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The Paleocene/Eocene boundary Global Standard Stratotype-section and Point (GSSP): Criteria for Characterisation and Correlation.

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WORKING GROUP ON THE PALEOCENE/EOCENE BOUNDARY *

Abstract:. The choice of a Paleocene/Eocene (P/E) Global Standard Stratotype-section and Point (GSSP) is complicated by the fact that there exists confusion on the exact denotation of the Paleocene and Eocene Series and their constituent lower rank (stage) units. While we can now resolve this problem by recourse to rigorous historical analysis, actual placement of the GSSP is further exacerbated by an embarrassment of riches (in regards to 7 criteria suitable for characterising and correlating a P/E GSSP but which span a temporal interval of >2 my).

Following the precept that the boundaries between higher level chronostratigraphic units are to be founded upon the boundaries of their lowest constituent stages in a nested hierarchy, we note that one of the criteria providing global correlation potential (a stable isotope excursion in marine and terrestrial stratigraphies) lies at a stratigraphic level more than 1my older than the base of the stratotypic Ypresian Stage to which the base of the Eocene Series has been subordinated until now. Lowering a chronostratigraphic unit by this extent risks a significant modification to the original geohistorical denotation of the Ypresian Stage and the Eocene Series.

We discuss here four options that are open to Voting Members of the Paleogene Subcommission. One solution consists in adjusting slightly the base of the Ypresian Stage (and, thus, the Eocene Series) so as to be correlatable on the basis of the lowest occurrence/First Appearance Datum (LO/FAD) of the calcareous nannofossil species *Tribrachiatus.digitalis*. Another solution would be to decouple series and stages so that the Ypresian Stage remains essentially unaltered but the base of the Eocene is relocated so as to be correlated on the basis of the Carbon Isotope Excursion (CIE).

Two (compromise) solutions consist in erecting a new stage for the upper/terminal Paleocene (between the Thanetian [*sensu* Dollfus] and Ypresian Stages) characterised at its base by the global stable isotope excursion. The P/E GSSP may then be placed at the base of the stratotypic Ypresian Stage (thus preserving historical continuity and conceptual denotation and stability) or at the base of the newly erected stage (facilitating correlation of the base of the Eocene series, at least in principle). Both GSSPs should be placed in suitable marine stratigraphic sections yet to be determined but upon which there is considerable current investigative activity.

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> "The history of the earth, with all its varied events, is written for us *only* in the sequence of rock strata making up the earth's crust. These strata carry the story, such as we can know it, like pages in a book. This book is already printed — without our help and without our advice. We can still divide it into chapters to suit ourselves, if we wish, but we can do this only by dividing it into groups of pages. There may be endless arguments among us to what events in the story should be the bases for the chapters, depending on individual interests and individual viewpoints, but the pages will remain the same regardless of how we group them. And, like the pages of the book, so the strata of the earth are our only fixed basis of reference for chapters in the history of the earth —for the definition of our chronostratigraphic scale."
> (Hedberg, 1961: 509-510)

INTRODUCTION

Stability in stratigraphic nomenclature and classification has become a necessity, both for the student of stratigraphy whose efforts in correlating distant sections is made difficult by the use of various stratigraphic concepts and lack of precise definition of chronostratigraphic units, and for the non-specialist who may be confused by the multitude of concepts hidden under a single chronostratigraphic term and/ or by the heterogeneous use of the same concept. The International Commission on Stratigraphy (ICS) has thus proposed rigorous definition of chronostratigraphic boundaries associated with the designation of a section to serve as reference for the boundary definition (Cowie, 1986; Cowrie et al., 1986; Remane *et al.,* 1996). Since then, various subcommissions on Stratigraphy have been active in describing Global Standard Stratotype - sections and Points (GSSPs). The Paleocene/Eocene (P/E) boundary is the last high-rank boundary still under consideration by the Subcommission on Paleogene Stratigraphy, the proposals for the Cretaceous/Paleogene, Eocene/Oligocene and Paleogene/ Neogene boundaries having been already ratified by the International Union of Geologist Scientists (IUGS).

After 10 years of active research and discussions, we are now in a position to select the criterion(ia) best suited to characterise the P/E boundary. The purpose of this paper is to describe seven events that occurred in Chron C24r and may serve to characterise the P/E boundary, and to evaluate their stratigraphic reliability and usefulness in order to provide the scientific community interested in this problem in Paleogene stratigraphy with the critical elements needed to make an informed choice of the boundary criterion/ia. Prior to this description, the shift in chronostratigraphic philosophy that has occurred since 1986 is briefly discussed so that the reader understands the issues to consider in selecting the criterion/a that will serve to characterise the P/ E boundary. Further discussion on these can be found elsewhere (Aubry *et al.,* 1999; Aubry, 2000).

ACTIVITIES OF THE WORKING GROUP ON THE P/E BOUNDARY AND IGCP 308

Since its inception in 1989 at the 28th International Geological Congress in Washington, the Working Group on the P/E boundary has been active under the auspices of UNESCO in the form of IGCP Project 308, and has devoted much of its efforts to describing and correlating marine (including deep sea) and terrestrial upper Paleocene-lower Eocene sequences in key areas of the world. Much effort has been placed on delineating the events that occurred during Magnetic Chron C24r, in a ~1.5my interval that encompasses various interpretations of the P/E boundary in marine and terrestrial stratigraphy (see Berggren & Aubry, 1996, 1998; Aubry, 2000).

The achievements of IGCP Project 308 were reviewed/ discussed at three successive meetings, a Penrose Conference in Albuquerque, New Mexico (Berggren et al., 1997), a Société géologique de France Séance Spécialisée in Paris, France (Thiry *et al.,* 2001) and an international meeting in Göteborg (Schmitz *et al.*, 2000). The magnitude and abruptness of changes that the earth underwent during Magnetic Chron C24r were never as well appreciated than as a result of these conferences. It has become clear that the world as we know it today largely stems from the major changes that took place during that time, a significant turning episode in the history of our planet.

Boundary Working Group activities have focused on two major issues. One is the characterisation of a boundary and its correlation, the other is the prospect for "boundary stratotype sections" in order to pinpoint the most suitable section to serve as the GSSP. In this context, among the greatest achievements of IGCP Project 308 are:

1. A composite chronologic succession of events constructed from fine scale analyses of disjunct stratigraphies in oceanic, shallow marine and terrestrial realms (Aubry et al., 1996; Berggren & Aubry, 1996, 1998).

2. The reappraisal of stratigraphic sections in key epicontinental areas such as northwestern Europe (e.g., Laga, ed. 1994; Knox *et al.*, eds., 1996), the Gulf Coast (e. g., Mancini & Tew, 1995) and the New Jersey Coastal Plain (e.g., Gibson *et al.*, 1993, 1994).

3. The detailed description of sections regarded as potential GSSPs.

Among these latter are outcrops in the Apennines (Corfield *et al.*, 1991), the central Negev (Benjamini, 1992), the eastern Pyrenees (Molina *et al.,* 1992), the Betic Cordillera (Molina et al., 1994; Canudo *et al.*, 1995; Lu *et al.*, 1996), the Basque Country (Canudo *et al.*, 1995; Orue-Extebarria, 1996), the Nile Valley (Schmitz et al., 1996; Aubry *et al.*, 1999) and the Tyrolian Alps (Egger, 1997).

Remane *et al.* (1996: 78) stress that ***"Correlation precedes definition"*** in the selection of a GSSP, adding however that "***it would be unrealistic to demand that a given boundary be recognisable all over the world before it can be formally defined***". We should like to point here that the two issues —correlation and definition— are quite distinct, at least with regard to the Cenozoic stratigraphic record.

Powerful correlation tools used in connection with time scales such as the Integrated Magneto-Biochronologic Scale (IMBS; Berggren *et al.,* 1995) provide a means towards rigorously estimating the completeness of stratigraphic sections, and, consequently, for establishing true temporal correlations (see Aubry, 1995, 1997, 1998b). Using the method of temporal interpretation of stratigraphic sections we have shown that most upper Paleocene-lower Eocene deep sea and land sections (among which those considered as potential GSSPs) constitute a discontinuous record of Chron C24r (Aubry *et al,* 1996, 2000; Aubry, 1998a, b). Of the two dozen deep sea and marine land sections that have been examined so far, only two can be confidently said to be essentially continuous across the carbon isotope excursion (CIE), one of the candidate criteria for characterising the P/ E boundary (see below). However, the same powerful tools have allowed us to construct a firm relative chronology of events from disjunct and/or discontinuous stratigraphic records. The consequence is that whereas there is a choice of criteria to characterise the P/E boundary and correlate it around the world, we have no suitable GSSP to propose. Because much effort has been placed in soundly correlating the numerous sections studied, we believe that decision on the criteria(ion) which will characterise the boundary prior to its definition (i.e., the formal designation of a lithostratigraphic horizon in a chosen section) is tenable.

PHILOSOPHICAL APPROACH TO CHRONO-STRATIGRAPHY: TWO OPPOSITE PRECEPTS

Strict application of the principles of chronostratigraphy dictates that the base of a series be defined by the base of its oldest constituent stage (see Hedberg, ed., 1976; see also Remane *et al.*, 1996, although formulation of this principle is unclear and commonly ignored by the ICS when GSSPs are ratified: see Aubry *et al.,* 1999). In this perspective, working groups involved with the definition of chronostratigraphic units should be concerned with the definition of the lowest stage of a series, i.e., in our case, the formal and ICS-ratified definition of the base of the Ypresian Stage (voted/approved as the lowest constituent stage of the Eocene Series by the International Subcommission on Paleogene Stratigraphy, 28th International Geological Congress, Washington D.C., 1989). Hedberg (ed., 1976: 85) recognised the need for mutual boundary stratotypes "to serve both as the top of one stage and the bottom of the next younger stage", and added (op. cit., p. 86) that "the boundary stratotypes between two stages could be selected so that certain ones could serve also as the boundary-stratotype between larger units (series, systems, etc.)", remarking that "The procedure thus lends itself readily to a complete hierarchical scheme of chronostratigraphic division with no gaps and no overlaps". Because all Paleogene stages are based on unconformable stratigraphic units (Hardenbol & Berggren, 1978; Aubry, 1985), mutual boundary stratotypes can only be defined outside of the type areas. Thus, following a strict Hedbergian approach to chronostratigraphy, the Working Group on the P/E boundary should be concerned with the designation of a Thanetian/Ypresian boundary stratotype in which the age of the boundary horizon is coeval with the base of the Ypresian Stage in its type area. We recognise here that there may be a correlation problem, as did Hedberg (ed., 1976), but definition is unique and stable. This would be in harmony with the philosophy followed in the establishment of Cenozoic chronostratigraphic schemes (e.g., Berggren et al., 1985; 1995; Haq *et al.*, 1987) in which the bases of the standard stages essentially correspond to the bases of the unit stratotypes in their type area.

The guidelines to chronostratigraphic procedure enunciated by Cowie *et al.* (1986) and codified by Remane *et al.* (1996) have introduced a fundamental change to the Hedbergian chronostratigraphic procedure. Stratigraphic units are also defined by their base (Cowie *et al.,* 1986: 8, stated: "Although there is no scientific principle involved in considering the base of a unit any more important than the top of a stratigraphic unit, ICS bodies (e.g., Subcommissions) are responsible by convention for the base of their units"), but the role of the stage so fundamental in Hedberg's vision, is now subordinated to the expediency of correlation (see Aubry *et al.*, 1999). The salient difference for our purpose is however of a different nature: where Hedberg recognised the importance of definition, the current ICS emphasises the importance of correlation. Whereas Hedberg's boundary stratotype preserves historical precedent (i.e., the definition of the base of a stage in its type area), the GSSP ignores it (Cowie, 186; Cowie *et al.,* 1986; Remane et al., 1996; see Aubry *et al.,* 1999, for quotes and discussion). The GSSP is chosen on the basis of its correlation potential, independently of prior, albeit informal, chronostratigraphic definition: "Even though a chronostratigraphic boundary is **defined** by a point in the rock, its **formal definition should be preceded by a thorough test of correlation potential** of the envisaged boundary level" (Remane, 1997: 3; bold in the original text). In summary, under the ICS rules, the mandate of the Working Group on the P/E boundary is to define a lithostratigraphic horizon that is essentially correlatable globally, and which will constitute the base of the redefined Ypresian Stage. Because this horizon may be of quite different age than the base of the stratotypic Ypresian Stage of the Belgium Basin (an age that has been accepted by most stratigraphers) ambiguity and confusion may quickly arise. If the base of the redefined stage is placed at a level either much younger/older than the regional/standard stage, the same term (stage name) will serve to characterise two extremely different concepts. To summarise, the situation is as follows:

1. Following Hedberg's guidelines, the base of the global Ypresian Stage essentially corresponds to the base of the regional/standard Ypresian Stage. Its definition is independent of any means of correlation.

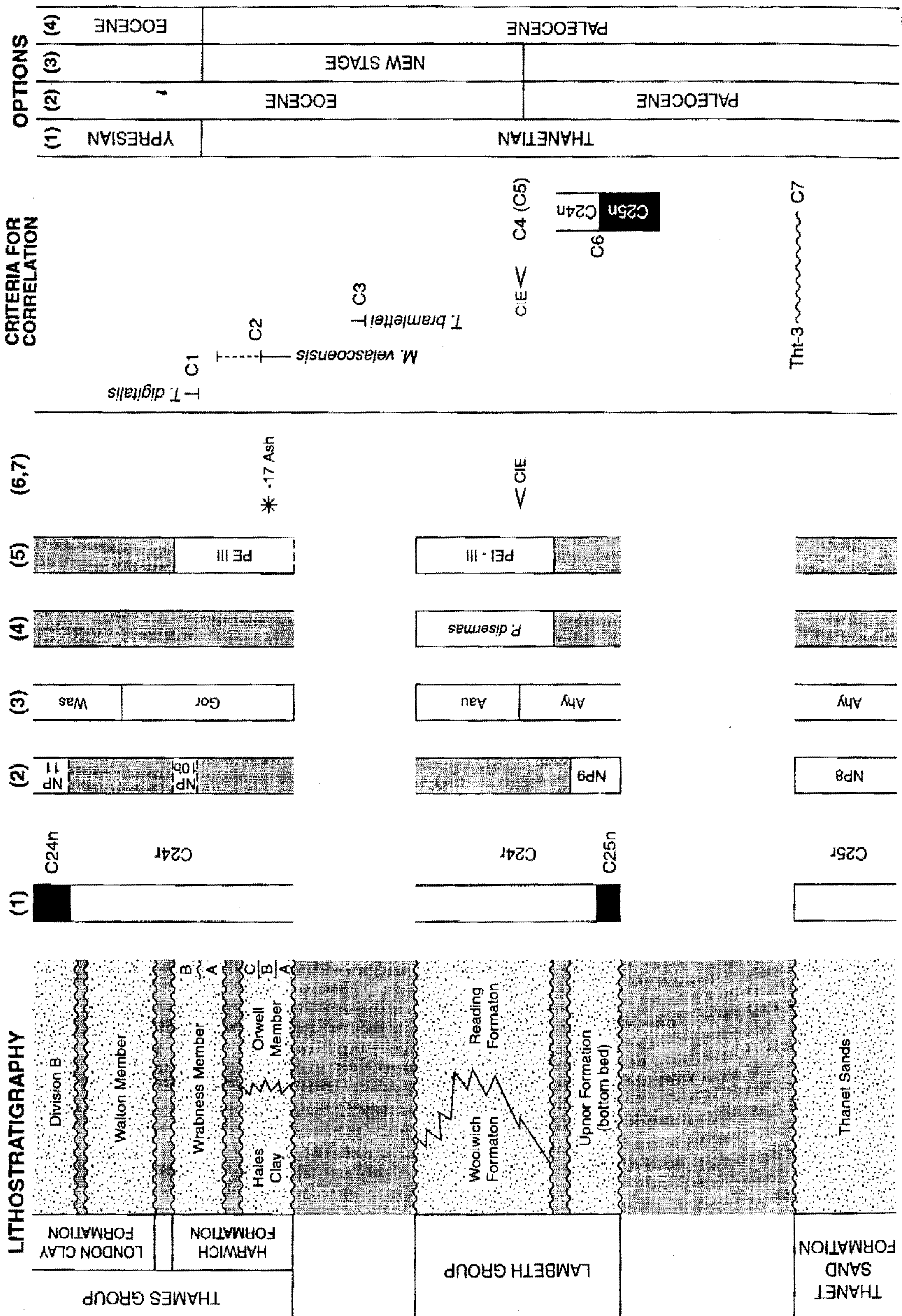
2. Following the guidelines expressed in Cowie *et al.* and Remane *et al.,* the base of the global Ypresian Stage would possibly not correspond to the base of the regional/standard Ypresian Stage. Redefinition of the base will be contingent upon the selection of a criterion for global correlation. However, with regard to this situation, one may ask how far above or below the base of the regional/standard Ypresian Stage can the base of the global (i.e., ICS-ratified) Ypresian Stage be located? There is no provision for this question in the current ICS guidelines (Remane *et al.,* 1996).

It is beyond the scope of this paper to present the unfortunate consequences of this situation thoroughly discussed in Aubry *et al.* (1999), Aubry & Berggren (2000a, b) and Aubry (2000). However, in response to possible concern over seemingly undue emphasis/ distinction placed here upon the regional versus the redefined Ypresian Stage, one should recall that the stratigraphic units that constitute Paleogene regional/ standard stages (and many other stages) are natural entities that reflect the geodynamic evolution of the basin where they were deposited. The Ypresian rock unit constitutes a broad synthem unconformable with both the Thanetian and the Lutetian synthems, and its base (Mont Héribu Member of the Ieper Clay, Walton Member of the London Clay Formation) corresponds to a major transgressive surface that can be followed throughout northwestern Europe (see for instance Knox, 1996; Steurbaut, 1998; Aubry *et al.,* 1999). The base of the standard Ypresian chronostratigraphic unit corresponds to this trangressive surface, with an estimated age of 54.37 Ma (see below). This particular surface has thus a double significance: one is chronostratigraphic (i. e., temporal), the other is geohistoric because the widespread Ypresian transgression was associated with the end of intensive compressional tectonism in the North Atlantic (Knox, 1996). It can be seen that redefining the Ypresian stage on the basis of a much older stratigraphic level (likely to reflect another event in historical geology) would create a confusing situation.

THE P/E BOUNDARY INTERVAL AND THE P/E BOUNDARY EVENTS

Aside from the potential problems alluded to above, the Working Group on the P/E boundary has been concerned that placement of the base of the redefined Ypresian Stage does not violate the historical definition of the successive regional/standard stages, Ypresian and Thanetian. The philosophy and methodology followed by the Working Group have been clearly expressed by Knox (1994) and Berggren and Aubry (1996, 1998). In short, the Working Group has delineated a stratigraphic interval, often referred to as the *Boundary Interval,* bracketed by the top of the Thanet Sand and the base of the Ieper Clay Formations (Text-figure 1) in order to determine which new location of the base of a redefined Ypresian Stage would not violate the original concepts of Thanetian and Ypresian Stages. The "Boundary Interval" represents a temporal duration of ~2.3my. Because the Eocene stratigraphic record in the London-Hampshire Basin(s) is more amenable to precise correlation with the deep sea record by means of biostratigraphy, magnetostratigraphy and tephrastratigraphy than that of Belgium (where the Ypresian stratotype is located (Dumont, 1849)), we have substituted the base of the London Clay Formation (= base of the Walton Member; Ellison *et al.*, 1994) to the base of the Ieper Clay (as defined by the base of the Mont Héribu Member, de Coninck *et al.,* 1983) as the informal definition of the base of the Eocene Series as followed by most stratigraphers. Through sequence stratigraphy it has been shown that the base of the Walton Member (= Unit A2; King, 1981) correlates with the base of the Mont Héribu Member; e.g., Steurbaut, 1998 and references therein).

Direct correlations indicate that the top of the Thanet Sand Formation lies within Magnetozone C25r and Biozone NP8 (Ali & Jolley, 1996), and has an estimated age of ~56.6 Ma (see Berggren & Aubry, 1996). The base of the London Clay Formation (= base of the Walton Member) lies ~60% above the base of Magnetozone C24r, very close to the NP10a/b bio(chrono)zonal boundary and has an age estimate of 54.37 Ma (see Berggren & Aubry, 1996, and Aubry, 1996; these age estimates are based on the Geomagnetic Polarity Time Scale [GPTS] of Cande and Kent, 1995 [see below]). As it happens, major paleontologic events occurred during the ~2.3my interval bounded by these two stratigraphic levels. There were, among others, a major turnover among terrestrial mammals (Wood *et al.,* 1941; Russell, 1968) that vertebrate stratigraphers have used to characterise their placement of the P/E boundary (e.g., Russell *et al.*, 1982; Gingerich, 1989, following Pomerol, 1977), the largest extinction of the Late Cretaceous Period and Cenozoic Era among the deep water benthic foraminifera (see Thomas, 1992, 1998), a distinct turnover among the calcareous nannoplankton (Aubry, 1998c; Aubry *et al.*, 2000) and the marine and


LITHOSTRATIGRAPHY
THAMES GROUP
LONDON CLAY FORMATION
HARWICH FORMATION
Division B
Walton Member
Wrabness Member
Orwell Member
Hales Clay
LAMBETH GROUP
Reading Formaton
Woolwich Formaton
Upnor Formation (bottom bed)
THANET SAND FORMATION
Thanet Sands
(1)
C24n
C24r
C25n
C25r
(2)
NP 11
NP 10b
NP9
NP8
(3)
Was
Gor
Aau
Ahy
(4)
P. disermas
(5)
PE III
PEI - III
(6,7)
-17 Ash
CIE
CRITERIA FOR CORRELATION
T. digitalis
C1
M. velascoensis
C2
T. bramlettei
C3
CIE
C4 (C5)
C24n
C25n
C6
Tht-3
C7
OPTIONS
(1) YPRESIAN
THANETIAN
(2) EOCENE
PALEOCENE
(3) NEW STAGE
(4) EOCENE
PALEOCENE

(Dockery, 1998; Hartman & Roth, 1998), and the global dispersal of the holozoic dinoflagellate *Apectodinium* spp. (Bujak & Brinkhius, 1998; Crouch *et al.*, 2000). In the meantime, there was also a reduction in the intensity of atmospheric circulation (Rea *et al.*, 1990), the warming of the high latitudes and of the deep sea, an event so distinctive, sharp and short-termed that it has been dubbed the Late Paleocene Thermal Maximum (LPTM, Zachos *et al.*, 1993), explosive volcanism in the North Atlantic (Morton and Parson, 1988; Knox, 1996) and in the Caribbean (Bralower *et al.*, 1997). Perhaps this time is best known, however, for the 3-4 ‰ negative excursion (CIE) in the carbon isotopic composition of the ocean first identified in Ocean Drilling Project (ODP) Hole 690B on Maud Rise, Antarctica, by Kennett & Stott (1991). This $\delta^{13}C$ anomaly, which is superimposed on a long-term Chron C26r to C24n decrease of the mean $d^{13}C$ of the ocean (Shackleton *et al.*, 1984; Shackleton, 1986; Zachos *et al.*, 1993) has now been identified in numerous marine (but see Aubry, 1998a, b) as well as terrestrial sections (Koch *et al.*, 1992; Stott *et al.*, 1996).

Whereas the changes in the marine and terrestrial biotas are now well documented (see papers in Aubry *et al.*, 1998a, Schmitz *et al.*, 2000, Thiry *et al.*, 2001), there remain large uncertainties on the oceanographic significance of the isotopic records. For instance some records suggest a temporary shift from high latitude temperature-driven to low latitude salinity-driven ocean circulation (Pak and Miller, 1992) that other records do not confirm (Schmitz *et al.*, 1996). As a whole, the cause(s) of the profound changes that occurred during Chron C24r remain(s) elusive, and modelling reveals how complex the situation is (e.g., Sloan and Thomas, 1998; Bice, 2000; Bice & Marotzke, 2000). It has been proposed (Bralower *et al.*, 1997) that intensive volcanism triggered dissociation of gas hydrates and subsequent release of methane into the atmosphere, causing a sharp global warming (Dickens *et al.*, 1995). Whereas active tectonism, including widespread volcanism in the NE Atlantic linked to rifting and spreading between Greenland and Eurasia (see Morton *et al.*, 1988; Knox, 1998), and in the Caribbean region (Bralower *et al.*, 1997), and massive metamorphism and erosion linked to the India-Asia collision (Kerrick & Caldeira, 1994; Beck *et al.*, 1995) are well documented, evidence is slowly building that supports the dissociation of gas hydrates (Katz *et al.*, 1999; Dickens, 2000), viewed by many as the most plausible mechanism to explain the CIE.

SEVEN CRITERIA TO CHARACTERISE THE P/E BOUNDARY

Seven potential criteria have been retained by the P/E WG as valuable for long distance correlations (Text-figure 1). They are introduced from younger to older in reference to the fact that, until now, the base of the regional/standard Ypresian Stage determines the base of the Eocene series. The criteria are of different nature: biostratigraphic, paleomagnetic and isotopic. Biostratigraphic events have been generally preferred to any other for the characterisation of chronostratigraphic boundaries, but magnetostratigraphic events have been recently proposed and accepted (e.g., Steininger *et al.*, 1997). The criteria are described, their correlation potential is given and their pros and cons are listed.

The estimated ages assigned to the different events are those derived from the GPTS (Cande & Kent, 1992, 1995) based on a composite reference stratigraphic section (Aubry et al., 1996; Berggren & Aubry, 1998). While we believe the relative chronology of events in Chron C24r to be firm, we recognise that the numerical chronology will require revision (although it is unclear how much). The location of the 55 Ma-calibration point in the chron used by Cande & Kent (1995) in their GPTS (1992, 1995) is unknown (Aubry, 1998b). In addition, a magnetostratigraphic reinvestigation concluded that Chron C25n is not represented in ODP Hole 690B (Ali *et al.*, 2000). A stratigraphic level in that hole thought to correspond to the Chron C25n/C24r reversal boundary served as a tie point in the construction of the composite reference section. Younger ages (~55 Ma) have now been proposed for the CIE based on independent methodologies (Norris and Röhl, 1999; Wing *et al.*, 1999). However, no revised numerical chronology for the whole of Chron C24r is available as yet.

CRITERION 1 (C1)

The First Appearance Datum (FAD) of *Tribrachiatus digitalis* or the NP10a/b subchronal boundary; estimated age 54.37 Ma (Aubry *et al.*, 1996; Berggren & Aubry, 1996)

Tribrachiatus digitalis Aubry 1996 is a recently introduced, characteristic calcareous nannofossil species with a wide geographic distribution. Its stratigraphic range defines Subzone NP10b. Its FAD immediately followed the end of eruptive volcanism (Ash Series 2.3, Knox, 1996) in the North Atlantic. Through indirect correlation between ash layers and biostratigraphy in DSDP Site 550 (Porcupine Abyssal Plain, at the seaward edge of the Goban Spur), it has been shown (Aubry, 1996) that the FAD of *T. digitalis* can be used to estimate the age of the base of the London

Text-figure 1.

Location of the seven potential criteria to characterise the P/E boundary with respect to the U.K. lithostratigraphy. Lithostratigraphic framework from King (1981), Ellison *et al.* (1994) and Jolley (1996); Magnetostratigraphy (1) from Ali *et al.* (1993), Ali and Jolley (1996) and Ellison *et al.* (1996); calcareous nannofossil stratigraphy (2) from Aubry (1985, 1996), Ellison *et al.* (1996), and Aubry & Curry (unpublished data); Dinoflagellate stratigraphy (3) from Powell *et al.* (1996); Charophyte stratigraphy (4) from Riveline (1986); Vertebrate stratigraphy (5) from Hooker (1996); Isotope stratigraphy (6) from Sinha (1997) and Thiry *et al.* (1998); (7) Tephrastratigraphy from Knox (1990).

The drawing of the lithostratigraphic units and the gaps that separate them are not to scale. It is difficult to infer the location of the NP9/NP10 bio(chrono)zonal boundary in this lithostratigraphic succession. It is located here in the stratigraphic gap that separates the Lambeth and Thames Groups, but it may be as low as in the uppermost part of the Woolwich-Reading Formation.

BY: base of the standard Ypresian Stage stratotype, = base of the Mont Héribu Member. Tht-3: upper surface of Thanetian sequence 3 of Powell *et al.* (1996) = surface Tht-4 of Hardenbol (1994). C1 to C7: criteria for correlation as discussed in the text. Ahy: *Apectodinium hyperacanthum* Zone; Aau: *Apectodinium augustum* Zone; Gor: *Glaphyrocysta ordinata* Zone; Was: *Wetzeliella astra* Zone, Wme:

Clay Formation (Ellison *et al.*, 1994; = Walton Member of King, 1981)). *Tribrachiatus digitalis* has now been identified at the base of the Thames Group (Aubry & Curry, unpublished data). In DSDP Site 550, the LO of the species is immediately above the ash series. Jolley (1996) distinguished two unconformable units in the Wrabness Member. The lower Unit A is a tuffaceous silstone whereas Unit B is a sand. Thus, tentatively, the LO of *T. digitalis* is located between Units A and B.

The terms Lowest Occurrence/First Appearance Datum and Highest Occurrence/Last Appearance Datum (LO/FAD and HO/LAD, respectively) are taken as defined by Aubry (1995), with LO and HO having stratigraphic and FAD/ LAD temporal significance. LO/FAD and HO/LAD are used in conjunction here to indicate that the LO is meant to represent a FAD, and HO a LAD

The pros and cons of this criterion are as follows:

Pro:

1: Use of this criterion would ensure continuity in stratigraphic nomenclature. The base of a formally-ICS-ratified Ypresian Stage would essentially correspond to the base of the regional/standard Ypresian Stage.

2: This criterion is applicable in almost all marine settings, from the deep sea to epicontinental areas.

3: This species has a very short range. Its biochron is estimated of ~0.2my (Aubry *et al.*, 1996)

4: The nannoliths of *T. digitalis* are diagenetically resistant and easily identified.

5: The FAD of *T. digitalis* appears to be correlative with the acme of *Deflandrea oebisfeldensis*

Con:

1: There is, as yet, no possible correlation with the terrestrial, particularly with the mammalian, record.

CRITERION 2 (C2)

The Last Appearance Datum (LAD) of *Morozovella velascoensis* or the P5/P6 biochronal boundary; estimated age: 54.48 Ma (Berggren & Aubry, 1998)

Planktonic foraminiferal stratigraphy has played an important role in chronostratigraphy and several planktonic foraminiferal datums serve to delineate series boundaries (e. g., the top of the Eocene is characterised by the HO/LAD of *Hantkenina* spp.; Premoli Silva & Jenkins, 1988). The highest occurrence (HO) of *M. velascoensis* defines the top of Zone P5 (Berggren & Miller, 1988). The LAD of this species is slightly older (~0.3my) than the base of the stratotypic Ypresian Stage. Cross correlation with DSDP Site 550 indicates that it would lie within the Harwich Formation (as defined by Ellison *et al.*, 1994), within the interval comprised between the upper part of the Orwell Member and Unit A of the Wrabness Member (as defined by Jolley, 1996).

Pro:

1: *Morozovella velascoensis* is a distinctive form.
2: An easy datum to delineate in oceanic settings
3: It is marginally older than the base of the regional/ standard Ypresian Stage.

Cons:

1: This criterion is not applicable in shallow (epicontinental) settings
2: There is, as yet, no indirect means of correlation with the terrestrial record
3: Because of possible reworking, an HO/LAD may not be as suitable as a lowest occurrence/First Appearance Datum (LO/FAD) to characterise a chronostratigraphic boundary.

CRITERION 3 (C3)

The FAD of *Tribrachiatus bramlettei*; estimated age: 55 Ma (Swisher and Knox, 1991)

The NP9/NP10 zonal boundary has become loaded with ambiguity, first for correlation reasons, second for taxonomic reasons.

The NP9/NP10 zonal boundary has often been used to approximate the P/E boundary. The base of the standard/ regional Ypresian Stage is younger (~0.63my) than the NP9/NP10 bio(chrono)zonal boundary (Aubry *et al.*, 1996 and Aubry & Curry, unpublished data). Reference to the P/ E boundary without indication that its recognition was based on the NP9/NP10 zonal boundary has thus caused confusion over the years. Further confusion has arisen from the use of secondary markers (the HO of *Fasciculithus* spp., the LO of *D. diastypus*) to determine the zonal boundary.

A lineage from *Rhomboaster* to *Tribrachiatus* involving a change in symmetry from rhombohedron-shaped forms (= genus *Rhomboaster*) to forms with a radial, six or three-fold symmetry (= genus *Tribrachiatus*) has been well established by Romein (1979; see also Aubry *et al.*, 2000). In this lineage, *Tribrachiatus bramlettei* is the first species with a radial symmetry, and its LO defines the base of Zone NP10 (Martini, 1971). The CIE occurs at ~mid-level in Zone NP9 and very close to the LO of *Rhomboaster* spp. The introduction of a synonymy between *T. bramlettei* and *Rhomboaster* spp. (Bybell & Self-Trail, 1995) has fueled an amicable controversy, and resulted in an unfortunate confusion because if the two taxa are regarded synonymous, the CIE is shown to occur at the NP9/NP10 zonal boundary, not in mid-Zone NP9. Failure to recognise the *Rhomboaster-Tribrachiatus* lineage results in the loss of significant stratigraphic and evolutionary information. The use of the HO's of *Fasciculithus alanii* and *F. tympaniformis* can help in locating the two main evolutionary steps in the *Rhomboaster-Tribrachiatus* lineage. The LO/FAD of *Rhomboaster* spp. (and the CIE) is essentially synchronous with the HO/LAD of *Fasciculithus alanii* whereas the HO/LAD of *F. tympaniformis* appears to be very close to the LO/FAD of *T. bramlettei*.

The NP9/NP10 zonal boundary (= LO of *T. bramlettei*) with an age of 55 Ma serves as a calibration tie-point in the GPTS of Cande and Kent (1992, 1995). In this GPTS, the P/E boundary was taken at the NP9/NP10 zonal boundary, and thus bears an age of 55 Ma.

Indirect correlations indicate that the NP9/NP10 zonal boundary probably falls within the stratigraphic gap between the Lambeth and the Thames Group.

Pro:

1: Use of the NP9/NP10 zonal boundary to characterise the P/E boundary would conform to the current GPTS
2: This criterion is applicable to practically all marine

environments
3: It has often been used to characterise the P/E boundary

Cons:

1: There are currently no known means of correlation with the terrestrial record
2: The taxonomic controversy regarding the *Rhomboaster-Tribrachiatus* lineage has not been resolved as yet, although the recent recognition of *bramlettei* as a discrete taxon ("*Rhomboaster bramlettei bramlettei*"; Von Salis in Von Salis *et al.*, 2000)—with the corollary that the CIE occurs in Zone NP9 not at the NP9/NP10 zonal boundary—constitutes a step towards settlement
3: *T. bramlettei* may be scarce in some settings

CRITERION 4 (C4)

The $\delta^{13}C$ excursion (CIE); estimated age: 55.52 Ma (Berggren & Aubry, 1996)

The CIE was initially identified at Site 690 on Maud Rise, Antarctic Ocean (Stott *et al.*, 1990). Since then, it has been reported from many deep sea sites (e.g., Pak & Miller, 1992; Bralower *et al.*, 1995; Norris & Röhl., 1999) and land sections from bathyal (e.g., Lu *et al.*, 1996; Schmitz *et al.*, 1996; Egger *et al.*, 2000) and epicontinental (e.g., Thomas *et al.*, 1997; Cramer *et al.*, 1999) settings. It has been shown, however, that many such excursions are pseudoevents that result from anomalous juxtaposition of isotopic records caused by unconformities (Aubry, 1998a, b; Aubry *et al.*, 2000). Correct identification of the excursion requires an isotopic decrease of 3 to 4 ‰, and correlation with mid-Zone NP9 (Aubry *et al.*, 1996; = NP9a/b subzonal boundary, Aubry, 1998a, Aubry *et al.*, 2000) and mid-Zone P5. In deep sea sections, the CIE is synchronous with the benthic foraminiferal extinction (BFE). In Tethyan, Atlantic and tropical Pacific sections, the CIE is associated with a rapid diversification in the calcareous plankton, including the occurrence of two compressed acarininid (*A. africana* and *A. sibayensis*) and a morozovellid (*M. allisonensis*) species (e.g., Kelly *et al.*, 1996; Lu *et al.*, 1996; Norris and Röhl, 1999) and of awkward, often asymmetrical calcareous nannofossils among which *Rhomboaster calcitrapa* and *Discoaster araneus* (Aubry, 1999; Aubry *et al.*, 2000). The CIE is also associated with the apparently global acme of the dinoflagellate *Apectodinium* (Bujak & Brinkhuis, 1998; Crouch *et al.*, 2000). The CIE marks the onset of the LPTM (Zachos *et al.*, 1993).

The CIE has also been identified in the North American terrestrial sections (Koch *et al.*, 1992, 1995) where it was shown to occur at the base of Wasatchian Zone Wa0 and to be associated with the mammal dispersal event (MDE; see Berggren *et al.*, 1997). In Europe, the CIE has been identified in the lower part of the Sparnacian Argiles Plastiques bariolées (Paris Basin), well below the Meudon mammalian fauna, and in the lower part of the Reading Formation (London Basin; Stott *et al*, 1996, Sinha *et al.*, 1996; Sinha, 1997; Thiry *et al.*, in review).

Pro:

1: It allows direct correlation between marine and terrestrial records
2: This is a major event in itself; the CIE is well characterised and of large amplitude
3: It is associated with two significant biotic turnovers, one in the deep sea benthic realm (the BFE), the other in the North American continental realm (the MDE)
4: It is further characterised by a rapid diversification in the marine calcareous plankton, with the occurrences of two compressed acarininid species and one morozovellid, of several short-range calcareous nannofossil taxa and the acme of *Apectodinum* spp. (Zone Aau of Powell et al., 1996)
5: It occurs in mid Zone P5 and at the NP9a/b subzonal boundary.

Cons:

1: It is >1 my older than the base of the Ypresian Stage as stratotypified in Northwest Europe
2: It falls within a lithostratigraphic unit (the Reading-Woolwich Formation of the Lambeth Group (Ellison *et al.*, 1994) that is currently (and has been traditionally) assigned to the Thanetian Stage
3: Biostratigraphic control is required for its firm identification

CRITERION 5 (C5)

The LAD of the *Stensionia beccariiformis* assemblage; estimated age: 55.52 Ma (Berggren & Aubry, 1996)

A significant change at bathyal and abyssal depths in benthic foraminiferal assemblages around the P/E boundary was first documented by Tjalsma & Lohmann (1983). However, the significance of this event was not fully appreciated until the discovery of its synchrony with the CIE as recognised at Maud Rise Site 690 (Thomas, 1990). Since then the benthic foraminiferal extinction and the CIE have been found in association in many deep sea (bathyal and abyssal) sections (see Thomas, 1998 for a review). The location of the benthic foraminiferal event with respect to calcareous microfossil stratigraphy is, as the CIE, in mid-Zone NP9 (at the NP9a/b subzonal boundary). A turnover in shallow water benthic foraminifera, but of lesser amplitude than in the deep sea faunas, has also been documented (Speijer, 1994; Thomas *et al.*, 1997; Cramer *et al.*, 1999).

Through association of this event with the CIE, the level of the BFE correlates in the shallow marine record of NW Europe with a level within the Sparnacian and within the Reading-Woolwich Formation.

As for the CIE, unconformities may truncate the record of the benthic foraminiferal extinction as discussed by Aubry (1998a, b).

Pro:

1: this constitutes a major (stratigraphic) event in the bathyal and abyssal realms
2: this deep water event is correlatable to the neritic realm
3: it is associated with the CIE
4: it provides indirect correlation with the terrestrial record via the CIE.

Cons:

1: It is >1my older than the base of the Ypresian Stage as stratotypified in Northwest Europe
2: Correlation with the terrestrial record is only indirect

CRITERION 6 (C6)

Chron C25n/C24r magnetic reversal; estimated age: 55.904Ma (Cande & Kent, 1995)

Chron C25n is represented in many of the sections investigated by IGCP Project 308. The Chron C25n/C24r reversal boundary has been identified at the base of the Upnor Formation in the Thanetian-Ypresian type area (Ali *et al.*, 1996; Ellison *et al.*, 1996) where it constitutes a valuable anchoring point for global correlations.

Pro:

1: A magnetic reversal is a nearly synchronous global event
2: Use of this criterion would permit correlation between the marine and terrestrial records.
3: In the marine record Chron C25n is easily identified through biostratigraphy (the LO/FAD of *D. multiradiatus* is associated with ~mid-Chron C25n and the HO/LAD of *Globanomalina pseudomenardii* is associated with Chron C25n(y) ; see Berggren *et al.*, 1995).

Con:

1: It is >1.5my older than the base of the Ypresian Stage as stratotypified in northwest Europe
2: The main events that make early Paleogene evolution so distinctive occurred about 0.4my after this magnetic reversal
3: Its identification requires biostratigraphic control.

CRITERION 7 (C7)

Top of the Thanet Sand Formation; estimated age: 56.6 Ma (Berggren & Aubry, 1996).

The top of the Thanet Sand Formation is an erosional surface which lies in Chron C25r (Ali & Jolley, 1996), calcareous nannofossil Biochon NP8 (Aubry, 1985) and dinoflagellate Biochron Ahy (*Apectodinium hyperacanthum* interval Zone; Powell *et al.*, 1996) It is the upper bounding surface of Sequence Th-4 of Hardenbol (1994) or Sequence Tht-3 of Powell *et al.* (1996). There is general agreement that the stratigraphic gap between the Reculver Silts and the Upnor Formation (ex Woolwich Bottom Bed) at the base of the Upnor Formation is the largest in the Thanetian-Ypresian succession in the London-Hampshire Basin (and probably of all NW Europe; e.g., Aubry *et al.*, 1986; Ali & Jolley, 1996).

Pro:

1: This level constitutes the top of the Thanetian Stage s.st. (= *sensu* Dollfus, 1880, not *sensu* Renevier, 1873, 1874; and not as currently understood) in its type area.

Con:

1: This level is poorly dated and cannot be correlated with any degree of confidence outside NW Europe.

DISCUSSION

It is clear from the list above that some criteria are better suited than others to characterise a chronostratigraphic boundary, but all are valid candidates, and should be considered. Differing views on how chronostratigraphic boundaries should be established would lead to different choices:

1. Chronostratigraphic boundaries may be simply arbitrary, in which case a criterion may be chosen for pragmatic reasons. Magnetic reversals serve this purpose well. The Chron C25n/C24r magnetic reversal would ensure global correlation of a "P/E" boundary.

2. Chronostratigraphic subdivisions may be drawn in such a way that they constitute natural divisions of the stratigraphic record. Both stages and series as originally conceived (Lyell, 1833; d'Orbigny, 1852) were natural subdivisions of the stratigraphic record, but based on different criteria. However, it is essential to recognise that chronostratigraphy must remain an independent means of subdividing the stratigraphic record, independent of any aspect of earth history, either paleobiologic, tectonic or climatic (Hedberg, 1976; see discussions in Aubry *et al.*, 1998b, 1999; Aubry, 2000; Van Couvering, 2000).

Two among the above criteria hold privileged places. They are the FAD of *T. digitalis* and the CIE. Choice of the FAD of *T. digitalis* would immediately guarantee continuity in stratigraphic nomenclature. It would favour traditional approaches to chronostratigraphy in which stages are the basic chronostratigraphic unit (as species are the basic element in taxonomic nomenclature). It would allow global marine correlation of the base of the standard/regional Ypresian Stage, and consequently of the base of the Eocene Series. We have currently no means of identifying this level in the terrestrial realm, but this does not imply that further research would not provide such means (see Van Couvering, 2000). We have established *a posteriori* that this level of chronostratigraphic significance dates a major geological moment in the history of northwestern Europe, i. e., a change in sedimentary regime following widespread transgression as the result of thermal subsidence of the North Atlantic region.

Choosing the CIE would ensure truly global correlation from the deep sea to the terrestrial record, and this criterion is supplemented by a host of additional means of correlation of the boundary level. We have established *a priori* that the CIE points to a decisive moment in the evolution of the planet, well documented, albeit unexplained. It would mark the time of fundamental changes in faunas and floras, much in agreement with Lyell's concept (1833) of epoch, although, as discussed in Aubry (2000), changes did not occur simultaneously at the time of the CIE, and they occurred at different rates in different paleontologic groups over a spread of ~ 1.5my or more. However, a drawback of concern is that the CIE is appreciably older (>1my) than the base of the standard/regional Ypresian Stage.

The following examples may help clarify concerns that have been enunciated above. An excellent means of global correlation of the Miocene/Pliocene (Messinian/Zanclean) boundary was available to the working group on that boundary. This was the base of the Gilbert Chron (= Chron C3r/C3An.1n reversal boundary). This event is only 0.6my older than the unconformable base of the standard/regional Zanclean Stage. However, it was not retained by the Subcommission on Neogene Stratigraphy (SNS; see van Couvering et al., 1998) because it would have resulted in the marine evaporites traditionally assigned to the Messinian Stage and Miocene Series being transferred to the redefined Zanclean Stage and Pliocene Series. Similarly, SNS emphatically rejected an ~0.8my lowering of the base of the Calabrian Stage in choosing a GSSP for the Pliocene/Pleistocene boundary. In that case, the Pleistocene would have been lowered well down into what has been classically part of the Lyellian Pliocene Series.

In our case, we may give serious consideration to several facts. First, use of the CIE would result in 1) lowering the base of the Eocene by >1my, and 2) reassigning to the Eocene a stratigraphic interval that all marine stratigraphers have assigned to the Thanetian Stage and Paleocene Series. Second, the placement of the P/E boundary in the continental record at levels (base of the Sparnacian; Clarforkian/Wasatchian Land Mammal Age boundary) that turn out to be close to the CIE has no relevance to our chronostratigraphic problem because chronostratigraphic schemes must remain independent of biologic evolution. Third, contrary to a general belief, Schimper's concept (1874) of Paleocene included the beds that immediately underlie the London Clay Formation (see discussion in Aubry, 2000).

A new chronostratigraphic framework around the P/E boundary?

The criterion that will be ultimately chosen will determine the chronostratigraphic framework around the P/E boundary (Text-figure 1). The choice of the FAD of *T. digitalis* would preserve the current "standard" chronostratigraphic framework, in which the base of the Ypresian Stage defines the base of the Eocene Series, with an age of 54.37 Ma (Option 1; Text-figure 1, columns 1 and 4 combined). The choice of any of the other 6 criteria would require an adjustment of the standard chronostratigraphic framework. Among these, the CIE is the preferred choice as a literature survey shows, and some authors already delineate (prematurely) the P/E boundary at the level of the CIE.

If the CIE is used to characterise the P/E boundary, the base of the Eocene Series will be defined by a horizon where the CIE occurs. Based on the current rules this will then lead to the adjustment of the base of the Ypresian Stage so as to fit *a posteriori* the base of the Eocene Series (as was done for the Rupelian in the case of the Eocene/Oligocene boundary; Premoli-Silva & Jenkins, 1988). The standard Ypresian Stage with its geohistorical significance will be replaced by an Ypresian Stage subordinated to the Eocene Series and thus deprived of any real significance except for the indirect chronostratigraphic significance imposed by the definition of the series.

While we agree with the ICS that a unified language among all stratigraphers has become a necessity, we see a need to preserve and maintain a certain amount of harmonious stability respectful of history and decades of active research in the field of chronostratigraphy. Thus, whereas we should take advantage of the correlation potential that the CIE represents, we may want to do so while bringing minimum conceptual changes to the standard chronostratigraphic scheme.

Aubry *et al.* (1999) have discussed the pitfalls of redefining stages on the basis of chronostratigraphic units of higher ranks (systems or series), and proposed that the decoupling of stages and series (for the Cenozoic Erathem) was a way to preserve the meaning of stages at the same time as complying with the ICS's requirement for globally correlative boundaries. They thus suggested that the P/E boundary could be characterised and correlated on the basis of the CIE, but that the base of the Ypresian Stage remain unchanged (Option 2; Text-figure 1, columns 1 and 2 combined).

Decoupling series from stages would constitute a fundamental break with Hedberg's principles and ICS rules, and may disrupt Phanerozoic chronostratigraphy in the sense that stages would remain the basic unit in pre-Cenozoic chronostratigraphy. Thus Aubry *et al.* (1999) and Aubry (2000) have proposed the insertion of a stage between the level of the CIE and the base of the Ypresian (Options 3 and 4). This stage would essentially correspond to 1.1my of as yet poorly resolved Earth history, starting with the LPTM. As pointed out by Hedberg (ed., 1976: 71): "If major natural changes ("natural breaks") in the historical development of the Earth can be identified at specific points in sequences of continuous deposition, these may constitute desirable points for the boundary stratotypes of stages". This stage would mostly correlate with the controversial Sparnacian Stage of Dollfus (1880).

The P/E boundary could then be defined either by the base of the new stage (Option 3; Text-figure 1, columns 2 and 3 combined) or by that of the Ypresian Stage (Option 4; Text-figure 1, columns 1 and 4 combined). If chronostratigraphy means providing a globally applicable correlation network, then Option 3 is clearly the most adapted to this purpose. However, in the interest of preserving current chronostratigraphic usage by most stratigraphers, the broadly accepted concept of Late Paleocene Thermal Maximum (the acronym LPTM and its current connotation), and the geohistoric significance of the base of the Ypresian rock unit, Option 4 would be the most suitable. It is also the best suited to reconcile Hedberg's guidelines with the ICS rules. If Options 3 or 4 are retained, two GSSPs will be needed, one for the base of the Ypresian Stage (correlated on the basis of the FAD of *T. digitalis*) and one for the base of the new stage (correlated on the basis of the CIE).

EPILOGUE

Chronostratigraphy is at the core of Earth history because it provides a relative measure of time based on selected stratigraphic units and their boundaries, and applicable in all geological settings. As Hedberg observed, the lithostratigraphic levels that mark the boundaries are comparable to dividers between chapters of a book. The story (i.e., Earth history) is written however, and for this reason there is a danger of strong disagreement as to where the dividers should be placed based on individual biases among scientists. The only manner in which chronostratigraphy can fulfil its objective is by rejecting the use of non-stratigraphic criteria in boundary definitions. Chronostratigraphy can be most efficient if it is arbitrary, and based solely on objectively chosen, *non-preselected strata*, because "like the pages of the book, so the strata of the earth are our only fixed basis of reference for chapters in the history of the Earth—for the definition of our chronostratigraphic scale".

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The Working Group was constituted at the onset of the first IGCP Project 308 meeting held on the 1st and 2nd June 1991 . the Natural History Museum, London and organized by R. O'B. Knox and J. Hardenbol. New members were welcomed in tl course of last year to replace retired or deceased members (J. de Coninck, L. Stover and G. Jenkins, respectively).

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As this paper goes to press, the WG has voted on these issues (December 1999). A majority of 86% of the WG members voted in favor of the introduction of a new stage while 58.8% of them voted for the lowering of the P/E at the level of the excursion. As a majority of 60% is an ICS requirement, the working group has submitted a proposal to the ISPS for introducing a new stage. It will re-vote regarding the location of the P/E.