

Paleocene depositional environments and depositional sequences in the Dababiya Quarry Corehole (Egypt)

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ABSTRACT: The Paleocene interval of the Dababiya Quarry Corehole (DQC) (at Dababiya, near Luxor, Egypt) comprises mainly hemipelagic sediments (calcareous claystone, marl and chalk), deposited in outer neritic to upper bathyal environments on the southern margin of Tethys. The earliest Danian is however represented by dark gray claystone deposited in shallower, mid neritic environments. The greatest water depths were reached in the mid-Thantetian.

The principles of identifying sequences and sequence tracts in hemipelagic settings are summarised. Nine depositional sequences are tentatively differentiated at Dababiya, based mainly on sedimentology, gamma-ray and magnetic susceptibility logs and foraminiferid assemblages. Comparisons are made with depositional sequences differentiated in other low and mid-latitude areas.

INTRODUCTION

The Dababiya Quarry Corehole, drilled close to the site of the base Eocene GSSP (Dupuis et al. 2003; Aubry et al. 2007; Berggren et al. 2013, this volume), has provided an opportunity for detailed analysis of Paleocene stratigraphy and the Cretaceous/Paleogene (K/P) boundary in the southern Nile Valley. This contribution provides an integrated interpretation of Paleocene depositional environments and depositional sequences. It is based on evaluation of lithological, sedimentological and paleontological data presented in other papers in this volume, together with personal observations, and comparison with data from other sections in Egypt, including Gebel Aweina, 40 km SE of Dababiya.

PALEO GEOGRAPHIC CONTEXT

The Paleocene sediments of southern and central Egypt were deposited on a passive margin forming the southern edge of the Tethys (Neotethys) Ocean, on a ramp-type shelf ('stable shelf'), in a largely tectonically quiescent setting, fringed to the south by the probably largely emergent Arabian-Nubian Craton (text-fig. 1). The shelf sloped very gently northwards from inner neritic environments (now largely removed by erosion) to upper bathyal depths [the neritic/bathyal boundary is here defined as 200 m water depth, as in Speijer 2003]. In the Luxor area, water depths of c. 150-300 m are envisaged through much of the Paleocene (Speijer 2003). The 'stable shelf' grades further north into the 'unstable shelf', characterised from Late Cretaceous through to Eocene by intermittent episodes of inversion and uplift of Mesozoic grabens of the Syrian Arc, leading to the development of localised basins and swells (Scheibner et al. 2003; Sprong et al. 2012; text-fig. 2). Except in proximal areas and in the early Danian, sedimentation is characterised primarily by hemipelagic sediments (calcareous claystones, marls and limestones), largely homogenised by bioturbation.

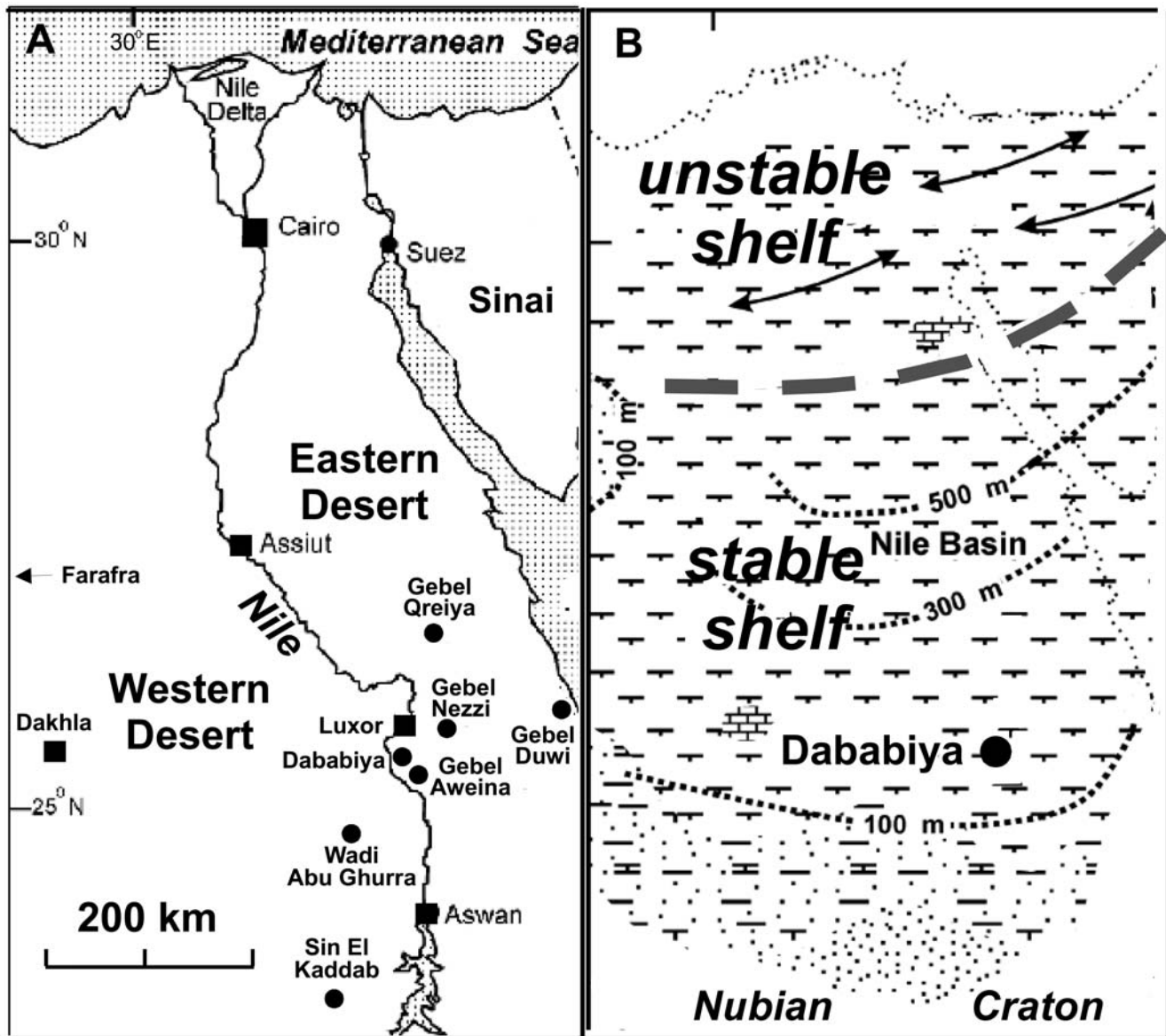
DEPOSITIONAL SEQUENCES IN HEMIPELAGIC SEDIMENTS

The problems of identifying depositional sequences and sequence tracts in hemipelagic successions are well documented (e.g. Luning et al. 1998; Ozsvárt 2004). In outer neritic and upper bathyal water depths, such as those represented in the DQC, below storm wave base, many of the sedimentological and paleontological criteria available in shallower marine environments are lacking. Minor sea-level changes can leave little trace, unless reflected by productivity fluctuations which can result in changes in carbonate content. Higher-order sequences may be only subtly recognisable. Identification and delimitation of sequence tracts can be even more uncertain. In these circumstances, techniques have been developed utilising vertical changes in sedimentary or paleontological characteristics appropriate to this context. These are summarised here, with reference to their relevance to the Dababiya section (text-fig. 2). Here and in following sections, sequence boundary is abbreviated as SB, the lowstand systems tract as LST, transgressive surface as TS, transgressive systems tract as TST, maximum flooding surface as MFS and highstand systems tract as HST.

Foraminiferids

P/B ratio

The P/B (planktonic/benthic foraminiferid) ratio is most effectively expressed as the proportion of planktonic foraminiferids in the total foraminiferid population (commonly but inaccurately described as a ratio). In order to better compare data from different sites and stratigraphic units, King (1989) proposed the standardised measure **P**, the percentage of planktonic foraminiferids in the total foraminiferid population, calculated from the 125-250 µm size fraction.



TEXT-FIGURE 1

A. Location of Dababiya and other sites cited in the text.

B. Paleogeographic context of the Dababiya Corehole, on the same scale as 1A. Based on Speijer (2003, figs 2 and 3). Generalised mid and late Paleocene paleobathymetry and facies are indicated (dots: sands; half-bricks: marls; bricks: limestones). The broken line separates the southern 'stable shelf' from the northern 'unstable shelf'. Axes of synsedimentary uplift along NE-SW oriented structures of the Syrian Arc are shown.

The P/B ratio has a general relationship to water depth, as documented in a number of settings (e.g. Gibson 1989; Nigam and Henriques 1992), with **P** increasing with depth in environmentally and geographically unrestricted settings, but the productivity of both planktonic and benthic foraminiferids is influenced by multiple water-mass properties. In the paleogeographic setting of the Paleocene in Egypt, these are most likely to be oxygenation and nutrient influx. Quantitative analysis of the Dababiya benthic foraminiferid assemblages (although rather broad-scale) (Alegret and Ortiz 2013, this volume) indicates relatively limited assemblage fluctuations, with no major episodes of high productivity, except in the Hanadi Member (late Thanetian). This suggests that productivity and oxygenation in the hemipelagic facies remained relatively con-

stant until late in the Paleocene. Similar results were obtained at Gebel Aweina (Speijer and Schmitz 1998). It seems probable that, as concluded by Luning et al. (1998) in the Paleocene of Sinai, the P/B ratio can be interpreted as primarily reflecting relative bathymetry (but see below).

A detailed study on the hemipelagic Paleocene succession in central east Sinai (Luning et al. 1998) discussed techniques for sequence analysis in hemipelagic successions, and analysed the principles involved. They concluded that the P/B ratio was the most valuable technique for identifying sequence boundaries and sequence tracts in hemipelagic sediments. They proposed that inflections in the P/B curve could be regarded as proxies for the transgressive surface (TS) and the maximum flooding sur-

face (MFS), in the absence of sedimentological criteria used in more proximal marine environments. Their ‘ffe’ (first marine flooding event), defined by a significant upward increase in the P/B ratio, was interpreted as reflecting the TS. They defined a ‘mfe’ (maximum marine flooding event) just below the following maximum proportion of planktonic foraminiferids, interpreted as a proxy for the MFS. Sequence boundaries were placed at falls in the P/B ratio. On this basis they identified three sequences in the Danian (DaSin1-3) and five in the Thanetian [Selandian and Thanetian in current terminology] (ThSin1-5).

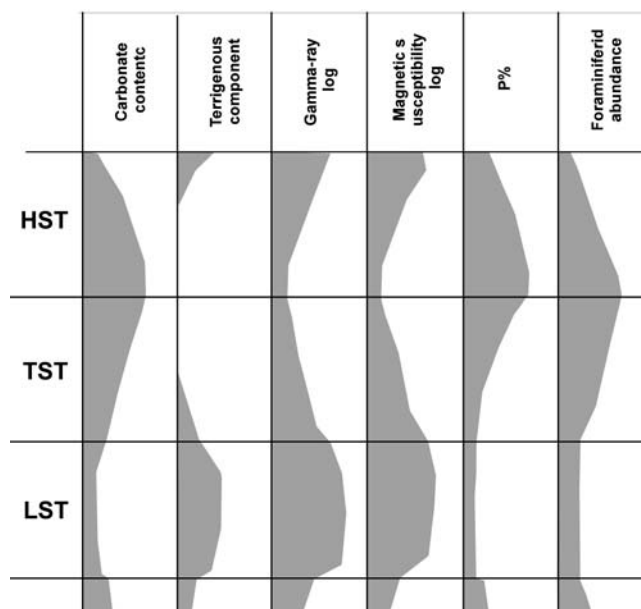
I would note, however, that judging by the published data, the P/B curves are based on a relatively limited database compared to the number of sequences and sequence tracts identified (for their Section C, approximately 34 datapoints for 10 sequences, with one sequence represented by a single sample!) (Luning et al. 1998, text-fig. 1). The location of the sequence boundaries identified (Luning et al. 1998, text-fig. 1) in many cases seems difficult to justify from the published data. Their database thus seems inadequate to support such a detailed interpretation, although the principles are likely correct.

In principle, abrupt falls in **P** are interpreted as representing a SB; **P** begins to increase again progressively at the TS, reaching its maximum at the MFS, and then decreasing. At Dababiya and in similar contexts, **P** is generally high (>85%) at most levels (except for the early Danian and exceptions noted below), reflecting near-bathyal water depths. The P/B ratio here and in similar contexts has a much smaller range than in the area studied by Luning et al., and cannot be used in isolation to identify sequences or sequence tracts.

The abrupt fall in the P/B ratio within the Tarawan Chalk Formation at Dababiya (text-fig. 3) is not reflected by any significant change in lithology, or other parameters, and appears to correspond approximately to the maximum depths identified from benthic foraminiferid assemblages in the Paleocene (Alegret and Ortiz 2013, this volume), as discussed below. It is a regional feature; a comparable abrupt fall is represented at Gebel Aweina (Speijer and Schmitz 1998) and appears to be recognisable in some sections in Sinai (Luning et al. 1998), although details are unclear (see below).

Benthic foraminiferid assemblages

Benthic foraminiferid assemblages are extensively used to determine paleobathymetry, but the distribution of individual species is controlled by many interacting factors which are generally only indirectly related to water depths. Depth-related assemblages are often poorly delimited in ramp-type settings, where changes in depth are gradual and there is no topographic ‘shelf to basin’ feature separating depth-related water masses. Depth ranges for Paleocene foraminiferid assemblages and for individual species have been extensively investigated (e.g. Berggren and Aubert 1975; Van Morkhoven et al. 1986; see also Alegret and Ortiz 2013, this volume). Relative water depths can generally be determined from assemblages, e.g. the Midway ‘shelf’ assemblage and the bathyal Velasco-type assemblages first differentiated by Berggren and Aubert (1975), but published studies and personal observations indicate that depth limits estimated for individual taxa can vary significantly from area to area, depending on the hydrographic context.



TEXT-FIGURE 2

Criteria for sequence stratigraphic interpretation in hemipelagic sediments.

The moderately diverse benthic foraminiferid assemblages in the Paleocene of Egypt and adjacent areas have been a primary means of determining relative and absolute water depths, based on semiquantitative and quantitative analysis (e.g. Speijer and Schmitz 1998). Samples from the Dababiya corehole have been analysed by Alegret and Ortiz 2013 (this volume) and some additional observations are made here. At Dababiya the assemblages are mainly of ‘Midway-type’, indicating outer neritic environments (Alegret and Ortiz 2013, this volume), but significant proportions of the ‘Velasco-type’ taxon *Nuttallides truempyi* occur at one level within the Tarawan Formation (Alegret and Ortiz 2013, text-fig. 2). This and other predominantly bathyal taxa were recorded at the same level at Gebel Aweina (Speijer and Schmitz 1998) (see below).

The benthic foraminiferid assemblages cannot be linked directly to specific sequence tracts, but abrupt depth-related changes or trends can indicate sequence and sequence tract boundaries. Increased proportions of ‘Velasco-type’ taxa within a predominantly ‘Midway-type’ assemblage are interpreted here as indicating the MFS and the succeeding early HST.

Foraminiferid abundance

Armentrout and others (e.g. Armentrout 1996) have related relative foraminiferid abundance to rates of sedimentation, and linked these to sequences and sequence tracts. In general, relatively high abundance is anticipated during the TST, when sediment input is reduced, culminating in highest abundance at the MFS. Luning et al. (1998) commented on the use of this technique in Sinai. Absolute abundance figures are not available for the DQC section, but some qualitative observations can be made. These indicate that foraminiferid abundance is characteristically highest immediately above omission surfaces. As these mark the TS or higher-order flooding surfaces, this is likely to reflect reduced clastic sedimentation during rising sea-levels.

Sedimentary components

Carbonate content

In open marine hemipelagic environments, the carbonate content comprises dominantly nannofossils and planktonic foraminiferids. Variations in carbonate content thus reflect primarily fluctuations in productivity, and/or changes in the influx of land-derived clastic material. As discussed above, the benthic foraminiferids at Dababiya do not indicate major fluctuations in productivity through most of the section; the primary control appears to be fluctuations in clastic input, in this context implicitly reflecting fluctuations in sea-level. This is confirmed by the frequent increase in carbonate content (often including foraminiferid concentrations) immediately above omission surfaces. These are interpreted as reflecting transgressive surfaces, as noted above. Carbonate content is in principle lowest during the LST, during which terrigenous input is likely at maximum, increasing at the TS as terrigenous input falls, rising to a maximum at the MFS and then decreasing through the HST.

Gamma-ray response

The sediments in the DQC section are composed essentially of clay and carbonate, with very low proportions of organic or coarse clastic components at most levels. The carbonate content is thus in general accurately reflected by the gamma-ray log. This is confirmed by comparison with the lithology log and with limited calcimetry data (Dupuis 2013, this volume; Dupuis et al. 2013, this volume; Knox et al. 2013, this volume), which enable quantitative calibration. Exceptions include high-gamma spikes indicating phosphate-rich levels, and a high gamma-ray response in claystones at some levels, which may reflect organic content, also indicated by darker coloration.

Magnetic susceptibility

Magnetic susceptibility (MS) is a quantitative measure of the proportion of magnetic components (mainly iron-bearing detrital minerals) and paramagnetic components (mainly illite) in a sample, and is thus a proxy for the terrigenous fraction of marine sediments (see Elwood et al. 2008 for details). Magnetic susceptibility in hemipelagic sediments thus reflects primarily the ratio between carbonate and clay, similarly to the gamma-ray log (Cramer 2013, this volume). Short-term (metre-scale) trends are considered to reflect cyclic climatic variation and hence can be linked to astrochronological cycles (see Cramer, this volume). Longer-term trends are interpreted as reflecting eustatic or tectonic controls, and in principle can be used to identify sequence boundaries and sequence tracts, and in some cases for long-range correlation.

Several studies have used MS logs to generate or confirm sequence stratigraphic interpretations, e.g. Whalen and Day (2008) who identified high MS levels related to the LST and early TST. They were able to correlate Devonian MS logs between Canada and Morocco. In the DQC the striking general parallelism of the gamma ray log and the MS log (text-fig. 3) confirms this relationship, although there are some divergences (discussed below), and the MS log appears to pick up some brief excursions not clearly identifiable from the gamma-ray log. The MS log was derived from measurements on the core rather than downhole logging, and there may be minor depth discrepancies between these logs.

Here, an abrupt increase in the MS is interpreted as indicating a sequence boundary; the succeeding fall is taken to reflect the TS. Decreasing and increasing trends generally parallel those for the gamma-ray log, and are similarly interpreted as representing the TST and HST respectively.

Sedimentology

Phosphate and glauconite concentration

Precipitation of authigenic minerals such as phosphate or glauconite characterises intervals of very reduced terrigenous and/or pelagic sedimentation. These are often regarded as characteristic of the MFS, but in mid-neritic and deeper environments can also occur at sequence boundaries, at a combined SB/TS, or in condensed TSTs (personal observations). In the DQC, phosphate has been identified macroscopically and/or chemical analysis at several levels (Dupuis 2013, this volume; Knox et al. 2013, this volume).

Coarse terrigenous influx

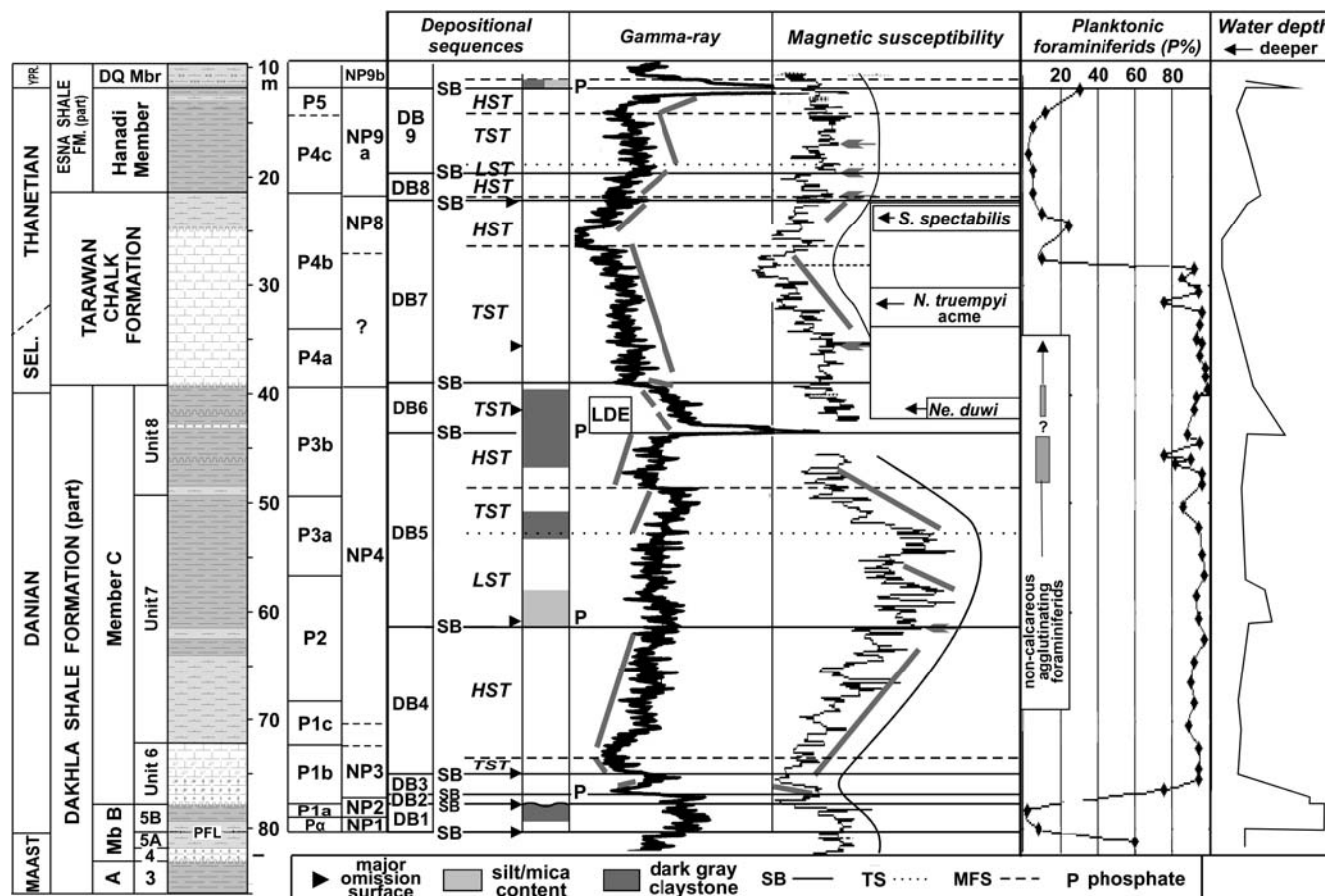
In the present context, 'coarse' comprises clastic particles of silt-grade and above, including mica. In ramp-type settings, below storm wave-base, sediment coarser than clay-grade is likely to be carried in only by occasional storm-generated episodes. In principle, their effects should be most pronounced during the LST, when sea-levels are lowest, and during the early TST, when marine transgression results in reworking of terrestrial soils.

Omission surfaces

Omission surfaces in offshore low-energy contexts are often poorly documented due to their frequently subdued lithological expression, but are critical for determining parasequence, sequence tract and sequence architecture. They represent episodes of interruption or major slowdown in sediment supply. In a sequence stratigraphic context, this can reflect either sea-level rise or fall. They generally occur at the base of sequence tracts (particularly sequence boundaries) or parasequences (these particularly within the TST, where they are often best expressed due to relatively slow depositional rates in offshore contexts).

A number of omission surfaces have been identified in the DQC (Dupuis and Knox 2013, this volume; Knox et al. 2013, this volume). They are represented by shallow-burrowed surfaces, mostly by *Chondrites*. They vary from prominent and complexly burrowed surfaces at lithological boundaries (e.g. at c. 75.30m) to levels with diffuse foraminiferid concentrations filling poorly defined burrows. The latter represent surfaces largely obliterated by subsequent bioturbation, and are often difficult to identify in core; they have probably been incompletely documented in the BQC. In all cases, foraminiferids are often concentrated in the immediately overlying interval (1-10 cm). This is interpreted as reflecting condensation during the slow initial resumption of sedimentation. The most prominent omission surfaces are (if supported by their overall context) interpreted as sequence boundaries or combined SBs and TSTs; omission surfaces within otherwise relatively homogenous intervals are interpreted as parasequence boundaries.

Thin beds of indurated calcareous marl or chalk are represented in the Paleocene of Sinai (Luning et al. 1998), in some cases associated with high proportions of benthic foraminiferids. These were interpreted as firmgrounds or immature hardgrounds, related to lowered sea levels, defining sequence boundaries. They



TEXT-FIGURE 3

Paleocene sequence stratigraphy of the Dababiya Corehole. Lithostratigraphy from Dupuis and Knox 2013 (this volume); biostratigraphy as discussed in text. Gamma-ray log and magnetic susceptibility log from Senosy and Abdel-Sabour 2013 (this volume). Gray bars alongside gamma-ray and magnetic susceptibility logs indicate vertical trends. Small discrepancies between geophysical logs and lithology reflect difference between log depths and core depths in some intervals. LDE: Latest Danian Event. MAAST.: Maastrichtian; SEL.: Selandian. S.: *Spiroplectammina*; N.: *Nuttallides*; Ne.: *Neoponides*. N.B: Gamma-ray interpretation is partly based on the original digital data, which contain more detail than the log shown here.

are apparently not represented at Dababiya; the indurated chalk unit in the Tarawan Formation (see below) is probably a deep-water unit.

Clay mineralogy

Published data on clay mineralogy, related to sequence stratigraphy in offshore deep-water contexts, are very limited. Most sequence stratigraphy texts discussing clay mineralogy (e.g. Catuneanu 2006) concentrate on non-marine and shallow marine environments. Kaolinite forms primarily in soils formed in warm humid environments; chlorite is associated with relatively deep continental erosion (Dupuis 2013, this volume). An increase in the proportions of these components can therefore reflect increased continental erosion. In principle this is likely to reflect sea-level fall (SB and LST), although reworking of soils will continue with rising sea-levels and marine transgression through the early TST. Clay mineralogy datapoints in the DQC (Dupuis, this volume) are rather widely spaced, and cannot be related in detail to the sequence stratigraphy proposed here, but some key points are noted below. More general and regional aspects are dealt with in Dupuis (this volume).

PALEOCENE OF THE DABABIYA QUARRY COREHOLE

Introduction

The DQC (see details in Berggren and Ouda 2013 this volume) was drilled close to the Paleocene/Eocene boundary stratotype (Aubry et al. 2007) in the Dababiya Quarry, c. 35 km south of Luxor. The corehole was spudded in the Esna Shale Formation (Mahmiya Member), just above the Dababiya Quarry Member, and cored a basal Eocene and Paleocene succession between the surface and 80.40 m, terminating in lower Maastrichtian strata at 140 m. Core recovery in the Paleocene was almost continuous, except between 42 m and 45.5 m, where there was significant core loss. Core recovery above 18 m was rather fragmentary at some levels. Multidisciplinary analysis of the core (see other papers in this volume) has provided the most comprehensive database available for a Paleocene section in Egypt. Relevant data have been assessed for the current contribution, in order to attempt a sequence stratigraphic interpretation which can serve as a reference for the middle Nile Valley, and prospectively much more widely for the southern margin of Tethys. The lithostratigraphic terminology used here (see text-fig. 3) follows Dupuis and Knox 2013 (this volume).

Stratigraphic framework

The nannofossil zonation is mainly from Aubry and Salem (this volume). Some divergence from their interpretation is discussed below. The planktonic foraminiferid zonation is based on Obaidalla 2013 (this volume) and Ouda et al. 2013 (this volume), but the 'P-zones' (e.g. Berggren and Pearson 2005) are used here in preference to the zonation introduced by Obaidalla et al. (2009). Ouda (2003) and Berggren and Ouda (2003) noted difficulty in identifying the P4/P5 zonal boundary in the Nile Valley, due to the scarcity and/or dissolution of the index species *Globanomalina pseudomenardii*.

The positions of the Danian/Selandian and Selandian/Thanetian boundaries are in part controversial, and are discussed below

Lithostratigraphic terminology is from Dupuis and Knox 2013 (this volume). The Paleocene section comprises the upper part of the Dakhla Shale Formation (upper part of Member B and Member C), the Tarawan Chalk Formation and the lower Esna Shale Formation (Hanadi Member). The upper Tarawan Formation is relatively argillaceous regionally. In the Dababiya Quarry section this was referred to as Tarawan Formation Unit B (Ouda et al. 2003) and at Gebel Aweina was included in the Esna Formation by Schmitz (1998).

DEPOSITIONAL SEQUENCES

Nine depositional sequences are tentatively differentiated within the Paleocene of the DQC, based on the criteria outlined above. These are designated DB1-DB10. It must be stressed that this interpretation should be regarded as provisional; a robust sequence stratigraphic model cannot be based on a single section. More detailed study of parts of the core, and of other sections in Egypt, particularly in more proximal settings, is needed to confirm or modify this model. In particular, no attempt has been made to identify a hierarchy of sequences, although it is clear from other sites, as noted below, that some sequence boundaries represent much more pronounced base-level changes than others. No attempt has been made here to differentiate a hierarchy within the sequences identified. Longer-term trends, probably representing higher-order sequences, can be seen on the MS log (see text-fig. 3).

Sequence DB1

Interval: 80.42–77.78 m (Dakhla Shale Formation, Unit 5B)

SB (80.42m) The 'pyritised fossil layer' (PFL) at 80.42 m (Dupuis and Knox 2013, this volume) is a surface with a concentration of pyritised fossils, associated with pyrite, ankerite and sphalerite. It corresponds to the K/P boundary (Aubry and Salem 2013b, this volume; Obaidalla 2013, this volume).

Biostratigraphic data indicate that the immediately underlying interval (80.6–80.4m) is latest Maastrichtian in age (nannofossil Subzone CC26b) (Aubry and Salem, this volume). The planktonic foraminiferid assemblage has been interpreted as indicating the *Pseudoguembelina palpebra* Zone (Obaidalla 2013, this volume), on the basis of the absence of *Plummerita hantkeninoides*, which is restricted to the highest/uppermost Maastrichtian *P. hantkeninoides* Zone of Li and Keller (1998). This would imply absence of the youngest/latest Maastrichtian strata (c. 33 ky). *Pseudoguembelina hantkeninoides* is, however, interpreted as having preferred eutrophic environments (Huber et al. 2008), and it is possible that its absence may be due to environmental factors. The occurrence of the ammonite

Indoscaphites pavana indicates that the top of the Cretaceous section is within 420 ky of the K/P boundary (Goolaerts and Dupuis 2013, this volume).

The base of the earliest Danian Zone NP1 is identified at 80.2 m (Aubry and Salem, this volume). The base of planktonic foraminiferid Zone Pa has been identified at 80.0 m (Obaidalla, this volume). The earliest Danian Zone P0 (0.03 my: Berggren and Pearson 2005) has not been identified, but this is generally very thin.

These biostratigraphic data indicate that there is at most a brief hiatus at the K/P boundary. The succession is thus probably more complete than at other localities studied in the Nile Valley or Western Desert, where there is generally a significant break at the K/P boundary, as noted by Dupuis and Knox 2013 (this volume), with early/lower Danian often unrepresented. The PFL is interpreted as marking a break in sedimentation, but it is unclear if there is a disconformity at this level. In any event, it qualifies as a sequence boundary due to the sedimentary discontinuity and the abrupt decrease in water depth indicated at this level.

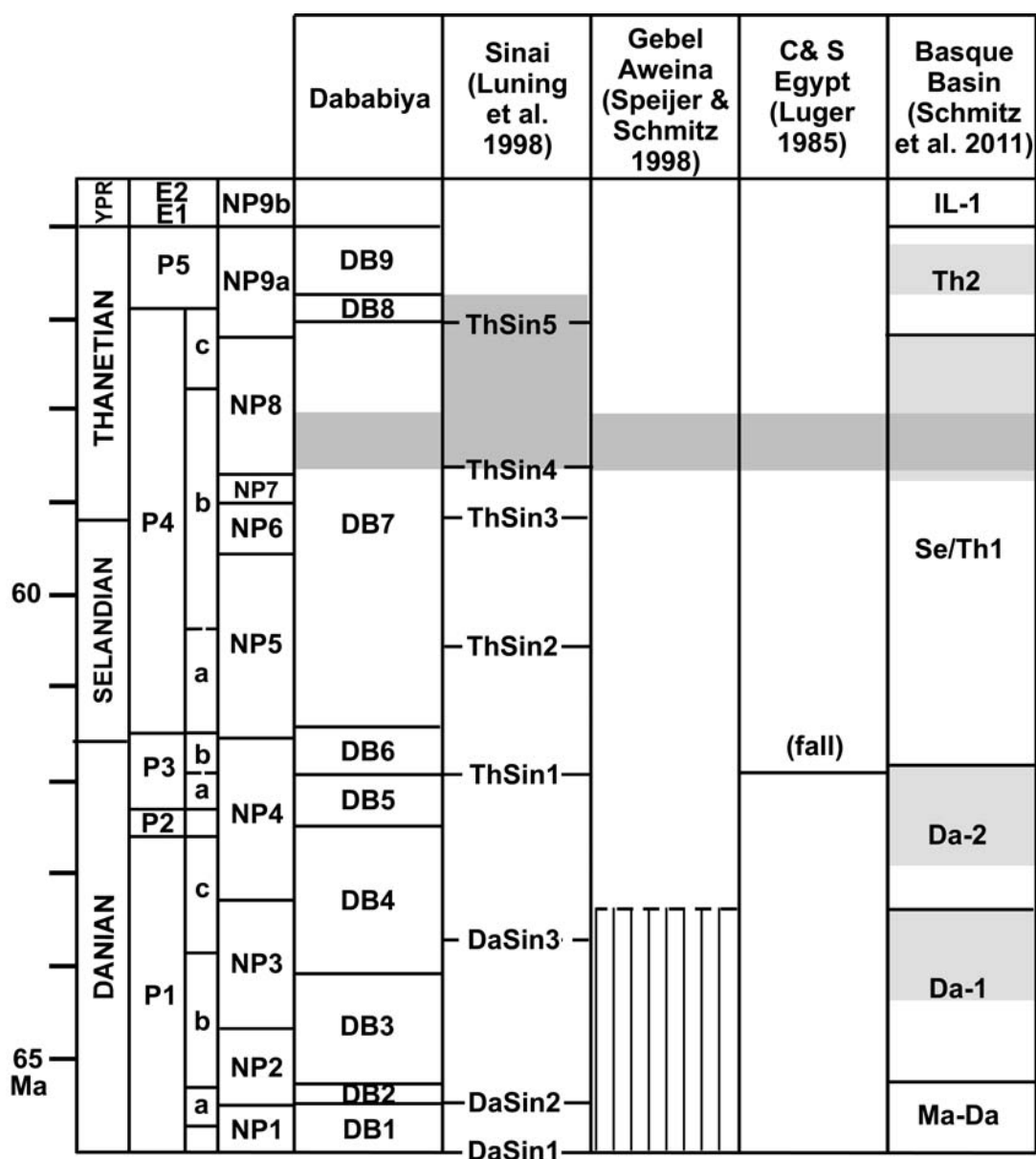
LST. At the PFL there is a sharp upward increase in the gamma-ray response, marking an upward change from blocky calcareous clay to dark grey shaly claystone, with the incoming of a small but significant proportion of silt. This boundary corresponds to a sharp decrease in **P** from 60% to <10%, and a major decrease in foraminiferid abundance. Benthic foraminiferids are relatively sparse, but include significant proportions of *Anomalinoidea* spp. and *Pulsiphonina prima* (personal observations). There is also a marked macrofaunal change at the K/P boundary. In the latest Maastrichtian, bivalves are frequent, represented by pyrite and 'limonite' moulds, difficult to identify but including probable small ?fragments of probable baculitid phragmocones. Above the K/P boundary small partially crushed bivalves, dominantly nuculids, are common to abundant, associated with small turreted gastropods and scaphopods. These are preserved in the lower part of this interval as pyrite and limonite moulds, but in the upper part the aragonitic shell is preserved, although partially decalcified. The upper part of this interval is dark brown and fissile, suggesting a dysoxic environment.

The macrofauna and benthic foraminiferids in this interval indicate relatively shallow water depths (mid-neritic; the shallowest water depths in the Paleocene of the DQC section). The low value of **P** may be somewhat misleading, as a significant proportion of the planktonic foraminiferid taxa (*Parvularugoglobigerina* and *Eoglobigerina*) in this interval are <120 microns in size and are not included in the count.

This interval is interpreted as probably a LST, on the basis of the 'coarse' terrigenous input, the relatively shallow water depths, and the probably highly organic content in the upper part, indicated by its dark color and fissility, suggesting a somewhat restricted environment.

LST and HST. The LST and HST appear to be unrepresented, indicating that the boundary between sequences DB1 and DB2 may be disconformable. This interpretation is supported by the erosional contact (see below).

Age: Early Danian: Zone NP1; Zone Pa and Subzone P1a.



TEXT-FIGURE 4

Comparison of sea-level changes and sequences identified in Egypt and in the Basque Basin (NW Spain). Marine intervals in the proximal parts of the Basque Basin are shaded; darker shading indicates interval with maximum water depths. Chronostratigraphy and biozones are based on Vandenberghe et al. (2012, text-fig. 28.3), but biozones around the Danian/Selandian boundary have been recalibrated following data summarised in this paper. NB: Calibration of sequence boundaries is only approximate.

Sequence DB2

Interval: 77.78m–76.70 m (Dakhla Shale Formation, Unit 6, part)

Combined SB/TS (77.78m). This boundary is placed at the contact between dark shaly claystone (Unit 5B) and argillaceous limestone (Unit 6). The boundary is sharp and slightly irregular, and there are clasts of black claystone in the basal 20 cm of Unit 6 (Dupuis and Knox 2013, this volume), indicating an erosional contact. This indicates a stratigraphic break, interpreted as a sequence boundary. The boundary corresponds approximately to the NP1/NP2 boundary (Aubry and Salem, this volume), but

the hiatus implied by the erosional contact is below current biostratigraphic resolution. The boundary also corresponds to the virtual disappearance of chlorite (Dupuis 2013, this volume).

TST: At the base of this interval there is an abrupt increase in **P** from < 5% to > 70%, and the earliest appearance of a typical Midway-type benthic foraminiferid assemblage (Alegret and Ortiz 2013, this volume). This is interpreted as indicating a transgressive surface. There is fine disseminated glauconite in this interval (personal observations), and a significant phosphate content (Dupuis 2013, this volume). This implies conden-

sation, and combined with the upward-decreasing gamma-ray response, indicates a TST.

HST: This is unrepresented, implying a hiatus at this level.

Age: Early Danian: Zones NP2 and NP3; Subzone P1a.

Sequence DB3

Interval: 76.70–75.10 m (Dakhla Shale Formation, Unit 6, part)

Combined SB/TS (76.70m): The abrupt gamma-ray fall at this boundary is interpreted as indicating a transgressive event. It corresponds to a burrowed omission surface.

TS: This thin interval comprises an intensely *Chondrites*-burrowed argillaceous limestone. The intensity of burrowing and the number of omission surfaces indicate that this interval is probably highly condensed, reflecting very limited input of terrigenous sediment, supported by the low MS response. It is interpreted as a TST. There is an upward decrease in the MS log response to a very low level at the top. The highest 0.20 m is complex, with light grey and dark gray burrow-fills, and at least one internal burrowed omission surface. The relatively high gamma-ray response at this level probably reflects the high phosphate content (Dupuis, this volume). These features indicate that the highest part of this interval may represent the MFS.

Age: Early Danian: Zone NP3; Subzone P1b.

Sequence DB4

Interval: 75.1–60.9 m (Dakhla Shale Formation, Units 6 and 7, part)

Combined SB/TS (75.1m). An inflection in the gamma-ray log at 74.9m marks a shift from an upward-increasing to upward-decreasing trend. A prominent gamma-ray spike at this point probably corresponds to a burrowed omission surface at 75.1 m, suggesting concentration of phosphate or other relatively radioactive components. This is interpreted as a sequence boundary.

TST. The rapid progressive decrease in the gamma-ray response between c. 75–c. 73 m is interpreted as reflecting a TST. Several burrowed omission surfaces within this interval probably mark parasequence boundaries.

HST. The MFS is taken at the lowest gamma-ray response in this interval (c. 73m). Above this level there is a decrease in the carbonate content (Dupuis and Knox 2013, this volume, text-fig. 3), a progressive (though irregular) increase in the gamma-ray response, and a corresponding increase in the MS log response, interpreted as increasing terrigenous input related to coastal progradation. Aubry and Salem 2013b (this volume) note an influx of terrigenous material at about this level. Fluctuations in the gamma-ray log probably reflect parasequences.

Age: Mid Danian: Zones NP3 and NP4; Subzone P1b and Zone P2.

Sequence DB5

Interval: 60.9m–c. 42.9 m (Dakhla Shale Formation, Units 6–8, part)

SB (60.9m). A foraminiferid concentration at c. 60.8–60.9 m is associated with dispersed phosphate grains. This corresponds approximately to an abrupt increase in the MS response and the

incoming of dispersed mica, indicating increased terrigenous input. It is interpreted as a sequence boundary.

LST: Very high MS levels through the interval c. 61 m – c. 53 m (the highest in the Paleocene section) indicate significant terrigenous input. Fluctuations within the interval suggest that several parasequences are probably represented. These are also suggested by foraminiferid concentrations at c. 60.05 (associated with a small phosphatised pebble) and at 59.30 m. The gamma-ray response is relatively high.

TST. A rapid decrease in the MS response from c. 53 m is taken to indicate the start of the TST. This is associated with an increase in the gamma-ray response, but this may reflect a higher organic content; the claystones between c. 52–c. 50.7 m are darker in colour than below. The interval between c. 53 m and c. 48.2 m is characterised by a progressive fall in the MS log response. There is an abrupt decrease in the gamma-ray response at c. 48.2 m. The lithology and calcimetry in this interval (Dupuis and Knox 2013, this volume) indicate that this does not correspond to an increase in carbonate content, but probably reflects a decrease in organic content.

HST. An abrupt decrease in the gamma-ray response at 49.0 is taken to mark the MFS. This also corresponds to the lowest MS response in this interval. The gamma-ray response generally increases from this level. In this interval non-calcareous deep-water agglutinating foraminiferids are relatively common (10–20% of the benthic foraminiferid assemblage), including *Ammodiscus*, *Bathysiphon*, *Glomospira* and *Karrerulina*. This suggests some degree of dysoxia at the seafloor. Above 45.5 m core recovery was poor.

Age: Late Danian: Zone NP4; Subzones P3a and P3b.

Sequence DB6

Interval: c. 42.9m–39.2 m (Dakhla Shale Formation, Unit 8, part)

SB. The very prominent gamma-ray spike at c. 42.9 m probably corresponds to a phosphatic limestone bed between 43.10–43.05 m (Dupuis and Knox 2013, this volume). Poor core recovery in this interval prevents detailed analysis, but as this bed falls at the inflection between upward-increasing and upward-decreasing gamma-ray trends, it is interpreted as a sequence boundary. Magnetic susceptibility could not be recorded in this interval due to the coring problems. This surface is tentatively interpreted as the base of the Latest Danian Event (LDE). The LDE ('Qreiya Bed(s)'/ 'Neo-Duwi Beds') is an interval characterised by a number of synchronous or approximately synchronous events, including a prominent shift in benthic foraminiferid assemblages, a carbon isotope excursion, the brief influx of the foraminiferid *Neoponides duwi*, and organic-rich claystones. It is recognised widely in Egypt and adjacent areas, and interpreted as reflecting a brief sea-level fall (e.g. Sprong et al. 2009, 2011). The base of the LDE is generally a prominent omission surface.

Obaidalla 2013 (this volume) has cited this bed as representing the LDE, on the basis of comparison with the Wadi El Maheer section (north Eastern Desert), based on the HO of *Praemurica carinata* (Obaidalla et al. 2009). However, Obaidalla cites the position of the limestone bed incorrectly as at 44.50 m (the level at which the correlative biostratigraphic event is identified). Aubry and Salem 2013b (this volume) identify the first radia-

tion of fasciculiths in the DQC between 45.2 m and 43.15 m. This event at Qreiya is just below the LDE.

Interpretation is hindered by the poor core recovery in part of this interval. At Gebel Qreiya the base of the LDE is an erosion surface (Sprong et al. 2011), and in Tunisia there is a disconformity at this level (Sprong et al. 2009). At Gebel Qreiya and elsewhere in Egypt the LDE has been interpreted as a combined SB/TST, followed by a brief episode of sea-floor dysoxia (Sprong et al. 2011, 2012), interpreted as transgressive, by comparison with similar Jurassic ‘black shales’.

TST. The very high-gamma-ray response at the base of this interval probably corresponds to the organic-rich claystone forming the lower part of the LDE at Qreiya (bed I of Sprong et al. 2011). Above this, the upward-decreasing gamma-ray response probably reflects decreasing organic content. This is interpreted as due to progressive sea-level rise.

A prominent, relatively deeply burrowed omission surface at c. 41.70 m probably corresponds to the gamma-ray spike at c. 41.4 m. Benthic foraminiferids are abundant immediately above the omission surface, including large *Fronicularia*, associated with dispersed molluscs (preserved as limonitic moulds), as seen at Qreiya, with common fish debris and echinoid spines. The foraminiferids *Neoponides duwi* and *Siphogenerinoides esnehensis* are recorded at 41.5 m (Alegret and Ortiz 2013, this volume). The brief influx of these taxa is characteristic of the upper part of the LDE (bed II of Sprong et al. 2011). This indicates that the LDE here is significantly thicker than at most other sites studied (> 1 m compared to 0.25 m at Qreiya); unfortunately core loss prevents a detailed study.

Water depths regionally within the LDE are interpreted as shallower than in the interval below the LDE (Sprong et al. 2009, 2012). Pyritic/limonitic moulds of gastropods and a solitary coral have been recorded at depths up to 40.7 m in the DQC. These suggest significantly shallower depths than at lower levels. Relatively shallow depths are also suggested at Qreiya by two thin localised channelled bioclastic units (Sprong et al. 2011), indicating episodic current activity. Benthic foraminiferid assemblages in and above the LDE at Qreiya are interpreted as indicating progressive deepening (Sprong et al. 2011). A detailed study has not been carried out in the DQC section, but **P** increases from c. 90% to c. 98% between 41.5 m and 39.4 m.

HST. At Qreiya there is evidence from benthic and planktonic foraminiferids for shallowing from c. 5 m above the base of the LDE (Sprong et al. 2011, text-fig. 4), probably indicating the base of the HST. The progressive decrease in the gamma-ray response up to the top of the Dakhla Formation, and the high **P** just below, indicates that this is still within the TST. The absence of any representative of the HST suggests truncation of this interval.

Age: Late Danian–earliest Selandian. (Zone NP4; Subzone P3b–Zone P4).

Obaidalla et al. (2009) identified the LO of *Igorina albeari*, defining the Subzone P3a/P3b boundary, c. 0.3 m below the base of the LDE at Wadi El Maheer (Eastern Desert). Sprong et al. (2011) identified this datum at a similar level (0.15 m below the base of the LDE) at Qreiya. Obaidalla 2013 (this volume) however identified the LO of *Igorina albeari* at 49.45 m in the

DQC, c. 6.5 m below the probable base of the LDE. It is not clear if this reflects differing rates of sedimentation, or a regional unconformity at the base of the LDE. These records are discordant with the dating of this event as early Selandian (e.g. Vandenberghe et al. 2012, fig. 28.1), but are consistent with its identification in the latest Danian elsewhere (e.g. Steurbaut and Sztrakos 2008). Problems with differing taxonomic conceptions of *I. albeari* were discussed by Sprong et al. (2009).

In the DQC the Zone P3b/P4 boundary (base of the *G. pseudomenardii*/*P. variospira* Zone) is just below the base of the Tarawan Formation (Obaidalla, this volume). At Gebel Aweina (Speijer and Schmitz 1998) it also corresponds approximately to the base of the Tarawan Formation. Sprong et al. (2011) were unable to clearly recognize this boundary at Gebel Qreiya, as ‘The typical, large *Globanomalina pseudomenardii*., a marker of Zone P4, was not encountered’ (Sprong et al. 2011, p. 172). They tentatively placed the boundary at the LO of *Morozovella velascoensis*, within the Dakhla Formation below the base of the Tarawan Formation. In other Egyptian sections both events are approximately coincident, within the uppermost Dakhla Formation (Ouda 2003). The detailed study by Obaidalla et al. (2009) identified the LO of *M. velascoensis* as preceding the LO of *G. pseudomenardii*, just below the top of P3b. The LO of *M. velascoensis* in the DQC is not cited by Obaidalla 2013 (this volume).

The base of P4 is close to the top of the Dakhla Formation in the DQC (39.6m). This corresponds approximately to the D/S boundary (as discussed below), and so the D/S boundary in the DQC is here placed at this level.

The Danian/Selandian boundary in Egypt and its relationship to the LDE

The Danian/Selandian [D/S] boundary in Egypt was defined by Obaidalla et al. (2009) on the basis of planktonic foraminiferids, at the HO of *Praemurica carinata*. This definition is followed by Obaidalla (this volume). It was however already superseded in 2007 by ratification of the boundary at Zumaia (Spain) (Schmitz et al. 2011). *Praemurica carinata*, originally described by El-Naggar (1966) [as *Globorotalia uncinata carinata*] was not cited or discussed in most later taxonomic compilations (e.g. Olsson et al. 1999) and has only recently been resurrected (e.g. Petrizzo et al. 2005). The HO of *P. carinata* was equated by Petrizzo et al. (2005) with the P3a/P3b boundary, but Obaidalla et al. (2009) placed it at a higher level. They split the *I. albeari* Zone (P3b) of Berggren and Pearson (2005) into the *I. albeari*/*P. carinata* Zone and the *I. albeari* Zone, with their boundary placed at the HO of *P. carinata*.

At Zumaia the D/S boundary is difficult to calibrate with planktonic foraminiferid zonations, due to imperfect preservation, but is immediately above the ‘second radiation of *Fasciculithus*’, in nannofossil Subzone NTP8b (see summary in Vandenberghe et al. 2012). Sprong et al. (2011) identified Subzone NTP8b c. c. 5 m above the LDE at Gebel Qreiya, and hence located the D/S boundary in this interval. Aubry et al. (2012, fig. 3) however placed the D/S boundary at Qreiya or below the LDE. The reasons for this were not specified. Aubry and Salem (this volume) propose to place the D/S boundary at the evolutionary appearance and rapid diversification of the fasciculiths *Diantholitha* and *Lithoptychius* (‘first radiation of fasciculiths’), c. 1 m below the LDE at Qreiya. However Monechi et al. (2013) demonstrated that a consistent succession of nannofossil events can be

recognised across the D/S boundary at Site 1262 (south Atlantic), in the Aquitaine Basin and at Qreiya, with minor discrepancies attributed to rarity of some taxa in parts of their vertical range and probable differences in taxonomic interpretation. These comparisons are consistent with magnetostratigraphy at Zumaia and Site 1262. They indicate that the 'first radiation of fasciculiths' is close to the Chron 27n/26r boundary, c. 0.6 my older than the D/S boundary, and confirm that the D/S boundary significantly post-dates the LDE.

The record of the LO of *Morozovella velascoensis* approximately coincident with the NTp8/NTp9 boundary at Qreiya (Sprong et al. 2011) indicates that the P3/P4 boundary is probably slightly younger than the D/S boundary (see comments above). This requires amendment of the current calibration, which places this at a higher level (Vandenbergh et al 2012, text-fig. 28.1). The P3a/P3b boundary also has to be relocated to below the D/S boundary, on the basis of the data from Egypt, also Tunisia (Van Itterbeeck et al. 2007) and the Aquitaine Basin (Steurbaut and Sztrakos 2008).

Sequence DB7

Interval: 39.2m–21.5 m (Tarawan Chalk Formation)

Combined SB/TS (39.2m): The base of the Tarawan Formation is a burrowed omission surface with an abrupt decrease in the gamma-ray response, marking an abrupt increase in carbonate content (Dupuis and Knox 2013, this volume, text-fig. 3), with foraminiferids concentrated immediately above. At this level there is an increase in P to almost 100%. This surface is interpreted as a combined SB/TS. The major decrease in kaolinite between 30 m and 40 m (Dupuis 2013, this volume) may correspond to this surface. At Gebel Aweina this boundary has been described as transitional (Speijer and Schmitz 1998), but is in fact a clearly defined *Thalassinoides*-burrowed omission surface with phosphate pellets in the burrows. It is also a burrowed omission surface at Gebel Qreiya (personal observations).

TST. An interval with relatively stable gamma-ray and MS values between c. 39.0 m and 35.0 m is followed by upward-decreasing trends in both gamma-ray and MS logs between 35.0m–c. 25.8 m is interpreted as the TST. Minor inflections in both probably reflect parasequence boundaries.

An abrupt decrease in P (from >90% to c. 10%) is recorded at c. 28.0 m. This does not correspond to a significant lithological boundary, or to any change in the benthic foraminiferid assemblage (Alegret and Ortiz 2013, this volume, text-figs 1, 2). It does not appear to be bathymetry-related, nor is it the result of selective dissolution. An identical feature is represented at Gebel Aweina (Speijer and Schmitz 1998, text-fig. 4), at the top of the Tarawan Formation (as they defined it, see comments above), but they did not comment on it. This event is not well-dated biostratigraphically in the DQC; correlation with the nearby Dababiya Quarry section (Dupuis et al. 2003, text-fig. 9) indicates that it is probably within Zone NP8. It is discussed below.

HST. An indurated limestone unit between c. 25.8–c. 24.1 m (log) is sharply defined on the gamma-ray and resistivity logs, although not so well-defined macroscopically. Its base is marked by an abrupt fall in the gamma-ray response, and is taken as the MFS. The layer of flint concretions in the adjacent Dababiya Quarry section (Dupuis et al. 2003, text-fig. 4) is probably in this unit. This limestone unit has the highest car-

bonate content, lowest gamma-ray response and (in part) the lowest MS recorded in the Paleocene succession at Dababiya. The lowest proportions of kaolinite in the Paleocene succession are at about this level (Dupuis 2013, this volume). All these features reflect very low terrigenous input, probably indicating relatively deep water and long distances from the coast.

From the top of the limestone unit there is a progressive upward increase in the gamma-ray response through the upper Tarawan Formation, corresponding to a progressive increase in the MS log response. The lithology log (Dupuis and Knox 2013, this volume, text-fig. 3) and calcimetry data from the nearby Dababiya Quarry section confirm that this reflects a decrease in carbonate content (Dupuis et al. 2003, text-fig. 9). 'Velasco-type' benthic foraminiferids within this interval (Alegret and Ortiz 2013, this volume) indicate bathyal water depths (> 200m) for the upper Tarawan Formation. Similar results were obtained at Gebel Aweina (Speijer and Schmitz 1998). In both cases the assemblage has been interpreted as representing the greatest water depths in the Paleocene succession. This is supported by the occurrence of the deep-water agglutinating foraminiferid *Spiroplectammia spectabilis* at 23.3–24.5 m (personal observations), also recorded at a comparable level at Gebel Aweina (Speijer and Schmitz 1998) [but interpreted as the top of the Tarawan Formation, see above]. The acme abundance of the characteristic bathyal indicator *Nuttallides truempyi* is recorded at c. 32 m.

Age: Selandian–mid Thanetian: Subzones P4a and P4b.

The varying distance of the P3b/P4 boundary below the base of the Tarawan Formation, from almost coincident in the BQC and at Gebel Aweina to c. 15 m below it at Gebel Duwi (Ouda 2003, text-fig. 3) is suggestive of a regional unconformity at the base of the Tarawan Formation, as indicated by previous studies (e.g. Luger 1985). This is supported by the nannofossil data (Aubry and Salem 2013b, this volume). Speijer and Schmitz (1998, p. 32) identified a 'paraconformity' at the base of the Tarawan Formation at Gebel Aweina, based on 'the very thin Zone NP5 and negligible overlap with Zone P4', as well as sharply defined isotopic and foraminiferal changes.

At Gebel Aweina and Qreiya, as in most other sections in Egypt, the NP4/NP5 boundary is within the uppermost Dakhla Formation (Speijer and Schmitz 1998; Ouda 2003; Sprong et al. 2011; Aubry and Salem 2013b, this volume), except in areas where the Dakhla/Tarawan contact is an unconformity. In the BQC, the NP4/NP5 boundary has been placed at a much higher level (31m), within the middle Tarawan Formation (Aubry and Salem 2013, this volume). The record of the base of P4a just below the base of the Tarawan Formation in the BQC (Obaidalla, this volume), which corresponds approximately to the base of NP5 (as discussed above; Vandenbergh et al. 2012, text-fig. 28.1) suggests that the poor preservation of nannofossils in the Tarawan Formation (Aubry and Salem 2013, this volume) may have hindered satisfactory zonal determination.

The Selandian/Thanetian boundary cannot be accurately identified in the DQC. Here Zones NP7 and NP8 are only doubtfully identified, between 22–24 m., and in the Dababiya Quarry section, the upper 7.5 m of the Tarawan Formation is dated mainly as NP8 (Dupuis et al. 2003, text-fig. 9). This discrepancy may again be due to poor preservation of nannofossils; here the record of NP8 from the Dababiya Quarry section is transferred to the BQC. The base of NP9 is at 22 m in the BQC, very close to

the top of the Tarawan Formation, as in the Dababiya Quarry section.

Sequence DB8

Interval: 21.5m–c. 18.4 m (Esna Formation, Hanadi Member, part)

SB and LST. There appears to be a transitional boundary between the Tarawan Formation and the Esna Formation in the DQC, but in the adjacent Dababiya Quarry section there is a thin ‘shale’ (claystone) unit with a low carbonate content at the base of the Esna Formation (Dupuis et al. 2003, text-fig. 6). This probably corresponds to the gamma-ray spike at 21.5 m in the DQC, associated with an abrupt increase in MS. This indicates a break in the depositional pattern at this level, here interpreted as probably a sequence boundary, with the ‘shale’ representing the LST.

TST. The gamma-ray log indicates a probable upward-decreasing trend between 22.0 m and 21.5 m (log), tentatively interpreted as the TST.

HST. There is an upward increase in the gamma-ray response from c. 21.0 m to c. 18.4 m.

Age: Late Thanetian: Subzone NP9a; Subzone P4b.

Sequence DB9

Interval: c. 18.4 m–11.85 m (Esna Formation, Hanadi Member, part)

Combined SB/TS. An inflection on the gamma-ray log at c. 18.4 m, between upward-increasing and upward-decreasing trends, corresponds approximately to an abrupt increase in MS. This probably corresponds to a *Chondrites*-burrowed omission surface at 18.35 m. It also corresponds approximately to an influx of kaolinite (Dupuis 2013, this volume, text-fig. 3), also identified in the Dababiya Quarry section (Dupuis et al. 2003, text-fig. 6). This is interpreted as a sequence boundary.

TST. There is an overall upward decrease in the gamma-ray response though the interval c. 18.4–c. 13.3 m, indicating an upward increase in carbonate content. This trend can be recognised lithologically (Dupuis and Knox 2013, this volume, text-fig. 3), although interpretation is hindered by the rather poor core recovery in this interval, and extensive gypsum veining. A *Chondrites*-burrowed omission surface is identified at c. 15.57m; there may be others.

As in the underlying intervals, the low levels of **P** clearly do not primarily reflect bathymetry, and their interpretation is uncertain. Alegret and Ortiz 2013 (this volume) noted evidence of partial dissolution of foraminiferid tests. This feature has also been noted in the same interval at Gebel Aweina [Owaina] and elsewhere (Speijer and Schmitz 1998; Ouda et al. 2003, text-fig. 3).

The high dominance of *Bulimina* throughout the Hanadi Member is interpreted as indicating increased nutrient flux (Alegret and Ortiz 2013, this volume); a similar feature is documented at Gebel Aweina (Speijer and Schmitz 1998). Increased productivity leading to eutrophication is documented widely on the southern Tethyan margin during this period (see publications cited in Speijer and Schmitz 1998; Guasti et al. 2005).

HST. An inflection in the gamma-ray log at 13.4 m marks the boundary between upward-decreasing and upward-increasing trends. It corresponds to an inflection on the MS log. Berggren and Ouda (2003, table 1) recorded a very high P/B ratio (88%) at about this level. This is interpreted as the MFS. The gamma-ray response increases from here up to the top of the Hanadi Member. In the highest 1.5 m of the El Hanadi Member at Dababiya, Berggren and Ouda (2003, table 1) recorded P/B ratios of 41–79%; Ernst et al. (2006) recorded P/B ratios of c. 50% in a similar interval (based on the >63 micron fraction). Moderate to high organic flux was suggested for this interval at Dababiya by Ernst et al. (2006).

Speijer and Wagner (2002) interpreted the ‘lower Esna’ (Hanadi Member) as representing a late HST and a following LST, although evidence for the LST (apparently based on shallowing-upwards benthic foraminiferid assemblages) was cited only for the Gebel Duwi section, which represents a shallower depositional environment. Ernst et al. (2006) and Schulte et al. (2011) interpreted the Hanadi Member as representing a HST.

Age: Late Thanetian (Subzone NP9a; Zone P5).

Earliest Eocene Sequence

Interval: 11.85 m - (Esna Formation, Dababiya Quarry Member and Mahmiya Member, part)

The base of this sequence corresponds to the Paleocene/Eocene boundary. This brief summary is added only for completeness, as data from the core add little to the detailed studies in the adjacent Dababiya Quarry sections.

Combined SB/TS. The base of the Dababiya Quarry Member in the Dababiya Quarry is an incised erosion surface, interpreted as a combined sequence boundary and TS (Dupuis et al. 2003; Schulte et al. 2011).

TST. Speijer and Wagner (2002) interpreted the organic-rich ‘black shales’ [Dababiya Quarry Member] in other sections in Egypt as a condensed unit deposited during a transgressive episode. This interpretation has been confirmed by detailed studies on the Dababiya Quarry section by Ernst et al. (2006) and Schulte et al. (2011).

HST. The MFS corresponds to the top of the CIE, just below the top of the Dababiya Quarry Member (bed 5), marked by a marly limestone with a ‘flood’ of planktonic foraminiferids (Speijer and Wagner 2002; Dupuis et al. 2003). Higher levels are discussed by Speijer and Wagner (2002) and Dupuis et al. (2003).

COMPARISON WITH OTHER SITES IN EGYPT AND TUNISIA

Luger (1985) identified broad-scale water depth fluctuations in sections in central Egypt. He identified a major rise in sea-level in the mid-Danian, a gradual fall at about the Danian/Selandian boundary, low sea-levels (often represented by a hiatus) in the Selandian, a major rise in sea-level at about the Selandian/Thanetian boundary, and a gradual fall in sea-level culminating at about the Paleocene/Eocene boundary [stage terminology here and elsewhere is adjusted to current definitions].

Speijer and Schmitz (1998) analysed sea-level fluctuations in the Gebel Aweina section, based on detailed analysis of planktonic and benthic foraminiferid assemblages and geochemical

criteria. Their conclusions were similar to those of Luger, with more precise timing and refined estimation of relative water depths. They identified probable stratigraphic breaks near the Danian/Selandian boundary and Selandian/Thanetian boundary (text-fig. 4), and proposed correlation with the depositional sequences of Hardenbol (1994) and Haq et al. (1997).

Luning et al. (1998) identified Paleocene sequences and sequence tracts at the northern edge of the 'stable shelf' in Sinai, based primarily on the P/B ratio and on benthic foraminiferid assemblages. Their detailed analysis, identifying nine sequences, is compromised by the limited database, as noted above. Luger (1985) and Speijer and Schmitz (1998) both identified the highest Paleocene sea-levels as mid-Thanetian, but Luning et al. (1998, text-fig. 3) recognised a major sea-level fall during this interval (Zones NP7/8 to lower NP9), with its base defining their ThSin-4 sequence boundary (text-fig. 4). This interpretation was based on the P/B ratio, although they noted that the Midway-type benthic foraminiferid assemblage and the shark fauna in this interval still indicated relatively deep neritic environments in this interval (Luning et al. 1998, p. 28). The abrupt decrease in planktonic foraminiferid proportions in NP7/8 probably corresponds to the similar fall identified at Dababiya and Gebel Aweina (accurate dating in the area studied by Luning et al. is difficult due to condensation and/or hiatuses), and does not appear to be depth-related. This invalidates this part of their sequence stratigraphic interpretation.

Tantawy et al. (2001) analysed Danian stratigraphy in the area between Dhakla and Farafra (Western Desert), identifying several hiatuses. Paleocene sea-level fluctuations, with some comments on possible sequence boundaries, have been studied in the El Kef section (Tunisia) (Guasti et al. 2005).

Detailed studies focused on the 'Latest Danian Event' (LDE) have been carried out at a number of sites in Egypt, and also in Tunisia (Speijer 2003; Guasti et al. 2005, 2006; Steurbaut et al. 2000; Van Itterbeeck et al. 2007; Sprong et al. 2009, 2011, 2012).

The degree of detail possible in the DQC is due to the extensive multidisciplinary studies carried out, and particularly the calibration with high-resolution gamma-ray and magnetic susceptibility logs. This detail is not currently available for other sections in Egypt, and thus comparisons are limited mainly to larger-scale events.

A sequence boundary at the K/P boundary (DaSin1), followed by a lowstand, was identified in Sinai by Luning et al. (1998). This corresponds to the base of sequence DB1. In most parts of southern and western Egypt the K/P boundary is an unconformity (e.g. Luger 1985; Speijer and Schmitz 1998; Tantawy et al. 2000, text-fig. 2), although an apparently continuous succession across the boundary (or with a discontinuity below the level of published biostratigraphic resolution) has been documented at localities including Gebel Duwi and Gebel Qreiya (Gebel Abu Had) (Tantawy et al. 2000). A second sequence boundary (DaSin2), interpreted as marked by only a slight fall in sea-level, was identified within NP1. This may correspond to the base of sequence DB2. Sequence boundary DaSin3, identified in Sinai (Luning et al. 1998), apparently marked by only a very small sea-level fall, is dated as within NP3.

In the area of the Western Desert studied by Tantawy et al. (2000) Danian depositional environments were considerably

shallower than at Dababiya. The earliest Danian unit represented in this area, the Bir Abu Minqar Member, unconformably overlies Upper Maastrichtian sediments. It comprises three beds of siltstone/sandstone with glauconite and phosphate, separated by burrowed omission surfaces, deposited in inner neritic environments. The lower two beds contain planktonic foraminiferid assemblages assigned by Tantawy et al. (2000) to Subzone P1c, but in the standard zonation (Berggren and Pearson 2005) the assemblage indicates Subzone P1b, compatible with the NP2 date from the middle bed [note that the definition of some Danian planktonic foraminiferid zones and subzones in Tantawy et al. differs from the standard scheme of Berggren et al. (e.g. Berggren and Pearson 2005)]. This interval is evidently complex, and probably corresponds to sequence DB2. An erosion surface overlying the Bir Abu Minqar Member can be interpreted as a combined SB/TS. It is followed by c. 8 m of siltstones and claystones with a basal glauconitic unit, marking a significant marine transgression, representing significantly greater water depths than the Bir Abu Minqar Member. The P1b [as here interpreted]/NP2 date, for (at least the lower part of) this interval indicates that it corresponds to sequence DB3. This unit is overlain by a thin limestone bed, whose top is a burrowed erosion surface. This surface can again be interpreted as a combined SB/TS, probably corresponding to the base of sequence DB5. It is overlain by a thin glauconitic bed, followed by claystones with a high proportion of planktonic foraminiferids, dated as Subzone P1c [P1d of Tantawy et al. 2001] and Zone NP4.

Depositional environments indicate an overall deepening-upwards succession, as in the corresponding interval at Dababiya. The more proximal environment implies that LSTs are represented by hiatuses, and that TSTs are probably highly condensed.

In many areas in Egypt (apart from Sinai) the earliest Danian is at about the base of NP4, within P1c (Tantawy et al. 2000), as at Gebel Aweina (Speijer and Schmitz 1998). This appears to correspond to the highest sequence boundary in the area studied by Tantawy et al., and appears to correspond to the lower HST of sequence DB4.

Sequences DB4 and DB5 cannot yet be differentiated elsewhere in Egypt. The base of sequence DB6 corresponds to the base of the LDE. This is a sequence boundary recognised widely in Egypt and adjacent areas, as discussed above (Speijer 2003; Sprong et al. 2011; Van Itterbeeck et al. 2007; Aubry et al. 2012). It corresponds to the ThSin-1 sequence boundary in Sinai, and to the sea-level fall in upper NP4 identified at Gebel Aweina (Speijer and Schmitz 1998).

Luning et al. (1998) identified a major sea-level fall in Zone NP5, marking the ThSin2 sequence boundary. This event cannot be identified at Dababiya.

The base of sequence DB7 (combined SB/TS) corresponds to the base of the Tarawan Formation. This has been previously identified as a significant transgressive surface; in many areas it is an unconformity/disconformity (e.g. Speijer and Schmitz 1998; Tantawy et al. 2001, text-fig. 2; Ouda 2003; Berggren et al. 2003). Tantawy et al. (2000, text-fig. 5) identified the absence of Zone NP5 beneath the Tarawan Chalk Formation at Gebel Aweina. Aubry (in Speijer and Schmitz 1998, text-fig. 2) identified a thin representative of NP5 here, but this has subsequently been revised (Aubry and Salem 2013b, this volume). In

the Wadi Abu Ghurra section (NW of Aswan) (Berggren et al. 2003) the lower Garra Formation (Zone P4), interpreted as a proximal equivalent of the Tarawan Chalk Formation, unconformably overlies the Dakhla Formation (Zone P1). This event clearly represents a major sea-level rise.

Aubry and Salem 2013b (this volume) noted discrepancies in nannofossil dating of the base of the Tarawan Formation, attributing it tentatively to relative water depths in different areas. However in the majority of sections the base corresponds to the NP5/NP6 boundary, as noted above, except where the base is younger (NP7/8) due to an unconformity at the base. Older dates for the base seem suspicious, bearing in mind the major transgression at this level. Its nannofossil dating in the DQC (Aubry and Salem 2013b, this volume) is inconsistent with the planktonic foraminiferid dating, as noted above.

The ThSin3 sequence boundary of Luning et al. (1998) cannot be recognised at Dababiya. The ThSin4 sequence boundary, within NP7/8, interpreted as representing a major sealevel fall, probably corresponds to the abrupt major fall in P within NP7/8 at Dababiya. As noted above, this appears unrelated to bathymetry.

At Sin El Kaddab, SW of Aswan, the lower Garra Formation is a shallowing-upwards section (Berggren et al. 2003). This probably corresponds to the HST of sequence DB6. Maximum Paleocene water depths at Dababiya and Gebel Aweina were achieved in the upper Tarawan Formation, within NP8 at Gebel Aweina (Speijer and Schmitz 1998), and probably at the same level at Dababiya (text-fig. 3). This is consistent with the upper Tarawan Formation and its correlatives overstepping older units southwards. Further detailed study of the proximal Wadi Abu Ghurra and Sin El Kaddab sections should provide significant information on the sequence architecture in this interval.

The base of the Esna Shale Formation marks the base of sequence DB8. This event seems isochronous on the basis of nannofossil dating. An abrupt increase in the proportion of planktonic foraminiferids, at the base of the upper Garra Formation, both at Sin El Kaddab and Wadi Abu Ghurra, is interpreted as indicating a possible rise in sea level (Berggren et al. 2003). This is at about the base of Subzone P4c, and may correspond to the base of Sequence DB8. Sequence DB8 has been differentiated at Dababiya.

The sequence boundary at the base of the Dababiya Quarry Member and its correlatives (base Eocene) has been identified widely in Egypt and adjacent areas, as noted above.

COMPARISON WITH OTHER AREAS

Detailed comparison with Paleocene sequence stratigraphy in other areas is beyond the scope of this study, and comparison with the sequence stratigraphic model of Hardenbol et al. (1998) is avoided due to uncertainties about its validity and calibration(s). It can however be noted that the nine depositional sequences tentatively identified in the Dababiya Quarry Corehole section are similar in number (allowing for the possible unconformity at the base of the Tarawan Formation) to those identified in the North Sea Basin, comprising four in the Danian (Thomsen 1995) and approximately six in the Selandian and Thanetian (Knox 1996) (although other publications have somewhat differing interpretations). It is clear that there is not a one-to-one correlation in every case, but a detailed comparison is difficult due to biostratigraphic imprecision. In the Basque

Basin, five major sequences are differentiated (e.g. Schmitz et al. 2011) (text-fig. 4). The sequence boundaries here can be tentatively calibrated with some of the surfaces in the DQC, and the greatest water depths appear to be synchronous between these areas. Much further work is needed to determine if (at least some) sequence boundaries are extra-regionally synchronous.

CONCLUSIONS

Nine depositional sequences are tentatively identified in the Dababiya Quarry Corehole, based on a number of criteria, but extensively utilising gamma-ray and magnetic susceptibility logs. These techniques have proved extremely valuable in subtly varying lithologies, and should be used where possible in similar contexts elsewhere. It must be re-emphasised that sequence stratigraphic interpretation cannot be based on a single section, but requires analysis of sections in both proximal and distal settings. Of the sequence boundaries/transgressive surfaces can be identified elsewhere. Comparison with sequences identified elsewhere requires more detailed regional and extra-regional biostratigraphic and sedimentological analysis. In spite of a possible stratigraphic break within the Selandian, the Dababiya section can be regarded as a key reference section for Paleocene sequence stratigraphy in Egypt and potentially beyond.

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