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# The Global Standard Stratotype-section and Point (GSSP) for the base of the Eocene Series in the Dababiya section (Egypt)

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*The GSSP for the base of the Eocene Series is located at 1.58 m above the base of Section DBH in the Dababiya Quarry, on the east bank of the Nile River, about 35 km south of Luxor, Egypt. It is the base of Bed 1 of the Dababiya Quarry Beds of the El Mahmiya Member of the Esna Formation, interpreted as having recorded the basal inflection of the carbon isotope excursion (CIE), a prominent (3 to 5%) geochemical signature which is recorded in marine (deep and shallow) and terrestrial settings around the world. The Paleocene/Eocene boundary is thus truly a globally correlatable chronostratigraphic level. It may be correlated also on the basis of 1) the mass extinction of abyssal and bathyal benthic foraminifera (Stensioina beccariiiformis microfauna), and reflected at shallower depths by a minor event; 2) the transient occurrence of the excursion taxa among the planktonic foraminifera (Acarinina africana, A. sibaiaensis, Morozovella allisonensis); 3) the transient occurrence of the Rhomboaster spp. – Discoaster araneus (RD) assemblage; 4) an acme of the dinoflagellate Apectodinium complex. The GSSP-defined Paleocene/Eocene boundary is approximately 0.8 my older than the base of the standard Eocene Series as defined by the Ypresian Stage in epicontinental northwestern Europe.*

## Introduction

The establishment of the Working Group (WG) on the Paleocene/Eocene boundary at the 28th International Geological Congress (Washington, 1989) was serendipitously coincidental with the report of significant, stratigraphically linked events in the biotic and isotopic record of Magnetic Chron C24 in the lower Paleogene record of the Southern Ocean, obtained during Ocean Drilling Program [ODP] Leg 113 (Barker, Kennett, et al., 1988). The search for a Global Standard Stratotype-section and Point (GSSP) for the Paleocene/Eocene (P/E) boundary soon became intertwined with the effort of a large and growing community of earth scientists to document and explain the flurry of remarkable events that occurred during the 2.55 m.y.-long Chron C24r. The selection of the GSSP for the base of the Eocene Series in the Dababiya section (Egypt) represents the close collaboration between this community and the WG, a collaboration that included several international meetings devoted to early Paleogene scientific problems, as well as field conferences in Europe, the Middle East, North and South America, and several special publications (Laga, Ed., 1994; Knox et al., eds. 1996; Aubry and Benjamini, Eds., 1996; Molina, et al., 1996a, b; Berggren et al., 1997; Aubry et al., Eds., 1998; Mancini and Tew, 1995; Ouda, ed., 1999; Schmitz et al., Eds., 2000; Fluegeman and Aubry, Eds., 1999; Huber and Wing., eds., 2001; Thiry and Aubry, Eds., 2001; Wing et al., Eds., 2003; Ouda and Aubry, eds., 2003). This close collaboration has been furthered with the conferences on Climate and Biotas of the Early Paleogene (CBEP) held every 3 to 4 years.

The documentation of the suite of biotic, climatic, oceanographic, sedimentologic, tectonic, and even perhaps extraterrestrial events that affected Earth for a short time within Chron C24r has reached a stage where we are confident that the event-stratigraphy upon which the GSSP is being proposed below is reliable. We stress, however, that there are critical areas that remain unsettled, among which is the precise numerical chronology in the vicinity of the GSSP, an area of primary significance for temporal correlations between stratigraphic sections. Future efforts will aim at resolving this problem in relation to the GSSP.

The proposal for locating the GSSP for the base of the Eocene was submitted to the International Subcommission on Paleogene Stratigraphy (ISPS) following a meeting of the WG members in Luxor, Egypt (16–18 February, 2002), organized at the initiative of Professors K. Ouda and C. Dupuis (the leading proponents of the Dababiya section as GSSP) and Professor M.-P. Aubry (Chairman of the P/E WG). The Luxor meeting was devoted to reviewing the Dababiya section and correlative sections in the Upper Nile Valley, and to organizing the ballot that followed. In the ballot, the members of the WG voted unanimously in favor of placing the GSSP for the base of the Eocene Series in the DBH partial section, located in the abandoned quarry of Dababiya, eastern side of the Upper Nile Valley, about 35 km south of Luxor, Egypt. The proposal was accepted by the ISPS (May 2003) and the ICS (August 2003) and ratified by the IUGS (August 2004).

The main objective of this paper is to describe and document the GSSP. However, it is essential to place it in a broad stratigraphic

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and geohistorical framework. Thus we first summarize the philosophical approach followed by the WG as it examined dozens of sections to understand the intricacies of Paleocene-Eocene stratigraphy, and then discuss the means of correlations available in the vicinity of the boundary, i.e., in Chron C24r. The details of the litho- and biostratigraphic and isotopic correlations in the GSSP area (from Gebel Abu Had near Qena to Gebel Owaina, near Esna, i.e., along a 100 km North-South axis parallel to the Nile Valley and centered on Luxor) were partly published in Dupuis et al. (2003). They are complemented in the forthcoming description of the Core (DBDco) taken in the Dababiya Quarry to obtain unweathered material of the GSSP interval and Paleocene section below.

### Conceptual framework

The placement of the Paleocene/Eocene boundary has long been clouded by inconsistent assumptions, which have been a constant source of miscorrelation (Berggren and Aubry, 1996, 1998). At least five different and unlinked criteria to identify the boundary were in common use in different disciplinary areas, such that the correlations, especially between marine and terrestrial P/E boundaries, were consistently offset by as much as 1.5 m.y. (Figure 1; see Berggren and Aubry, 1998, Lucas, 1998). In view of the evidence for a number of closely associated global events in Chron C24r that could bring stability to the Paleocene/Eocene boundary, magnetobiostratigraphic studies integrated with stable isotope stratigraphy and, when feasible, with sequence stratigraphy of sections from as many different settings as possible (deep sea, shallow marine, terrestrial, low, mid and high latitudes) around the world have now contributed to a detailed relative chronology of the Chron C24r-events (Figure 1). The framework for this chronology has been northwest Europe, the type area of the Thanetian (Renevier, 1873), Sparnacian (Dollfus, 1880), and Ypresian (Dumont, 1849) stages, the key units in the chronostratigraphy of the transitional interval as well as the Eocene (Lyell, 1833) and Paleocene (Schimper, 1874) themselves (Aubry, 2000; Aubry et al., 2003). In addition, radioisotopic dating of the "–17 Ash" interbedded with highly fossiliferous Mo Clay in the Fur Formation of Mors (Denmark) calibrates the stratigraphic succession of northwest Europe in the Paleocene-Eocene transition (see Figure 1). This stratigraphically well constrained ash, with an <sup>40</sup>Ar/<sup>39</sup>Ar date of 54.5 Ma (Swisher and Knox, 1991; Berggren et al., 1995)

was used as an indirect calibration point for the Global Polarity Time Scale (GPTS; Cande and Kent, 1992, 1995) and ultimately in the Integrated Magnetobiochronologic Scale (IMBS) (Berggren et al., 1995). It has been recently redated to 55.12 ± 0.12 Ma (FCT= 28.02 Ma)(Storey et al., 2007). Current age estimates for the Paleocene/Eocene boundary (base PETM) vary from 55.75 Ma (Storey et al., 2007; FCT=28.02Ma), 55.8 Ma (Ogg and Smith, 2004) to 55.93 Ma (Westerhold et al., 2007), the latter two estimates based on astrocyclicty. Reconciliation of the age differences between the astronomically based ages and isotopic ages may require an older age for the FCT standard (Kuiper et al., 2004; 2005; Villeneuve, 2004).

Among the Chron C24r-events, seven that appeared to be suitable for characterizing and correlating a P/E GSSP were identified by the WG in 1997, and were examined for strength and weakness (Berggren et al., 1997; Aubry et al., 2002; Figure 1). Three widely observed biostratigraphic criteria were identified as the best means of correlating the GSSP in an open marine setting: (1) the First Appearance Datum [FAD] of the calcareous nannofossil *Tribrachiatulus digitalis*, (2) the Last Appearance Datum [LAD] of the planktonic foraminifera *Morozovella velascoensis*; and (3) the LAD of the benthic foraminifera *Stensioeina beccariiiformis*. Two non-paleontological criteria, the Chron C25n/C24r magnetic reversal and the prominent negative carbon isotopic excursion [CIE] at the center of the Chron C24r cluster of events, were considered for trans-facial global correlations. Ultimately, the CIE, a globally recognizable and unambiguous feature, was judged to be the most suitable for characterisation of a worldwide chronostratigraphic horizon (see Aubry, 2000; Aubry et al., 2002), even though it can only be observed instrumentally. The CIE occurs both in marine and terrestrial stratigraphies; its amplitude of 2.5 to 4‰ is a conspicuous and unmistakable signal; and its association with several other equally unique events ensures its unequivocal identification.

This is the first time that an isotopic excursion has been selected as the primary criterion of a GSSP, and may be the first example of a truly global correlation criterion, one that is directly observable in both marine and terrestrial stratigraphies. Unlike purely geophysical criteria, however, and more in accord with the conventional employment of physical stratigraphic evidence, the CIE (particularly in complete fine-grained settings, such as the proposed boundary stratotype section) is directly associated with distinct lithologic and biotic changes.

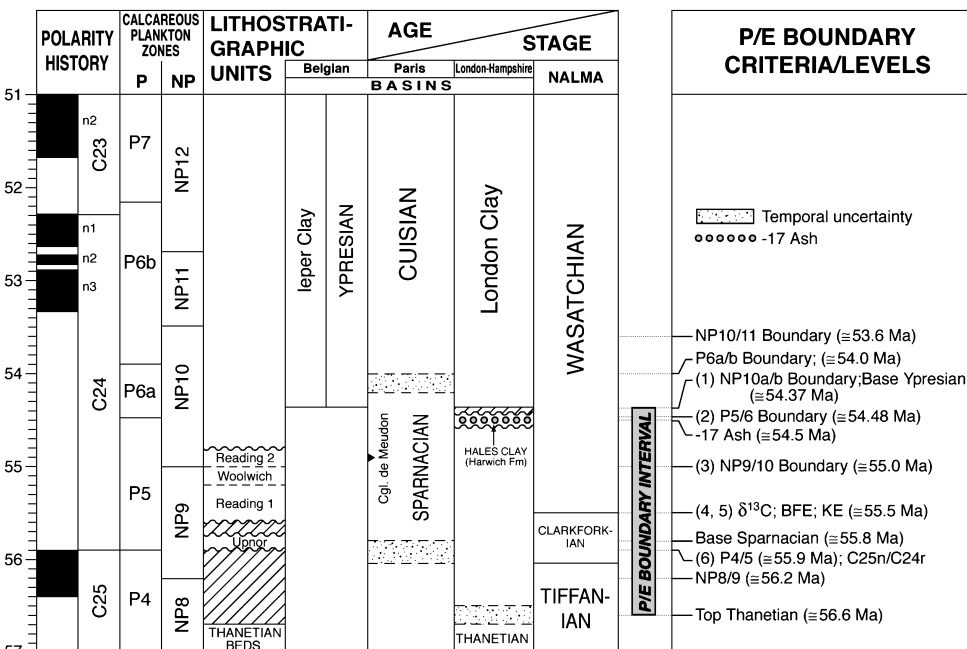


Figure 1 showing correlation events for choice of GSSP after Berggren and Aubry 1998.

### Elements of correlation

#### The Carbon Isotope Excursion (CIE)

The outstanding geochemical feature in the lower Paleogene stratigraphic record is a negative 2.5 to 4‰ carbon isotope excursion that occurs in the lower to mid-Magnetozone C24r, superimposed on a long-term Magnetozone C26r to C24n decrease of the mean δ<sup>13</sup>C of the ocean (Shackleton et al., 1984; Shackleton, 1986; Miller et al., 1987; Zachos et al., 1993, 2001). This excursion reflects a major perturbation of the global carbon cycle (e.g., Kennett and Stott, 1991), the immediate cause of which remains controversial (Dickens et al., 1995, 1997; Katz et al., 2002; Kent et al., 2001; Pagani et al., 2006; Svensen et al., 2004; Higgins and Shrag, 2006), but one which is reflected in major sedimentological and biological changes.

The CIE is, however, unquestionably related to one of the most sudden and dramatic global warming events of the Phanerozoic Era, originally referred to as the Late Paleocene Thermal Maximum (LPTM; Zachos et al., 1993, 2001) and now termed the P/E boundary Thermal Maximum (PETM). We discourage the use of the less descriptive and less precise expression "Initial Eocene Thermal Maximum (IETM)".

The CIE is registered in the carbon isotopic composition of such varied systems as marine (e.g., Kennett and Stott, 1991; Bralower et al., 1995; Katz et al., 1999; Bains et al., 1999) and lacustrine (Cojan et al., 2000) carbonates, carbonate soil nodules (Koch et al., 1992; 1995; Sinha et al., 1996; Bowen et al., 2001), mammalian tooth enamel (Koch et al., 1992), and in organic matter both terrestrial (Stott et al., 1996; Sinha et al., 1996; Magioncalda et al., 2001, 2004; Thiry et al., 2006) and marine (Stott, 1992; Dupuis et al., 2003). Detailed sampling shows that the CIE has a complex sequential structure with smaller excursions separated by transient plateaus that offer intersite correlation (e.g., Bains et al., 1999). It also shows that the onset (base) of the excursion is registered at slightly different stratigraphic levels by different foraminiferal species, by whole rock (e.g., Kennett and Stott, 1991; Charisi and Schmitz, 1995; Cramer et al., 1999) and by carbonates and organic matter in the same section (Magioncalda et al., 2004). Recent studies additionally show that the CIE itself was preceded by extremely rapid 1 to 3‰ transient isotopic excursions (Aubry et al., 2006). Based on cyclostratigraphy, the CIE is estimated to have spanned  $150 \pm 20$  kyr (Norris and Röhl, 1999; Röhl et al., 2000) with a current age estimate 55.6 Ma to 55.9 Ma for its initiation (Westerhold et al., 2007).

The CIE has been identified at numerous deep sea sites (e.g., Stott et al., 1990; Bralower et al., 1995; Thomas and Shackleton, 1996; Stott et al., 1996; Katz et al., 1999), in bathyal deposits exposed in land sections (e.g., Contessa sections, Italy: Corfield et al., 1991; Zumaya section, western Pyrénées, Spain: Schmitz et al., 1997; Anthering Formation, Austria: Egger et al., 2000; Egger and Wägreich, 2001; Alamedilla section, Betic Cordillera, Spain: Lu et al., 1996), in shallow water marine sections (e.g., Owaina and Duwi sections, Egypt, Schmitz et al., 1996; Qreiya section, Egypt, Knox et al., 2003; Tawanui section, New Zealand: Kaiho et al., 1996; Bass River section, New Jersey Atlantic margin: Thomas et al., 1997; Cramer et al., 1999; Gibbs et al., 2006), in lacustrine sediments (e.g., Aix-en-Provence Basin, southern France: Cojan et al., 2000), and in terrestrial deposits in North America and Europe (Wasatchian paleosols, Wyoming, USA: Bowen et al., 2001; Magioncalda et al., 2004; northwest Europe: Thiry et al., 1998, 2006; Magioncalda et al., 2001).

In marine settings, the CIE occurs in (calcareous nannofossil) Zone NP9 and (planktonic foraminifera) Zone P5 (now correlated with the recently defined Zone E1; Berggren and Pearson, 2005). Regionally, it occurs in the (dinoflagellate) Zone P6b (Bujak and Brinkhuis, 1998) in shallow deposits of the North Sea area, and in the NZE1 Zone in New Zealand (Crouch et al., 2001). In the lacustrine/brackish succession of northern Europe, the CIE occurs within the (charophyte) *Peckichara disermas* Zone (Thiry et al., 1998, 2006; Magioncalda et al., 2001; Aubry et al., 2005).

Because of its occurrence in both the marine and terrestrial records, the CIE constitutes a unique means for truly global correlations, and its choice as a primary vehicle for inter-regional correlation of a major chronostratigraphic boundary is well justified, particularly in view of the fact that it is associated with specific paleontologic events that help to make its recognition unambiguous, even in unconformity-ridden sections (Aubry, 1998; Aubry et al., 2000). In northwest Europe, the CIE occurs at the base of the Sparnacian deposits, at a level that is ~1 m.y. older than the base of the Ypresian Stage (Thiry et al., 2006), the former standard for the base of the Eocene.

## Secondary elements of correlation in the marine record

The CIE is associated with four significant paleontologic events that probably reflect a sharp and complex change in oceanic environment, namely 1) a notable extinction event in benthic foraminifera, 2) the transitory occurrence of a so-called "planktonic foraminiferal excursion fauna", 3) a similarly transitory occurrence of calcareous nannoplankton excursion taxa and 4) an acme in the dinoflagellate *Apectodinium* complex of species. Additionally, marked turnovers in ostracode and deep-water agglutinated fauna occur regionally.

### *The benthic foraminiferal extinction event (BFE)*

The CIE has been found in association with a benthic foraminiferal extinction event (BFE) in many deep sea (bathyal and abyssal) sections (see Thomas, 1998, 2003, for a review).

During the Paleocene deep water habitats were populated by two (calcareous) benthic foraminiferal assemblages: a predominantly abyssal, *Nuttallides*-dominated group, and a bathyal assemblage of predominantly relict Cretaceous species dominated/characterized by *Stensioeina beccariiiformis* (Tjalsma and Lohmann, 1983; Thomas, 1992). During the late Paleocene a gradual expansion of the bathymetric range from abyssal to middle bathyal depths of the *Nuttallides*-dominated assemblage at the expense of the *Stensioeina beccariiiformis*-dominated assemblage resulted in the replacement of the latter biofacies by the former and the abrupt extinction of over 50% of the Paleocene deep-water assemblages. This extinction event—the BFE—was the most dramatic event in the evolution of deep water benthic foraminifera since the mid-Cretaceous. Among deep water taxa that became extinct are *Stensioeina beccariiiformis*, *Angulogavelinella avnimelechi*, *Coryphostoma midwayensis*, *Aragonia velascoensis*, *A. ouzzanensis*, *Gavelinella hyphalus*, *G. rubiginosus* (= *G. danica*), *G. velascoensis*, *Neoflabellina jarvis* and *N. semireticulata*, *Neoepionides hillebrandti*, *Osangularia velascoensis*, and *Pullenia coryelli*. The benthic foraminiferal extinctions may have been caused by a combination of factors, including elevated water temperatures, greater corrosivity of sea water, lower dissolved oxygen levels and a decrease in food supply (see Thomas, 2003, for a review). Over the following ~200 kyrs, surviving species were gradually joined by newly evolved taxa that repopulated the ocean. Pre-CIE benthic foraminiferal fauna were remarkably uniform across a wide depth range, whereas the post-extinction fauna were diverse and showed depth-related distribution, most likely reflecting increase depth-related variations in physical/chemical properties of sea water (Tjalsma and Lohmann, 1983; Katz and Miller, 1991; Thomas, 1998).

In neritic to upper bathyal environments (the so-called Midway benthic foraminiferal fauna), the extinction of benthic foraminifera is also evident but less pronounced. *Angulogavelinella avnimelechi*, *Tritaxia midwayensis*, *Anomalinoidea praeacutus* and *Cibicidoides succedens*, i. al., were eliminated from this habitat (Speijer and Wagner, 2002; Thomas et al., 1997; Cramer et al., 1999; Alegret et al., 2005; Ernst et al., 2006).

### *The planktonic foraminiferal PETM assemblage, or "planktonic foraminifera excursion taxa" (PFET)*

In low latitude sections, the interval of the CIE is characterized by a suite of short-ranging morphotypes of planktonic foraminifera that reflect transient diversification among the genera *Morozovella* and *Acarinina* during the PETM (Kelly et al., 1996; Kelly et al., 1998). These excursion taxa (*Acarinina africana*, *A. sibaiyaensis*, and *Morozovella allisonensis*) have been identified in association with the CIE in sections from the Pacific Ocean, the Tethys, and the Atlantic margin (Lu et al., 1996; Kelly et al., 1998; Cramer et al., 1999; Norris and Röhl, 1999; Berggren and Ouda, 2003a, b; Ouda et al., 2003; Berggren et al., 2003).

### *The calcareous nannoplankton PETM assemblage, or the Rhomboaster-Discoaster araneus (RD) assemblage*

A distinctive calcareous nannoplankton assemblage occurs in association with the CIE. It comprises several short-range taxa with unusual structure/morphology, including *Discoaster araneus*, *D. anartios*, *Rhomboaster calcitrapa* and *R. spineus*. These forms are very abundant in neritic sediments, as well as being common in deep sea settings. This assemblage is restricted stratigraphically to the CIE and geographically to the Atlantic-Tethys-western Indian Ocean and western Pacific Ocean (Aubry et al., 2000; Aubry, 2001; Kahn and Aubry, 2004; Raffi and et al., 2005).

The FAD of the RD is correlative with the FAD of the planktonic foraminiferal excursion taxa and with the base of the CIE (Cramer et al., 1999) and both are restricted to the CIE, thus characterizing it (Dupuis et al., 2003; Kahn and Aubry, 2004).

### *The Apectodinium Acme*

A change in dinoflagellate diversity is seen in Chron C24r at low and mid-latitudes, when diversified assemblages with few *Apectodinium* spp. became replaced by low-diversity assemblages heavily dominated by *Apectodinium* spp. (Bujak and Brinkhuis, 1998). A similar shift in dominance was also observed subsequently at high latitudes. This shift represents a global acme of *Apectodinium* spp. which coincides precisely with the CIE (Crouch et al., 2003).

Whereas the global *Apectodinium* acme appears to be a unique event, regional *Apectodinium* acmes also occur at other levels (Bujak and Brinkhuis, 1998), so that an *Apectodinium* acme isolated from other data would not constitute a sufficient criterion for identification of the base of the Eocene Series. A useful, although regionally restricted, criterion here is the consistent occurrence of *A. augustum*, which is restricted to the CIE interval.

### **Secondary elements of correlation in the terrestrial record**

The CIE has been identified in North American terrestrial sections (Koch et al., 1992, 1995; Bowen et al., 2001; Magioncalda et al., 2004) where it is associated with the P/E Mammal Dispersal Event (MDE; see Berggren et al., 1997). The MDE, which defines Zone Wa0 at the base of the Wasatchian Land Mammal Age of the Big Horn Basin, consists of the sudden appearance and apparently rapid spread of the earliest species in new orders of mammals including perissodactyls, artiodactyls and euprimates (Rose, 1981; Gingerich, 2001).

A detailed analysis of the stratigraphic range of mammals in the upper Clarkforkian-lower Wasatchian deposits in 80 m of the thick (2300 m) South Polecat Bench section in Wyoming has identified four intervals with characteristic mammal associations (Gingerich, 2001). Clarkforkian Zone Cf3 is characterized by *Proathyopsis praecursor*, *Apheliscus nitidus*, *Aletodon gunnelli* and *Haplomylys simpsoni*. The thin Interval "Wa0?" is marked by the common occurrence of *Meniscotherium priscum* (a condylarth) but no other mammals, and a notable abundance of the indestructible endocarps of *Celtis* (the elm-related hackberry), suggesting reduced diversity after an ecological collapse, in beds with a distinctive brown color. The CIE is initiated in strata just below the base of this interval, at which the Clarkforkian/Wasatchian boundary is defined. The thin "Wa0?" Interval is succeeded by beds with abundant *Copecion davisii*, *Hyracotherium sandrae*, *Arfia junnei*, *Cantius torresi* and *Diacodexis ilicis*, characterizing Zone Wa0, while *Haplomylys speirianus*, *Cantius ralstoni* and *Diacodexis metsiacus* characterize Zone Wa1.

The CIE straddles the Clarkforkian/Wasatchian boundary (Bowen et al., 2001), with its inception at level 1500 m in the Polecat Bench section, 11 m below the base of Zone Wa0 and 6.5 m below the base of Interval "Wa0?". Its end is apparently slightly above the top of Zone Wa0 in an unfossiliferous interval. On this basis the P/E boundary occurs in the very uppermost part of the Clarkforkian North American Land Mammal Age.

The CIE is associated in the Big Horn Basin with floras comprising a mixture of native and migrant lineages and with large and rapid (~10,000 years) plant range shifts (Wing et al., 2005). The floras are indicative of 5°C warming and of low precipitation at the beginning of the event. Subtropical flora were affected by a major extinction (Harrington and Jaramillo, 2007).

In Europe, where the terrestrial record is discontinuous, the CIE has been identified in the lower part of the Sparnacian Argiles Plastiques bariolées (Paris Basin), and well below the Conglomérat de Meudon (thus not correlative with Zone Wa0; cf. Gingerich, 1989), and in the lower part of the Reading Formation (London Basin) (Stott et al., 1996, Sinha et al., 1996; Sinha, 1997; Magioncalda et al., 2001; Thiry et al., 2006). Also in the London Basin, the CIE is associated with charcoals indicative of episodic fires and runoff (Collinson et al., 2007). The CIE has also been identified in Asia (Bowen et al., 2001).

### **Magnetostratigraphy**

Magnetostratigraphy is a primary means of correlation in Cenozoic stratigraphic intervals. However, it is not useful for correlation at the precise level of the proposed Paleocene/Eocene boundary, identified by the CIE and associated events. The duration of Chron C24r is currently estimated at 2.556 m.y. (Cande and Kent, 1995) while the CIE occupies about 0.0150 m.y. somewhere within the early part of the chron (see above). The cryptochrons described by Cande and Kent (1992) have not proven useful for correlation (Flynn and Tauxe, 1998).

### **Other elements of correlation**

Recognition of the CIE, like other stratigraphically restricted features (i.e., BFE) is greatly complicated when unconformities are present (Aubry, 1998; Aubry et al., 2000). A reliable identification should include an isotopic decrease of 3 to 4‰, and association with at least one of the secondary elements of correlation described above. In turn, these latter permit us to predict the position of the CIE in the section, and are thus important elements for correlation of the base of the Eocene Series.

The CIE and its associated biotic events are bracketed by a number of FAD and LAD of taxa, which help determine essentially globally the completeness of sections around the P/E. These are, in stratigraphic order:

nannoplankton: below the CIE, the LAD of *Fasciculithus alanii*, and a simultaneous decrease in the abundance of *Fasciculithus* spp. Above the CIE, the FAD of *Discoaster mahmoudii* and the LAD of *Fasciculithus* spp.

planktonic foraminifera: (below) the LADs of *Igorina albeari* and *I. tadjikistanensis*; the FADs of *Igorina broedermanni*, *Acarina wilcoxensis*; and (above) the FAD of the planispiral taxon *Pseudohastigerina wilcoxensis* (Ouda and Berggren, 2003) and the LAD of *Morozovella velascoensis*.

### **Regional correlation in the marine record**

A number of biostratigraphic events and turnovers have been described that correlate regionally the P/E boundary. In addition, regional lithologic changes may help delineate the boundary.

#### *Biostratigraphic events and turnovers*

Ostracodes: In the southern high latitudes, the CIE is associated with the replacement of an assemblage of large, heavily calcified, mostly epifaunal taxa (*Kritho*/OTG6) by an assemblage of small, thin-walled, generalist taxa (*Cytheropteron* s.l., *Propontocypris* and OTG2 and 3) (Steineck and Thomas, 1996). A marked turnover has also been described from middle neritic setting in Egypt (Speijer and Morsi, 2002).

Deep water agglutinated foraminifera: In the Tethyan realm, deep water agglutinated foraminifera underwent a marked turnover

slightly before the onset of the CIE. The sequential FADs of *Karreculina coniformis*, *K. horrida*, and *Reophax elongatus*, LAD of *Cribrostomoides trinitatensis* coincident with the FAD of *C. trinitatensis* all fall within the CIE, and the bloom of *Repmanina charoides* immediately above it may provide fine regional correlations (Galeotti et al., 2000).

**Siliceous microfossils:** The stratigraphic range of diatoms and radiolarians in Chron C24r-sediments is poorly established due to the rarity of upper Paleocene-lower Eocene siliceous microfossil-bearing sediments (e.g., Fourtanier, 1991; Sanfilippo and Nigrini, 1998; Sanfilippo and Hull, 1999; however, see Radionova et al., 2001).

A potentially stratigraphically useful event is an acme of large diatoms of the genera *Trinacria* and *Craspedodiscus* found in association with the CIE and the *Apectodinium* spp. acme in a Tethyan section (Egger et al., 2000).

As established through indirect correlations (Sanfilippo in Aubry, 1999), the CIE occurs in the lower part of the (radiolarian) *Bekoma bidartensis* Zone, and is bracketed between the LOs of *Podocyrtes papalis*, *Phormocyrtes turgida* and *Giraffospyris lata* below and the LOs of *Theocotylissa auctor* and *Calocycloma castum* above.

**Dinoflagellates:** An acme of *Deflandrea oebisfeldensis* occurs above the CIE in the North Sea region.

#### Lithologic/mineralogic changes

In the Southern Ocean, New Jersey margin, North Sea area, southern Tethys, and New Zealand, the CIE is associated with a significant increase in the kaolinitic component of clay mineral assemblages (Robert and Kennett, 1992; Gibson et al., 1993; Gibson and Bybell, 1994; Kaiho et al., 1996; Knox, 1998; Cramer et al., 1999; Dupuis et al., 2003; Ernst et al., 2006).

In numerous sections, much of the CIE interval is marked by a calcite-free, leached clay or claystone (e.g., Orue-Etxebarria et al., 1996; Bolle et al., 1999; Baceta et al., 2000). While the absence of microfossils in such leached clays hampers precise biostratigraphic correlation, the clay itself usually shows a distinctive color (red) and constitutes an excellent field guide.

In other regions, such as the southern margin of the Tethys and specifically including the outer-shelf deposits of northeastern Egypt and the Sinai, the lower part of the CIE interval is associated with regional dysoxia, represented by a phosphatic coprolite-rich laminite with abundant fish teeth (Benjamini, 1992; Speijer, 1994; 1995; Dupuis et al., 2003).

## Motivation for selection of the boundary level

Deep sea and onshore cores are the best records of physical, chemical and paleontologic events occurring over long periods of time. Such cores have provided the data upon which a composite reference stratigraphic section for Chron C24r has been constructed (Aubry et al., 1996). In turn, this reference section has guided our choice among land sections of marine (from neritic to bathyal) deposits of the most suitable section to serve as GSSP for the P/E boundary.

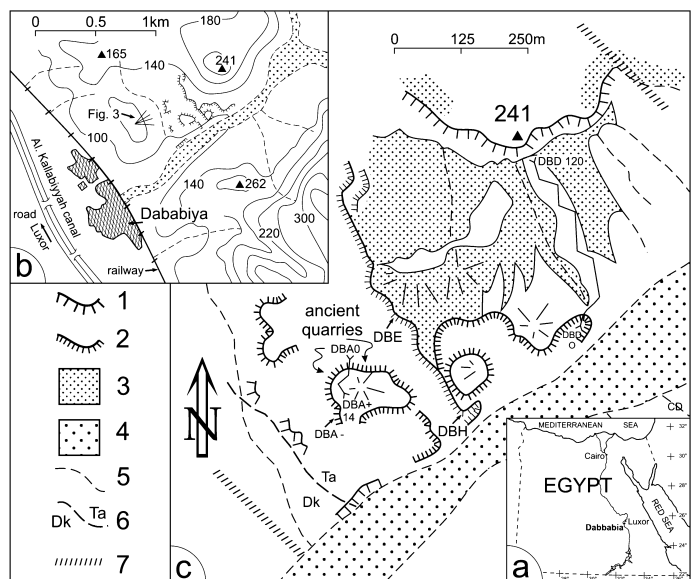
Twenty three land sections were investigated, and from among these nine merited closer examination as possible candidates for the P/E boundary GSSP (Benjamini, 1992; Molina, 1994; Molina et al., 1994, 1999; Molina and Arenillas, 1998; Orue-Etxebarria et al., 1996, 2001; Aubry et al., 1999; Ouda and Aubry, eds., 2003). Ultimately, two sections—Zumaya in northern Spain and Dababiya in the Upper Nile Valley of Egypt—gathered the most support.

The Dababiya section (Figures 2–7) has been selected for the quality of its biostratigraphic and geochemical (isotopic) record (Figures 8, 9). The carbon isotopic composition of organic matter clearly shows the CIE, whose onset is coincident with the base of the

Dababiya Quarry Member (= base of Dababiya Quarry Bed 1) at 1.58 m above the base of the section. The BFE, PFET and RD are all well represented in association with the CIE.

In choosing the DBH section at Dababiya for the P/E GSSP, we emphasize specific benefits:

- The GSSP is located at a sharp corner in an artificial face in the Esna Shale, 5 to 10 m high, that exposes the stratigraphy of the GSSP laterally for approx. 200 m without a break (Figures 3, 4, 7a). The section at the GSSP is in an uninterrupted, finely-laminated Paleocene-lower Eocene interval (Figures 3–6), spanning Chron C26n to C23r, and possibly younger (Aubry et al., 1999; Dupuis et al., 2003). Located as it is in a vertical, but readily accessible face, the DBH section is already well studied and characterized.
- The GSSP level and its stratigraphic context can be followed through variously-oriented vertical faces in excavations across a large area (approx. 0.5 x 0.5 km) in Dababiya Quarry (Figures 2–4), offering a three-dimensional view of stratal relationships.
- The GSSP level can be followed throughout northeastern Egypt (e.g., Owaina, Qreiya sections) to outcrops in the western Desert (Kharga oasis and New Valley; Ouda et al., unpublished manuscript), to South of Aswan in Gebel Abu Ghurra (Ouda et al., 2003), to the Red Sea (Duwi) (Schmitz et al., 1996; Aubry et al., 1999) and beyond across the Sinai (Speijer, 1995; Speijer et al., 1997) and the Negev (see above).
- The regional monocline of Upper Cretaceous-Upper Eocene outer shelf strata, exposed across the NE Egyptian desert in mesas and ridges, offer unparalleled opportunities to study the boundary regionally in uncomplicated, highly fossiliferous, continuously exposed sections.
- The proposed section is suitable for coincident establishment of the presently undefined boundary of a basal Eocene global standard stage.
- The GSSP section and its local context, because of its completeness, fine layering, uncomplicated exposure and relatively expanded thickness, offers the potential for cyclostratigraphic analysis of quarry faces and cores in the immediate vicinity, fol-



**Figure 2** Location maps redrawn from the 1/50000 topographic maps Al-Uqsir (Luxor) NG 36 F6a and Isna NG 36 F3c. **a, b:** location of quarries near Dababiya, east bank of the Nile River; **c:** detailed map of outcrops and quarries, including antique quarries, and location of partial sections DBA, DBD, DBE and DBH (P-E GSSP). DBA0= reference level for measuring the whole section; this is a flint bed. Subsection DBA is measured as DBA- below DBA0 and DBA+ above DBA0.

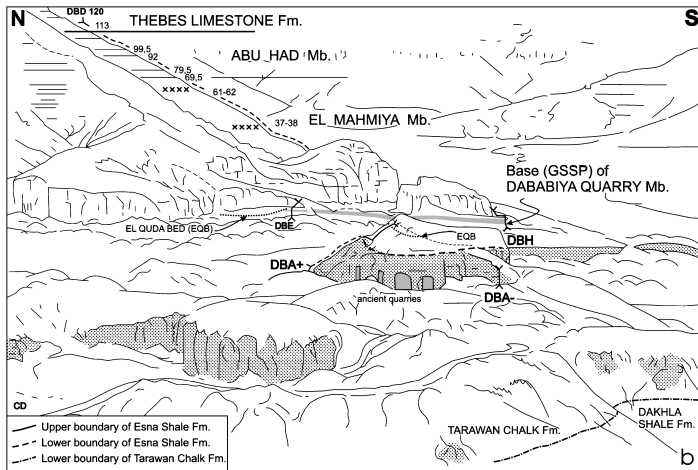


Figure 3 Oblique east-facing view of the outcrops in the Dababiya Quarry (see Figure 2b) as seen from the hill immediately to the north of the village of Dababiya. Sketch outlining the exposures of the main lithostratigraphic units: Dakhla Shales, Tarawan Chalk, Esna Shale and its four members [Hanadi, Dababiya Quarry, El Maayil and Abu Had] and Thebes Limestone. The four partial sections DBA, DBD, DBE and DBH (P/E GSSP) are shown.

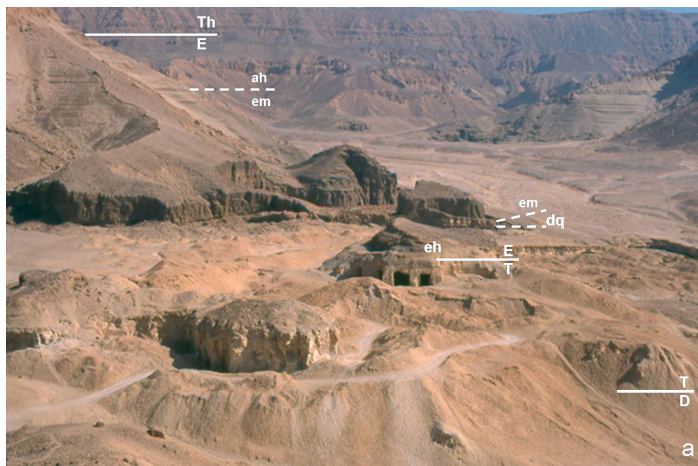


Figure 4 Oblique east-facing view of the outcrops sketched in Figure 3. Lithostratigraphic boundaries delineated as in Figure 3.

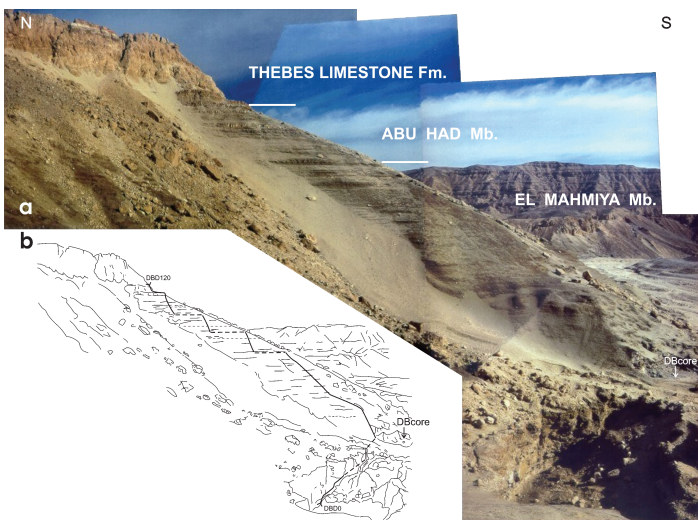


Figure 5 Upper part of the Esna Formation (El-Mahmayia and Habu Had members) and contact with the Thebes Limestone. a: photograph; b: diagrammatic sketch. DBDco: location of DBD core: DBH03.

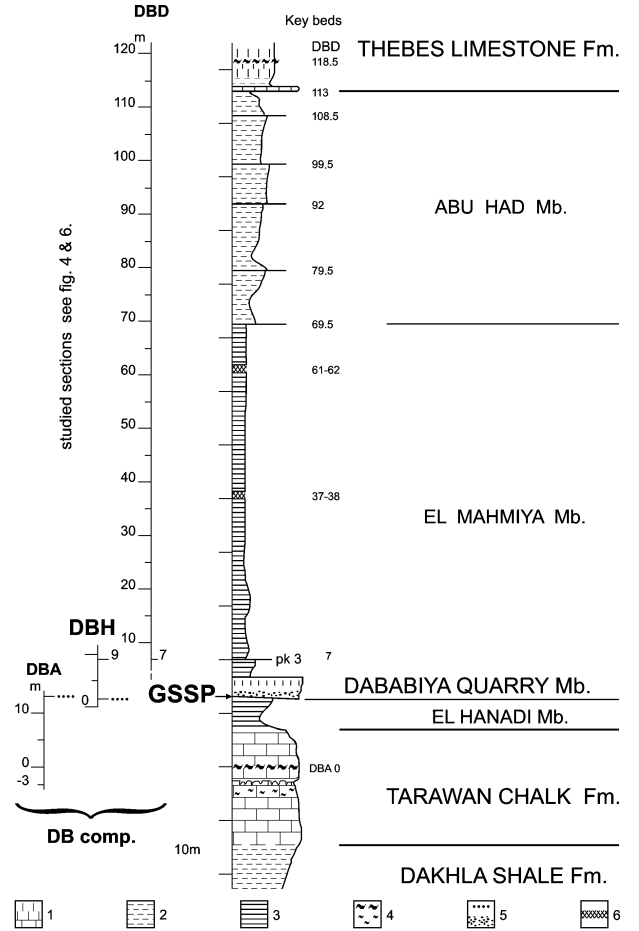


Figure 6 Composite lithostratigraphic section at Dababiya, from the Dakhla/Tarawan to the Esna Shale/Thebes Limestone formational contacts. Key beds for local lithologic correlations are shown. 1: Limestones; 2: marls and shales; 3: shales; 4: flint concretions; 5: Phosphates; 6: variegated shales.

lowing standard methodologies (e.g., Shackleton et al., 1999; Cramer, 2001). In the quarry and on the hillside behind it, a continuously exposed, unvegetated section ~ 160 m thick, with abundant well-preserved microfossils, extends from the Tarawan Chalk and Esna Shale to mesa-forming upper Ypresian Thebes Limestone (Figures 2–6). Analyses are in progress to characterise the GSSP in terms of astronomical cycles, like the Miocene/Pliocene Boundary GSSP (Van Couvering et al., 2000), giving a precise age and correlation of the GSSP.

## Lithostratigraphy

Because of concurrent formal and informal lithostratigraphic frameworks for the upper Paleocene-lower Eocene of Upper Egypt, we formalise here a lithostratigraphic framework in which the GSSP for the base of the Eocene is precisely positioned (Table 1). We divide the Esna Shale Formation into 4 members, retaining 2 previously introduced names and introducing two new ones.

### Esna Shale Formation

This formation was defined by Said (1960), as extending from the top of the Tarawan Chalk to the base of the massive limestones of the Thebes Formation. We follow this definition. On this basis, the Esna Shale Formation comprises, from base to top, the El-Hanadi, Dababiya Quarry, El-Mahmiya, and Abu Had members.

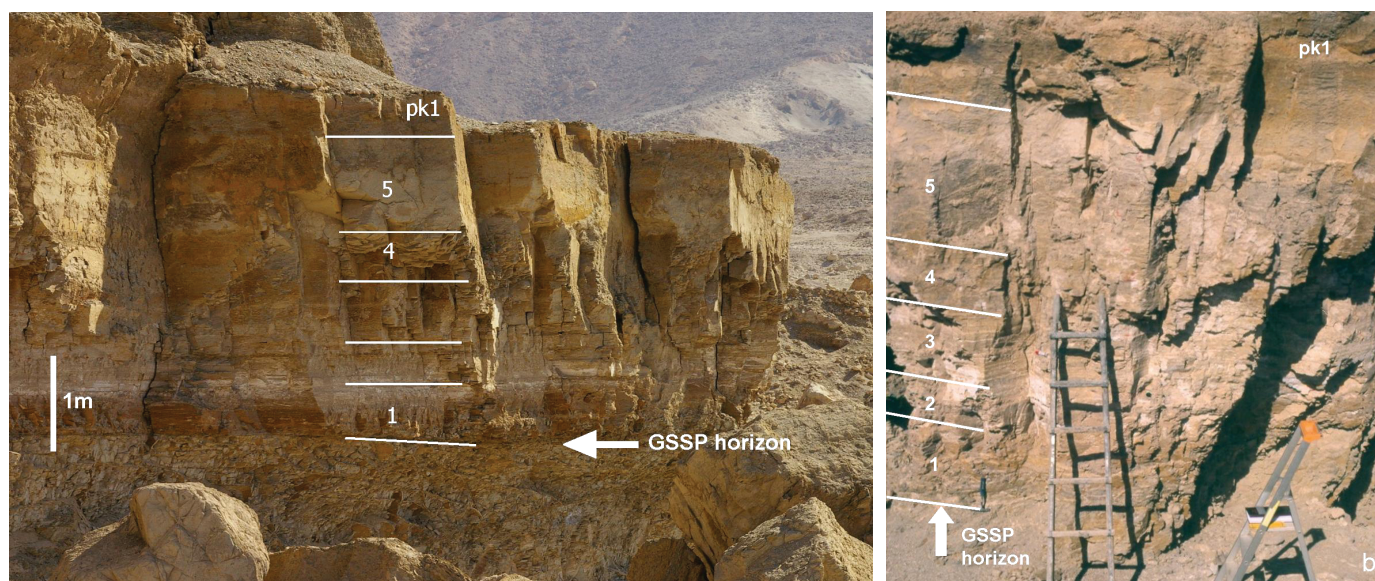


Figure 7 Dababiya Quarry Member (Subsection DBH; see Figure 3). a. general view. b. Detail of the 5 beds (DBQ Beds 1 to 5).

Table 1 The historical division and lithostratigraphic correlation of the Esna Formation.

Said (1960) A wad & Ghobrial (1965)	El Naggat (1966)	Khalifa (1970)	Abdel Razik (1972)	Dupuis et al. (2003)	This paper
Thebes Formation Said(1960)	Thebes Formation	Thebes Formation	Shaghab Mb.	Serai Limestone Mb.	Thebes Limestone Mb.
			Dabbabiya Mb.		
			Hamidat Mb.		
Esna Shale Said (1960)	Thebes Formation	Esna Shale	Abu Had Mb.	Esna 3	Abu Had Member
			Esna Shale		"E1 Shaghab" Mb.
	Owaina Formation	Upper Owaina Shale Mb.		Esna Formation	
			Dababiya Quarry Beds		Dababiya Quarry Member
Tarawan chalk A wad & Ghobrial, (1965)	Middle Owaina Chalk Mb.	Tarawan Chalk	E1 Hanadi Mb.	Esna 1	E1 Hanadi Member
					Tarawan Chalk

### El Hanadi Member emended

**Emendation:** This member was introduced by Abdel Razik (1972), as extending from the Tarawan/Esna formational contact to the top of a phosphatic bed in the lower part of the Esna Shale. We have identified this latter bed as the El-Quda Bed of the El-Mahmiya Member (see below). We thus emend the definition of the El Hanadi Member to restrict it to the Esna Formation below the El-Quda Bed in the Hanadi section. We further restrict it to the Esna Formation below the El Dababiya Quarry Member, implying that the El Hanadi Member corresponds to Esna Unit 1 of Dupuis et al. (2003) (Table 1).

**Lithology:** The member consists essentially of light gray, massive, compact calcareous shales with conchoidal fracture.

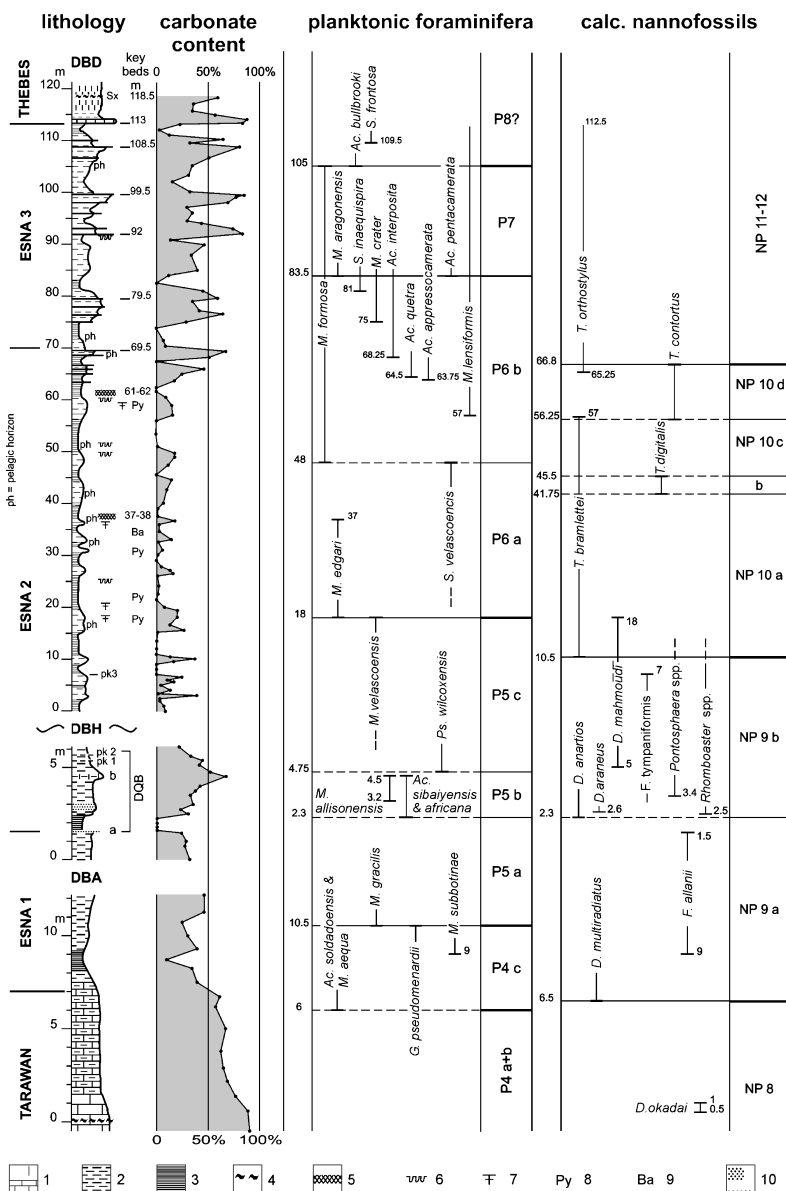
**Boundaries:** The lower boundary (with the Tarawan Chalk) is well exposed at El-Hanadi, in the Dababiya Quarry (Figures 2–4), and in the Qreiya section. The upper boundary is well exposed in the

(6 km to the North) Dababiya exposures (Subsections DBA and DBH, Figures 2–4, 6, 7a, b; ~ 10 km north of El-Hanadi).

**Thickness:** The El Hanadi Member (= Unit Esna 1) is 7 m and ~ 5 m thick in the Dababiya and Quda sections, 7 m in the Qreiya section to the North, 12 m and 14 in the Awaina and Kilabiya sections to the south (Ouda and Aubry, eds., 2003).

**Regional correlations:** To the West (Kharga Oasis) the El Hanadi Member is correlative with white chalky lithologies reminiscent of the Tarawan Chalk. To the south (Abu Gurrha section) it is correlative with the upper part of the Garra Formation (Hermina, 1990).

**Biostratigraphic characterization and age:** The member belongs to (planktonic foraminiferal) Zone P4b-c and P5a (Ouda and Aubry, 2003; now P5 sensu Berggren and Pearson, 2005), and (calcareous nannoplankton) Subzone NP9a. The Tarawan Chalk/Esna Shales contact corresponds essentially to the NP8/NP9 zonal boundary (Figure 9).



**Figure 8** Biostratigraphy of the composite section (Figure 6) at Dababiya. Biozonal boundaries and lowest and highest occurrences of selected planktonic foraminifera and calcareous nannoplankton taxa are shown. 1–limestones with DBA0 flint concretions, 2–marly limestone, 3–marls, 4–shales, 5–phosphatic shale and coprolites, 6–bioturbated surface, 7–macrofossils, 8–pyrite nodules, 9–baryte nodules, 10–phosphate beds. The following horizons were used to correlate the subsections: 1) the base of the Dababiya Quarry Member (a); marker b in the calcarenite (~60% carbonate); 2) three pink layers in the lower part of Unit Esna 2, just above the DQB (pk1, pk2, pk3).

Genetic interpretation: This unit was deposited in an outer neritic to upper bathyal, well oxygenated environment (Ernst et al., 2006).

### El Dababiya Quarry Member

Name: From the Village of El Dababiya, 35 Km south of Luxor  
Type section: El Dababiya Quarry, Subsection DBH.

Lithology: Lithologic ensemble of gray clay and laminite, typically consisting of the succession of 5 characteristic beds (Figure 7), from base to top:

Bed 1 (0.63 m thick): dark gray, non-calcareous, laminated shale with occasional cylindrical phosphatic coprolites;

Bed 2 (0.50 m thick): phosphatic brown laminated shale with numerous cylindrical coprolites;

Bed 3 (0.84 m thick): cream-colored, laminated phosphatic shale with sparse cylindrical coprolites and abundant, lens-shaped, pale pink phosphatic inclusions, 1 cm to several centimeters in diameter (?flattened coprolites);

Bed 4 (0.71 m): grey calcareous shale;

Bed 5 (1 m): marly calcarenitic limestone, forming a prominent light gray bed.

Characteristically, the contacts between the beds are regular, without any trace of bioturbation.

Boundaries: The lower boundary is a sharp contact between light-gray bioturbated neritic shale (El Hanadi Member) and a 63 cm dark shale. The upper boundary is a transitional contact from a marly calcarenitic limestone to a gray shale (El Mahmiya Member).

Thickness and distribution: The thickness of the member varies regionally, from 3.68 m and 3.77 m in the type (DBH) and Qreiya sections, respectively, to ~2 m and ~1 m in the El Quda, Gebel Aweina and El Kilabyia sections to the south of El Dababiya. It varies also considerably locally, as in the El Dababiya Quarry, from a maximum of 3.68 m (Subsection DBH) to less than 1.45 m. It is 2.40 m in the El Dababiya Core. Individual beds also vary in thickness, with Bed 1 and Beds 2–3 locally as thin as 5 cm and 2 cm, respectively.

Regional correlation: The El Dababiya Quarry Member occurs throughout the Upper Nile Valley, and in the Western (Kharga Oasis) and Eastern (Duwi Section) deserts. To the South, at Wadi Abu Ghurra, the El Dababiya Quarry Member correlates with the upper 3 m of the Garra Formation (Ouda et al., 2003).

Biostratigraphic characterization and age: This member belongs to the (planktonic foraminiferal) Subzone P5b (Ouda and Aubry, eds., 2003; now redefined as Zone E1, Berggren and Pearson, 2005) and (calcareous nannofossil) lower Subzone NP9b (Dupuis et al., 2003) (Figure 9).

Genetic interpretation: The El Dababiya Quarry Member reflects the unfolding of the sedimentary, biotic and geochemical events associated on the southern Tethys platform with global warming at the Paleocene/Eocene boundary. Bed 1 through 3 were deposited under euxinic conditions leading to mass mortality; Bed 4 and 5 reflect the progressive return to oxygenated conditions.

### El-Mahmiya Member

Name: From the name of Natural Park n°26 erected for protection of the GSSP of the base of the Eocene Series.

Type section: El Dababiya Quarry (Subsections DBH and DBD)

Lithology: Monotonous, dark, clayey shales without marked bedding, and low (<50%) calcium carbonate content and with clear cyclic color variations.

Boundaries: The lower boundary is the top of the calcarenitic limestone of El Dababiya Quarry Bed 5. The upper boundary is the base of a prominent (lowest) limestone bed at 69.5 m in section DBD (Figure 5).

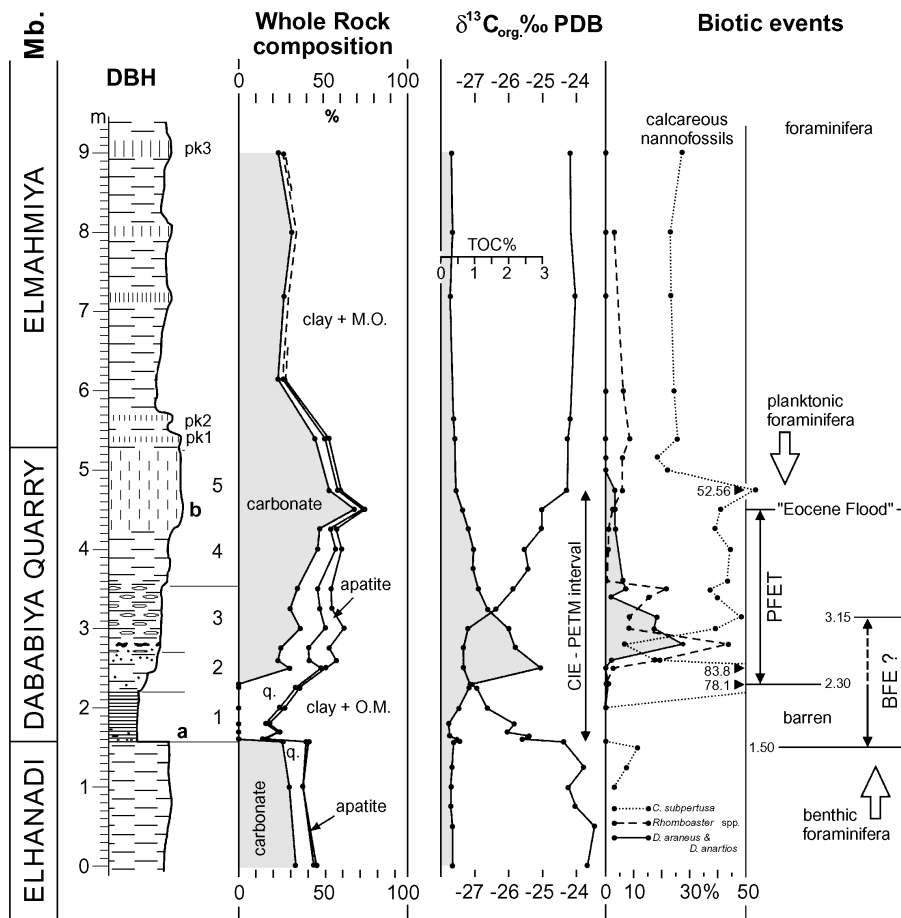
Thickness and distribution: The member is 65 m thick in the El Dababiya Quarry, 34 m in the Qreiya section, 31 m in the Gebel Owaina section and 18 m in the El Kilabyia section.

Regional correlation: This member extends throughout much of Egypt, from the Red Sea coast to the Western Desert. In southern Egypt (Wadi Abu Ghurra section) it correlates with the Lower clastic Member of the Dungul Formation Ouda and Berggren, 2003).

Biostratigraphic characterization and age: This member belongs to the (planktonic foraminiferal) Subzone E2-3 [formerly Subzone P5c (partim) to P6a (partim)] and (calcareous nannofossil) Subzone NP9a (partim) through Zone NP10. The boundary between the El-Mahmiya and Abu Had Members is almost equivalent to the NP10/NP11 zonal boundary (Ouda and Berggren, 2003).

Genetic interpretation: Deposited in outer neritic to upper bathyal (Dupuis et al., 2003).





**Figure 9** Litho-bio- and isotope stratigraphy of the upper El Hanadi, Dababiya Quarry and lower El-Mahmiya Members (Subsection DBH). The GSSP of the base of the Eocene is located at the base of the Dababiya Quarry Member (= base of Dababiya Quarry Bed 1) at 1.57 m above the base of section DBH.

**El-Quda Bed**

Name: From the village of El-Quda  
 Type section: El-Quda section, 25° 28,4'N, 032° 32,79'E  
 Lithology: This is, predominantly, a thin (10–30 m) calcarenite, generally with accumulations of cyclindrical coprolites, phosphatic and shale clasts and a variable amount of glauconite at the base. Coprolites are scattered in the upper part. Locally passes into a glauconitic clayey calcarenite, with few coprolites.

Boundaries: The lower boundary is an irregular, bioturbated erosional contact with the El Hanadi Member (Dababiya Quarry; Hanadi), or the El Dababiya Quarry Member (El Quda section, El Dababiya Quarry).

Thickness and distribution: The El-Quda Member is readily characterized when it occurs at the bottom of deep-cutting channels (contact with the El Hanadi or El Dababiya Quarry Member). It is difficult to identify laterally between channels, and may only be a bioturbated surface difficult to characterize in the drab lithologies of the El-Mahmiya Member.

Genetic Interpretation: The El-Quda Bed differs from beds of the El Dababiya Quarry Member by 1) the presence of glauconite, and 2) the erosive and bioturbated contact with the underlying lithology. The El Dababiya Quarry Member is non-glaucanitic, and the contacts between its beds are always smooth, without bioturbation or reworking. The El Quda Bed contains reworked coprolites from El Dababiya Quarry Beds 2 and 3 and clasts reworked from them or the El Hanadi Member. It implies deposition in a well oxygenated, high energy environment.

**Abu Had Member**

The Abu Had Member was introduced by Abdel Razik (1972) as part of the Thebes Limestone Formation for the alternating shales and limestone at the transition between the monotonous shales of the Esna and the massive limestones of the Thebes. We assign the Abu Had Member here to the Esna Shales Formation because of the clear-cut contact between the massive limestones and the shale facies (as behind the temple of Queen Hatshepsut at Thebes/Gurna). At El Dababiya, the member is 43.5 m, and belongs to Zone E4 (partim) – Zones E5-E6 (of Berggren and Pearson, 2005) formerly Zones P6b (partim) through P8 (Berggren et al., 1995) and Zones NP11-12 undifferentiated (Berggren and Ouda, 2003a). In the Qreyia section (Gebel Abu Had) the member, 5 m thick, is unconformable with both the El Mahmiya Member and Thebes Formation, and belongs to the lower part of Zone E5 (= lower part of Zone E7) (Berggren and Ouda, 2003b). The member is absent in the Gebel Owaina and El Kilabiya sections (Ouda et al., 2003)

**The Eocene Global Standard Stratotype-Section and Point**

**Name of the boundary:** Base of the Eocene.

**Rank and status of the boundary:** Series/Epoch GSSP.

**Position of the defined unit:** Base of the middle series of the Paleogene System, between the Paleocene Series and the Oligocene Series.

**Type locality of the GSSP:** A face (section DBH) exhibiting the lower part of the Esna Shales in the inactive Dababiya Quarry. Section DBH (9 m thick) is part of a 120 m-thick composite vertical section (DBcomp) through the Esna Shales.

**Geological setting:** The suite of gebels that overlook the upper Nile Valley, from south of Esna up to Assyut (Figure 10), display continuous exposures of Paleocene to lower Eocene epicontinental (neritic to upper bathyal) sediments (Said, 1990) divided into formations (in stratigraphic order) of the Dakhla Shales (Said, 1960), Tarawan Chalk (Awad and Ghobrial, 1965), Esna Shale (Said, 1960) and Thebes Limestone (Said, 1960). The Dababiya quarry (Figures 2–4) offers a remarkable three-dimensional cross section through the Esna Shale Formation. Minor local tectonics has tilted the Tarawan Chalk (which was exploited for building stone in Pharaonic times) in the western part of the quarry so that its contact with the Esna Shale is visible (Figures 3, 4). As elsewhere in the area, the Esna Shales/Thebes Limestone formational contact is easily accessible in the Dababiya Quarry

**Geographic location:** The Dababiya section is located on the right (east) bank of the upper Nile Valley, 23 km south of Luxor and ~30 km North of Esna, Type locality of the Esna Shales (Figure 10).

**Coordinates:** Lat. 25° 30' N., Long. 32° 31' 52" E

**Map:** The stratotype section is represented on the Geological Map of Egypt (Klitzsch et al., 1981) and precisely located on the geological map established for the Qena-Luxor-Esna area by Khalifa (1970).

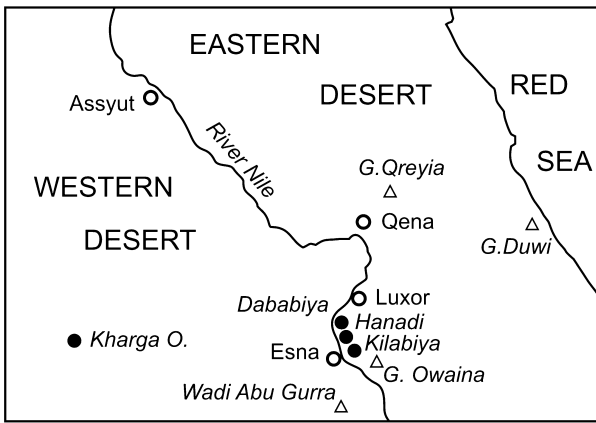


Figure 10 Location of main P/E sections in Egypt.

**Accessibility:** Access to the inactive quarry is unrestricted, at all times. The quarry is easily reached from the village of Dababiya, on the Luxor-Aswan road, by an unpaved ~1 km track that traverses the valley extending inland from the village. The GSSP horizon can easily be followed throughout the quarry (e.g., Sections DBA, DBE; Figures 3, 4, 5, 6) on foot or by car.

**Conservation:** The Dababiya site (Figures 2–4), including the deeply-cut ancient quarries in the Tarawan Chalk, and the international boundary point for the base of the Eocene in the adjoining Dababiya clay quarry, has been designated by Eng. Maged George of the Ministry of the State for Environmental Affairs and Qena Governate as Natural Park No 26 and approved by Dr. Ahmed Nazif, Prime Minister of Egypt. Access to the site is under the supervision of the Geology Department of the University of Assiut who will provide formal permits. Please contact Prof. Khaled Ouda (*kh\_ouda@yahoo.com*) and/or Dr. Nageh Obaidalla (*nageh46@hotmail.com*).

**GSSP definition:** The base of the thin dark gray clayey horizon (Dababiya Quarry Bed 1) that underlies the 2m-thick phosphatic

laminite (Dababiya Quarry Beds 2 to 5) in the Dababiya DBH partial section constitutes the GSSP for the base of the Eocene Series (Figure 7a, b). This level is firmly located in the lowest part of the CIE, which spans a brief interval of ~0.015 m.y. Current research (Gradstein et al., 2004; Luterbacher et al., 2004; Westerhold et al., 2007; Storey et al. 2007) based on re-dating of the -17 Ash and/or integrated radioisotopic age dating and astronomical calibration is converging around an age of ~55.8–55.9 Ma for the P/E boundary.

**Identification in the field:** The Esna Shales are unmistakably identified as a thick, uninterrupted body of marine shales between the Tarawan Chalk and the Thebes Limestones. Three pinkish limy shale beds, 10 to 20 cm thick and easily seen from the distance, form distinct markers in the lower part of the Esna Shale (Figures 4, 5). They lie respectively 3.8, 6.0 and 7.4 m above the GSSP. A distinctly laminated unit of black and yellow coprolite-rich phosphatic shale (i.e., Dababiya Quarry Beds), that weathers as a single rough-surfaced grey stratum, lies immediately above the GSSP (Figure 7a, b). The clay horizon (i.e., base of Dababiya Quarry Bed 1) at the GSSP is marked by a metal tag in the section.

**Completeness of the section:** The contact between the bioturbated gray shales, below, and the dark clay layer at the GSSP is a sharp but apparently continuous transition when seen close up, representing an abrupt change in depositional regime. From a distance, however, this horizon gives the appearance of being draped over a subdued topography. Carbon isotopes in samples from the lower part of the DBH section (Figure 9) can be interpreted to mean that the excursion in isotopic values begins below the GSSP level, so that the deflection or notch at the transition is not an indication of missing section. On the other hand, the basal part of the curve and a part of the underlying shales may be missing in a minor discontinuity, despite visual evidence to the contrary. In either case, the GSSP falls about 10%–20% up from the inception of the excursion, as it does in the more expanded Polecat Bench section (Magioncalda et al. 2004). There is no other suggestion of missing or condensed interval in the DBH exposure. In particular, the benthic foraminiferal fauna indicates a remarkably consistent water depth throughout the Dababiya

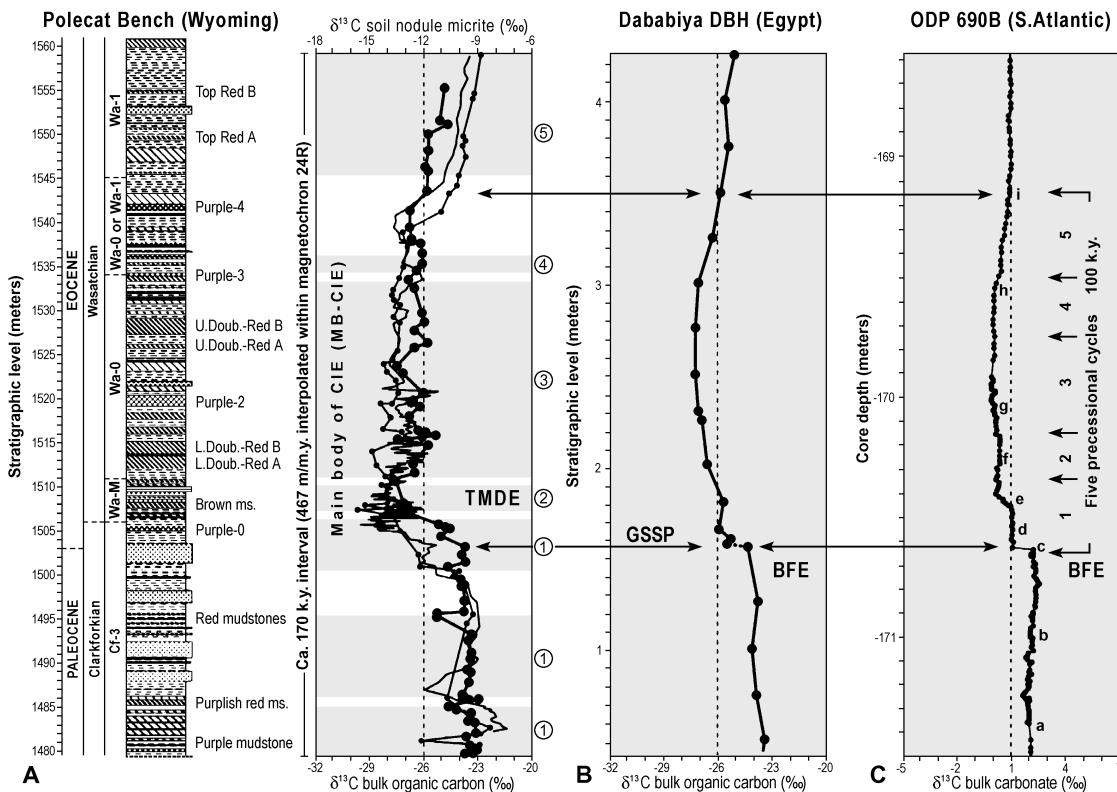


Figure 11 Correlation of the GSSP of the base of the Eocene Series Base of Bed 1 of the Dababiya Quarry Bed, Dababiya) to the Deep Sea (ODP site 690) and terrestrial (Pole Cat Bench, Wyoming) stratigraphies. (modified from Magioncalda et al., 2004).

section. This stability suggests a fairly similar environment of deposition throughout the interval represented.

**Global correlation:** Multiple tools for global correlation of the base of the Eocene have been identified following integrated studies of numerous sections. They are summarized above. The GSSP is reliably correlated globally as follows (Figures 7a, b, 9, 11; Ouda and Aubry, Eds., 2003):

**Chemostratigraphy:** The CIE, with an amplitude of 3.5‰, is well represented in the DBH section. Constant  $\delta^{13}\text{C}_{\text{org}}$  values of  $\sim -24\text{‰}$  occur between the base of the section up to the level of the GSSP. A sharp decrease occurs across the GSSP horizon from  $\sim -24\text{‰}$  in DBH 1.60 to  $\sim -26.5\text{‰}$  in DBH 1.65 and above a short plateau values decrease again from  $-25.82\text{‰}$  in DBH 1.80 to  $\sim -27.5\text{‰}$  in DBH 2.00.  $\delta^{13}\text{C}_{\text{org}}$  values remain constant up to DBH 3.00 and then increase progressively until pre-excursion values are reached at DBH 4.75 m. Above this level and up to the top of the section values remain constant.

The shape of the carbon isotope record in section DBH derived from organic matter mimics other high resolution carbon isotope records derived from carbonates (e.g., Bains et al., 2001; Bowen et al., 2001; Magioncalda et al., 2004). Carbon isotope records derived from carbonates in the DBH section and in nearby sections, although of similar amplitude, failed to register the characteristic pattern of the CIE (Schmitz et al., 1996; Aubry et al., 1999; Dupuis et al., 2003).

The base of the CIE is registered differently in different marine carbonates (whole rock, tests of different species of planktonic foraminifera; see above). While the initial shift would appear to have the greatest correlatability, the inflection point does not occur at exactly the same stratigraphic level when different carbonates are being compared. This implies a built-in, albeit small, uncertainty in correlations that use the base of the CIE. In addition, there is also an offset between the inflection points recorded by marine carbonates and by organic matter (Magioncalda et al., 2004). For these reasons, the WG has chosen to locate the GSSP at a distinctive lithologic change (definition) that lies at or close to the isotopic shift rather than specifically at the initial negative shift (correlation) in carbon isotopic values.

**Benthic foraminifera:** Midway Assemblage species are dominant throughout the section, although deeper water Velasco Assemblage species are consistently present. An outer(most) neritic (150–250 m water depth) paleoenvironment is inferred based on the presence of both typical outer neritic (*Cibicidoides allenii*, *C. succedens*, *Anomalinoidea midwayensis*, *Alabamina midwayensis*, *Osangularia plummerae*, *Bulimina midwayensis*) and upper bathyal (*Angulogavelinella avnimelechi*, *Tritaxia midwayensis*, *Anomalinoidea rubiginosus*) species.

The largest change observed in the benthic fauna occurs in the interval of the PETM between samples DBH1.5 and DBH3.6. Samples below this interval are dominated by species of *Cibicidoides*, *Anomalinoidea*, and *A. avnimelechi*. Samples above this interval are dominated by lenticulinids and buliminids with a gradual return of *Cibicidoides* and *Anomalinoidea* species over  $\sim 10$  m. This transition is correlative with the prominent benthic foraminiferal extinction event observed in bathyal and abyssal sections (Tjalsma and Lohmann, 1983; Thomas, 1990; Katz et al., 1999).

The level of the benthic foraminiferal extinction event (BFE) is typically taken at the last occurrence of *Stensoeina beccariiiformis*. Although this species is absent in the Dababiya section, the last occurrence of the similar species *A. avnimelechi* may be taken as correlative with the deep-sea extinction event. The disappearance of *A. avnimelechi* also defines the BB1/BB2 boundary in the bathyal benthic foraminiferal zonation scheme of Berggren and Miller (1989). In the DBH section, this level occurs just above a carbonate-free interval. No benthic foraminifera were observed in samples DBH1.6–DBH2.8; very few benthic foraminifera were observed in sample DBH3.15. *Angulogavelinella avnimelechi* was observed in samples DBH3.4, but not in sample DBH3.6 and above. Similarly, rare occurrences of *S. beccariiiformis* within the CIE interval have been reported from other sections; where available, carbon isotope

data have confirmed that these specimens were reworked from below the CIE (e.g., Katz et al., 1999; Cramer et al., 1999). It is therefore likely that most of the benthic foraminifera in the samples just above the barren interval at DBH were redeposited, in which case the BFE would be placed within the barren interval. However, with no supporting evidence for reworking, we place the extinction event in the interval between DBH3.4–DBH3.6.

**Planktonic foraminifera:** Section DBH belongs to Zone P5. Characteristic features of this section are as follows:

- 1 Planktonic foraminifera are absent or exceedingly rare in the lower 3 m of the Esna Shale with the exception of samples DBH 0.0, 1.0 and 1.5. Faunas referable to Zone P5 occur in these three samples and are characterized by *Morozovella acuta*, *M. aequa*, *M. apantesma*, *M. subbotinae*, *M. velascoensis*, *Igorina lodoensis*, *Acarinina soldadoensis*, *Subbotina patagonica* and *S. velascoensis*.
- 2 The black, quartz-rich unit and quartz rich sands and silts of lithologic unit 2 are barren.
- 3 The phosphate (apatite) rich layer (Unit 3) is essentially barren in its lower part (samples DBH2.5, 2.6, 2.8, 3.15). However, extremely rare *Acarinina sibaiyaensis* were found at level 2.3.
- 4 The CIE/PETM interval (as registered in the  $\delta^{13}\text{C}_{\text{org}}$ ) actually corresponds to the interval from DBH1.60 to 5 ( $\sim 3.4$  m thick). The interval from DBH3.4 to 5 contains a "foraminiferal mud" (which, when observed in the form of washed residues under a microscope has the appearance of a pelagic ooze because of its high percentage of planktonic foraminifera). The significant clay component, however, indicates that the term "foraminiferal mud" may be a more appropriate descriptive term. Within this interval the planktonic foraminiferal excursion taxa (PFET) have been observed from DBH 3.4 to 4.25 ( $\sim 1$  m thick): *Acarinina sibaiyaensis* (common), *Ac. africana* (rare) and *Morozovella allisonensis* (infrequent and atypical, consisting predominantly of relatively high conical morphotypes intermediate between the typical end members of *velascoensis* and *allisonensis* as illustrated by Kelly et al., 1998, text-figure 8).

The PFET (and associated Subzone P5b/E1 faunal elements) is seen to span the ascending (return) limb of the CIE ( $\sim 26.5\text{‰}$ – $25\text{‰}$   $\delta^{13}\text{C}_{\text{org}}$ ) and to span/represent  $\sim 30\%$  of the total stratigraphic interval of the CIE/PETM at this section. Several taxa have been observed to have their lowest occurrences (LO) in the interval of the PFET: *Acarinina pseudotopilensis*, *Ac. wilcoxensis*, *Igorina broedermanni* and the distinctive planispiral taxon *Pseudohastigerina wilcoxensis* (confirming its biostratigraphic utility in denoting the Paleocene/Eocene boundary) together with its (relatively common) immediately ancestral taxon *Globanomalina luxorensis*, which is characterized by having a slightly asymmetrical test/aperture.

The remainder of section (DBH4.5 to 9) contains typical Subzone P5c/E2 faunal components.

**Calcareous nannofossils:** Section DBH belongs to Zone NP9. Six distinct assemblages occur as follows:

- 1 Calcareous nannofossils (CN) are abundant and preservation is moderately good from DBH0.0 to DBH1.5. The assemblages, of very high diversity, include *Chiasmolithus consuetus*, *Cruciplacolithus delus*, *Discoaster falcatus*, *D. multiradiatus*, *Ellipsolithus distichus*, *E. macellus*, *Ericsonia subpertusa*, *Fasciculolithus alanii*, *F. lilianae*, *F. schaubi*, *F. tonii*, *F. tympaniformis*, *Heliolithus megastypus*, *Sphenolithus primus*, *Towieus callosus*, *T. eminens*, *Zygrhalthus kerabyi*. These are typical low latitude late Paleocene assemblages.
- 2 Levels DBH1.6 and DBH2.00 are essentially barren.
- 3 CN are common at level DBH2.3 but diversity is very low and preservation is poor. *Ericsonia subpertusa* is predominant at this level. *Discoaster multiradiatus* (rare) co-occurs with a few specimens of an unidentified discoaster, here referred to as *D. sp. cf. D. pacificus*.
- 4 CN are common and moderately well preserved at level DBH 2.5. The low diversity assemblage includes *E. subpertusa*, *Discoaster anartios*, *D. sp. cf. D. pacificus*, *F. tympaniformis*, *Rhomboaster cuspis*, *Towieus pertusus*.

- 5 Between DBH2.6 and DBH4.25, the CN are abundant with good preservation. Assemblages are characterized by the common to abundant occurrences of *Discoaster araneus*, *R. cuspidis*, *R. spineus*, with *E. subpervusa*, *D. helianthus*, *D. lenticularis*, *D. multiradiatus*, *F. liliana*, *F. schaubi*, *F. tympaniformis*, *Z. kerabyi*. In this interval, *D. araneus* and *Rhomboaster* spp. first dominate the assemblages and subsequently dwindle progressively as general diversity increases.
- 6 From level DBH4.5 and up to level DBH9.0, the CN assemblages are well diversified, and similar to assemblages below DBH1.6, except for the occasional occurrences of *D. araneus*, and *Rhomboaster* spp. Of interest are the absence of *F. alanii* (HO in DBH1.5; a few, isolated occurrences are believed to reflect reworking), the LO of *D. mahmoudi* at DBH5.4 and the LO of *Pontosphaera plana* at DBH8.0.

The changes that occur in the CN assemblages between level DBH 2.5 and 4.5 have been reported from other sections (Aubry, 1999; Aubry et al., 2000) and are characteristic of the CIE, as seen in other sections. A sudden dominance of *E. subpervusa* occurs in association with the CIE at ODP Site 865 (Kelly et al., 1996). The *Rhomboaster* spp.–*D. araneus*-dominated assemblage between DBH2.6 and 4.5 represents the RD, restricted here as in the New Jersey margin Bass River section and the Alamedilla section (Spain) to the duration of the CIE (Cramer et al., 1999; Kahn and Aubry, 2004).

#### Other means of correlation

The magnetic signal in surface exposure at Dababiya is largely overprinted (Kent and Dupuis, 2003) and no dinoflagellate cysts are preserved (Ali Soliman, personal communication, 2002). It was hoped that outcrop remagnetization resulted from superficial weathering in subtropical climate. However, the Dababiya Core is also entirely remagnetized (D. V. Kent, pers. comm. November 2005), implying that magnetic overprinting is a regional phenomenon in the Nile Valley, likely resulting from fluid flow during the Late Neogene tectonics in the valley (Kent and Dupuis, 2003).

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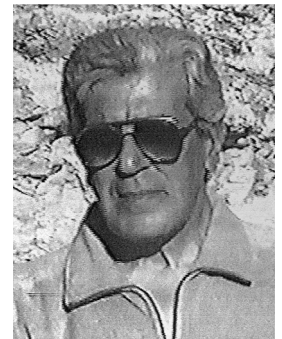
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Note: The details of P/E sections examined by the WG on the P/E boundary, and the postal and e-mail addresses of the Working Group Members can be found at <http://geology.rutgers.edu/~aubry/EoceneGSSP/>

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