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High-resolution sequence stratigraphy of the Maastrichtian-Ypresian succession along the eastern scarp face of Kharga Oasis, southern Western Desert, Egypt

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ABSTRACT

A thick Maastrichtian-Ypresian succession, dominated by marine siliciclastic and carbonate deposits of the regionally recognized Nile Valley and Garra El-Arbain facies associations, is exposed along the eastern escarpment face of Kharga Oasis, located in the Western Desert of Egypt. The main objectives of the present study are: (i) to establish a detailed biostratigraphic framework; (ii) to interpret the depositional environments; and (iii) to propose a sequence stratigraphic framework in order to constrain the palaeogeographic evolution of the Kharga sub-basin during the Maastrichtian-Ypresian time interval. The biostratigraphic analysis suggests the occurrence of 10 planktonic zones; two in the Early Maastrichtian (CF8b and CF7), four in the Palaeocene (P2, P3, P4c and P5) and four in the Early Eocene (E1, E2, E3 and E4). Recorded zonal boundaries and biostratigraphic zones generally match with those proposed elsewhere in the region. The stratigraphic succession comprises seven third-order depositional sequences which are bounded by unconformities and their correlative conformities which can be correlated within and outside Egypt. These depositional sequences are interpreted as the result of eustatic sea-level changes coupled with local tectonic activities. Each sequence contains a lower retrogradational parasequence set bounded above by a marine-flooding surface and an upper progradational parasequence set bounded above by a sequence boundary. Parasequences within parasequence sets are stacked in landward-stepping and seaward-stepping patterns indicative of transgressive and highstand systems tracts, respectively. Lowstand systems tracts were not developed in the studied sections, presumably due to the low-relief ramp setting. The irregular palaeotopography of the Dakhla Basin, which was caused by north-east to south-west trending submerged palaeo-highs and lows, together with the eustatic sea-level fluctuations, controlled the development and location of the two facies associations in the Kharga Oasis, the Nile Valley (open marine) and Garra El-Arbain (marginal marine).

Keywords Biostratigraphy, Kharga Oasis, Maastrichtian-Ypresian deposits, palaeoenvironment, sequence stratigraphy.

INTRODUCTION

The continuous exposures, wide range of ages, great thickness, lateral facies variations, palaeo-environmental changes and sedimentation breaks are all characteristic features of the Cretaceous/Eocene succession present in the southern and central oases of the Western Desert of Egypt. The regional geology of the Western Desert is complex due to lateral facies changes and sedimentation breaks that vary in duration. Three regional facies associations within the Cretaceous-Eocene succession, the Nile Valley, Garra El-Arbain and Farafra, coexist laterally (Issawi, 1972). The spatial and temporal organization of these deposits results from the interplay between the relative sea-level changes, tectonic events, and subsidence and palaeoenvironmental changes. A robust sequence stratigraphic framework for these deposits would contribute significantly to the sub-surface geology of the northern Western Desert which is one of the main petroleum provinces in Egypt. There, the Upper Cretaceous/Eocene sediments are potential source rocks and hydrocarbon reservoirs locally. In addition, these outcrop analogues offer the opportunity to develop a predictive guide to aid in the understanding of the depositional character and distribution pattern of these sediments. Finally, coeval sediments elsewhere in northern Africa, such as the Sirte Basin in Libya, contain important economic resources.

This study uses a combination of high-resolution biostratigraphy and sequence stratigraphy to unravel the lateral relationships between these major facies associations and changes in relative sea-level. The result of this integrated outcrop-based study enhances the ability to correlate these facies at the basin and regional scale, and improves understanding of the nature and timing of the Cretaceous/Eocene regional relative sea-level change.

The intent of the present study, therefore, is to address the sedimentary facies characteristics and high-resolution sequence stratigraphy of two of these laterally coeval facies associations along the eastern escarpment face of the Kharga Oasis. In particular, lateral facies distributions and palaeoenvironmental changes are interpreted in terms of relative sea-level changes and patterns of basin subsidence/uplift in order to reconstruct the stratigraphic evolution of the Maastrichtian-Ypresian time interval.

After reviewing the regional geology and lithostratigraphy, the sedimentary characteristics and biostratigraphic zonation of the Nile Valley and Garra El-Arbain facies associations are described within the framework of their corresponding Maastrichtian-Ypresian Formations and then interpreted with regard to their depositional environments. Afterwards, the sequence stratigraphic concepts are used to identify parasequence stacking patterns, systems tracts and depositional sequences within the stratigraphic succession. The sequence stratigraphic framework developed in the Kharga Oasis is then compared with other Maastrichtian-Ypresian sequences elsewhere within and outside Egypt. Finally, the available data and resulting interpretation are used to reconstruct the palaeogeographic evolution of the Kharga sub-basin during the Maastrichtian-Ypresian time interval.

REGIONAL SETTING

Kharga Oasis is a large topographic depression located in the southern Western Desert of Egypt between 24°30′00″N and 26°00′00″N and 29°30′00″E and 31°00′00″E (Fig. 1). Kharga Oasis is important because of the presence of thick phosphate-rich sediments in the Campanian Duwi Formation at Abu Tartur Plateau, the thickest such deposits in Egypt. The topographic depression of the Kharga Oasis is bounded to the north and east by escarpments and high plateaux (Fig. 1). The eastern plateau extends eastward to join the west Nile Plateau in the area between Idfu and Luxor (200 and 230 km south of Assiut City, respectively). The northern Kharga Plateau extends westward to form the plateau overlooking Dakhla Oasis. The latter extends north-westward to join the east Farafra Plateau.

The surface geology of the Kharga Oasis has been the subject of numerous studies over the past century, including those by Ball (1903), Nakkady (1959), Awad & Ghobrial (1965), Hermina (1967, 1990), Abdou & Abdel-Kireem (1969), Issawi *et al.* (1978), El-Deftar *et al.* (1978), El-Hinnawi *et al.* (1978), Garrison *et al.* (1979), Schrank (1984), Hendriks *et al.* (1984), Hewaidy & Cherif (1984), Faris (1985), Cherif & Hewaidy (1987), Anan & Sharabi (1988), Bassiouni & Luger (1990), Hewaidy (1990), Bassiouni *et al.* (1991), Faris *et al.* (1999), Ouda *et al.* (2004) and Obaidalla *et al.* (2008). These studies have established the stratigraphy, biostratigraphy and palaeontology of the exposed Upper Cretaceous to Lower Eocene succession. Unfortunately, no detailed sequence stratigraphic study for the whole exposed succession has been published so far. The present study is the first to interpret the high-resolution sequence stratigraphic framework of the Kharga succession. Several pertinent sequence stratigraphic studies conducted in the nearby areas include El-Azabi & El-Araby (2000), Tantawy *et al.* (2001), Khalil & El-Younsy (2003) and Hewaidy *et al.* (2006) in the Dakhla-Farafra region.

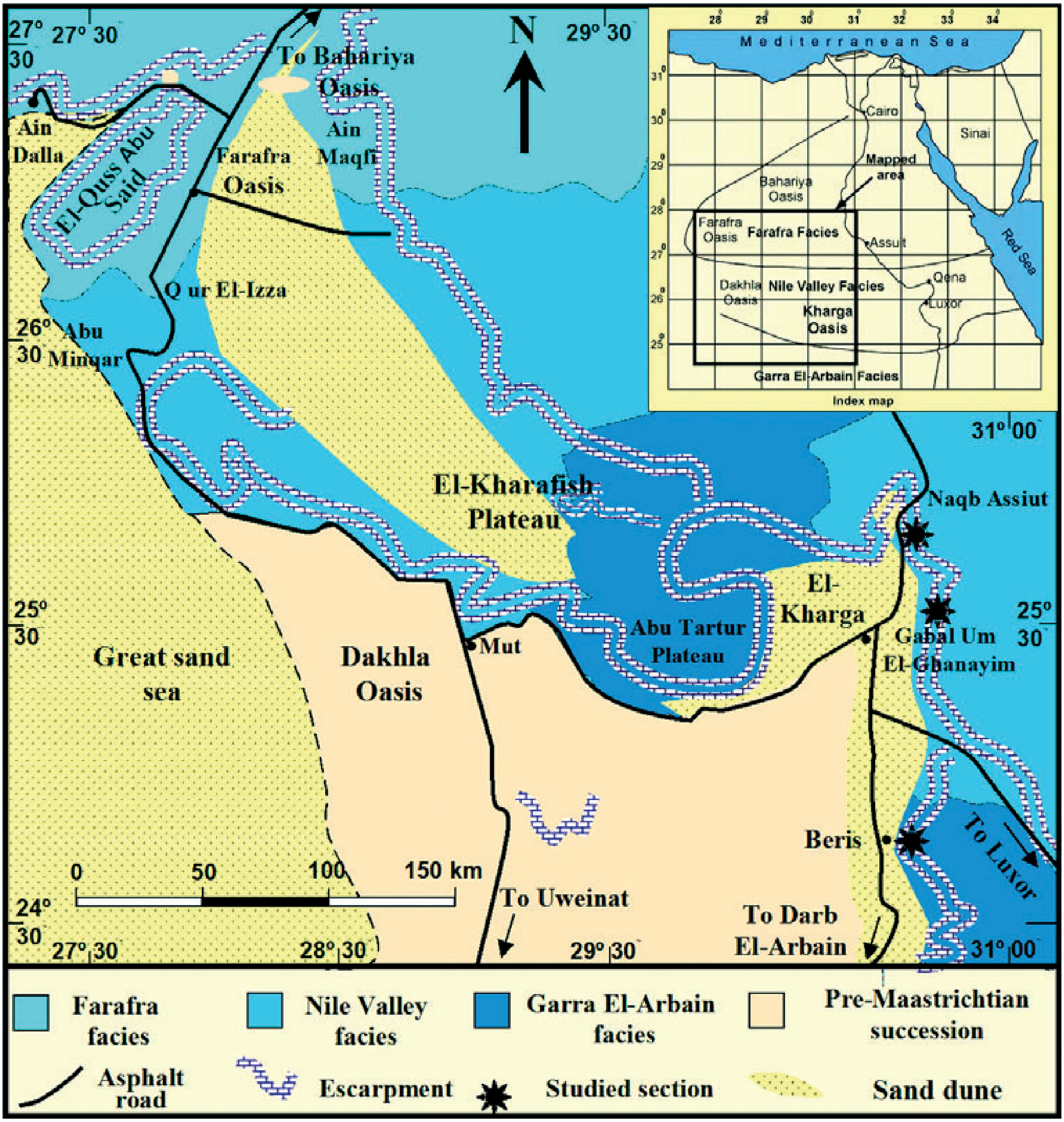

Fig. 1. Location map of the Kharga Oasis and environs showing the distribution of the different Maastrichtian-Ypresian facies types, southern Western Desert, Egypt.

The Cretaceous-Eocene succession of the central part of Egypt has been deposited in two major sedimentary basins, the Dahkla Basin in the west and the Assiut Basin in the east (Hendriks *et al.*, 1987). Kharga Oasis is located in the south-eastern part of the Dakhla Basin; together with the Assiut Basin this was a persistent feature in the central part of Egypt from the Late Jurassic. The succession exposed in the Kharga Oasis ranges in age from Albian to Quaternary (Fig. 2). Older sediments are exposed to the south at Gabal Abu Bayan El-Bahari, where the Jurassic Six Hills Formation overlies pre-Cambrian basement and underlies the Cretaceous Sabaya, Maghrabi and Tarf Formations (Hermina, 1990). These formations form the floor of the Kharga Oasis. The base of the eastern escarpment of the Kharga Oasis is formed of claystone and sandstone of the early

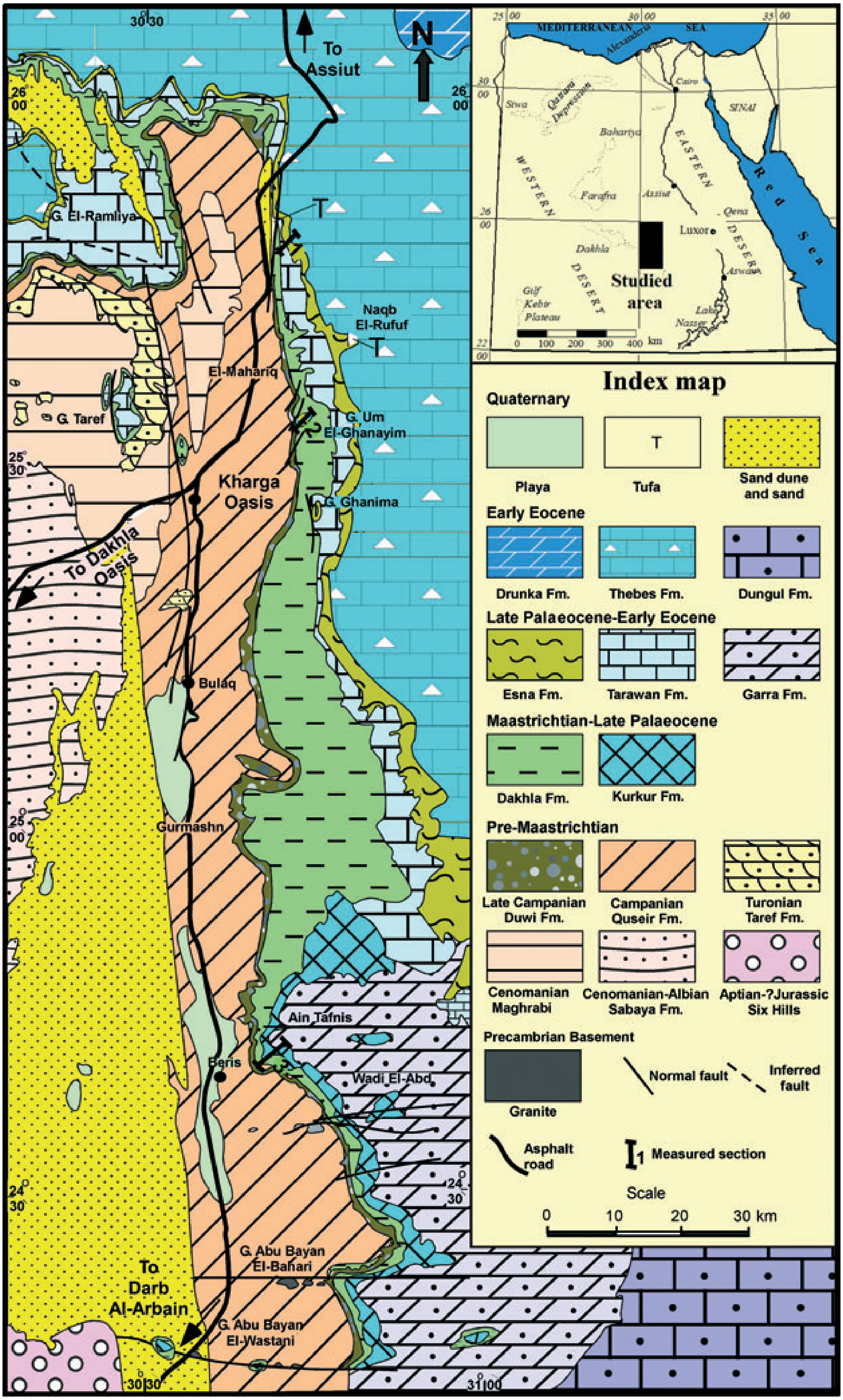

Fig. 2. Geological map of the Kharga Oasis, southern Western Desert, Egypt (simplified after the Geological map of Egypt, 1987, EGPC/CONOCO map sheet of Luxor).

Middle Campanian Quseir Formation (Youssef, 1957) which is overlain by phosphate-rich sediments of the Upper Campanian Duwi Formation. This formation consists of shale, marl and oyster banks with a single phosphate-rich bed, 0·5 to 1 m thick, at the top. It grades upwards into thick shale with mudstone and limestone interbeds of the Lower Maastrichtian to Upper Palaeocene Dakhla Formation (Said, 1961). From base to top, this formation is subdivided into the Mawhoob Shale, Beris Mudstone and Kharga Shale members, respectively (Awad & Ghobrial, 1965). The Kharga Shale Member is classified further by Luger (1985) into two informal units, Lower and Upper Kharga Shale, which are separated by an unconformity representing the Cretaceous/Palaeogene (K/Pg) boundary. The Dakhla Formation is unconformably overlain by chalky limestone of the Upper Palaeocene Tarawan Formation (Awad & Ghobrial, 1965). The latter is conformably overlain by shale sequences with limestone interbeds comprising the latest Palaeocene to Early Eocene Esna Formation (Said, 1960). This formation is conformably overlain by the Lower Eocene Thebes Formation. The latter consists of bedded limestone intercalated with shale and chert bands. The Thebes Formation forms the upper escarpment face and plateau surface in the north-eastern part of the Kharga Oasis. Surficial deposits include Pleistocene travertine, well-developed along the eastern escarpment of the Kharga Oasis, and common playa deposits up to 15 m thick. Linear sand dunes and sheets are ubiquitous, having migrated into the depression from the northern plateau.

In the south-eastern escarpment face of the Kharga Oasis, as well as in Abu Tartur Plateau, the Palaeocene to Lower Eocene sequences of the Nile Valley facies association exhibit a lateral facies change into the Garra El-Arbain facies (Fig. 3). The lower part of the Upper Kharga Shale is replaced by limestone with shale interbeds of the

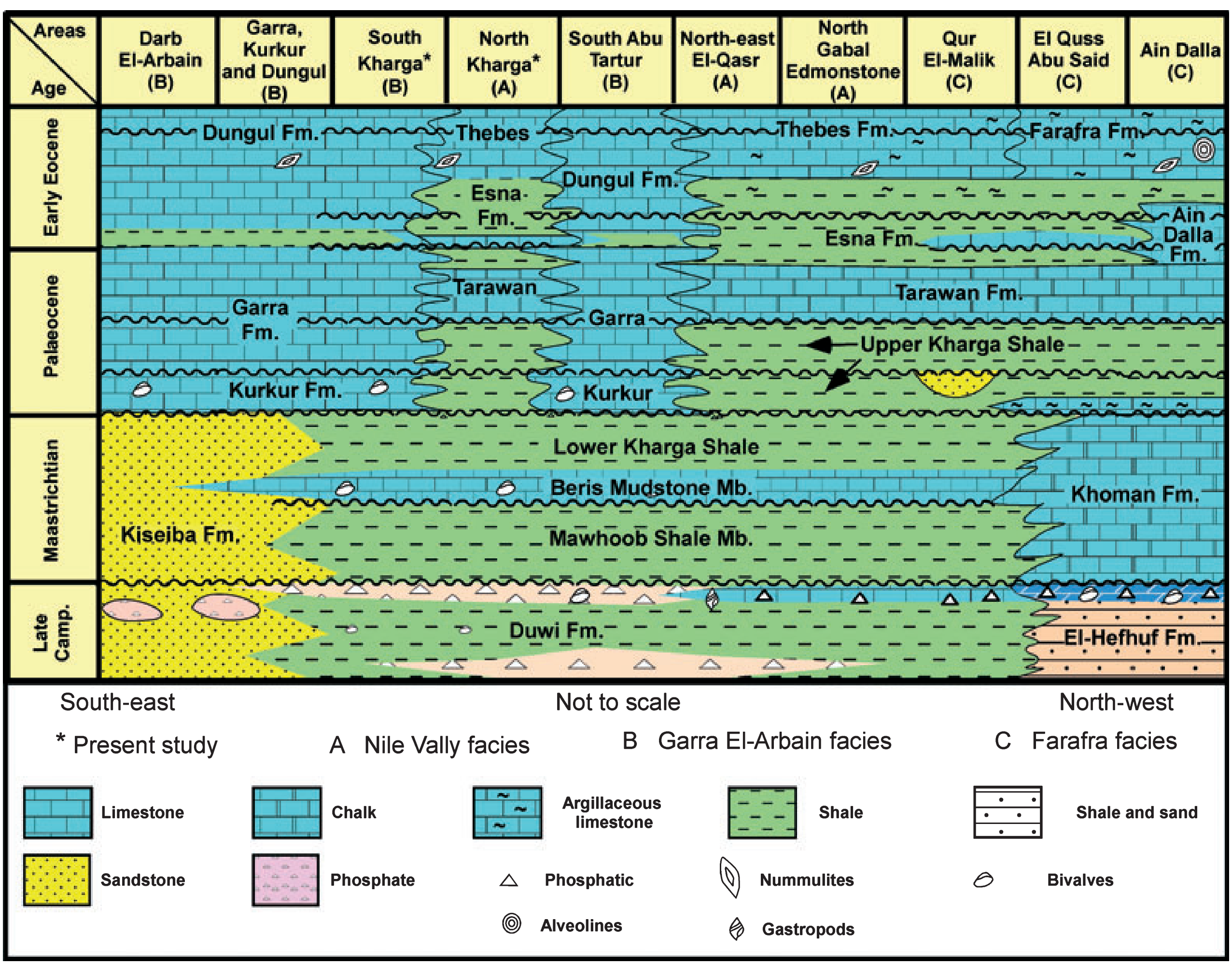

Fig. 3. The Upper Cretaceous-Lower Tertiary rock units of the Nile Valley facies and their time correlatives of Garra El-Arbain facies exposed in the southern Western Desert of Egypt (modified after El-Azabi & El-Araby, 2000).

Kurkur Formation (Issawi, 1968). The latter is unconformably overlain by another limestone that belongs to the Upper Palaeocene to Lower Eocene Garra Formation, corresponding to the upper part of the Dakhla Formation, the Tarawan Formation and the lower part of the Esna Formation (Fig. 3). The Garra Formation is overlain by the Lower Eocene Dungul Formation on the south-eastern plateau surface of the Kharga Oasis.

MATERIALS AND METHODS

In the present study, three stratigraphic sections were measured and sampled to record the sedimentary characteristics of the Nile Valley and Garra El-Arbain facies associations along the eastern escarpment face of the Kharga Oasis (Fig. 2). The Nile Valley facies association is represented by two sections, one at Naqb Assiut, north Kharga (25°48′26″N, 30°42′57″E) and the other at Gabal Um El-Ghanayim, 40 km south of Naqb Assiut (25°34′04″N, 30°43′37″E). These two sections contain the Duwi (upper part), Dakhla, Tarawan, Esna and Thebes Formations from base upwards (Fig. 4A). The Garra El-Arbain facies association is represented by a third section measured at Beris (24°42′01″N, 30°40′44″E). It contains, in ascending order, the Dakhla, Kurkur and Garra Formations (Fig. 4B). In these sections, descriptions focused on lithological aspects, facies types, faunal content and lateral changes in facies and thickness. In turn, these descriptions led to the interpretation of palaeoenvironments, stratal geometries, parasequence stacking patterns, sequence boundaries and other bounding surfaces. Faunal palaeoenvironmental interpretation is based on faunal types, diversity and abundance, and foraminiferal planktonic/benthonic ratio (Murray, 1976; Olsson & Nyong, 1984). The sedimentological characteristics of these sections and their biostratigraphic, environmental and sequence stratigraphic interpretation are depicted in Figs 5 to 7. Most of the collected data are summarized in Table 1. The dominant planktonic and benthonic foraminiferal species found in the studied formations are shown in Table 2; they are grouped into 10 planktonic zones. Marker foraminiferal species are illustrated in Fig. 8. The Maastrichtian interval is classified according to the biostratigraphic zonal schemes of Li & Keller (1998a,b) and Li *et al.* (1999). These authors divided the Maastrichtian into nine zones, labelled CF1 to CF7, CF8a and CF8b. For the Palaeocene to Early Eocene interval, the zonal scheme of Berggren & Pearson (2005) was used where an alphanumeric notation for the Palaeogene zones was provided using the prefix 'P' for Palaeocene and 'E' for Eocene to achieve consistency with the recent shorthand notation for other Cenozoic zones. The numerical ages for various zonal boundaries quoted in the present work are consistent with the time scale of Berggren & Pearson (2005). The sequence stratigraphic interpretation is based upon bounding surface characteristics, vertical cycle stacking patterns and spatial and temporal variations in depositional facies and their interpreted environments.

STRATIGRAPHY OF THE MAASTRICHTIAN-YPRESIAN SUCCESSION

The sedimentary sequences exposed in the Kharga Oasis include two markedly contrasting facies associations: the Nile Valley and the Garra El-Arbain (Fig. 1). These facies associations and their interpreted depositional environments are described in detail below within the framework of their corresponding Maastrichtian-Ypresian Formations.

NILE VALLEY FACIES ASSOCIATION

The Nile Valley facies association has a widespread distribution in the southern Western Desert. It is well-developed along the north-eastern escarpment face of the Kharga Oasis, exhibiting a variety of shallow and deep marine sediments. This facies consists of shale, mudstone, limestone and chalk with varied faunal elements. It displays distinctive lateral facies and thickness changes towards the north-west and south-east which are interpreted as being related to deposition on an irregular shelf with submerged structural highs and lows. The Maastrichtian-Ypresian succession of the Nile Valley facies is interrupted by multiple unconformities (sequence boundaries) representing short-term and long-term sedimentation breaks. It is marked by the following formally defined formations, arranged from oldest to youngest.

Dakhla Formation – Early Maastrichtian to Late Palaeocene

Description

The Dakhla Formation forms the lower/middle escarpment face of the northern and eastern

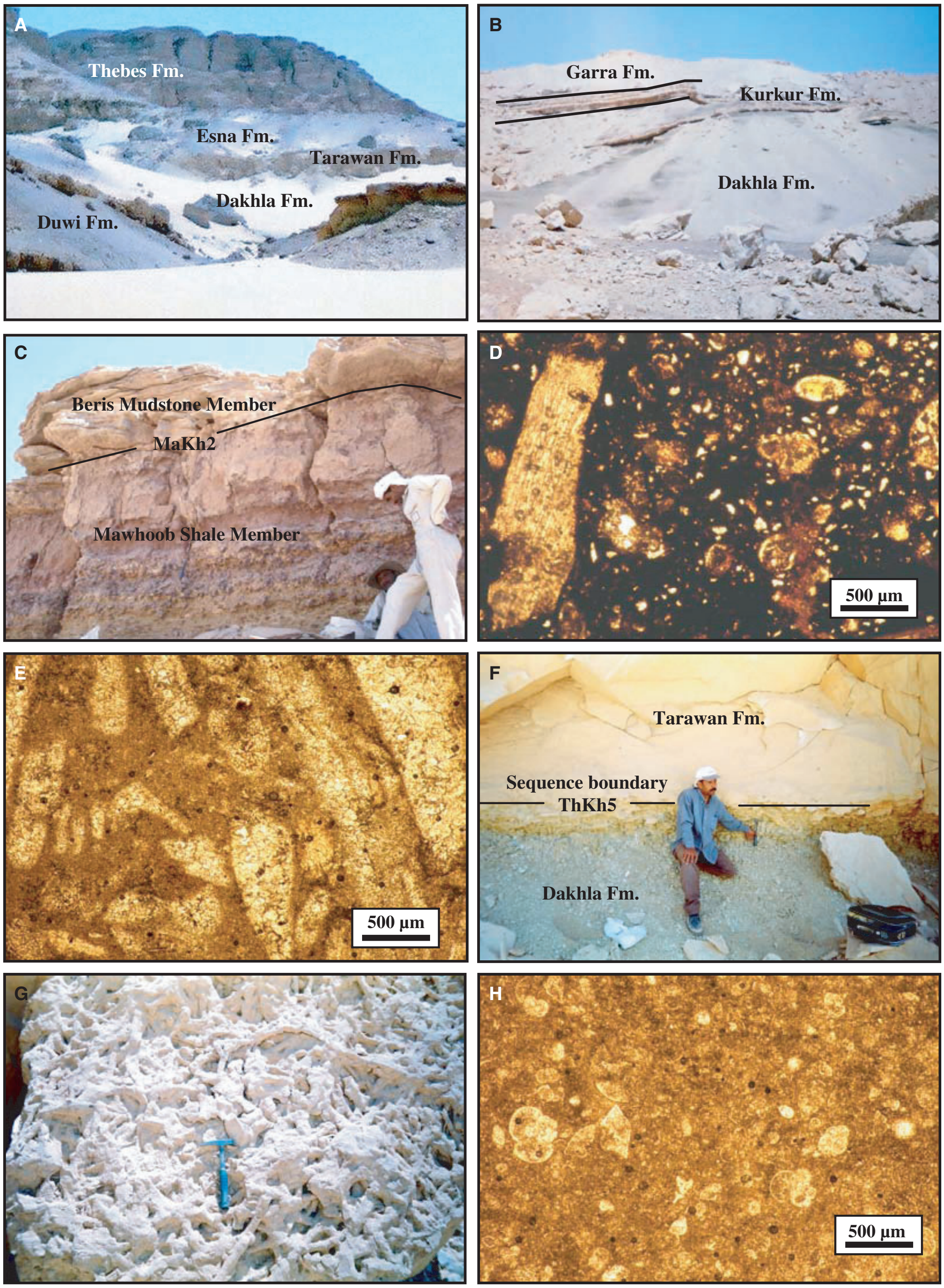

Fig. 4. (A) The siliciclastic/carbonate deposits of Nile Valley facies cropping out at Gabal Um El-Ghanayim, eastern scarp face of the Kharga Oasis. The vertical cliff in the background is *ca* 60 m thick. Photograph is looking north-east. (B) Dakhla, Kurkur and Garra Formations of Garra El-Arbain facies exposed at Beris. The outcrop is 150 m long. Photograph is looking north-east. (C) The unconformable contact between the Mawhoob Shale and Beris Mudstone members, south Beris. Person for scale is *ca* 1·8 m tall. (D) A highly oxidized and intensively bioturbated hardground with reworked clasts that defines the unconformity at the top of Mawhoob Shale Member, ferruginous silty claystone, Gabal Um El-Ghanayim. P.P.L. (E) Highly obliterated bivalve debris packed in a lime-mud matrix, shallow sub-tidal oyster bioclastic packstone, Beris Mudstone Member, Beris, Bed 30. P.P.L. (F) The unconformable contact between the Tarawan Formation and the underlying Upper Kharga Shale of the Dakhla Formation, Naqb Assiut. (G) Close-up view of the lower unconformable contact of the Tarawan Formation showing the intensive burrow system of *Thalassinoides*. (H) Abundant planktonic foraminifera randomly disseminated in a dense lime-mud, shallow middle to outer shelf foraminiferal wackestone/packstone, Tarawan Formation, Gabal Um El-Ghanayim, Bed 29, P.P.L.

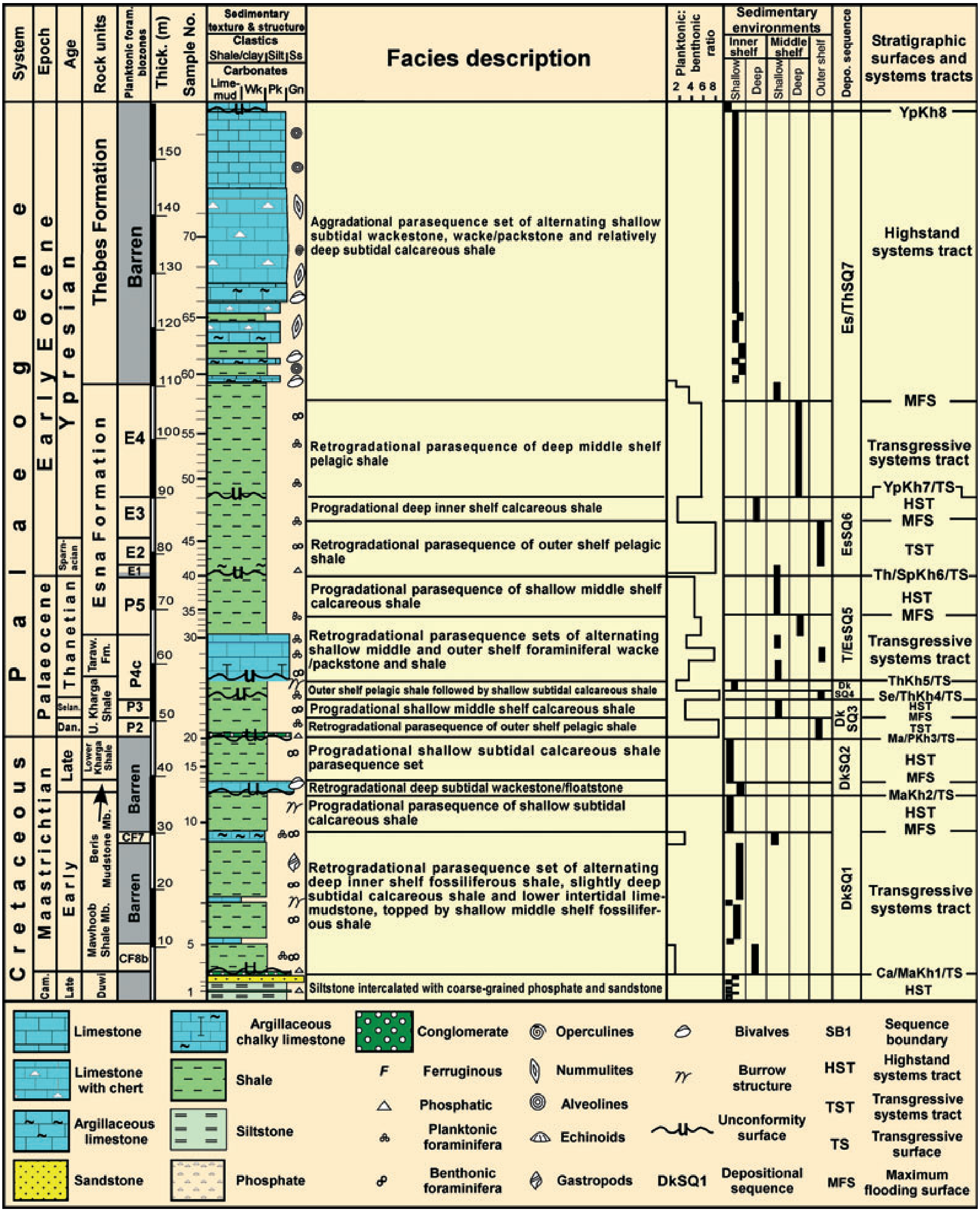

Fig. 5. Representative stratigraphic section showing the sedimentological characteristics, palaeoenvironments and sequence stratigraphic interpretation of the Maastrichtian-Ypresian succession exposed at Gabal Um El-Ghanayim, Kharga Oasis, southern Western Desert (for location, see Fig. 1).

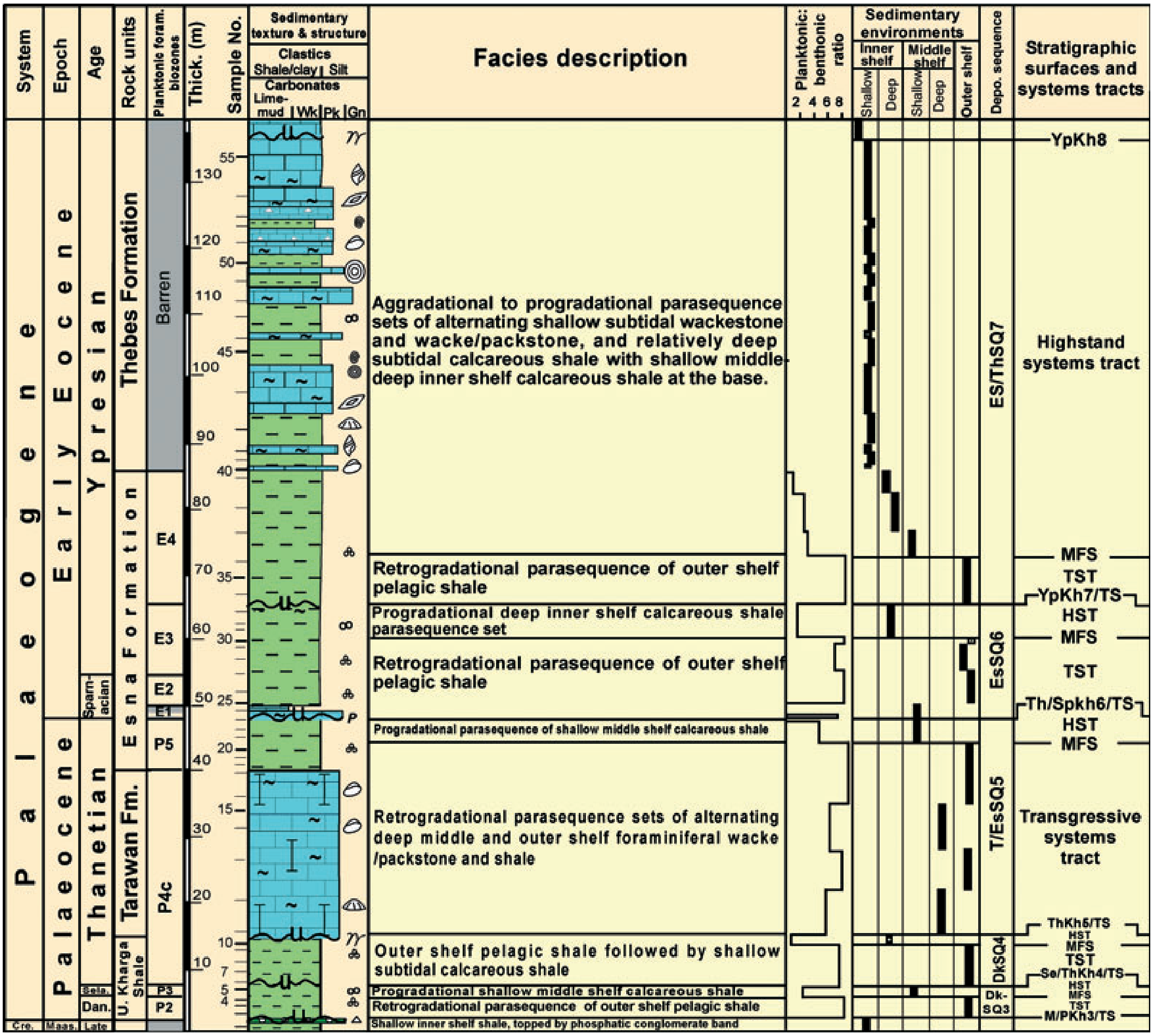

Fig. 6. Representative stratigraphic section showing the sedimentological characteristics, palaeoenvironments and sequence stratigraphic interpretation of the Maastrichtian-Ypresian succession exposed at Naqb Assiut, Kharga Oasis, southern Western Desert (for location, see Fig. 1 and for symbols and key see Fig. 5).

plateaux surrounding the Kharga Oasis. The exposed uppermost part of the underlying Duwi Formation consists of alternating siltstone, phosphate and sandstone beds. A white limestone bed which normally delimits the top of the Duwi Formation in the Dakhla-Farafra region is missing at the Kharga Oasis. This bed was referred to as the Qur El-Malik Member by Barthel & Herrmann-Degen (1981). It is ascribed to latest Campanian Zone CF8a (Tantawy *et al.*, 2001). The Dakhla Formation is composed of a thick succession of shale with limestone and siltstone interbeds. It spans a time interval from Early Maastrichtian to Late Palaeocene. In the Dakhla-Farafra region, the basal part of the Dakhla Formation was assigned to the latest Campanian due to the presence of heteromorphic ammonites (Barthel & Herrmann-Degen, 1981). Later, these ammonites are dated to the earliest Maastrichtian Zone CF8b (Tantawy *et al.*, 2001). In Farafra, the Maastrichtian part of the Dakhla Formation exhibits a radical facies change to the chalk of the Khoman Formation (Hermina, 1990). The Palaeocene part of this formation is also replaced by limestone with shale interbeds of Kurkur and Garra Formations to the south of Kharga. In the eastern escarpment face of the Kharga Oasis, the Dakhla

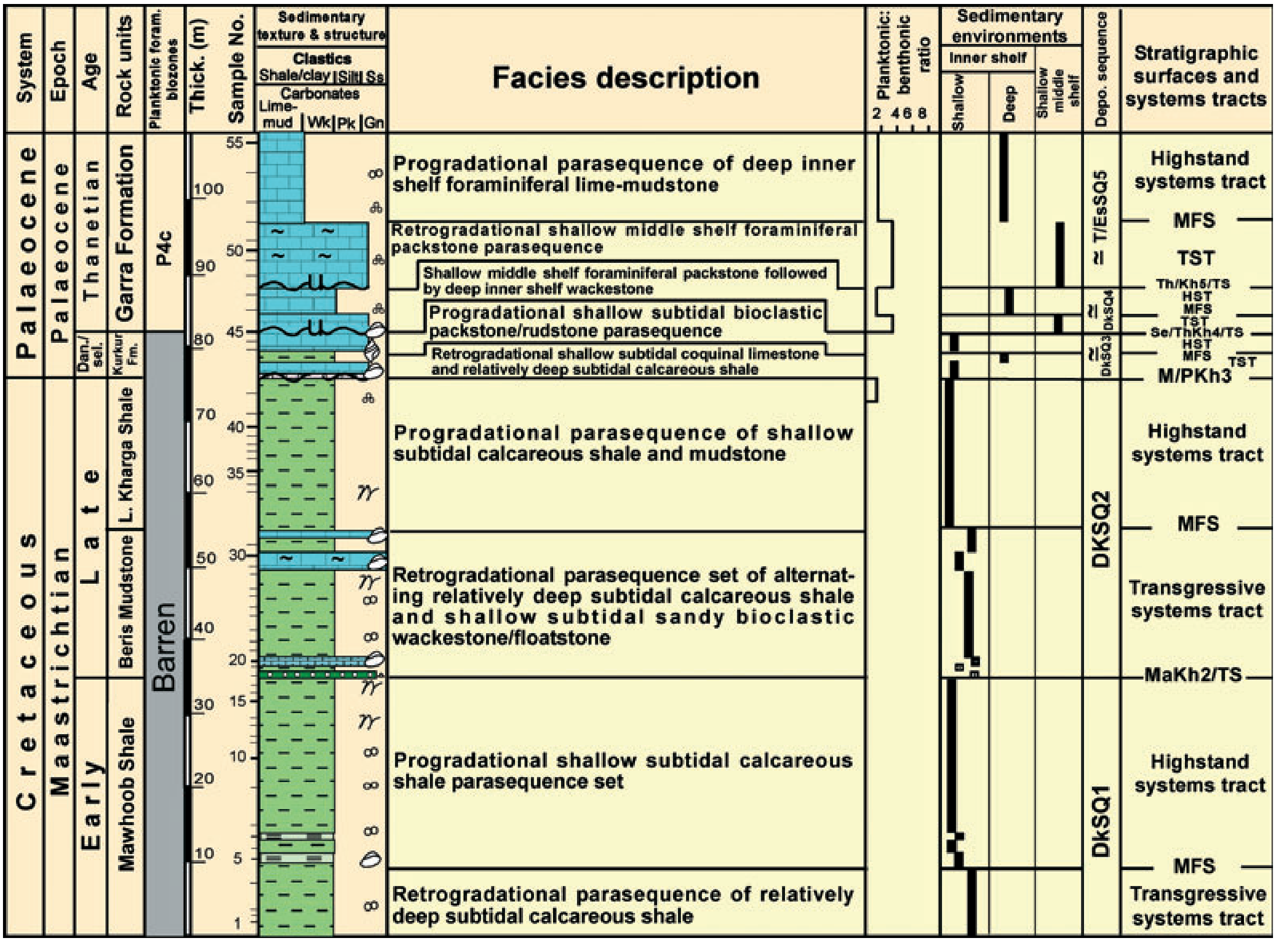

Fig. 7. Representative stratigraphic section showing the sedimentological characteristics, palaeoenvironments and sequence stratigraphic interpretation of the Maastrichtian-Ypresian succession exposed at Beris, Kharga Oasis, southern Western Desert (for location, see Fig. 1 and for symbols and key, see Fig. 5).

Formation has its tripartite subdivision; Mawhoob Shale, Beris Mudstone and Kharga Shale members, in ascending order. These members are interpreted as having formed under repeated shallow and deep marine settings due to sea-level oscillations. This observation led El-Azabi & El-Araby (2000) to divide the three members of the Dakhla Formation into 10 depositional cycles based upon facies distribution patterns, stratal geometry and frequency of the associated fauna. The deposits of this formation have been formed in inner to outer shelf settings under a warm, wet tropical to sub-tropical climate marked by heavy rainfall and predominantly chemical weathering in nearby hinterlands (Schrank, 1984; Ganz *et al.*, 1990). The following is a description of the Dakhla tripartite subdivision and the interpreted depositional settings.

Mawhoob Shale Member – Early Maastrichtian

Description

The Mawhoob Shale Member, marking the lower member of the Dakhla Formation, is formed of shale interbedded with limestone (Figs 5 and 7). The shale is grey, calcareous and partly silty. It yields rare to common agglutinated benthonic foraminifera of low species diversity such as *Ammobaculites* and *Haplophragmoides*. At Gabal Um El-Ghanayim, two intervals enriched in well-preserved planktonic foraminifera with some calcareous benthonic foraminifera are located at the base and near the top of the Mawhob Shale Member (Fig. 5). The dominant species are *Rugoglobigerina hexacamerata*, *R. macrocephala*, *Globotruncana aegyptiaca*, *G. arca*, *Globotruncanita stuarti*, *Gl. stuartiformis*, *Heterohelix reussi*,

Table 1. Sedimentary facies and palaeontological aspects of the exposed Maastrichtian-Ypresian formations along the eastern scarp face of the Kharga Oasis and their environmental interpretation, southern Western Desert, Egypt.

Formations	Lithological aspects	Faunal types, diversity and abundance	Major taxa	Microfacies types	Sedimentary environments
Dakhla Formation (58-76 m thick)	Fissile shale, slope-forming, calcareous, micaceous and fossiliferous, intervening with argillaceous limestone and siltstone interbeds	Rare/common agglutinated benthonic species with two planktonic-rich intervals in lower part. Common planktonic species in upper part. Large oysters in Beris Mudstone Mb.	*Ammobaculites khargensis* at base, *Exogyra overwegi* at middle, *Acarinina Praemurica* at top	Calcareous shale, pelagic shale, lime-mudstone, sandy bioclastic wackestone/floatstone, partly oyster rudstone (Pl. 1E)	Alternating shallow inner to outer shelf
Tarawan Formation (7-25 m thick)	Massive to thick-bedded snow white chalky limestone, highly fossiliferous	Abundant and highly diversified planktonic species, common benthonic species, few echinoids and gastropods	*Acarinina*, *Morozovella*	Foraminiferal wacke/ packstone and packstone (Pl. 1H)	Shallow middle-outer shelf
Esna Formation (45-48 m thick)	Fissile shale, slope-forming intercalated with massive argillaceous limestone forming ledges in lower part	Moderate/abundant, highly diversified planktonic and benthonic species in lower part. Common, moderate diversified benthonic species in upper part.	*Morozovella*, *Acarinina*,	Pelagic shale, calcareous shale, glauconitic lime-mudstone	Deep inner-outer shelf
Thebes Formation (50-55 m thick)	Thick-bedded, cliff-forming limestone with chert bands and nodules as well as intercalations of calcareous shale in its lower part, thin-bedded algal limestone in upper part	Abundant, low diversity larger foraminifera and macrofossils which decrease in abundance at upper part	*Nummulites*, *Operculina*, *Alveolina*, *Assilina*, bivalves and gastropods	Nummulitic bioclastic wackestone, Nummulitic wacke/packstone, Nummulitic assilina packstone, bioclastic foraminiferal packstone (Pl. 2D-E), calcareous shale	Shallow inner shelf (lower intertidal-relatively deep subtidal)
Kurkur Formation (6 m thick)	Massive coquinal limestone, highly fractured, intervening with calcareous shale	Abundant bivalves and echinoids of low diversity, few gastropods	*Ostrea orientalis*, *Nemocardium fecundum*	Oyster bioclastic packstone/rudstone (Pl. 2G)	Shallow inner shelf
Garra Formation (27 m thick)	Limestone, massive to well-bedded, hard to moderately hard, partly chalky and argillaceous	Moderately abundant and diversified planktonic and benthonic species, badly preserved	*Morozovella*, *Acarinina*	Foraminiferal wackestone and packstone, foraminiferal lime-mudstone at top (Pl. 2H)	Alternating deep inner to shallow middle shelf

H. striata, *Rugotruncana subcircumnodifer* and *Gansserina gansseri* among many others (Table 2, Fig. 8). These species are indicative of Early Maastrichtian *Rugoglobigerina hexacamerata* Interval Zone CF8b at the base of the member, and to *Gansserina gansseri* Partial Range Zone CF7 near its top part. The base of the Maastrichtian is placed at the base of Zone CF8b, while the Early/Late Maastrichtian boundary is defined at the base of Zone CF4 (Li *et al.*, 1999; Fig. 9). Calcareous benthonic foraminifera found in the planktonic-rich intervals include *Cibicides libycus*, *Orthokarstenis oveyi*, *Neoflabellina reticulate*, *Nodosaria zippei* and *Vaginulina cretacea* (Table 2). The Mawhoob Shale Member displays a brick red, oxidized unconformable contact at its top characterized by intense bioturbation and reworked clasts (Fig. 4C and D).

Facies interpretation

The Mawhoob Shale Member is interpreted as having been deposited under variable depositional settings alternating from shallow inner shelf to shallow middle shelf (Figs 5 and 7). The sediments containing rare to common agglutinated benthonic foraminifera of low species diversity denote deposition in shallow to slightly deep sub-tidal water under an adverse environmental stress (restricted marine influence and/or oxygen deficiency). The sediments containing a high planktonic species richness, deeper-water species (globotruncanids) and a low abundance of benthonic foraminifera relative to planktonic foraminifera, for example in the two intervals of Gabal Um El-Ghanayim, indicate deposition in an open water, deep inner/shallow middle shelf site. The alternating depositional environment, i.e. from restricted, brackish and/or hypoxic marine, to normal salinity, well-oxygenated open marine, is interpreted as being related to alternating periods of abundant clastic input derived from the south and south-west hinterland via rivers and periods of relatively low clastic input. These alternations may relate to relative sea-level fluctuations and/or climatic changes.

Beris Mudstone Member – Late Maastrichtian

Description

The Beris Mudstone, comprising the middle member of the Dakhla Formation, is made up of limestone intercalated with shale (Figs 5 and 7). The limestone is brown, moderately hard and argillaceous with a bed thickness never exceeding 0·5 m. It contains large oysters (*Exogyra overwegi*) and small bivalves. The first remarkable appearance of *E. overwegi* denotes the lower limit of this member. These oysters occur as scattered shells, many of which are still in life positions, or as dense, crowded assemblages forming fossil banks; their presence is of great value as a stratigraphic marker, typifying the Beris Mudstone Member and marking the Upper Maastrichtian sediments of the Western Desert. The intercalated shales are grey and calcareous, and partly phosphatic; they are barren of planktonic foraminifera but contain abundant simple-walled agglutinated species of *Haplophragmoides glabra*, *Trochammina globigeriniformis* and *Ammobaculites khargensis*.

Facies interpretation

The limestone facies of the Beris Mudstone Member ranges from bioclastic wackestone to oyster floatstone or rudstone (Fig. 4E). It is interpreted as having been deposited in a sheltered shallow sub-tidal lagoon (wackestone/floatstone) with scattered oyster biostromes or banks (rudstone). Limestone was deposited during periods of high carbonate productivity and low clastic influx. Deposition took place in a warm, arid climate with restricted circulation and water depths less than 5 m. The intercalated shales, dominated by low diversity agglutinated benthonic foraminifera, are interpreted as having been deposited in relatively deep, oxygen-poor, subtidal conditions.

Kharga Shale Member – Late Maastrichtian to Late Palaeocene

Description

The Kharga Shale Member, designating the upper member of the Dakhla Formation, is composed largely of shale with a few mudstone interbeds (Figs 5 to 7). The shale is grey, calcareous and partly phosphatic and organic-rich. This member is split into upper and lower units by a 20 to 30 cm thick, phosphatic conglomerate in its middle part. This conglomerate marks the well-defined hiatus at the K/Pg boundary, with the latest Maastrichtian through to mid-Danian biostratigraphic zones absent in the studied locality. Following Luger (1985), the present authors divide the Kharga Shale Member into two informal units, the Lower and Upper Kharga Shale, with a distinct palaeoenvironmental turnover occurring across the K/Pg boundary. The Lower Kharga Shale is a restricted, shallower marine sub-tidal facies, devoid of planktonic

Table 2. The dominant planktonic and benthonic foraminiferal assemblages recorded in the exposed Maastrichtian-Ypresian succession along the eastern scarp face of the Kharga Oasis and their corresponding planktonic foraminiferal biozones. Late Cretaceous biozones are after Li & Keller (1998a,b) and Li *et al.* (1999) and Palaeocene to early Eocene biozones after Berggren & Pearson (2005).

Age	Rock units		Planktonic biozones	Dominant planktonic species	Characteristic benthonic species	P/B ratio	Calc. ratio
Early Maastrichtian	Dakhla Formation	Mawhoob Shale Mb.	CF8b-CF7	*Rugoglobigerina hexacamerata, R. macrocephala, R. rugosa, Globotruncana arca, G. aegyptiaca, G. orientalis,G. bulloides, Globotruncanita stuarti, Gl. stuartiformis, Heterohelix reussi, H. navaroensis, H. globulosa, H. striata, Contusotruncana fornicate, Rugotruncana subcircumnodifer* and *Gansserina gansseri* in planktonic-rich intervals	Common agglutinated benthonic foraminifera of low species diversity such as *Ammobaculites, Reophax* and *Haplophragmoides*. Calcareous benthonic species found in planktonic-rich intervals are *Orthokarstenis oveyi, Neoflabellina reticulate, Vaginulina cretacea, Nodosaria zippei, Cibicidoides zitteli, Bulimina kickapooensis* and *Cibicides libycus*	*ca* 30% P in planktonic-rich intervals	90–100% A
Late Maastrichtian	Dakhla Formation	Beris Mudstone Mb.	Barren	–	High occurrence of simple-walled agglutinated species of *Trochammina globigeriniformis, Haplophragmoides glabra* and *Ammobaculites khargensis*	–	100% A
Late Maastrichtian	Dakhla Formation	Lower Kharga Shale	Barren	–	Few agglutinated benthonic foraminifera of low species diversity such as *Haplophragmoides glabra* and *Ammobaculites subcretaceus*	–	100% A
Palaeocene	Dakhla Formation	Upper Kharga Shale / Kurkur Fm.	P2	*Globanomalina compressa, Gl. pseudomenardii, Praemurica uncinata, Pr. inconstans, Pr. trinidadensis* and *Morozovella praeangulata*	*Angulogavelinella avnimelechi, A. abudurbensis, Gyroidinoides girardanus, Loxostomum limonense* and *Marssonella oxycona*	80–90% P / Barren	<10% A
Palaeocene	Dakhla Formation	Upper Kharga Shale / Kurkur Fm.	P3	*Morozovella conicotruncata, M. praecursoria, M. angulata,* and *Igorina albeari*	Low diversity of genera such as *Lenticulina, Cibicidoides* and *Cibicides*	*ca* 30% P / Barren	<10% A
Palaeocene	Dakhla Formation / Tarawan Fm.	Upper Kharga Shale / Garra Fm.	P4c	*Globanomalina pseudomenardii, M. velascoensis, M. acuta, M. aequa, Acarinina soldadoensis, Ac. mckannai Ac. primitive, Ac. nitida* and *Subbotina velascoensis*	*Frondicularia phosphatica, Marginulinopsis tuberculata, Spiroloculina proboscidea* and *Buliminella cushmani*	Variable from 20–90% P	<5% A
Palaeocene	Esna Formation	Unit Esna 1	P5	*Acarinina angulosa, Ac. interposita, Ac. esnaensis, Morozovella occlusa, M. parva, M. Acuta, M. velascoensis, M. Subbotinae, M. gracilis* and *M. edgari*		50–90% P	<8% A
Eocene	Esna Formation	Dababiya Quarry Beds	E1	*Acarinina sibaiyaensis, A. africana and Morozovella allisonensis*	*Marginulina wetherellii, Loxostomoides applinae, Stilostomella paleocenica, Frondicularia wanneri, Bulimina farafraensis, B. quadrata, Pseudonodosaria manifesta, Chilostomella czizeki* and *Dentalina gracilis*	90% P	<5% A
Eocene	Esna Formation	Unit Esna 2 & 3	E2–E4	*Pseudohastigerina wilcoxensis, Morozovella formosa, M. velascoensis, M. subbotinae, M. marginodentata, M. aragonensis, M. gracilis, Subbotina triangularis, S. linaperta and Acarinina pseudotopilensis*		Variable from 20–90% P	<15% A
Eocene	**Thebes Fm.**		Barren	–	Abundant, low diversity larger foraminifera such as Nummulites, Operculina and Alveolina	–	–

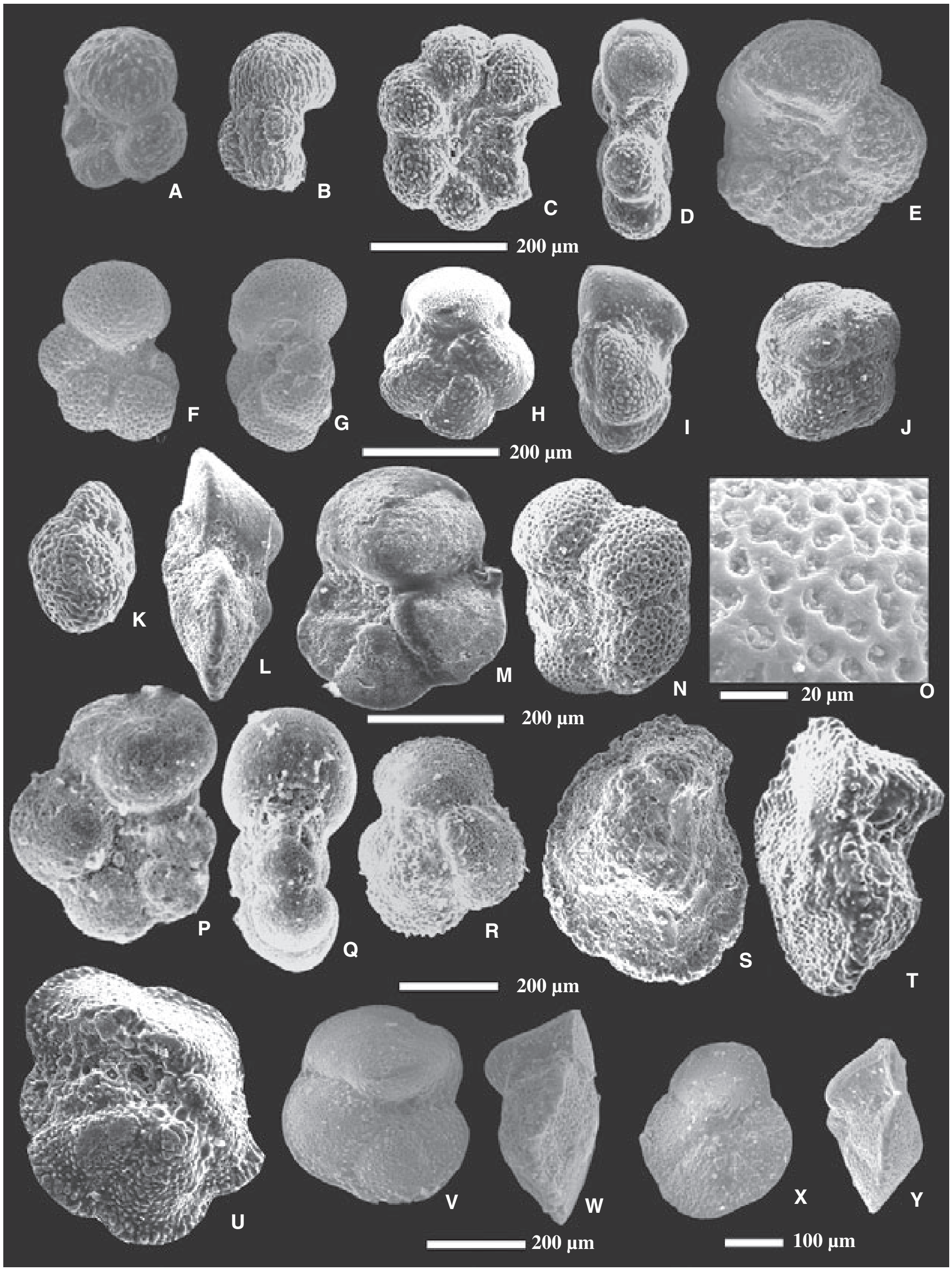

Fig. 8. Some selected planktonic foraminiferal species present in the Maastrichtian-Ypresian succession of the Kharga Oasis. (A) and (B) *Rugoglobigerina macrocephala* Brönnimann, Gabal Um El-Ghanayim, Mawhoob Shale Member, Sample 4. (C) and (D) *Rugoglobigerina hexacamerata* Brönnimann, Gabal Um El-Ghanayim, Mawhoob Shale Member, Sample 4. (E) *Rugotruncana subcircumnodifer* (Gandolfi), Gabal Um El-Ghanayim, Mawhoob Shale Member, Sample 4. (F) and (G). *Praemurica uncinata* (Bolli), Naqb Assiut, Upper Kharga Shale unit, Sample 2. (H) and (I) *Morozovella angulata* (White). Naqb Assiut, Upper Kharga Shale unit, Sample 4. J-K. *Igorina albeari* (Cushman & Bermudez), Naqb Assiut, Upper Kharga Shale unit, Sample 4. (L) and (M) *Globanomalina pseudomenardii* (Bolli), Baris, Garra Formation, Sample 53. (N) and (O) *Acarinina sibaiyaensis* (El Naggar), Naqb Assiut, Esna Formation, Sample 23. (P) and (Q) *Pseudohastigerina wilcoxensis* (Cushman & Ponton), Gabal Um El-Ghanayim, Esna Formation, Sample 45. (R) *Morozovella subbotinae* (Morozova), Naqb Assiut, Esna Formation, Sample 30. (S) *Morozovella velascoensis* (Cushman), Gabal Um El-Ghanayim, Upper Kharga Shale unit, Sample 27. (T) and (U) *Morozovella formosa formosa* (Bolli), Naqb Assiut, Esna Formation, Sample 30. (V) and (W) *Morozovella lensiformis* (Subbotina), Naqb Assiut, Esna Formation, Sample 30. (X) and (Y) Transitional form between *Morozovella lensiformis* (Subbotina) and *Morozovella aragonensis* (Nuttall), Naqb Assiut, Esna Formation, Sample 38.

foraminifera but containing a few agglutinated benthonic foraminifera of low species diversity (e.g. *Haplophragmoides glabra* and *Ammobaculites subcretaceus*) and rare calcareous benthonic foraminifera (e.g. *Orthokarstenia oveyi*). The Upper Kharga Shale, on the other hand, is an open marine, deeper sub-tidal facies flooded with well-diversified planktonic and benthonic foraminifera. The number of planktonic foraminifera is many times higher than that of benthonic foraminifera (80 to 90%P). The planktonic foraminifera percentage decreases in the middle part of this unit (*ca* 30%P). The most common planktonic foraminifera are *Globanomalina compressa*, *Gl. pseudomenardii*, *Praemurica uncinata*, *Pr. inconstans*, *Morozovella praeangulata*, *M. conicotruncata*, *M. angulata*, *M. velascoensis*, *Igorina albeari*, *Acarinina soldadoensis* and *Ac. mckannai* among others (Table 2, Fig. 8); they belong to the late Danian *Praemurica uncinata* Interval Zone P2 in the lower part of the Upper Kharga Shale, the Selandian *Morozovella angulata* Interval Zone P3 in its middle part and the late Thanetian *Acarinina soldadoensis*/*Globanomalina pseudomenardii* Sub-zone P4c 'lower part' in its upper part. The latter sub-zone extends into the overlying Tarawan Formation. The Selandian Zone P3 in the middle part of the Upper Kharga Shale is further divided into two sub-zones, *Igorina pusilla* Partial-range Sub-zone P3a below and *Igorina albeari* Interval Sub-zone P3b above. The Danian/Selandian boundary occurs at the base of Zone P3 (Fig. 9). Planktonic biostratigraphy provides evidence for the presence of a hiatus near the top of the Kharga Shale Member (Se/ThKh4; Figs 5 and 6), due to the lack of the late Selandian to Thanetian sub-zones P4a-b. Another hiatus is interpreted as being present at the top of the Kharga Shale Member (ThKh5), based on the occurrence of an intensively bioturbated hardground at the contact with the overlying Tarawan Formation.

Facies interpretation

The few agglutinated benthonic foraminifera of low species diversity present in the Lower Kharga Shale, coupled with the rare calcareous benthonic foraminifera, marks deposition in a shallow sub-tidal setting under brackish water conditions and high oxygen depletion. Calcareous benthonic foraminifera are rare because of the high organic content in the environment, as high organic influx tends to develop low pH bottom conditions, which may exclude calcareous taxa or dissolve their tests (Nagy *et al.*, 2001). The diverse, high abundance planktonic foraminifera (80 to 90%) and common, diverse benthonic foraminifera in the Upper Kharga Shale indicate deposition in an open marine regime below effective wave base, up to 200 m water depth. This environment marks the greatest water depth reached during the depositional history of the Dakhla Formation. Deposition is interpreted as having taken place under a warm semi-arid climate, well-oxygenated waters, fair circulation with the open sea, constant high clastic supply, and enhanced upwelling activity. Planktonic foraminifera are interpreted as having their highest abundance in areas with enhanced upwelling of deeper nutrient-rich waters. The diverse fauna abruptly decreases in abundance at the top of the Upper Kharga Shale, denoting deposition in a shallow sub-tidal setting (Figs 5 and 6).

Tarawan Formation – Late Palaeocene

Description

The Tarawan Formation forms the top middle escarpment face of the northern and eastern plateaux surrounding Kharga. It unconformably overlies the Dakhla Formation and conformably underlies the Esna Formation. The lower unconformable contact is marked by a zone of large *Thalassinoides* burrows that extend down from the contact 40 to 60 cm (ThKh5, Figs 5 and 6). The burrows, filled with the overlying chalky limestone, are 15 to 35 cm in length and 2 to 3 cm in width (Fig. 4F and G). The Tarawan Formation is made up of massive to thick-bedded chalky and argillaceous limestone. The limestone is snow white, moderately hard and fossiliferous with high diversity, well-preserved planktonic and benthonic foraminifera. It contains the characteristic *Echinocorys fakhri*. Southwards, the formation is replaced by the upper part of the Garra Formation south of Kharga (Fig. 3). The most common planktonic species of the Tarawan Formation are *Morozovella velascoensis*, *M. acuta*, *Acarinina soldadoensis*, *Ac. primitiva*, *Ac. mckannai*, *Subbotina velascoensis* and *Globanomalina pseudomenardii* (Table 2). These species are indicative of the upper part of the late Thanetian *Acarinina soldadoensis*/*Globanomalina pseudomenardii* Sub-zone P4c. The Dakhla/Tarawan formational boundary is located within Sub-zone P4c. The planktonic foraminifera increase in abundance upwards, indicating increased productivity towards the latest Palaeocene. This observation is consistent with the interpretation that upwelling in Egypt gradually intensified during the latest

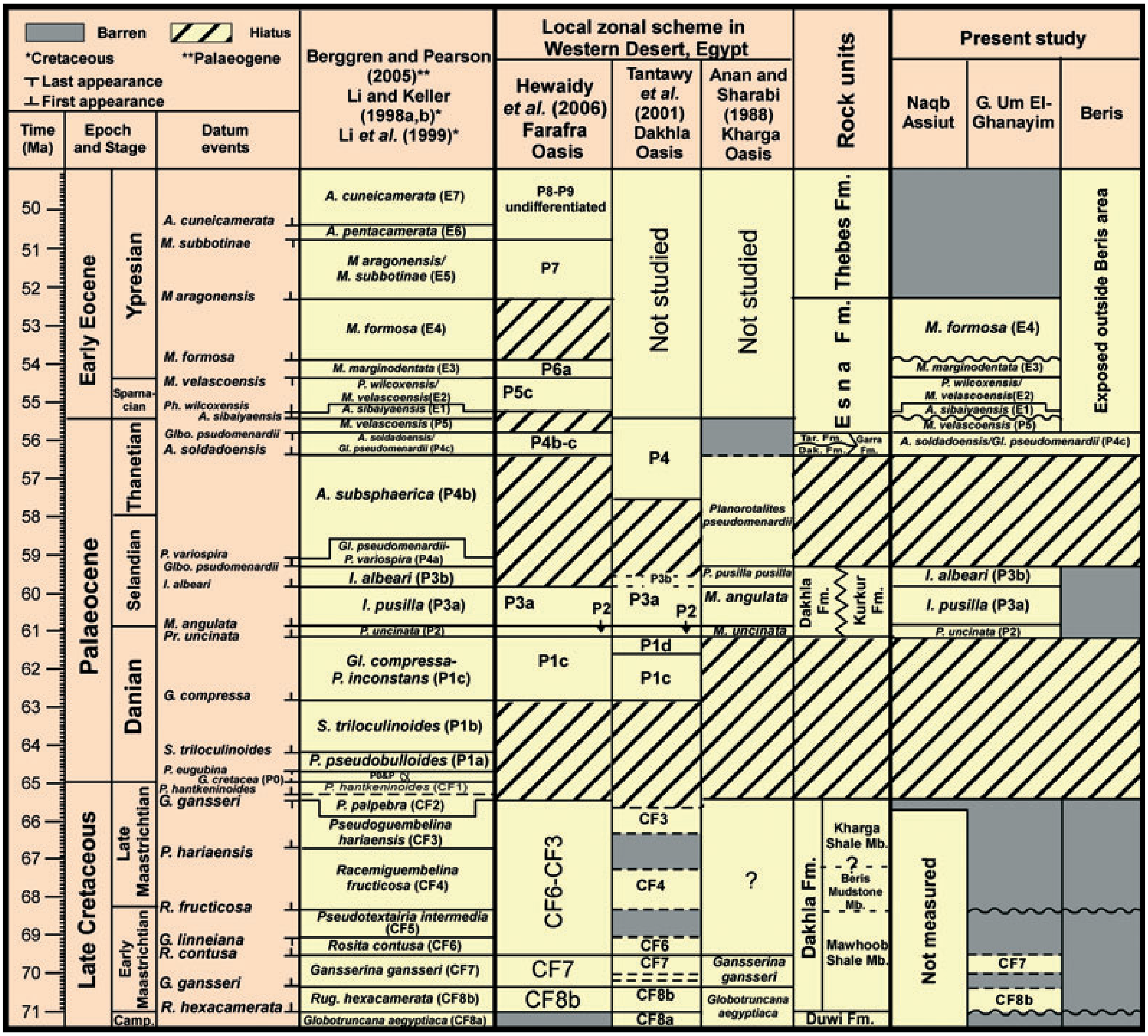

Fig. 9. The Maastrichtian-Ypresian planktonic foraminiferal zones identified along the eastern scarp face of the Kharga Oasis and their equivalents proposed in the nearby areas. The age estimates and datum events are based on the standard planktonic foraminifera zonal schemes of Li & Keller (1998a,b) and Li *et al.* (1999) for the Late Cretaceous and on the scheme of Berggren & Pearson (2005) for the Palaeocene to Early Eocene.

Palaeocene after an Early Palaeocene low productivity phase (Speijer *et al.*, 1996).

Facies interpretation

The limestone of the Tarawan Formation is dominated by foraminiferal wackestone/packstone and packstone (Figs 4H, 5 and 6). These facies are indicative of open marine, deep water environments of a shallow middle to outer shelf setting, as evident from the diversity and high abundance of planktonic foraminifera (high P/B ratios with up to 90%P values), with common benthonic foraminifera; they are interpreted as having been deposited during a rapid sea-level rise attributed to low clastic input, which allowed calcareous foraminifera to flourish. Deposition took place in a subsiding basin under prevailing high-productivity conditions of warm waters, normal salinity, high oxygenation, high nutrient supply and open marine circulation.

Esna Formation – latest Palaeocene to Early Eocene

Description

The Esna Formation forms the upper escarpment face of the northern and north-eastern plateaux surrounding the Kharga Oasis (Fig. 2). It conformably overlies and underlies the Tarawan and Thebes Formations, respectively. The lower contact marks a lithological change from limestone below to shale above (Fig. 10A). The upper contact is gradational and is interpreted as occurring at the first appearance of a thick limestone enriched in larger foraminifera. The formation consists of grey shale with argillaceous limestone in its lower part (Figs 5 and 6). The shale facies yields common to abundant highly diversified planktonic species such as *Acarinina sibaiyaensis*, *Ac. africana*, *Ac. angulosa*, *Pseudohastigerina wilcoxensis*, *Morozovella velascoensis*, *M. subbotinae*, *M. allisonensis*, *M. occlusa*, *M. formosa*, *Subbotina linaperta*, *S. velascoensis* and *S. triangularis* (Table 2, Fig. 8). Some intervals contain shale extremely enriched in planktonic foraminifera with percentages ranging from 80 to 90%. In addition, moderately well-preserved and highly diverse benthonic foraminifera of a typical neritic Midway-type (*sensu* Berggren & Aubert, 1975) are also present. Planktonic enrichment exhibits a sharp drop in abundance and diversity in the upper part of the Esna Formation. The recorded planktonic foraminifera are representative of five biostratigraphic zones that span a time interval from latest Thanetian to Ypresian. These zones are: (i) latest Thanetian *Morozovella velascoensis* Zone P5 and (ii) earliest Sparnacian *Acarinina sibaiyaensis* Lowest-occurrence Zone E1, both in the lower part of the formation; (iii) earliest/late Sparnacian *Pseudohastigerina wilcoxensis/Morozovella velascoensis* Zone E2 and (iv) latest Sparnacian-early Ypresian *Morozovella marginodentata* Partial-range Zone E3, both in the middle part of the formation; and (v) early Ypresian *Morozovella formosa* Lowest-occurrence Zone E4 in its upper part (Fig. 9). Thus, the Palaeocene/Eocene (P/E) boundary occurs in the lower part of the formation at the lowest occurrence of *Acarinina sibaiyaensis* (base of Zone E1). This boundary lies 8 to 10 m above the base of the Esna Formation.

The base of the Eocene sediments is marked by a dark grey, non-calcareous, organic-rich shale, 20 cm thick, that contrasts with the subjacent light grey calcareous shale of the basal part of the Esna Formation. It marks a major faunal anomaly where the Palaeocene benthonic foraminifera suffered a notable extinction along the P/E boundary (Benthonic Foraminiferal Extinction Event). Thus, the base of the dark grey shale closely coincides with the global P/E warming event; the Palaeocene/Eocene Thermal Maximum (PETM) and the concomitant Carbon Isotope Excursion (CIE) interval. This shale is marked by regional dysoxia marked by the presence of a phosphatic, coprolite-rich layer with abundant fish remains in the outer shelf deposits of north-east Egypt (Speijer, 1994). In addition to the abrupt extinction of benthonic foraminifera, the planktonic foraminifera disappear temporarily within the dark grey shale and only reappear in the overlying 20 cm thick, phosphate-bearing shale bed, where excursion fauna of *Acarinina sibaiyaensis* and *Ac. africana* are recorded. Thus, the top of dark grey shale marks the level of the first appearance of the Planktonic Foraminiferal Excursion Taxa (PFET) that reflects a transient diversification during the PETM (Kelly *et al.*, 1996). The phosphate-bearing bed is, in turn, overlain by 2·5 m of a limestone that is enriched in planktonic species. The benthonic taxa reappear *ca* 2 m above the base of this limestone, whereas its top marks the top of the PETM interval. These beds (*ca* 3 m thick) that contain the CIE/PETM stratigraphic interval belong to Zone E1; this suggests that the north-eastern escarpment of Kharga has a complete biostratigraphic zonation along the P/E boundary similar to that detected in the Dababiya Quarry Beds (DQB) at Dababiya Quarry, south of Luxor, Egypt, which is the Global Standard Stratotype-section and Point (GSSP) of the P/E boundary (Dupuis *et al.*, 2003). The latter subdivided the Esna Formation in Dababiya Quarry into three informal units: a lower shale unit (Unit Esna 1) about 6 m thick, a middle clay unit (Unit Esna 2) about 70 m thick, and an upper unit of intercalated marl and limestone (Unit Esna 3) about 45 m thick overlain by the Thebes Formation. The DQB constitutes the lower part of Unit Esna 2 and their base defines the P/E boundary (Aubry *et al.*, 2002). Aubry *et al.* (2007) elevated the DQB to a higher stratigraphic rank as the Dababiya Quarry Member; these authors also renamed Units Esna 1, 2 and 3 of Dupuis *et al.* (2003) as the El-Hanadi, El-Mahmiya and Abu Had members, respectively. This subdivision can be applied successfully to the Nile Valley facies of the Kharga Oasis (Fig. 10A), with the only reservation being that the Abu Had Member, as previously defined by Abdel Razik (1972), is a part of the Thebes Formation, forming its lower intervening shale and limestone. This concept is followed in the present work.

Facies interpretation

The Esna Formation is interpreted as having formed in wide depositional regimes grading from deep inner to outer shelf. Relying on facies characteristics and frequency of associated fauna, the formation is grouped into three depositional regimes: deep middle/outer shelf, shallow middle shelf and deep inner shelf (Figs 5 and 6). The deep middle/outer shelf is marked by the prevalence of well-preserved, high diversity deep open marine planktonic species (70 to 90%), in addition to a moderate occurrence of Midway benthonic foraminifera of typical neritic water depths. This environment is commonly marked by enhanced upwelling, which is important for planktonic foraminifera as it brings nutrient-rich bottom water to the photo-synthetic zone. A shallow middle shelf regime is interpreted for beds characterized by moderately abundant foraminifera, with planktonic foraminifera values declining from 90 to 50% and moderate benthonic foraminifera diversity. The deep inner shelf regime is marked by low to moderate foraminiferal content and diversity with a distinct drop in P/B values to 20 to 30% planktonic foraminifera. Generally, these depositional regimes were bathed in warm, well-aerated waters of normal marine salinity and open sea circulation.

Thebes Formation – Early to late Early Eocene

Description

The Thebes Formation forms the upper escarpment face and plateau surface surrounding the northern and north-eastern parts of the Kharga Oasis (Figs 2 and 10B). It overlies the Esna Formation with a gradational contact, while the contact with the overlying rocks is not reached along the Kharga escarpment face. The formation consists of limestone, with shale and chert interbeds in the lower part (Figs 5 and 6). Some authors have assigned the lower interbedded limestone and shale to the subjacent Esna Formation (Berggren & Ouda, 2003, Unit Esna 3; Aubry *et al.*, 2007, Abu Had Member); however, the faunal content of these limestones and shales and their interpreted depositional environments justify their inclusion in the Thebes Formation. The limestone is thick-bedded and argillaceous, partly chalky. It grades upwards from interbeds of limestone in shale that become thicker, more closely spaced and more indurated upwards until they grade into pure bedded limestone (Figs 5 and 6). The formation is highly karstified near its top part (Fig. 10C). It is barren of planktonic foraminifera, but holds abundant, low diversity larger foraminifera (e.g. Nummulites, Alveolina and Assilina) together with bivalves and echinoids. The Thebes Formation is dated as early-latest Ypresian based on its stratigraphic setting and biostratigraphic correlation with adjacent areas (Zones P7 to P9, Krasheninnikov & Ponikarov, 1964; Said, 1990; Berggren & Ouda, 2003). This zonal interval is redefined now as Zones E5 to E7 in the zonal scheme of Berggren & Pearson (2005).

Facies interpretation

The Thebes limestone is dominated by three facies: nummulitic bioclastic wackestone, nummulitic wackestone/packstone and nummulitic bioclastic foraminiferal packstone (Fig. 10D and E). Facies characteristics and faunal content reflect cyclic deposition during minor sea-level fluctuations from lower (wackestone) to upper (wackestone/packstone) shallow sub-tidal settings, which are in accordance with the regressive nature of the Thebes Formation (Figs 5 and 6). These facies have been formed during periods when clastic input ceased, under conditions of warm waters, moderate wave energy, normal salinity, high oxygen content and rather rich organic detritus, optimal conditions for larger foraminiferal development. The prevailing warm, nutrient-rich, normal marine salinity conditions were favourable for the rapid evolution of Nummulites and Alveolinids (Kecskeméti, 1989). The intervening shale in the lower part of the Thebes Formation, dominated by low benthonic foraminifera abundance and diversity, is interpreted as having been deposited in a low-energy, sub-wave base, shallow inner shelf setting under restricted water circulation and in water depths of about 10 m.

GARRA EL-ARBAIN FACIES ASSOCIATION

The Palaeocene to Lower Eocene succession displays a relatively rapid lateral facies change from the deeper water Nile Valley facies association along the north-eastern escarpment face of the Kharga to shallower water facies towards its south-eastern escarpment face and towards the Abu Tartur Plateau in the north-west (Figs 1 and 3). The shallower water facies association was termed the Garra El-Arbain facies (Issawi, 1972). The Garra-Kurkur stretch, south of the studied area, is the type locality of this facies. The strata comprising this facies association are subdivided into the Kurkur, Garra and Dungul Formations, from the base upwards. The Dungul Formation is not addressed in the present study as its outcrop distribution is found on the plateau surface of the Kharga distant from the south-eastern escarpment face.

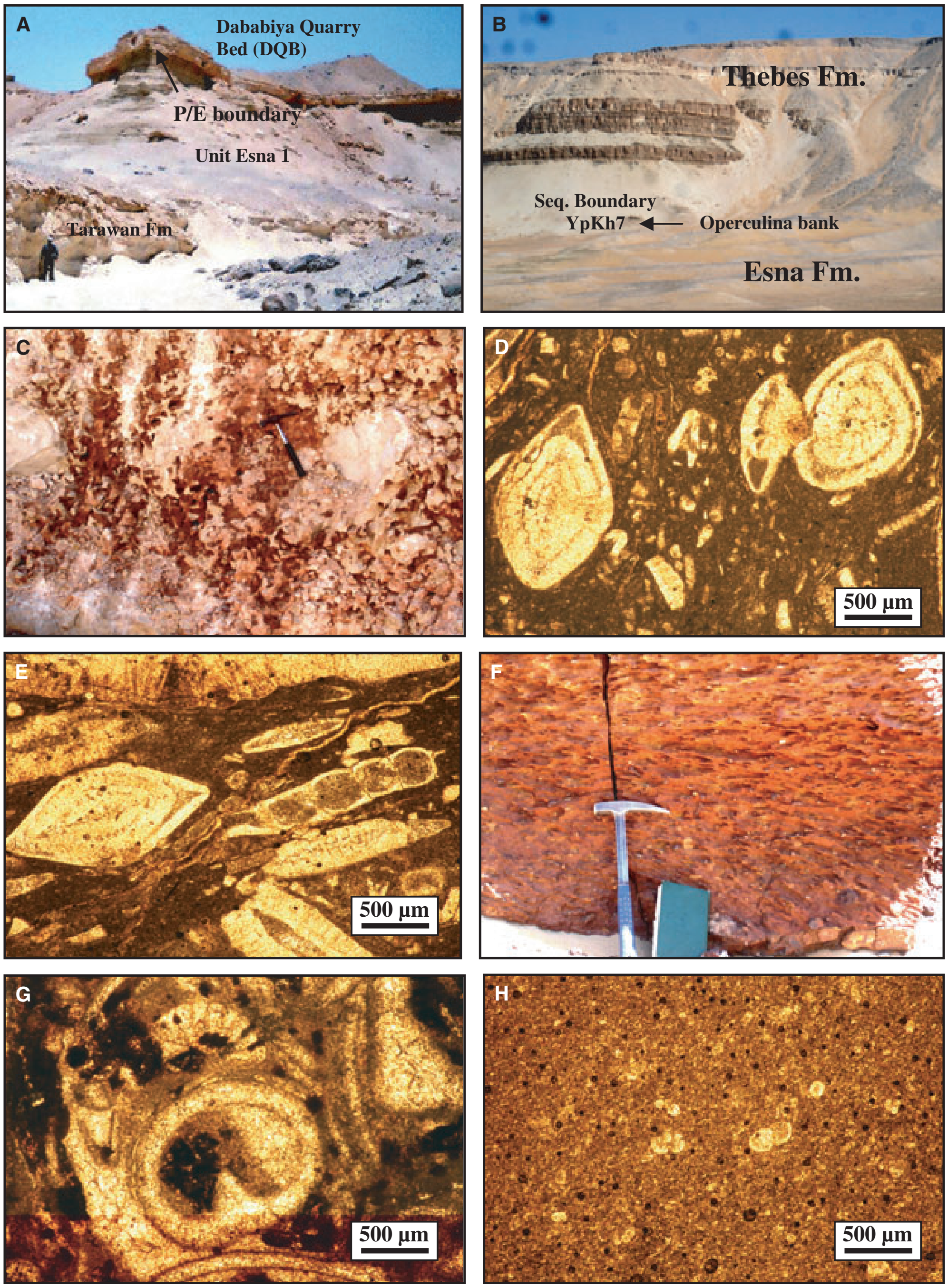

Fig. 10. (A) The concordant contact between the Esna Formation and the underlying Tarawan Formation. Notice the P/E boundary between the lower part of the Esna Formation (Unit Esna 1) and the limestone ledge of Dababiya Quarry Bed, Naqb Assiut. Photograph is looking north-east. Person for scale is *ca* 1.8 m tall. (B) Thebes Formation forming the upper scarp face and plateau surface of the Kharga Oasis along Kharga-Luxor road. Notice sequence boundary YpKh7 at the top of the Operculina bank. The outcrop is 200 m long. Photograph is looking ENE. (C) A distinct karst feature stained with iron oxides present near the top of the Thebes Formation which defines the sequence boundary YpKh8, Kharga-Luxor road. Hammer for scale is 35 cm long. (D) Nummulites and shell debris disseminated in a partially recrystallized lime-mud, Nummulitic wackestone, Thebes Formation Naqb Assiut, Bed 54. (E) Nummulites and other large benthonic foraminifera packed in a dense lime-mud, Nummulitic wackestone/packstone, Thebes Formation, Naqb Assiut, Bed 44. (F) A conglomerate bed with reworked carbonate/chert gravels embedded in a ferruginous clayey matrix which marks the lower unconformable contact of Kurkur Formation, Beris. Hammer for scale is 45 cm long. (G) Badly preserved molluscan debris packed in a ferruginous lime-mud, molluscan bioclastic packstone, Kurkur Formation, Beris, Bed 43. (H) Few foraminiferal tests scattered in a partially recrystallized lime-mud, foraminiferal lime-mudstone, Garra Formation, Baris, Bed 53.

Kurkur Formation – Late early to Early late Palaeocene

Description

The Kurkur Formation has a wide distribution in the southern Western Desert extending from south Kharga though the Garra-Kurkur stretch to Dungul near Aswan. It is introduced as a facies variant to the Palaeocene part of the Dakhla Formation (Issawi, 1972; Luger, 1985; Hendriks *et al.*, 1987). The current study confirms that the formation substitutes for the lower part of the Upper Kharga Shale of Danian/Selandian age. The Kurkur Formation unconformably overlies and underlies the Lower Kharga Shale unit and the Garra Formation, respectively. The lower contact is marked by a 1 m thick conglomerate with gravels embedded in a ferruginous clay-rich matrix, which marks the K/Pg boundary (Fig. 10F). The upper contact is a sharp erosional surface separating very different facies and inferred environments. The Kurkur Formation consists of a 6 m thick, coquinal limestone with shale interbeds (Fig. 7). The limestone is brown, massive and fossiliferous with bivalves and echinoids. The formation is barren of planktonic and benthonic foraminifera which make its proper age assignment difficult. However, its age can be bracketed between the K/Pg boundary and the Thanetian Sub-zone P4c of the overlying Garra Formation. The unconformity at the top of the Kurkur Formation probably represents the missing sub-zones P4a-b, which would imply that the formation spans the interval from the late Danian Zone P2 to the Selandian Zone P3. The time span of the Kurkur Formation actually appears to vary from place to place; it is assigned to the planktonic foraminifera Zone P4 in the Abu Tartur Plateau (El-Deftar *et al.*, 1978), to Zones P2 to P4 in Kharga-Sinn El-Kaddab (Hendriks *et al.*, 1984) and to Zones P3 to P4c in the Garra-Kurkur stretch (Hewaidy, 1994). This discrepancy in ages is probably a consequence of the irregularity in palaeorelief of the Dakhla Basin, as well as a result of the differing interpretations of its lower and upper contacts. Luger (1985) divided this formation into a lower transgressive oyster-bearing unit, a middle regressive sandy unit (together equivalent to Zones P1 to P3), and an upper transgressive calcareous unit (equivalent to Zone P4). Luger identified an unconformity at the top of the second unit. The present authors believe that this hiatus belongs to the upper boundary of the Kurkur Formation, and the overlying upper transgressive unit is more reasonably assigned to the Garra Formation.

Facies interpretation

The limestone of the Kurkur Formation is bioclastic packstone/rudstone (Fig. 10G) which is interpreted as having been deposited in a shallow inner shelf setting under warm, moderate wave energy, normal marine salinity and restricted circulation conditions during periods of low clastic sediment input and high carbonate productivity. The lack of benthonic foraminifera and the dominance of bivalves and echinoids point to a shallow sub-tidal depositional setting. The intervening shale represents a relatively deep sub-tidal facies formed during periods of abundant clastic influx. Deposition took place in quiet water below fair-weather wave base, at water depths of *ca* 10 m.

Garra Formation – Late Palaeocene

Description

The Garra Formation marks the upper part of the south-eastern escarpment face and part of the plateau surface of the Kharga Oasis (Fig. 2). It consists of moderately hard, bedded limestone which holds a low to moderately abundant and diversified planktonic fauna such as *Morozovella acuta*, *M. velascoensis*, *M. angulata*, *Acarinina mckannai*, *Ac. soldadoensis*, *Ac. primitiva* and *Globanomalina pseudomenardii*. This assemblage decreases in abundance and diversity upsection. It belongs to late Thanetian *Acarinina soldadoensis*/*Globanomalina pseudomenardii* Sub-zone P4c. In G. Abu Ghurra, south of Aswan, the upper part and topmost 3 m of the Garra Formation are correlated with Unit Esna 1 and Dababya Quarry Beds, respectively (Berggren *et al.*, 2003). These units contain planktonic foraminifera assigned to latest Thanetian Zone P5 and earliest Sparnacian Zone E1. The exposed part of the Garra Formation, which is 27 m thick in Kharga, probably is equivalent to the Late Palaeocene foraminiferal Zone P4c.

Facies interpretation

The limestone of the Garra Formation consists of foraminiferal lime-mudstone, wackestone and packstone with a variable occurrence of planktonic and benthonic foraminifera (Fig. 10H). These facies are interpreted as having been deposited in a relatively deep marine setting with oscillations from deep inner to shallow middle shelf water depths (Fig. 7). Deposition was associated with a marked, more prolonged, sea-level rise in the late Thanetian interrupted by minor relative sea-level falls in the lower and upper parts of the formation. It took place under conditions of warm water of normal marine salinity and oxygenation, high carbonate productivity, and open marine circulation.

DEPOSITIONAL SEQUENCES AND SEQUENCE BOUNDARIES

The integrated high-resolution sedimentological and biostratigraphic studies carried out along the eastern escarpment face of the Kharga Oasis provide a framework for sequence stratigraphic interpretation of the exposed Maastrichtian-Ypresian succession. The succession is subdivided into seven third-order depositional sequences corresponding to Early Maastrichtian, Late Maastrichtian, late Early to early Late Palaeocene, Late Palaeocene, Late to latest Palaeocene, Sparnacian to early Ypresian and early to late Ypresian. The characteristics of these sequences are listed in Table 3, including stratigraphic intervals, planktonic foraminiferal zones, parasequence stacking patterns and systems tracts. The sequences are bracketed by easily traceable, basin-wide sequence boundaries characterized by sedimentation/faunal hiatuses (e.g. erosional/indurated/karst surfaces, hardgrounds, biozonal breaks) and predominantly abrupt changes in lithological character and P/B ratios across a sharply defined surface. The sequence boundaries are of varied time span denoting either minor or prolonged hiatuses. The timing of the depositional sequences and the extent of their hiatuses as well as their correlative sequences in nearby areas are determined within the resolution of the planktonic foraminiferal biostratigraphy. In the current work, a shorthand notation of the formation names (Dk, T, Es and Th) combined with the sequence number (SQ1, SQ2, etc.) is adopted for ease of communication in local/regional correlations (DkSQ1, T/EsSQ5, etc.). In addition, sequence boundaries are named using an abbreviation of their assigned age along with the name of the studied area (Ca/MaKh1, MaKh2, etc.). Three internal unconformities, marking regional and eustatic sea-level falls, divide the Dakhla Formation into four depositional sequences (DkSQ1 to DkSQ4). These sequences were recorded by El-Azabi & El-Araby (2000) in the west Dakhla-Farafra area in their study of Dakhla Formation facies characteristics and cyclicity. The fifth designated sequence in the Kharga Oasis comprises the Tarawan Formation (with its margin coeval to the upper part of the Garra Formation) and the lower part of the Esna Formation (T/EsSQ5). The sixth depositional sequence marks the middle part of the Esna Formation (EsSQ6), while the seventh sequence invokes the upper part of the Esna Formation and most of the Thebes Formation (Es/ThSQ7).

Each of the studied sequences typically contains a lower retrogradational parasequence set bounded above by a marine-flooding surface and an upper progradational parasequence set bounded above by a sequence boundary. Parasequences within parasequence sets are stacked in distinctive transgressive (landward-stepping) and regressive (seaward-stepping) patterns indicative of transgressive and highstand systems tracts (TST and HST), respectively. These stacking patterns are commonly expressed as deepening-upward (transgressive) and shallowing-upward (regressive) biofacies assemblages, and are accompanied by changes in the sediment grain size, in the type, diversity and frequency of foraminifera, and/or in the P/B ratio. Foraminiferal abundance patterns in terms of P/B ratio are used as a palaeobathymetric indicator for periods of relative sea-level decrease or increase. The retrogradationally stacked parasequence sets were typically deposited under conditions of a rapid relative rise of sea-level and generally exhibit highly diverse foraminifera with high planktonic foraminifera values. These sets are marked by a rapid flooding event and sediment accumulation under conditions of increasing accommodation space. The progradationally stacked parasequence sets are characterized by a major faunal turnover from a high diversity fauna mainly composed of planktonic foraminifera to a lower diversity fauna increasingly dominated by benthonic foraminifera, commonly coupled with only a few species dominating because of increasing environmental stress. This feature denotes deposition under increasingly restricted conditions due to long-term fall of relative sea-level with a decrease in accommodation space. The maximum flooding surfaces (MFS) are typically interpreted at the position marking the maximum P/B value, in combination with lithological and biofacies stacking patterns, distinctive lithologies and other parameters. The defined sequences and their sequence boundaries in the Kharga Oasis are compared with their coeval sections in nearby areas (Lüning *et al.*, 1998; El-Azabi & El-Araby, 2000; Hewaidy *et al.*, 2006), with the eustatic cycle chart of Haq *et al.* (1988), with the Western

European sea-level curve of Hardenbol *et al.* (1998) and with the sea-level curve of Miller *et al.* (2005) recorded on the New Jersey margin to test their consistency with global sea-level changes and regional tectonic influences. A full description of the recognized sequences, including their boundaries, parasequence stacking patterns, nature of other bounding surfaces, environmental changes across these surfaces and systems tracts with the integrated lithofacies and biofacies data, is given below in stratigraphic order.

Sequence 1: Lower Maastrichtian sequence (DkSQ1)

The first depositional sequence in the Kharga Oasis coincides with the Lower Maastrichtian Mawhoob Shale Member of the Dakhla Formation (DkSQ1; Figs 5 and 7). It contains the early Maastrichtian zones CF8b and CF7. A tentative age estimate for this sequence suggests that it spans at least 1·4 Myr (71·0 to 69·6 Ma; Fig. 11), as its upper part lies within a barren interval which could be attributed to Zones CF6 to CF5. Sequence DkSQ1 is defined at the base by sequence boundary Ca/MaKh1, recognized by the presence of a phosphatic bed with reworked phosphate debris and quartz pebbles. This boundary delineates a sedimentation break at the top of the Duwi Formation accompanied by low sedimentation rates, concentration of phosphatic debris and radical environmental change.

The Lower Maastrichtian sequence is 32 m thick. It consists of a retrogradationally stacked parasequence set deposited from shallow inner shelf to shallow middle shelf settings in the lower part (Fig. 5). This parasequence set was deposited during a rapid relative rise of sea-level and is assigned to the TST. No underlying lowstand systems tract has been recognized. In this case, the transgressive surface (TS) at the base of the TST coincides with the sequence boundary Ca/MaKh1. This surface records the onset of the early Maastrichtian marine incursion across the Kharga Oasis. At Gabal Um El-Ghanayim, the base of the transgressive deposits is composed of deep inner shelf shale with planktonic foraminifera indicative of Zone CF8b (Fig. 5), which grades upwards into restricted shallow inner shelf shale, with thin lime-mudstone, in which only agglutinated benthonic foraminifera such as *Ammobaculites* and *Haplophragmoides* are found. This assemblage exhibits low species diversity, coupled with high dominance, indicating deposition under oxygen-depleted bottom conditions. This shale is overlain by shallow middle shelf shale with planktonic foraminifera of Zone CF7. The MFS is placed at the top of the second shale bed enriched in planktonic foraminifera which shows a highly diverse, normal marine character (Fig. 5). This surface marks a period of condensed sedimentation and fossil concentration. Intervals of high microfossil abundance/diversity are normally referred to in sequence stratigraphic interpretation as condensed sections and are associated with the MFS of a sequence (Loutit *et al.*, 1988). At Beris, the MFS is placed at the peak abundance of benthonic foraminifera (10 m from base, Fig. 7) where the relatively deep sub-tidal shale with low diversity benthonic foraminifera below is assigned to the TST. At Gabal Um El-Ghanayim, the transgressive deposits are followed by a progradational parasequence of shallow sub-tidal shale (HST; Fig. 5). These highstand deposits mark the top of the Mawhoob Shale Member (probably zones CF6 to CF5; Fig. 11); they denote an abrupt environmental change from normal marine to restricted conditions as revealed by the sharp decrease in fauna. The benthonic foraminifera are rare, probably as a result of inhospitable conditions owing to oxygen depletion. At Beris, highstand deposits are marked by shale with some agglutinated benthonic foraminifera of very low diversity and dwarf molluscs. These fauna indicate deposition in shallow inner shelf (shallow sub-tidal) palaeowater depths.

Sequence 2: Upper Maastrichtian sequence (DkSQ2)

The second depositional sequence in the Kharga Oasis is made up of the Upper Maastrichtian Beris Mudstone Member and the Upper Maastrichtian part of the overlying Kharga Shale Member (Lower Kharga Shale), both forming the middle part of the Dakhla Formation (DkSQ2; Figs 5 and 7). The exact age dating of this sequence is difficult to determine as its sediment is barren of any diagnostic planktonic foraminifera. The *E. overwegi* Zone that marks the Beris Mudstone Member is characteristic of the late Maastrichtian in the Western Desert. This sequence could be tentatively attributed to late Maastrichtian Zones CF4 to CF3 (Fig. 9), which mark the same stratigraphic interval in the deeper parts of the Dakhla Basin (Tantawy *et al.*, 2001; Hewaidy *et al.*, 2006). It is estimated to span *ca* 2·8 Myr from 68·3 Ma at the base to 65·5 Ma at the top (Zones CF4 to CF3; Fig. 11).

Table 3. Summary of the sequence stratigraphic interpretation of the depositional sequences detected along the eastern scarp face of the Kharga Oasis, southern Western Desert; their timing, marked planktonic foraminiferal zones, systems tracts and parasequence stacking patterns are shown as well as their lithological and environmental characteristics.

Depositional sequences	Stratigraphic interval	Planktonic biozones	Time (Myr)	P/B ratio	Parasequence stacking patterns; their lithological and environmental characteristics	Systems tracts
1. Lower Maastrichtian sequence, DkSQ1 (32-34 m thick)	Mawhoob Shale Mb.	CF8b-CF7	>1.4	Barren with two intervals contain up to 30%P	Retrogradational parasequence set of shallow and deep inner shelf calc. shale with thin lower intertidal lime-mudstone capped by shallow middle shelf shale. Relatively deep subtidal calc. shale in Beris	TST
		Barren		–	Progradational parasequence of shallow subtidal calc. shale	HST
2. Upper Maastrichtian sequence, DkSQ2 (10-41 m thick)	Beris Mudstone Mb.	Barren	–	–	Retrogradational parasequence set of deep subtidal shale with shallow subtidal bioclastic wackestone to floatstone	TST
	Lower Kharga Shale			–	Progradational shallow subtidal calc. shale parasequence set	HST
3. Upper Danian-Selandian DKSQ3 (6-7 m thick)	Upper Kharga Shale (lower part) and its lateral coeval Kurkur Fm.	P2	*ca* 2·0	80–90%, very low in Beris	Retrogradational parasequence of outer shelf pelagic shale replaced by shallow subtidal coquinal limestone and deep subtidal calc. shale in Beris	TST
		P3		*ca* 30%, nil in the south	Progradational parasequence of shallow middle shelf calc. shale change to shallow subtidal packstone/rudstone in Beris	HST
4. Upper Thanetian sequence DkSQ4 (3-7 m thick)	Upper Kharga Shale (upper part) and its lateral coeval lower part of Garra Fm.	P4c (lower part)	–	*ca* 90%	Retrogradational parasequence of outer shelf pelagic shale change to shallow middle shelf packstone in the south	TST
				20–30%	Progradational parasequence of shallow subtidal shale change to deep inner shelf wackestone in the south	HST

Table 3. (Continued)

Depositional sequences	Stratigraphic interval	Planktonic biozones	Time (Myr)	P/B ratio	Parasequence stacking patterns; their lithological and environmental characteristics	Systems tracts
5. Upper-uppermost Thanetian sequence T/EsSQ5 (19-33 m thick)	Tarawan Fm. and its lateral coeval Garra Fm. (upper part), and lower part of Esna Fm. (Unit Esna 1)	P4c (upper part)-P5	>0·4	40–90%	Retrogradational parasequences of shallow middle/outer shelf foram. wackestone/packstone and shale change to shallow middle shelf foram. packstone in Beris	TST
				10–40%	Progradational shallow middle shelf calc. shale parasequences change to deep inner shelf lime-mudstone in Beris	HST
6. Sparnacian-lower Ypresian sequence EsSQ5 (14-17 m thick)	Middle part of Esna Fm. (Unit Esna 2)	E1–E3	1·5	90%	Retrogradational outer shelf pelagic shale parasequence set	TST
				20–30%	Progradational deep inner shelf calc. shale parasequence set	HST
7. Lower-Upper Ypresian sequence Es/ThSQ7 (69-73 m thick)	Upper part of Esna Fm. (Unit Esna 3) and Thebes Fm.	E4-E5 and long barren interval	>3·2	10–90%	Retrogradational parasequences of deep middle to outer shelf pelagic shale	TST
				Barren to few planktonic species	Aggradational parasequence set of shallow to deep subtidal limestone/shale with shallow middle-deep inner shelf shale at the base in Naqb Assiut	HST

TST, transgressive systems tract; HST, highstand systems tract.

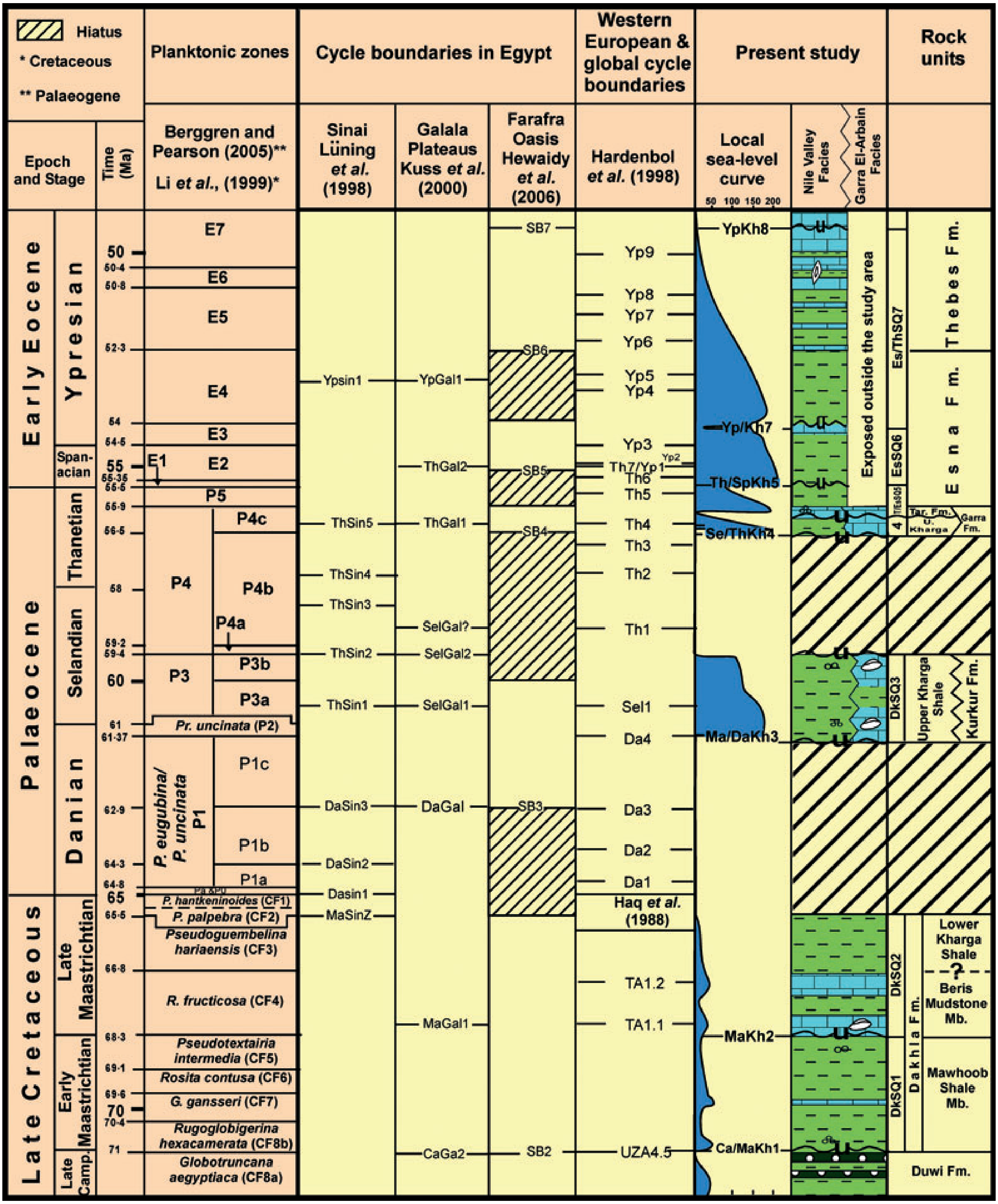

Fig. 11. Summary of the currently used planktonic foraminiferal zonal schemes and age estimates of the detected hiatuses, barren intervals and biozones along the eastern scarp face of the Kharga Oasis and their correlation with the cycle boundaries in the Western Desert, Eastern Desert and Sinai as well as the European (Hardenbol *et al.*, 1998) and global (Haq *et al.*, 1988) cycle boundaries with local sea-level curve. Comparisons of cycle boundaries are based on absolute ages.

Sequence DkSQ2 is delineated at the base by sequence boundary MaKh2 represented by a highly oxidized and intensively bioturbated hardground with reworked ferruginous clasts (Figs 5 and 7). It separates the Beris Mudstone Member from the underlying Mawhoob Shale Member (Fig. 4C and D). This boundary is a sub-marine erosional surface indicating a short-lived break in sedimentation coupled with a relative sea-level drop at the top of the early Maastrichtian. This sea-level drop may have caused a lowering of wave base or have been associated with more frequent storm-generated bottom currents capable of winnowing and/or eroding the top sediments of sequence DkSQ1.

The Upper Maastrichtian sequence has a thickness varying from 10 to 41 m (Figs 5 and 7). This thickness variation probably is linked to basin irregularity, varied rate of sediment supply and intensity of the subsequent erosion. This sequence starts with relatively deep sub-tidal shale interbedded with shallow sub-tidal bioclastic wackestone/floatstone that forms the Beris Mudstone Member. These sediments are stacked in a retrogradational parasequence pattern that is interpreted as a TST. Thus, the lower limit of sequence DkSQ2 is an amalgamated surface consisting of the sequence boundary MaKh2 and the TS denoting the base of the TST (Figs 5 and 7). This surface marks the beginning of a more rapid sea-level advance over the shelf. The transgressive deposits are marked by high dominance and low diversity agglutinated benthonic foraminifera and large oysters (Table 2). These benthonic foraminifera are dominated by *Haplophragmoides* and *Ammobaculites* typical of a shallow-water regime. The MFS is located at the top of the Beris Mudstone Member coincident with benthonic foraminiferal abundance maxima. It is overlain by a progradational shallow sub-tidal shale parasequence set, which yields a sparse low diversity assemblage of agglutinated benthonic foraminifera. This set is assigned to the HST; this denotes a seaward shift in facies and a decrease in accommodation which culminated with a complete emergence at the top of the progradational set. This restricted marine facies forms the Lower Kharga Shale unit of the Kharga Shale Member. It confirms that the relative deepening of the depositional regime that occurred in the Beris Mudstone Member was followed by a significant drop in relative sea-level accompanied by a high level of environmental stress in the Lower Kharga Shale.

Sequence 3: Upper Danian-Selandian sequence (DkSQ3)

The third depositional sequence in the Kharga Oasis is attributed to the late Early to early Late Palaeocene portion of the Kharga Shale Member (i.e. the lower part of the Upper Kharga Shale) and its lateral correlative the Kurkur Formation (DkSQ3; Figs 5 to 7). This sequence spans the late Danian Zone P2 (61·37 to 61·0 Ma) and the Selandian Zone P3 (61·0 to 59·4 Ma), with an estimated duration of *ca* 2 Myr (Fig. 11).

Sequence DkSQ3 is marked at the base by the basin-wide K/Pg boundary with the mass extinction of the Cretaceous tropical/sub-tropical planktonic foraminifera (Ma/DaKh3; Figs 5 and 7). It records a major hiatus that spans *ca* 4 Myr due to a lack of the latest Maastrichtian Zones CF2 to CF1 and early to late Danian Zones P0 to P1 (65·5 to 61·37 Ma; Fig. 11). This boundary is marked by a phosphatic conglomerate, 20 to 30 cm thick, carrying a crushed and reworked late Maastrichtian fauna at the middle of the Kharga Shale Member; sometimes littered with an intensive burrowing. At Beris, the sequence boundary is marked by a 1 m thick conglomerate with carbonate and chert gravels embedded in a clayey matrix (Fig. 10F). This bed overlies an undulating erosive surface that truncates the underlying Lower Kharga Shale.

The Upper Danian-Selandian sequence is 6 to 7 m thick and was deposited between 59·4 and 61·37 Ma at a slow sedimentation rate of 3·5 m Myr^{-1}. The reduced thickness of this sequence is most likely to be explained by the low clastic flux accompanied by its brief duration of *ca* 2 Myr. Conglomerate at the base of sequence DkSQ3 is interpreted as a basal transgressive lag, which preceded a rapid relative rise of sea-level. It is overlain by a back-stepping parasequence set composed of outer shelf pelagic shale that denotes the TST (Figs 5 and 6). The TS at the base of these transgressive deposits reflects the initial advance of the Early Palaeocene transgression across the Kharga Oasis with the resultant deepening of the depositional basin. These deposits show high planktonic foraminifera values (*ca* 90%) with good preservation and a marked increase in *Praemurica* and *Parasubbotina* sp. maintaining deposition in normal marine salinity and oxygenation with open sea circulation. The planktonic enrichments are attributed to the condensed sedimentation associated with the maximum extent of the marine incursion. The MFS matches with the contact between Zone P2 and Zone P3. It is coincident with the maximum abundance of planktonic foraminifera and marks a change from deepening-upward to shallowing-upward biofacies deposits. Thus, these transgressive deposits are dated to late Danian Zone P2. At Beris, the transgressive deposits are replaced by a retrogradational parasequence set of shallow sub-tidal limestone capped by deep sub-tidal shale of the Kurkur Formation (Fig. 7). These deposits exhibit a 1 m thick, fluvial conglomerate at the base which is interpreted as an incised valley fill of lowstand wedge strata deposited during a slow relative rise of sea-level. This fluvial facies would be expected to extend landward (i.e. southward) towards the basin margin into a fluvial-channel system that fed the basin during the relative fall in sea-level and succeeding relative rise. The basinal equivalent of the inner shelf limestone/shale facies of the Kurkur Formation (i.e. the lower part of the Upper Kharga Shale) suggests deposition in water depths of 150 to 200 m as inferred from the planktonic foraminifera enrichment. The interpreted overlying HST consists of a progradational parasequence set of shallow sub-tidal packstone/rudstone (Fig. 7). At Gabal Um El-Ghanayim and Naqb Assiut, the transgressive deposits are succeeded by a progradational parasequence set of shallow middle shelf shale (HST; Figs 5 and 6). These highstand deposits display a drop in planktonic foraminifera percentage (*ca* 30%) coupled with an increase in benthonic species denoting a slow relative rise of sea-level. During this regressive phase the foraminifera retain their normal marine and well-oxygenated character, in accordance with a direct connection to the open sea. With regard to age, the highstand deposits are referred to the Selandian Zone P3.

Sequence 4: Upper Thanetian sequence (DkSQ4)

The fourth depositional sequence in the Kharga Oasis includes the Late Palaeocene part of the Kharga Shale Member (i.e. the upper part of the Upper Kharga Shale) and its lateral equivalent the lower part of the Garra Formation (DkSQ4; Figs 5 to 7). This sequence is assigned to the lower part of the late Thanetian Sub-zone P4c. The precise age estimate of this sequence is difficult to determine as its delineating upper boundary lies within Sub-zone P4c.

Sequence DkSQ4 is defined at its base by sequence boundary Se/ThKh4, which is interpreted as a hiatus due to the absence of the late Selandian to Thanetian sub-zones P4a-b. This break is traceable near the top of the Kharga Shale Member, in its Upper Kharga Shale (Figs 5 to 7), and spans *ca* 3 Myr (59·4 to 56·5 Ma). The material evidence for the hiatus is primarily palaeontological owing to lithological homogeneity across the break. At Beris, this hiatus is marked by an unconformity between the Kurkur and Garra Formations. This unconformity is an irregular erosional surface coincident with a sudden faunal turnover which reflects the onset of a marine incursion. An unconformity surface is also developed at the Kurkur/Garra contact in Darb El-Arbain (Issawi, 1971).

The Upper Thanetian sequence varies in thickness from 3 to 7 m. It contains two stacked parasequence sets separated by a major marine-flooding surface. These parasequence sets represent the lower transgressive and upper regressive deposits of the TST and HST, respectively (DkSQ4; Figs 5 and 6). The transgressive deposits display a retrogradational parasequence stacking pattern of outer shelf pelagic shale that formed during a short period of rapid relative sea-level rise; they exhibit a high dominance of planktonic foraminifera with values of *ca* 90% and more diversified Morozovellids. The MFS is set at the top of the transgressive deposits as indicated by faunal abundance, which shows distinct maxima. The overlying regressive deposits, comprising the top of the Dakhla Formation, consist of a progradational shallow sub-tidal shale parasequence set which exhibits a clear drop in P/B values from 90% to 20%P with a general decrease in faunal diversity; this denotes a sharp drop in relative sea-level from *ca* 200 m in the transgressive deposits to a water depth of a few metres. At Beris, the lower transgressive deposits are substituted by retrogradational shallow middle shelf packstone facies of the Garra Formation (Fig. 7). These facies exhibit moderately abundant planktonic foraminifera with relatively highly diversified benthonic species. These facies are overlain by a progradational deep inner shelf wackestone with low planktonic values and diversity of the upper regressive deposits. The boundary between the lower transgressive and upper regressive deposits defines the MFS and dates the maximum rate of relative sea-level rise and peak abundance of foraminifera.

Sequence 5: Upper-Uppermost Thanetian sequence (T/EsSQ5)

The fifth depositional sequence in the Kharga Oasis constitutes the entire Upper Thanetian

Tarawan Formation (with its time correlative, the upper part of the Garra Formation) and the lower part of the Esna Formation of latest Palaeocene age (T/EsSQ5; Figs 5 to 7). This sequence comprises the upper part of the late Thanetian Sub-zone P4c and the latest Thanetian Zone P5.

Sequence T/EsSQ5 is delimited at its base by sequence boundary ThKh5 which is a minor hiatus marked by a pervasive bored hardground with *Thalassinoides*. These burrows extend 60 cm into the subjacent shale from a semi-lithified marine firmground surface (Fig. 4F and G) and support a minor sedimentation break within the late Thanetian Sub-zone P4c. This hiatus has a limited time span, denoting a lack of parts of Sub-zone P4 only. It marks a drastic facies and environmental change from regressive shale below to transgressive chalky limestone above. East of Bulaq, along the middle part of the eastern escarpment face of Kharga, this boundary is marked by a thin conglomerate at the Dakhla/Tarawan contact with limestone clasts embedded in a clay-rich matrix. In Beris, the boundary ThKh5 is marked by a change in parasequence stacking patterns from progradational deep inner shelf wackestone below to retrogradational shallow middle shelf foraminiferal packstone above (Fig. 7).

The thickness of the Upper-Uppermost Thanetian sequence ranges from 19 to 33 m. It initiates in retrogradationally stacked parasequences of shallow middle to outer shelf foraminiferal wackestone/packstone and shale of the TST (Figs 5 and 6). The boundary ThKh5 at the base is then an unconformity that coincides with the TS. These deposits exhibit diversified and abundant foraminifera with 70 to 90% planktonic and benthonic foraminifera of shallow/deep Midway-type, suggesting deposition in 50 to 200 m water depth. Species common to Velasco-type fauna (*sensu* Berggren & Aubert, 1975) of more than 200 m water depth are rare. Foraminiferal abundance and P/B ratio, which cyclically increase upwards, are interpreted as an indicator of periods of relative deepening and shallowing in water depth corresponding to higher frequency relative sea-level cycles superimposed on the continuous advance of the marine transgression. The MFS is documented in the lower part of the Esna Formation (4 to 5 m from its base) and coincides with the greatest abundance of planktonic foraminifera. Its age is latest Thanetian, belonging to Zone P5. At Beris, the MFS is characterized by a major faunal turnover from high diversity planktonic foraminifera to low diversity benthonic foraminifera, which reflects the onset of a marked relative sea-level fall. The MFS separates a retrogradational shallow middle shelf packstone below from a progradational deep inner shelf lime-mudstone above, both within the Garra Formation (Fig. 7). At Gabal Um El-Ghanayim and Naqb Assiut, the MFS is overlain by a highstand progradational parasequence set made up of shallow middle shelf shale (HST; Figs 5 and 6). Faunal analysis suggests that only a minor (perhaps 10 to 20 m) sea-level change occurred during deposition of this shale prior to the P/E boundary. A similar observation was made at G. Aweina in the Nile Valley, where relative sea-level changes were of low magnitude across the P/E boundary (Speijer *et al.*, 1996).

Sequence 6: Sparnacian-Lower Ypresian sequence (EsSQ6)

The sixth depositional sequence in Kharga marks the middle part of the Esna Formation of Sparnacian-early Ypresian age (EsSQ6; Figs 5 and 6). It represents the Early Eocene Zones E1 to E3 that extend from *ca* 55·5 Ma in the early Sparnacian (base Zone E1) to *ca* 54·0 Ma in the early Ypresian (top Zone E3; Fig. 11).

The base of sequence EsSQ6 is interpreted as a short-term hiatus, defined by a slightly bioturbated bedset, 20 cm thick, containing reworked pebbles, red colouration and an irregular upper surface. This interpreted hiatus is located near the base of the Esna Formation in Naqb Assiut and suggests a period of non-deposition at the P5/E1 zonal boundary (Th/SpKh6; Fig. 6). An irregular surface with pebbles and bioturbation is also observed at the P/E boundary in Naqb Assiut (Obaidalla *et al.*, 2008). A correlative conformable contact with no biozonal break marks the P/E boundary at Gabal Um El-Ghanayim. Correlative conformities are common in deep marine localities with ongoing pelagic sedimentation (Van Wagoner *et al.*, 1988). This conformable contact is overlain by a thin, barren shale interval at the base of Zone E1 which is interpreted as being indicative of low oxygen conditions above the P/E contact. The absence of foraminifera in this interval is interpreted as being related to the well-established global elevated water temperatures at the P/E boundary, coupled with an abrupt extinction of benthonic foraminifera. A similar conformable relationship is indicated at the P/E boundary in the deep marine facies of the Palmyrides and Anti-Lebanon, Syria (El-Azabi & Yzbek, 2000).

The 14 to 17 m thick Sparnacian to Lower Ypresian sequence (Figs 5 and 6) was deposited during *ca* 1·5 Myr, at a sedimentation rate of 9·3 m Myr^{-1} in Gabal Um El-Ghanayim and 11·3 m Myr^{-1} in Naqb Assiut. The sequence contains a basal TST consisting of retrogradational deep marine pelagic shale deposited in an outer shelf water depth (*ca* 150 to 200 m) during a rapid relative rise of sea-level. These deposits are characterized by abundant, highly diversified and well-preserved planktonic foraminifera and sparse benthonic foraminifera. These transgressive deposits, which overlie the thin basal Zone E1 barren shale bed, yield the deepest facies interpreted within the Kharga Palaeogene succession. The MFS of sequence EsSQ6 coincides with the top of the pelagic shale where the bathymetrically deepest interval, containing the maximum frequency of planktonic foraminifera, is located at *ca* 10 to 12 m above the base (Figs 5 and 6). The age of the MFS is early Ypresian, apparently corresponding to Zone E3, and is apparently correlative with the MFS described by Hewaidy *et al.* (2006) from the lower part of the Esna and Ain Dalla Formations in El Quss Abu Said and Shakhs El-Obeiyid, respectively. The transgressive deposits grade upwards into a progradational HST composed of a deep inner shelf shale parasequence set exhibiting a pronounced drop in the P/B ratio, induced largely by an increase in the benthonic foraminiferal assemblage (Figs 5 and 6). The planktonic foraminifera percentages decrease from as much as 90% to 30% or 20%.

Sequence 7: Lower-Upper Ypresian sequence (Es/ThSQ7)

The uppermost depositional sequence in the Kharga Oasis is developed within the upper part of the Esna Formation and the overlying Thebes Formation, both of Early to late Early Eocene age (Es/ThSQ7; Figs 5 and 6). This sequence comprises the early Ypresian Zone E4 in addition to a long barren interval belonging to the Thebes Formation, which is dated to the early-latest Ypresian Zones P7 to P9 (now E5 to E7, *sensu* Berggren & Pearson, 2005) in nearby areas (Krasheninnikov & Ponikarov, 1964; Said, 1990; Berggren & Ouda, 2003). A tentative, minimal estimate for the duration of sequence Es/ThSQ7 is at least 1·7 Myr (Zone E4: 54·0 to 52·3 Ma; Fig. 11) as its upper sediments are barren of planktonic foraminifera.

Sequence boundary YpKh7, which delineates the lower limit of sequence Es/ThSQ7, is a minor hiatus marked by a well-indurated calcareous marl bed at the top middle part of the Esna Formation (Figs 5 and 6). The early, sub-marine cementation of this bed denotes a period of reduced sedimentation/non-deposition interpreted as being caused by a short-term, relative sea-level fall in the early Ypresian. Along the Kharga-Luxor road, this hiatus is represented by a conglomerate at the top of an Operculina bank containing pebbles and small boulders (Fig. 10B). The upper limit of sequence Es/ThSQ7, sequence boundary YpKh8, is a minor hiatus marked by the presence of a microkarst surface stained with iron oxides near the top of the Thebes Formation (YpKh8; Figs 5, 6 and 10C). This surface documents the occurrence of sub-aerial exposure and pedogenesis prior to deposition of the overlying sediments.

The Lower-Upper Ypresian sequence has a thickness ranging from 69 to 73 m (Figs 5 and 6). At its base it contains a retrogradational parasequence set of deep middle/outer shelf pelagic shale that records a rapid transgressive event and sediment accumulation. At Gabal Um El-Ghanayim, the MFS at the top of this TST lies near the Esna/Thebes contact (Fig. 5). It is dated as topmost, or immediately below the top, early Ypresian Zone E4. At this level, a sharp facies change occurs from shale to the overlying limestone-dominated rocks that mark the highstand deposits. The change from transgressive shale facies to limestone-dominated facies is attributed to reduced clastic sediment influx and shoaling related to a relative stillstand and fall of sea-level. The clastic sediment influx at the depositional site completely ceased in the upper part of the Thebes Formation. The highstand deposits consist of interbedded shallow to relatively deep subtidal limestone/shale parasequences stacked in an aggradational pattern; they make up the entire succession of the Thebes Formation. These shallow inner shelf deposits, enriched in larger benthonic foraminifera, correspond to the final regression in the Kharga Oasis area prior to long-term sub-aerial exposure. The regressive deposits developed on a northerly prograding, moderate-energy carbonate shelf. In Naqb Assiut, the MFS is defined at *ca* 11 m below the Esna/Thebes contact as indicated by the faunal dominance, which shows a distinct maximum (Fig. 6). This MFS corresponds to a flooding surface occurring in the middle part of the Esna Formation at El Quss Abu Said and Ain Maqfi (Hewaidy *et al.*, 2006). The interval from the MFS to the Esna/Thebes contact in Naqb Assiut exhibits an overall upward-shallowing tendency from shallow middle to deep inner shelf shale with stepwise progradation (interpreted as early HST). The P/B ratio decreases gradually upwards, indicating a period of gradual shallowing and progressively decreasing water depth with the continuous retreat of the Eocene Sea; this is followed by shale-limestone parasequences which stack vertically into an aggradational parasequence set (interpreted as late HST). These deposits contain abundant larger benthonic foraminifera with species indicative of shallow water habitats such as Nummulites and Alveolines.

DISCUSSION

Local, regional and global comparisons

The lowermost sequence boundary, Ca/MaKh1, recorded at the base of the Dakhla Formation (Fig. 5) was defined by Hermina (1990) in Kharga due to the absence of early Maastrichtian zones. This hiatus was identified in the Kharga-Beris stretch (Luger, 1985), west Dakhla-Farafra (El-Azabi & El-Araby, 2000), Dakhla (Tantawy *et al.*, 2001) and Farafra (Hewaidy *et al.*, 2006). The latter authors attribute this hiatus to the uplift of the Bahariya Arch during initiation of the Syrian Arc Fold System. A correlative hiatus, coincident with a short-duration regressive event in the early Maastrichtian, defines the Duwi/Dakhla contact in the Eastern Desert (Hendriks & Luger, 1987; Hendriks *et al.*, 1987). This sea-level lowstand is well-documented at the El Kef section, north-west Tunisia (Li *et al.*, 1999). The boundary Ca/MaKh1 apparently coincides with a major global cooling event and eustatic sea-level drop at *ca* 71 Ma (Haq *et al.*, 1988; Li & Keller, 1998a; Miller *et al.*, 2005).

The sequence boundary MaKh2, defined at the top of the Mawhoob Shale Member (Figs 5 and 7), has been recorded in west Dakhla-Farafra by El-Azabi & El-Araby (2000) as a sub-marine hardground. On the Galala plateaux, along the western coast of the Gulf of Suez, a correlative sequence boundary (MaGal1) was recorded by Kuss *et al.* (2000). The boundary MaKh2 most probably corresponds to a worldwide, short-lived sea-level fall during the early late Maastrichtian at the top of the *Gansserina gansseri* Zone (now top of Zone CF5, *sensu* Li *et al.*, 1999) at 68 Ma (Haq *et al.*, 1988). This sea-level lowstand was traced in the sea-level curve of Miller *et al.* (2005) established for the New Jersey passive continental margin.

The sequence boundary Ma/DaKh3, defined at the top of the Lower Kharga Shale (Figs 5 and 7) and belonging to the K/Pg boundary, is interpreted as one of the largest recorded sea-level falls in the Kharga succession due to its clearly erosive character and long biozonal hiatus. In fact, the time gap associated with the K/Pg hiatus differs from location to location based on basin palaeotopography. The sequence boundary coincides with the absence of Zones P0 to P1c in west Dakhla-Farafra (El-Azabi & El-Araby, 2000), with Zones CF2 to P1b and Zones CF2 to P1d in Dakhla and Farafra, respectively (Tantawy *et al.*, 2001), and with Zones CF2 to P1b in Farafra (Hewaidy *et al.*, 2006). The Ma/DaKh3 sequence boundary may be correlated with sequence boundary Ma-Sin-Z given by Lüning *et al.* (1998) in central east Sinai. In north-central Tunisia, the K/Pg boundary was interrupted by three short hiatuses at Ain Settara which lies *ca* 50 km south-west of El Kef where the K/Pg boundary GSSP occurs (Luciani, 2002). In the Kesra plateau, central Tunisia, the K/Pg boundary represents a major hiatus lasting 19 Myr, and is described at the top of the Maastrichtian by Jorry *et al.* (2003). A similar hiatus is indicated between the late Maastrichtian and the early Lutetian in north-east Cyrenaica, Libya (Jorry, 2004). A major tectonic uplift during the Palaeocene could explain this long hiatus. A relative sea-level drop is also recorded during the latest Maastrichtian in the global eustatic cycle charts of Haq *et al.* (1988) This sea-level lowstand recorded at *ca* 65·5 Ma is coincident with the latest Maastrichtian maximum cooling (Li & Keller, 1998b).

The sequence boundary Se/ThKh4 identified near the top of the Kharga Shale Member (Figs 5 to 7) is recorded in a number of areas, including G. El-Teir/Tarawan, Kharga Oasis (Faris *et al.*, 1999; lack of Zone NP6), Dakhla (Tantawy *et al.*, 2001; lack of Zone NP5) and El-Qusaima area, north-east Sinai (Ayyad *et al.*, 2003; lack of Zone NP6). In Farafra, the hiatus at this boundary is represented in most cases by the absence of subzones P3b, P4a and P4b (Hewaidy *et al.*, 2006; Fig. 11). A similar time gap has also been documented in west central Sinai (Abdel-Fattah & Molisso, 1997), where it was attributed to local tectonic uplift following deposition of Zone P2, which later amalgamated with the Selandian/Thanetian hiatus into one major unconformity. In the Palaeocene deposits of central east Sinai, the Se/ThKh4 boundary is interpreted as a composite sequence boundary representing an amalgamation of the sequence boundaries

ThSin-2, ThSin-3 and ThSin-4 given by Lüning *et al.* (1998) at the P3b/P4 zonal boundary and within Zone P4, respectively (Fig. 11). This boundary is also synchronous with the SelGal2 sequence boundary of Kuss *et al.* (2000), traced in the Galala plateaux, and with the Th1 sequence boundary of the Western European sea-level curve of Hardenbol *et al.* (1998). It also coincides with a major eustatic sea-level fall at the base of Zone P4 in the Palaeocene cycle chart of Haq *et al.* (1988).

Sequence boundary ThKh5 at the Dakhla/Tarawan Formation contact (Figs 5 and 6) was recorded in the Dakhla-south Farafra (Barthel & Herrmann-Degen, 1981) and the Kharga-Dungul stretch (Luger, 1985; Bassiouni & Luger, 1990). In the Eastern Desert of Egypt, a correlative hiatus is indicated in the Kom Ombo-Qena area at the Dakhla/Tarawan contact (Hendriks *et al.*, 1987). The ThKh5 sequence boundary can be correlated with the sequence boundaries SB5 of El-Azabi & El-Araby (2000) in the west Dakhla-Farafra, with ThGal1 of Kuss *et al.* (2000) in the Galala plateaux, and with ThSin-5 of Lüning *et al.* (1998) in central east Sinai. This boundary corresponds well with the sequence boundary Th4 of Hardenbol *et al.* (1998). It has no apparent correlation with the global eustatic sea-level chart of Haq *et al.* (1988), but it can be detected clearly in the New Jersey sea-level curve of Miller *et al.* (2005).

Sequence boundary Th/SpKh6, recorded near the base of the Esna Formation and marking the P/E boundary (Figs 5 and 6), is a major hiatus in Farafra Oasis (Hewaidy *et al.*, 2006). At Farafra, the P/E hiatus is recognized at the top of the Upper Thanetian Tarawan Formation and is indicated by the lack of all or parts of the latest Palaeocene to earliest Eocene Zones P5 to E2. This longer time hiatus is attributed to tectonic uplift occurring around the base of Zone P5, which later amalgamated with the Thanetian/Sparnacian hiatus. Boundary Th/SpKh6 may be synchronous with sequence boundaries ThGal2 and Th6 of Kuss *et al.* (2000) and Hardenbol *et al.* (1998), respectively, both traced within the undifferentiated Zone P5. It probably matches with a worldwide, short-lived sea-level fall within Zone P5 in the Eocene cycle chart of Haq *et al.* (1988) and of Miller *et al.* (2005).

Sequence boundary YpKh7 defined in the top middle part of the Esna Formation (Figs 5 and 6) is also found in Farafra Oasis, where it corresponds to the basal Eocene sequence boundary SB6 of Hewaidy *et al.* (2006) present in the lower part of the Esna Formation. This early Ypresian boundary exhibits an irregular surface with a centimetre-thick, iron-stained hardground and reworked Late Palaeocene fauna. Hewaidy *et al.* (2006) also traced the SB6 boundary to the top of the Maqfi Member in north-east Farafra, where it is characterized by intensive dolomitization coupled with the absence of Zone E4. An approximately age-equivalent sea-level fall was described from the central east Sinai by Lüning *et al.* (1998, YpSin-1) and from the Galala plateaux by Kuss *et al.* (2000, YpGal1). A correlatable sequence boundary exists at the base of Sub-zone P6b (now Zone E4, *sensu* Berggren & Pearson, 2005) in the global eustatic sea-level chart of Haq *et al.* (1988) and in the New Jersey sea-level curve of Miller *et al.* (2005).

Sequence boundary YpKh8, located near the top of the Thebes Formation (Figs 5 and 6), is also identified in the upper part of the Lower Eocene Farafra Limestone at El Quss Abu Said and at Ain Maqfi (Hewaidy *et al.*, 2006); there, it is marked by a 1 m thick, *Thalassnioides* burrowed unit as a sub-marine lateral break formed shelf-wide of the Kharga Oasis. This boundary could be matched with the SB1 sequence boundary detected by Jorry (2004) at the top of Zone P9 in north-east Cyrenaica, Libya, which corresponds to the Ypresian/Lutetian contact. As the precise age of sequence boundary YpKh8 is difficult to determine with confidence, due to the poor stratigraphic resolution based on larger foraminifera alone, it is possible to match it with the youngest eustatic sea-level drop recorded in the late Early Eocene, close to the Ypresian-Lutetian boundary (Haq *et al.*, 1988 cycle charts; Miller *et al.*, 2005 sea-level curve).

In summary, a comparison of sequence boundaries established for the Maastrichtian-Ypresian succession of the Kharga Oasis with those postulated in the eustatic cycle charts of Haq *et al.* (1988) and in the sea-level curve of Miller *et al.* (2005) displays good agreement. The sequence boundaries Ca/MaKh1, MaKh2, Ma/DaKh3, Se/ThKh4, Th/SpKh6 and YpKh7 correlate well with the Haq *et al.* (1988) chart, which suggests a greater control of eustatic sea-level on sequence boundary formation versus local tectonics (Fig. 11); this supports the contention that the Kharga Oasis area was lying in a tectonically quiescent region. Discrepancies in the correlation of sequence boundaries with the curves of Haq *et al.* (1988) and Miller *et al.* (2005) may be related to local tectonics, suggesting that tectonism cannot be ruled out completely. However, there is a good correspondence between Kharga sequence boundaries Se/ThKh4, ThKh5, Th/SpKh6 and YpKh7 with the Western European sea-level curve of Hardenbol *et al.* (1998). This correspondence also exists between the depositional sequences and sequence boundaries recorded in Farafra Oasis (Hewaidy *et al.*, 2006) and those of the Kharga Oasis (Fig. 11). However, hiatuses coeval to sequence boundaries MaKh2 and Thkh5 are not evident in the Khoman and Tarawan Formations of Farafra Oasis, probably due to the lithological homogeneity and lack of physical boundaries in that section. Sequence boundaries Se/ThKh4, Th/SpKh6 and Ypkh7 have much less of a time gap in Kharga relative to their corresponding SB4, SB5 and SB6 boundaries in Farafra (Fig. 11), which may relate to regional tectonics and higher subsidence rates in the Kharga Oasis. Correlation of the Kharga Oasis section with the sea-level curve given by Lüning *et al.* (1998) for the central east Sinai points to some similarities, especially for the relative sea-level falls associated with the MaSin-Z, ThSin-2, ThSin-5 and YpSin-1 sequence boundaries (Fig. 11). Discrepancies with other regional studies (Lüning *et al.*, 1998; Kuss *et al.*, 2000) might be explained by differential sediment preservation, un-deciphered unconformities, lateral diachrony and differences in taxonomic concepts (Lüning *et al.*, 1998). In addition, these discrepancies may be related to limited biostratigraphic resolution due to sample spacing, faunal changes at stratigraphic boundaries and the rarity of planktonic foraminifera in some intervals.

Biostratigraphic limitation

The sequence stratigraphic interpretation of the Kharga Oasis is based largely on the biostratigraphic data collected from the Maastrichtian-Ypresian succession (faunal types, diversity and abundance, and P/B ratio). These data are valuable for age dating and palaeoenvironmental interpretation in the Palaeocene to Early Ypresian interval (Zones P2 to E4), which is enriched in well-preserved and diverse planktonic foraminifera and contains abundant calcareous benthonic species (Table 2). Exceptions to this are noted in the highstand systems tracts of this interval, which are marked by a sudden drop in P/B ratios and in planktonic foraminifera diversity due to water restriction and oxygen deficiency (Table 3). The biostratigraphic validity, in terms of age assignment, in the sequence stratigraphic interpretation of late Maastrichtain and late Ypresian is limited owing to the poor fossil record (Table 2). The limitation in the late Maastrichtain is due to the rarity and poor preservation of the foraminifera, which hampers their identification. In addition, the position of the upper boundary of the early Maastrichtian is uncertain due to the presence of a barren interval (Fig. 5). In the late Ypresian, no planktonic foraminifera could be separated from the Thebes Formation, and the recorded benthonic foraminifera are not age indicative. The Nummulites and Alveolines species present are long-ranging and, therefore, provide a less accurate determination of the proper age of the hiatus at the top of the Thebes Formation. Regardless, a comparison with other areas was undertaken to resolve the limited biostratigraphic resolution. The Palaeocene to early Ypresian succession of the Beris, which contains from poor (the majority of the succession) to moderately abundant planktonic foraminifera (i.e. the Garra Formation) with rare to common benthonic foraminifera, has low resolution age control (Fig. 7, Table 1). The foraminiferal content that has been collected shows moderate to high dissolution which thus severely altered the calcareous components. However, in shallow marine settings where biostratigraphic data are often lacking, sequence boundaries are more clearly developed in terms of erosion and stratal truncation, karst or pedogenesis, and lithofacies stacking patterns. Nevertheless, comparison of the present study with the Beris area has added significantly to the understanding of the age control of the Beris area.

Basin palaeogeography

During the late Jurassic, the structural relief of North Africa changed drastically due to the disintegration of Pangea. As a result, large parts of North Africa were tilted towards the NNW with the initiation of two north-west to south-east striking intra-shelf basins in central Egypt; the Dakhla and Assiut (Hendriks *et al.*, 1987). The Dakhla Basin was bordered on the south and south-west by the Aswan and Gilf El-Kebir-Uweinat uplifts, respectively. These uplifts date back to the Late Carboniferous to Early Jurassic (Klitzsch & Schandelmeier, 1990) and are interpreted as the main source for sediment supply in central Egypt. The Dakhla Basin was opened to the north, the passage being restricted by the Bahariya Arch. It was marked by the presence of north-east to south-west trending submerged palaeo-highs and lows with a symmetrical outline, large amplitude and very gentle dip (for example, Farafra, Dakhla and Kharga palaeo-lows; Qur El-Malik and Abu Tartur palaeo-highs; El-Azabi & El-Araby, 2000). These elongated palaeo-highs and lows, which shaped the configuration of the Dakhla Basin, initiated from the vertical differential movements in deep-seated basement blocks; they were prominent during the Palaeocene to Early Eocene, but were being hardly exposed during maximum fall of sea-level. The submerged palaeo-highs are dominated by thin marginal marine facies with a common occurrence of benthonic foraminifera, reworked lithoclasts and bioturbation. The sub-basins separating these palaeo-highs exhibit thicker and deeper marine facies. The Kharga sub-basin was situated in the south-eastern part of the Dakhla Basin (Fig. 12). It was defined in the north-west and south-east by the Abu Tartur and Beris submerged palaeo-highs, respectively. This sub-basin was the subject of sea-level fluctuations throughout Maastrichtian to Palaeogene time. The major interpreted controls on lateral/vertical variations in sedimentation pattern, thickness and faunal content in the Kharga sub-basin area were eustatic sea-level fluctuations, basin palaeotopography, sediment influx and, partly, local tectonics. These elements controlled the development and location of the two major facies associations in the Kharga Oasis, the Nile Valley (open marine) and Garra El-Arbain (marginal marine).

The cyclic transgression and regression of the Tethys onto the northern African margin greatly affected the position of the palaeo-shoreline of the Dakhla Basin and, hence, the palaeoenvironments that prevailed in the Kharga sub-basin. Marine incursions, which occurred during the late Danian to Selandian, late Thanetian, late Thanetian to latest Thanetian and Sparnacian to early Ypresian, typify the most remarkable transgressions that reached the Kharga sub-basin throughout Maastrichtian to Palaeogene times. The palaeo-shoreline of the Palaeocene incursions is believed to occur in north Sudan, where fluviatile-lacustrine siliciclastic facies extend up to the Abyad Basin (Wycisk, 1991); they graded northwards to shallow marine carbonate, and further north into mixed deeper carbonate and siliciclastic facies in central and northern Egypt (Fig. 12B). During the regressive events, which occurred during the late Maastrichtian and late Ypresian, the marginal marine facies shifted north-westwards causing the prevalence of shallow inner shelf deposits in the Kharga sub-basin (Fig. 12A and C).

Palaeoenvironmental reconstruction of the Kharga sub-basin

The sedimentary history of the Dakhla Basin is marked by numerous transgressive and regressive cycles during Maastrichtian to Palaeogene times, as documented in the Kharga Oasis area. During the early Maastrichtian, a major marine incursion of the Tethyan Sea occurred, which exhibited open marine conditions throughout central Egypt and extended a shallow marginal sea towards the south and west of the Kharga Oasis. The marginal marine setting was influenced partly by higher frequency sea-level oscillations. As a result of a rapid relative sea-level rise at the beginning of the early Maastrichtian, retrogradational parasequence sets of shallow inner to shallow middle shelf shale were deposited over the Kharga Oasis forming the lower part of the Mawhoob Shale Member (DkSQ1, Zones CF8b to CF7; Figs 5 and 7). These fine clastics were derived largely from the south and south-west and transported to the marine setting by river run-off during wet seasons. Afterwards, as the rate of relative sea-level rise slowed, a decrease in accommodation space led to the deposition of progradational shallow sub-tidal shale with low diversity benthonic foraminifera (HST; Figs 5 and 7), deposited in a more restricted, shallow inner shelf setting. These highstand deposits were terminated by a minor eustatic sea-level fall and sedimentation break during the late early Maastrichtian, with the formation of sequence boundary MaKh2 at the top of the Mawhoob Shale Member.

During the early late Maastrichtian, a major marine invasion flooded the Kharga Oasis area causing the deposition of sequence DkSQ2 (Figs 5 and 7). This flooding event started with the deposition of retrogradationally stacked parasequences of deep sub-tidal shale alternating with shallow sub-tidal wackestone/floatstone. These transgressive deposits of the Beris Mudstone Member mark a rapid increase in accommodation space. Later, as the rate of accommodation increase started to decline, a progradational shallow sub-tidal shale parasequence was deposited (HST; Figs 5 and 7). Deposition of these regressive deposits of the Lower Kharga Shale denote the beginning of a regional uplift which, along with eustatic sea-level fall (Haq *et al.*, 1988), caused complete emergence of the area during the latest Maastrichtian through to early-late Danian with the initiation of sequence boundary Ma/DaKh3. Due to this emergence, the deposits belonging to Zones CF2 to CF1 and P0 to P1 are

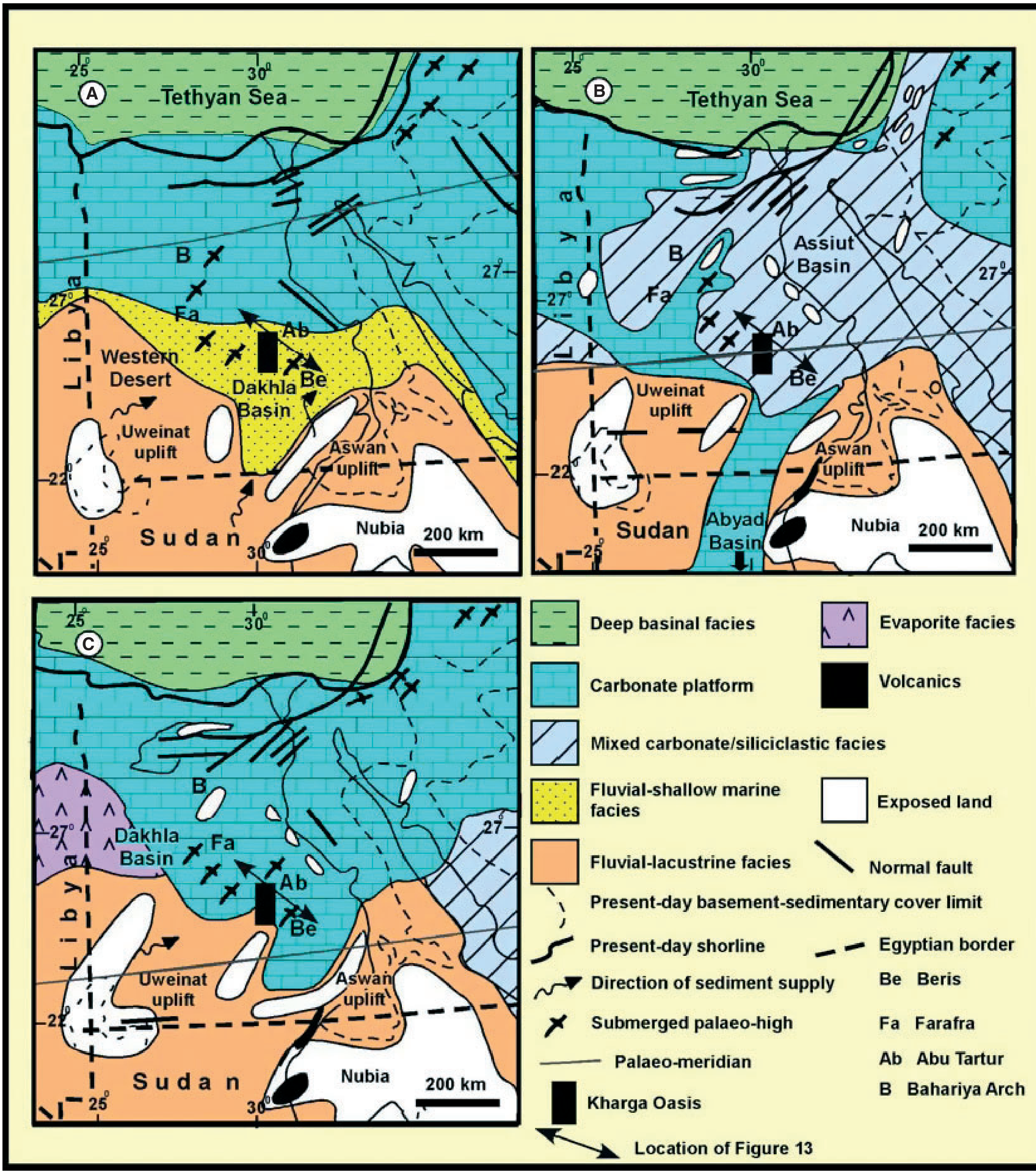

Fig. 12. Late Maastrichtian to Late Ypresian palaeogeographic maps of Egypt showing the depositional setting of the Dakhla Basin (modified after Guiraud & Bosworth, 1999 and Guiraud *et al.*, 2001). (A) Late Maastrichtian (*ca* 67 to 68 Ma); (B) Late Palaeocene (*ca* 56 to 58 Ma); and (C) Late Ypresian (*ca* 50 to 52 Ma).

missing in the Kharga Oasis (Figs 9 and 11). The latest Maastrichtian sea-level fall coincided with the basin-wide K/Pg impact and mass extinction. The K/Pg impact has resulted in the initiation of many palaeo-highs and lows, which played a major role in facies distribution of the subsequently deposited Palaeocene to Eocene sediments.

During the late Danian, an extensive marine transgression took place, leading to the landward shift of the shoreline as far south as north Sudan (Luger, 1985). This transgression denotes a major regional expansion of the Dakhla Basin, which led to an increase in water circulation and enhanced oxygenation of the water column. These conditions persisted during deposition of most of the Upper Kharga Shale, Tarawan and Esna sediments. Deposition is interpreted as having taken place in topographically irregular sub-basins within the larger Dakhla Basin (Fig. 13). In the Kharga sub-basin, the late Danian relative sea-level rise started with the formation of landward-stepping outer shelf pelagic shale strata (DkSQ3, Zone P2; Figs 5 and 6), which was succeeded by progradational, shallow middle shelf shale during the Selandian Zone P3 due to a slow relative sea-level fall. Age-equivalent shallow sub-tidal coquinal limestone facies capped by deep sub-tidal shale of the Kurkur Formation were developed on submerged palaeo-highs occupying the south-eastern escarpment face of the Kharga Oasis and the Abu Tartur area (TST; Figs 7 and 13). These transgressive facies are followed by a progradational, shallow sub-tidal packstone/rudstone parasequence set (HST; Fig. 7). A subsequent short-lived relative sea-level fall with a regional hiatus led to the development of sequence boundary Se/ThKh4, which terminated sequence DkSQ3. This hiatus represents the time span of the Late Palaeocene sub-zones P4a-b (Fig. 11).

During the late Thanetian, the Kharga Oasis area was transgressed again resulting in the formation of sequence DkSQ4, which started with deposition of a retrogradational outer shelf pelagic shale that formed during a short period of rapid relative rise of sea-level (TST; Figs 5 and 6). This transgressive shale is followed by regressive, shallow sub-tidal progradational shale comprising the top part of the Upper Kharga Shale. Towards the south-east, these facies are equivalent to a retrogradational shallow middle shelf packstone and a progradational deep inner shelf wackestone, respectively (*ca* DkSQ4, TST and HST; Fig. 7), both within the lower part of the Garra Formation. These time correlative limestone facies were developed on a submerged palaeo-high developed beneath the south-eastern escarpment face of the Kharga Oasis (Fig. 13). Sequence DkSQ4 was terminated by a local tectonic disturbance coupled with a short-term sea-level fall and sedimentation break during late Thanetian Zone P4c (ThKh5; Fig. 11).

During the late/latest Thanetian, another marine transgression interpreted as a global eustatic sea-level rise took place in the Kharga Oasis area. This transgression continued until the Early Eocene with short-term interruptions due to minor regressive phases evidenced by sub-aerial/sub-marine erosion. The transgression started with the deposition of retrogradationally stacked parasequences of shallow middle/outer shelf foraminiferal wackestone/packstone and shale (T/EsSQ5, TST; Figs 5 and 6). These facies, which belong to the Tarawan Formation and the basal part of the Esna Formation, typify the deepest environment reached in the area; they are marked by abundant, highly diversified and well-preserved planktonic and benthonic foraminifera (Sub-zone P4c 'upper part' to Zone P5). The benthonic foraminifera are dominated by elements of the so-called Midway fauna typical of neritic water depths, down to 200 m. These facies were succeeded by the deposition of progradational shallow middle shelf shale (HST; Figs 5 and 6). On the submerged palaeo-highs of the south-eastern escarpment face of Kharga and of Abu Tartur Plateau, age-equivalent shallower water facies formed of a retrogradational, shallow middle shelf packstone capped by a progradational, deep inner shelf lime-mudstone of the upper part of the Garra Formation were developed (Figs 7 and 13). A short-term hiatus terminated sequence T/EsSQ5 at the P5/E1 zonal boundary (Th/SpKh6, Fig. 11); the hiatus may have been related to the global elevated water temperatures reached during the P/E boundary as described below.

An abrupt environmental change occurred at the P/E boundary due to a brief global warming causing a temporary collapse of marine/terrestrial productivity, the formation of uniformly warm, low-oxygen, corrosive bottom waters, widespread $CaCO_3$ dissolution and the dramatic mass extinction of benthonic foraminifera (Berggren & Aubry, 1998). As a result, the majority of the Palaeocene benthonic foraminifera suffered a temporary elimination. The lack of planktonic foraminifera at the P/E boundary is attributed to the coupled and strong effect of oxygen-deficiency and carbonate dissolution (Berggren & Ouda, 2003). Shortly above the base of the P/E boundary, the first and only recorded examples of transient planktonic foraminifera are the warm-water-tolerant Acarininids, of which *Acarinina sibaiyaensis* is by far the most common PFET to have appeared. At this interval, no Morozovellids, subbotinids or benthonic foraminifera are recorded, presumably due to environmental stress. The abundance of the planktonic foraminifera increases gradually upwards and their assemblages became relatively more diversified due to a progressive return to

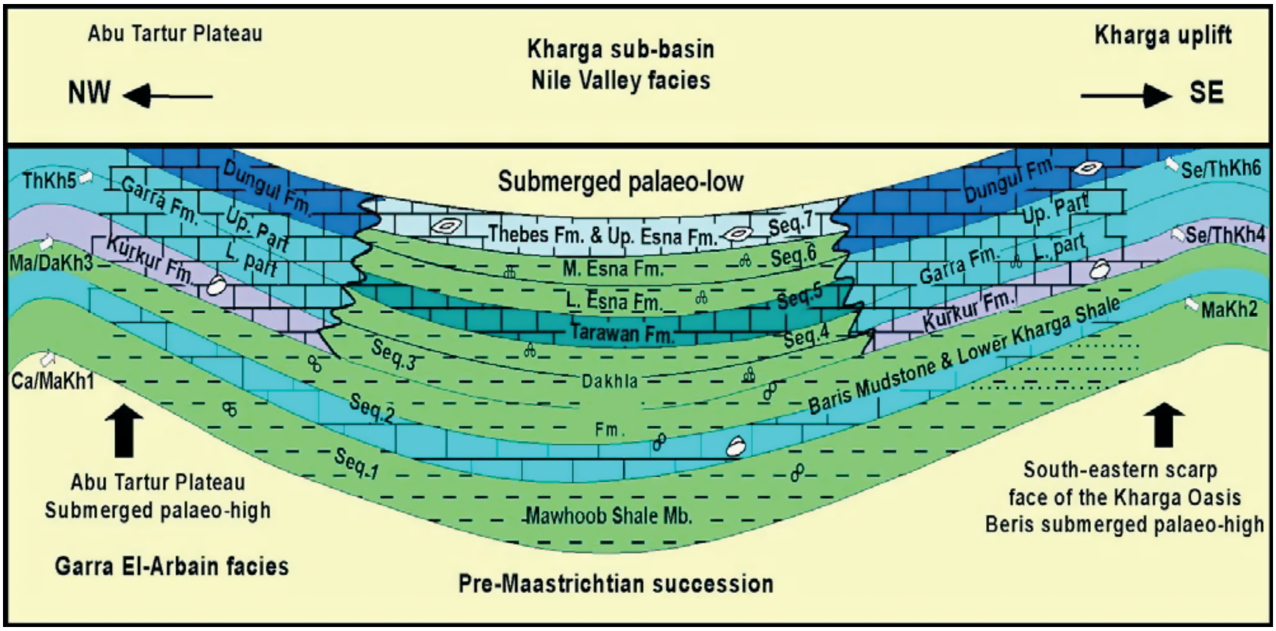

Fig. 13. North-west to south-east schematic depositional diagram showing the lateral variation in facies between the Palaeocene to Lower Eocene successions of the Nile Valley and Garra El-Arbain facies along Abu Tartur Plateau/ south-eastern scarp of the Kharga Oasis, south-eastern part of the intra-shelf Dakhla Basin (not to scale). For location, see Fig. 12 and for symbols and key, see Fig. 5.

well-aerated conditions. As a result, a retrogradational parasequence of outer shelf pelagic shale was deposited during a rapid eustatic sea-level rise (EsSQ6, TST; Figs 5 and 6). This transgressive facies is capped by the deposition of a progradational parasequence set of deep inner shelf shale, as the accommodation space decreased due to a slowing relative rise in sea-level (EsSQ6, HST; Figs 5 and 6). This sequence was ended by a marked relative drop in sea-level with the formation of a minor sub-marine hiatus at the top of the sequence (YpKh7; Fig. 11).

During the early Ypresian, a marked transgression took place in the Kharga Oasis area which resulted in the prevalence of deep water conditions (Zone E4); this caused the deposition of a retrogradational parasequence set of deep middle/outer shelf pelagic shale during a rapid relative rise of sea-level (Es/ThSQ7, TST; Figs 5 and 6). This transgressive event, represented by the upper part of the Esna Formation, marks the last great water depth reached by the Eocene Sea which had earlier pushed its way across the southern borders of Egypt into north Sudan. After this event the Eocene Sea retreated northwards almost continuously, leaving the Kharga Oasis area to shallow marine conditions until a minor hiatus with sub-aerial exposure occurred in the late Ypresian. As a result, aggradational to progradational upward-shallowing parasequences of alternating shallow sub-tidal wackestone/packstone and relatively deep sub-tidal shale were deposited, driven by high-frequency sea-level oscillations superimposed on a slowing long-term relative rise of sea-level to long-term relative fall (HST; Figs 5 and 6). These regressive deposits comprise the early to latest Ypresian Thebes Formation (Zones E5 to E7; Fig. 11).

CONCLUSIONS

Sequence stratigraphic analysis of the Maastrichtian-Ypresian succession, across the Nile Valley and Garra El-Arbain facies associations along the eastern escarpment face of the Kharga Oasis, led to the recognition of seven third-order depositional sequences and their associated systems tracts, sequence boundaries and maximum-flooding surfaces. This analysis was based on integrated stratigraphic, sedimentological and high-resolution planktonic and benthonic foraminiferal data. The succession extends from the Dakhla Formation (Zones CF8b to P4c, lower part), through the Tarawan (Zone P4c, upper part) and Esna Formations (Zones P5 to E4) to the Thebes Formation (barren interval). Recorded zonal boundaries and biostratigraphic zones to a great extent match with those proposed in nearby regions. Gabal Um El-Ghanayim represents one of the most complete stratal records across the Palaeocene/Eocene (P/E) boundary, similar to the newly proposed Global Standard Stratotype-section and Points in Egypt. It marks the thickest and most complete Maastrichtian-Ypresian succession with the deepest palaeo-water depths. The recorded depositional sequences are punctuated by hiatuses correlated within and outside Egypt. Sequence boundary Th/SpKh6 traced along the P/E contact in Gabal Um El-Ghanayim is the only boundary which exhibits no significant hiatus. However, there is a distinct erosional surface associated with the P/E boundary at Naqb Assiut. The depositional sequences contain both transgressive systems tracts and highstand systems tracts. Lowstand systems tracts were not developed in the studied sections, presumably due to the low-relief ramp setting. During subsidence coupled with rapid relative sea-level rise, retrogradational parasequence sets composed of deep shelf deposits were accumulated, while during relative high sea-level stands, aggradational to progradational parasequence sets formed and regressive shallow shelf facies were deposited. Most of the sequence boundaries compare well with the global cycle chart of Haq *et al.* (1988), with the Western European sea-level curve of Hardenbol *et al.* (1998) and with the sea-level curve of Miller *et al.* (2005), suggesting that global eustasy was primarily responsible for their development. Some of the sequence boundaries suggest that local tectonism was also an important control on sedimentation.

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