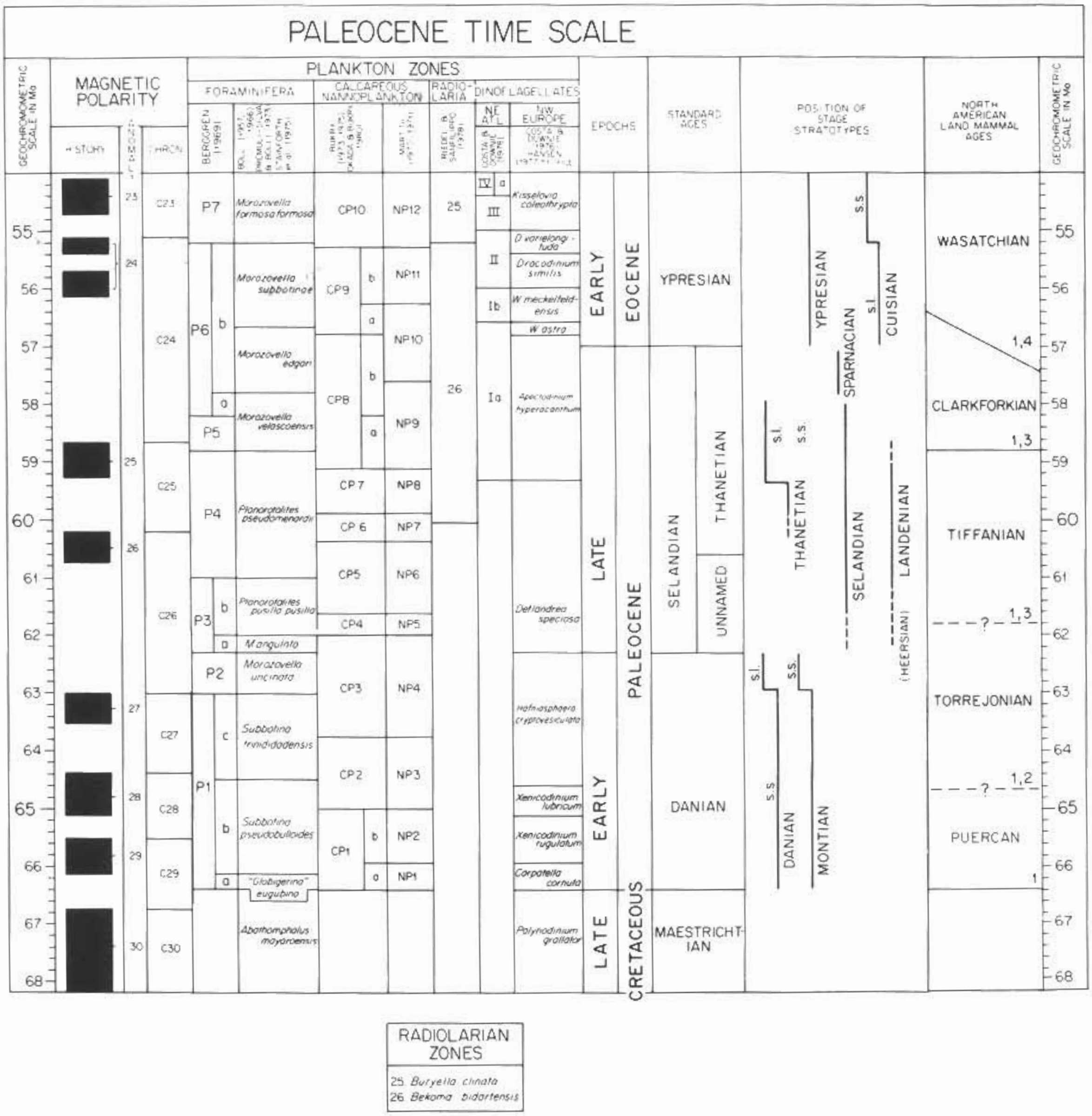

Fig. 6. Paleocene geochronology. The geochronologic scale is based on the work of Berggren et al. [1985b]. The position of zonal boundaries is based, for the most part, upon direct (first-order) correlation between biostratigraphic datum levels and paleomagnetic stratigraphy as determined in deep-sea cores or continental outcrops of marine sediments. The extent (duration) of standard time-stratigraphic units and their boundaries and the position of stage stratotypes are estimated on the basis of their relationship to standard plankton biostratigraphic zones. The geochronology of Paleocene North American Land Mammal Ages is shown on the right (footnote numbers at boundaries refer to sources used in determining the temporal position of these boundaries). Explanation of sources denoted by footnote numbers in this figure (and in Figure 7 below) are listed by Berggren et al. [1985b, Figure 3) and Berggren et al. [1985a, Figure 3), from whom this figure is modified.

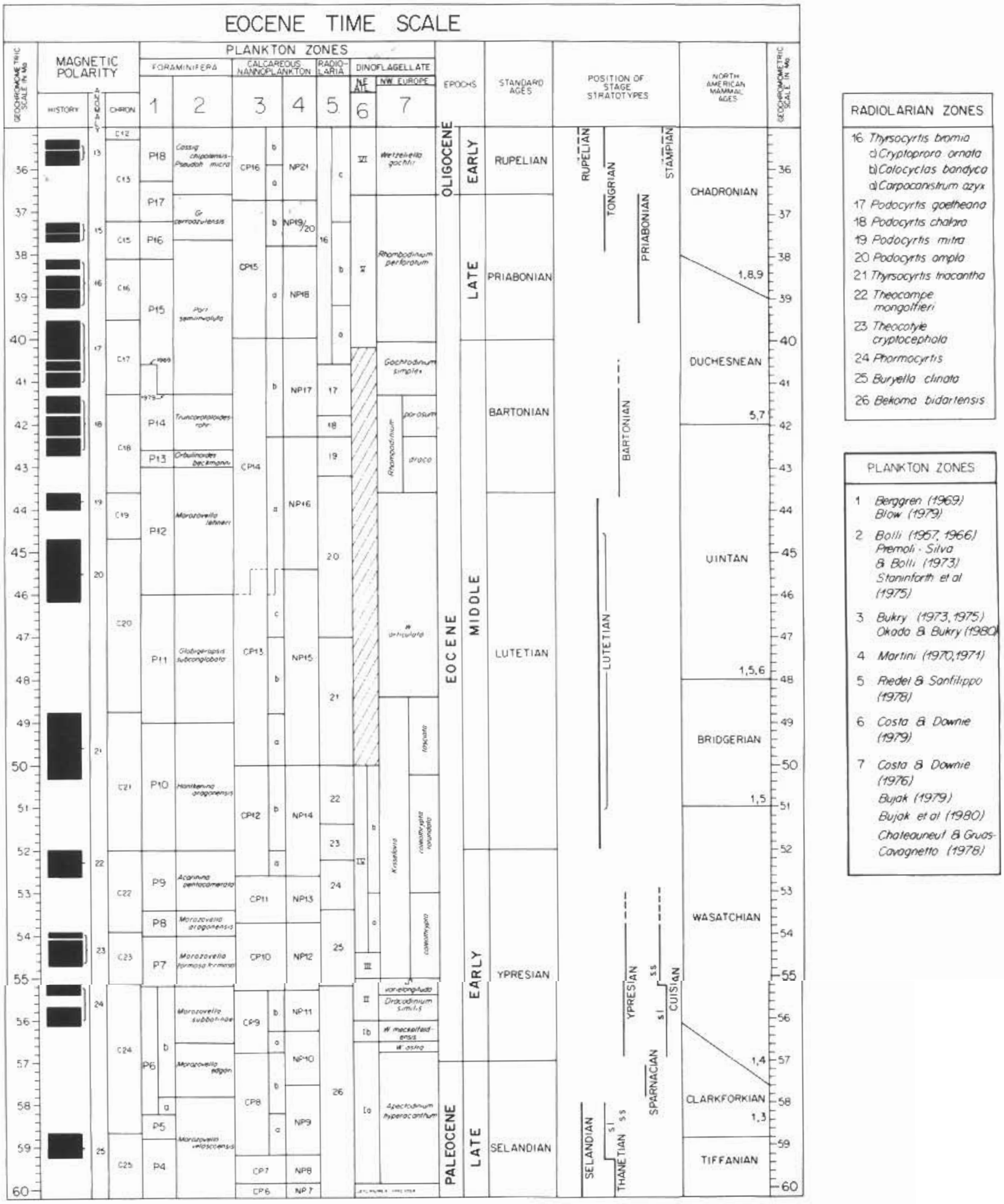

Fig. 7. Eocene geochronology (explanation as in Figure 6; modified from Berggren et al. [1985b, Figure 4) and Berggren et al. [1985a, Figure 5].

his zones P14 and P15 and drew the boundary at the FAD of Porticulasphaera semiinvoluta, i.e., within the upper part of the range of T. rohri. This emendation of Blow's zonation is shown by Berggren et al. [1985b, Figure 4) and Berggren et al. [1985a, Figure 5). However, the LAD of T. rohri (in mid Chron 17N at 40.6 Ma [Berggren et al., 1985a, p. 190]) was inadvertently drawn at 40.2 Ma. This is corrected here in Figure 7. The boundary between the T. rohri/Globigerapsis semiinvoluta Zone of Bolli [1957] (based originally on the LAD of T. rohri) was drawn at 41.2 Ma (estimated age of the FAD of Porticulasphaera semiinvoluta). This is in keeping with Bolli's [1966] (re)definition of his Globigerapsis semiinvoluta Zone based on the FAD of the nominate taxon (see also Blow [1979, p. 291]).

5. The top of Zone CP13 is shown by Berggren et al. [1985b, Figure 4; 1985a, Figure 5] with an alternate top at 45.0 Ma (LAD Nannotetrina fulgens) and 46.0 Ma (FAD Reticulofenestra umbilica). The correct value for the former should be 45.4 Ma, and this is corrected accordingly in Figure 7 in this paper.

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