PLANKTONIC FORAMINIFERA AND CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY THROUGH THE MIDDLE TO LATE EOCENE TRANSITION AT WADI HITAN, FAYUM PROVINCE, EGYPT

BY

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Abstract — Four Eocene formations are recognized in Wadi Hitan. These are, from lowest to highest (oldest to youngest): El Gharaq, Gehannam, Birket Qarun, and Qasr El Sagha. All are well exposed. The lower boundary of the Birket Qarun Formation is revised in Wadi Hitan to match the lower boundary in the type section near Birket Qarun. The Qasr El Sagha Formation starts at the base with the first bed of the large anomiid bivalve *Carolia placunoides* and ends at the top with the 'Bare Limestone.' Informative calcareous plankton are restricted to the lower part of the succession (El Gharaq Formation, Gehannam Formation, and the basal part of the Birket Qarun Formation).

Three planktonic foraminiferal zones have been identified in this interval. These are the *Truncorotaloides rohri* (or *Acaranina rohri*) zone (P14), the *Turborotalia pseudoampliapertura* zone (between P14 and P15 sensu stricto), and the *Globigerinatheka semiinvoluta* zone (P15). In other parts of the world, an interval equivalent to the *T. pseudoampliapertura* zone is either not present, overlooked, included at the top of zone P14, or included at the base of zone P15. Foraminiferal 'P' zones are used rather than the 'E' zones of Berggren and Pearson because *Morozovelloides crassatus* has not been found in Wadi Hitan sections. This species is required to distinguish E13 and E14 in the Bartonian-Priabonian or middle-to-late Eocene transition. Within the sequence at Wadi Hitan, we recognize a twofold division of zone P15: a *T. pseudoampliapertura* subzone (P15a) and a *G. semiinvoluta* subzone (P15b).

Two calcareous nannofossil zones are recognized at Wadi Hitan: a *Discoaster saipanensis* zone (NP17) and a *Chiasmolithus oamaruensis* zone (NP18). Several authors found that the lowest occurrence of *Chiasmolithus oamaruensis* is a poor criterion for defining the base of zone NP18, which is confirmed here. The same criticism has been applied to the lowest occurrence of *Isthmolithus recurvus*, which defines the NP18/NP19-20 zonal boundary. It is generally agreed that zone NP19-20 falls in the Priabonian late Eocene. However, *I. recurvus* is identified here in an association indicative of zone P14, an undoubted middle Eocene (Bartonian) zone. Planktonic foraminifera are more useful for correlation outside Wadi Hitan than calcareous nannofossils are at present.

We see a clear separation of strata bearing muricate planktonic foraminifera such as *Morozovelloides*, *Acarinina*, and *Truncorotaloides* characteristic of the Bartonian stage/age of the middle Eocene, in lower samples in our sections, from overlying strata bearing *Globigerinatheka semiinvoluta* characteristic of Priabonian stage/age of the upper Eocene. A glauconite-rich layer called the Wadi Hitan Glauconite Layer or WHGL approximates this separation in the field, suggesting that sea level sequence stratigraphy should also be considered in choosing a global stratotype for the Bartonian-Priabonian boundary.

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INTRODUCTION

Wadi Hitan or 'Valley of Whales' is a World Heritage Site in the Western Desert of Egypt, some 140 kilometers southwest of Cairo and 60 kilometers west of Fayum (Fig. 1). The valley has long been famous for its late Eocene fossil whales, including numerous specimens of *Basilosaurus isis* and *Dorudon atrox* that are exceptionally complete and well preserved (Andrews, 1906; Gingerich et al., 1990; Uhen, 2004). The site is also interesting because of the thick sequence of middle and late Eocene marine strata exposed there (Beadnell, 1905; Gingerich, 1992; Peters et al., 2009, 2010). These beds were deposited on the southern margin of the proto-Mediterranean Eocene sea called Tethys.
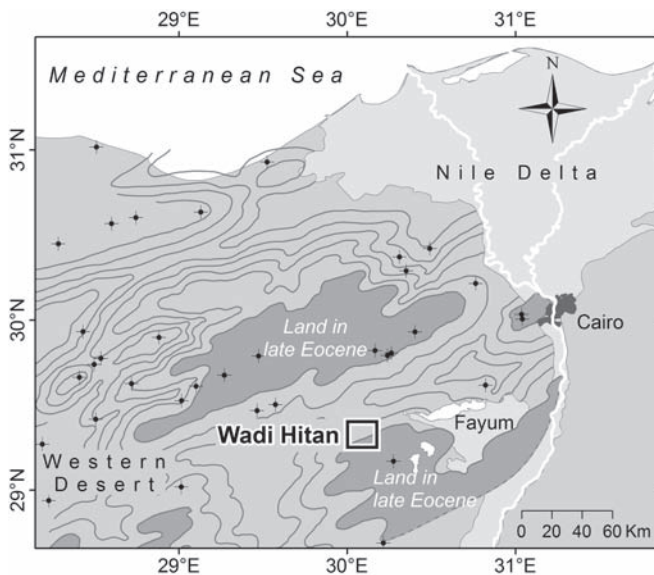

FIGURE 1 — Location map showing the paleogeography and paleobathymetry of northern Egypt in the middle and late Eocene. Black outline shows the location of the Wadi Hitan World Heritage Site on the southern margin of a marine strait separating two Eocene land masses. Contours are 50-meter isopachs for late Bartonian and Priabonian strata. Oil well symbols show the locations of well cores used by Salem (1976) to reconstruct paleogeography.

Sedimentary rocks exposed in the Fayum Basin belong almost exclusively to the Eocene and Oligocene epochs. A regional tilt of strata northward toward the Mediterranean Sea means that middle Eocene strata (Lutetian and Bartonian) are exposed south of Fayum, in and around Wadi Muweilih and Wadi El Rayan, while late Eocene strata (Priabonian) are exposed in Wadi Hitan itself. Oligocene strata are exposed farther north, west of Fayum, including Oligocene-to-Miocene basalt sheets at Widan El Faras in the northern part of the Fayum Basin.

One striking feature of middle Eocene deposits in central Egypt, east and west of the Nile River, is the large volume of clastic sediment. Age-equivalent strata farther north are more calcareous, being predominantly limestones and marls. Another

difference between north and south is the much greater thickness of late Eocene (Priabonian) strata in Fayum, which, in addition, contain some land mammals. These features probably reflect the proximity of highlands to the south, with emergent uplifts like the Kattaniya Horst and other Syrian Arc structures flanking the basin (Blanckenhorn, 1902; Salem, 1976; Dolson et al., 2002).

The succession of Eocene strata in Wadi Hitan begins at the base with the upper part of the El Gharaq Formation, rich in large nummulites, which is exposed in the southern part of the area (Fig. 2). The succession ends in the Qasr El Sagha and overlying Gebel Qatrani formation exposed in the northwestern part of the area. In local chronostratigraphic terms, the Eocene interval in Wadi Hitan covers the Mokattamian divisions MK7 (part) through MK12, representing the upper Bartonian and the entire Priabonian (Strougo 2008). The Gebel Qatrani Formation is Oligocene in age and not of interest here.

A voluminous literature containing a great deal of new information has been gathered on the vertebrate fauna of Fayum during the past thirty years. Surprisingly, calcareous plankton (planktonic foraminifera and calcareous nannofossils) and larger foraminifera, the most widely used biostratigraphic tools for age calibration, have seldom been studied, and then only in very localized sections (Abdou and Abdel Kireem, 1975; Strougo and Haggag, 1984; Haggag, 1990; Faris and Strougo, 1992; Haggag and Bolli, 1995; 1996, Boukhary et al., 2003; Boukhary and Kamal, 2003). The only published work to date in Wadi Hitan is that of Abd El-Azeam (2008), who examined planktonic foraminifera of the Gehannam Formation. Abd El-Azeam recognized one zone only: the *Globigerinatheka semiinvoluta* zone. The purpose of the present study is to analyze the planktonic foraminifera and calcareous nannofossils of the Eocene succession at Wadi Hitan. Many sections have been sampled but only four have yielded reliable, age-diagnostic microfossils. These are unfortunately restricted to the lower part of the succession, the El Gharaq, Gehannam, and basal Birket Qarun formations. In compensation, the interval with calcareous plankton was found to fall at the transition from the middle to late Eocene, enabling us to reassess the evidence employed in standard biostratigraphic schemes concerning this transition. There is still uncertainty in the definition and recognition of global geological stage and age boundaries like the Bartonian-Priabonian boundary (Agnini et al., 2011; Wade et al., 2012), and this study adds evidence from a new geographic area.

LITHOSTRATIGRAPHY

The lithostratigraphic terminology commonly used for Eocene deposits of the Fayum was initially proposed by Beadnell (1905) and subsequently given formal status by Said (1962). Four units were recognized initially: these were, from lower to upper (older to younger) the Wadi Rayan Series or formation, the Ravine beds or Gehannam Formation, the Birket Qarun series or formation, and the Qasr El Sagha series or formation (Fig. 3). Iskander (1943) divided the Wadi Rayan Series into four units of formational rank, distinguished by their
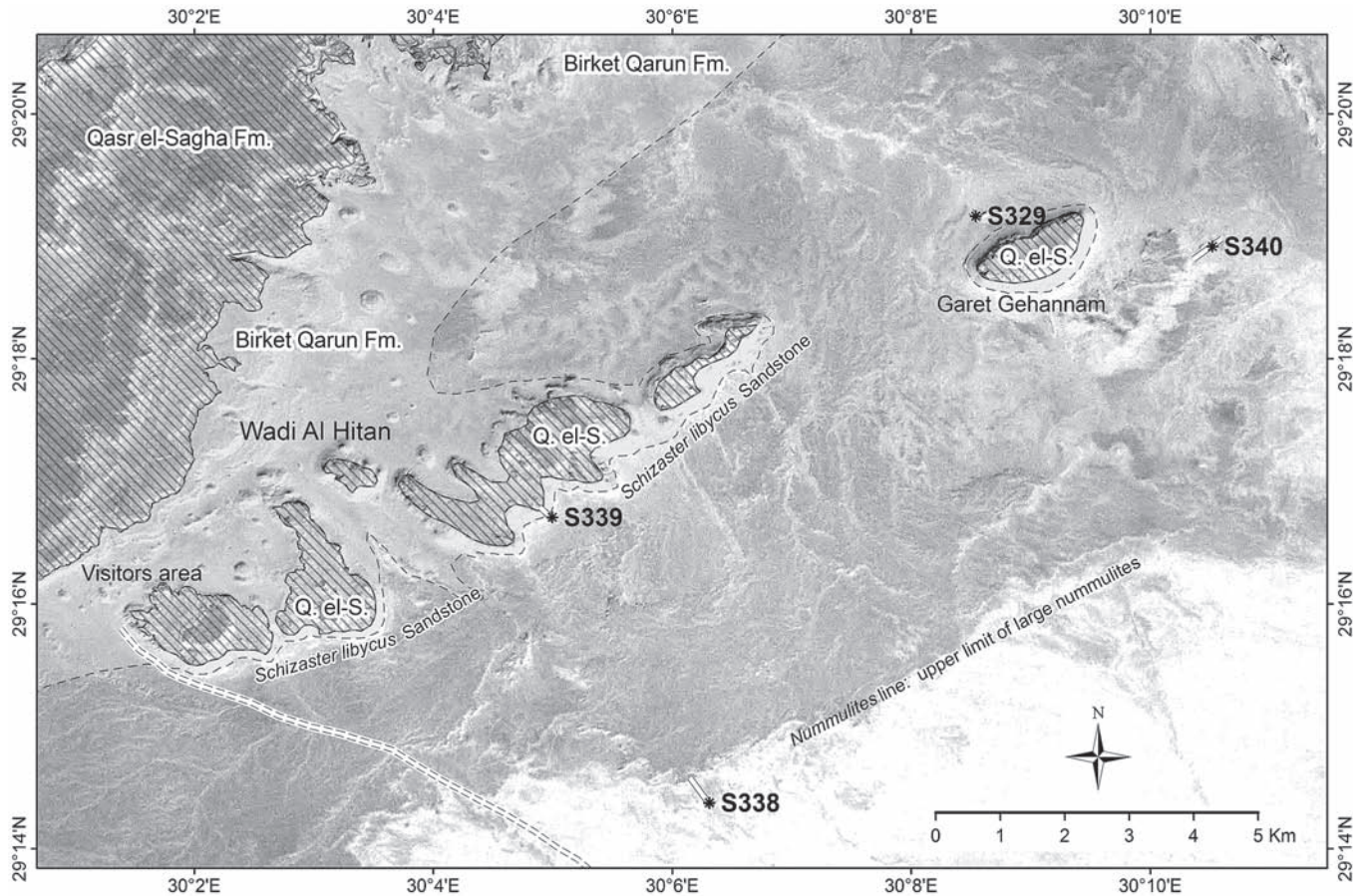
FIGURE 2 — Geological map of the southern part of the Wadi Hitan World Heritage Site showing locations of the four stratigraphic sections, S329, S338, S339, and S340 studied here (marked by asterisks). The El Gharaq and Gehannam formations cover all of the lower part of the map south and east of the *Schizaster libycus* Sandstone outcrop belt. Birket Qarun and Qasr El Sagha formations overly the *Schizaster libycus* Sandstone to the north and west. Individual sections are shown in Figures 5, 7, 9, and 11. Dashed lines trace the road into the Wadi Hitan visitors area.

lithology and fossil content. Iskander named these subdivisions of the Wadi Rayan Formation, again from lower to upper (older to younger): Muweilih Formation, Midawara Formation, Sath El Hadid Formation, and El Gharaq Formation. The only subdivision that concerns us here is the one at the top, the El Gharaq Formation, which is equivalent to Beadnell's uppermost Rayan Series or Wadi Rayan Formation. The practical value of Iskander's subdivision of the Wadi Rayan 'group' has been established during the past twenty-five years, through the work of various investigators in the southern part of Fayum (Strougo, 1986; Strougo and Boukhary, 1987; Boukhary et al., 1993; El Safori, 1996; Boukhary and Kamal, 2003; Strougo and Elattaar, 2005; Underwood et al., 2011; Abu El Ghar, 2012; Gingerich et al., 2012).

El Gharaq and Gehannam Formations

The oldest exposures in Wadi Hitan are part of the El Gharaq Formation. When discussing the upper boundary of the El Gharaq Formation in Wadi Rayan and vicinity, Iskander (1943, p. 18)

wrote: "The upper contact [of the El Gharaq Formation] with what Beadnell called 'Ravine Beds' [Gehannam Formation] is not exposed in [Wadi Rayan], but the writer examined it at Garet Gehannam,… where it is the plain between the Nummulitic limestone and gray-green, gypsiferous, saliferous, fossiliferous shales, which weather papery." This contact is nicely exposed in the low buttes rimming the prominent hillmass of Garet Gehannam on both the north and south sides. The uppermost part of the El Gharaq Formation is a white to light gray limestone, highly charged with large-sized nummulites and discocyclinids passing rapidly upward into a gray calcareous shale that marks the base of the Gehannam Formation. The shales in the lower part of the Gehannam are interbedded with several yellow marl layers, and with subordinate impure, more or less glauconitic sandstones; one of these sandstones is particularly noticeable by its dark green color, being extremely rich in glauconite, which we designate the Wadi Hitan Glauconite Layer (WHGL).

The upper part of the Gehannam Formation is a prominent, well-bedded, ledge-forming, dirty-white calcareous sandstone, 16 m thick, forming the tops of the buttes on the north and
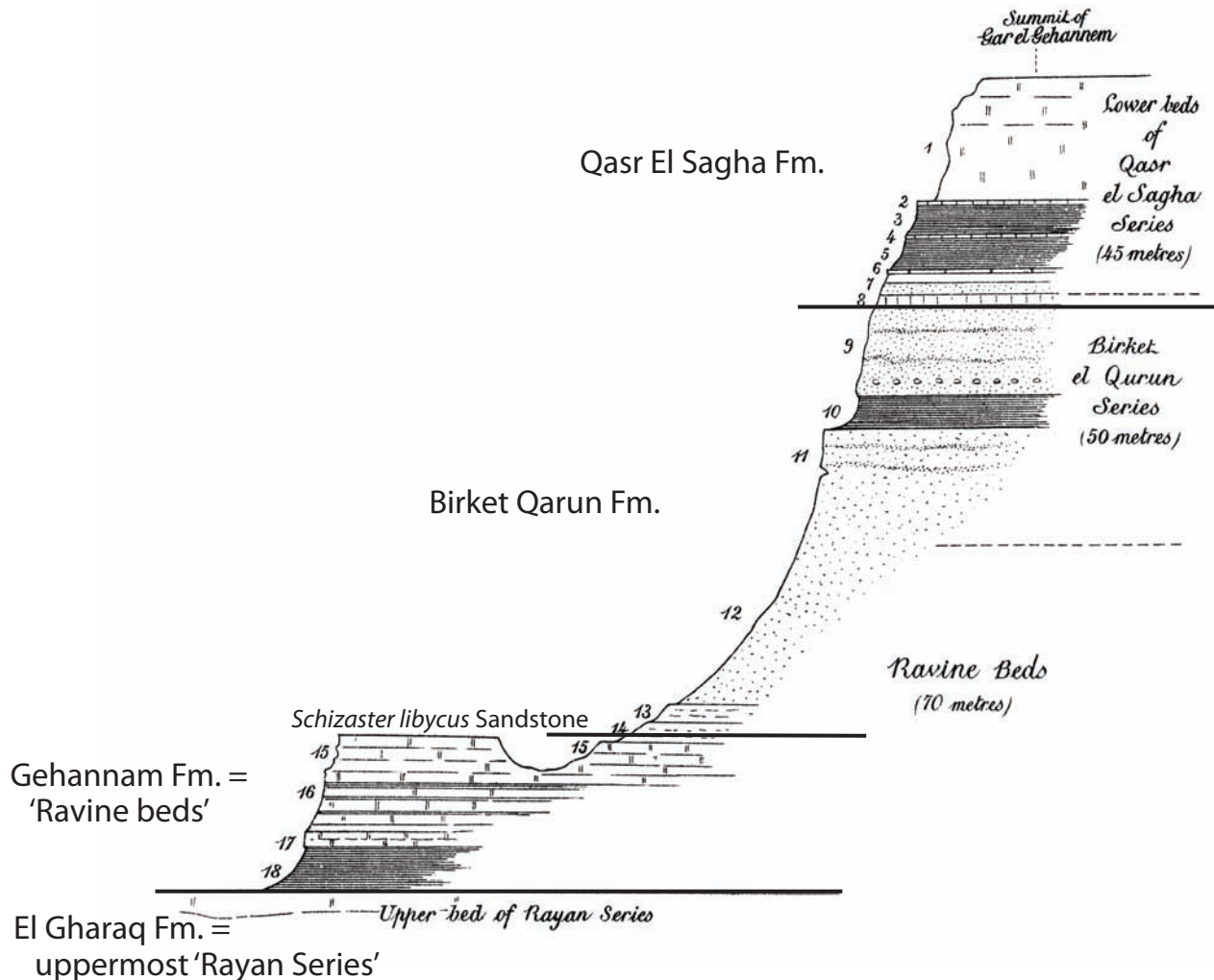
FIGURE 3 — Stratigraphic section on the southeast side of Garet Gehannam illustrated by Beadnell (1905, fig. 2). This section is representative of upper middle Eocene and upper Eocene strata spanning the Bartonian-Priabonian middle-to-late Eocene boundary in Wadi Hitan. Beadnell recognized four units: his Rayan Series, Ravine Beds, Birket el Qurun Series, and Qasr el Sagha Series. These are now regarded as El Gharaq, Gehannam, Birket Qarun, and Qasr El Sagha formations, respectively. The only difference in dividing strata is that we regard the boundary between the Gehannam and Birket Qarun formations as lying at the top of the *Schizaster libycus* Sandstone — within Beadnell's bed 14, and not in the middle of bed 12 indicated by the dashed line of Beadnell (note that Beadnell numbered beds sequentially down from the top). A boundary within bed 14 conforms closely to the position of the base of the Birket Qarun Formation in the type section of the formation at the west end of Birket Qarun.

southeast sides of Garet Gehannam (Figs. 4-5). At Garet Gehannam itself, the Gehannam Formation lies at the extreme base of the succession and its upper surface makes a wide bench. This is bed 15 and the basal part of bed 14 ('Yellow-white marls and marly limestone') of Beadnell (1905, p. 38; see Fig. 3). It was named the 'Vicinalis Sandstone' by Strougo (2008) because of common presence of an echinoid identified as *Schizaster vicinalis*. Further study has shown this to be *Schizaster libycus* (Strougo and Elattaar, 2012). We follow Strougo (2008) and Strougo and Elattaar (2012) in considering the *Schizaster libycus* Sandstone to be the uppermost bed of the Gehannam Formation.

Beadnell (1905), as discussed by Gingerich (1992), placed the contact between the Gehannam Formation and the Birket Qarun

Formation within a 48 m thick sandstone unit (dashed line bed 12 of Beadnell; see Fig. 3). Gingerich (1992, p. 32) wrote that "there is no lithological or other reason to include this sandstone in the Gehannam Formation," and shifted the lower contact of the Birket Qarun Formation to the base of Beadnell's bed 12 sandstone. We go one step farther and move the underlying gypseous clays (bed 13 and most of bed 14 of Beadnell) from the top of the Gehannam Formation to the base of the Birket Qarun Formation (for reasons that will be explained below when discussing the Birket Qarun Formation).

Some authors working in Wadi Hitan have regarded the Gehannam Formation as a clastic unit overlying the nummulitic limestone of the upper El Gharaq Formation (Dolson et

al., 2002; Abd El-Azeam, 2008; Abdel-Fattah et al., 2010; Underwood et al., 2011; Gingerich et al., 2012). However, it is possible that the Gehannam Formation recognized in the vicinity of Garet Gehannam in the east changes facies lithically, becoming El Gharaq Formation farther west (Strougo, 2008). Following Strougo, the oldest beds of the El Gharaq Formation are not exposed in Wadi Hitan itself but can be seen in the low undulating hillocks scattered in the plain southeast of the park entrance of Wadi Hitan (Figs. 6-7). Here, section S338 begins at the base with a white limestone packed with large nummulites, which passes upward, gradationally, to marly limestones and sandy marls with scattered nummulites and abundant discocyclinids, and finally to marly sandstones and sandstones occasionally containing larger foraminifera (mainly *Orbitolites*). Disseminated glauconite imparts a slightly green color to this succession, and, as in the Gehannam Formation, the upper part of the succession is cut by a dark green, glauconitic sandstone (the WHGL mentioned above). The El Gharaq Formation in section S339 is capped by the *Schizaster libycus* Sandstone, which retains the same thickness from east to west (Figs. 8-9). The *Schizaster libycus* Sandstone is an important timeline for correlation of the El Gharaq Formation in the central part of Wadi Hitan and the Gehannam Formation farther to the east (Strougo 2008).

Birket Qarun Formation

The type locality of the Birket Qarun Formation is in cliffs bordering the northern shore of lake Birket Qarun (Said 1962), and the type-section is thus the steep-faced precipitous escarpment described by Beadnell (1905) at the western end of the lake. There Beadnell (1905: p. 46 and fig. 5) described the succession as starting at the bottom with gray and brown clays, 18 m thick (Beadnell's bed 14), followed upward by 17 m of "soft light yellow sandstones with harder shelly bands and occasional concretionary beds, forming vertical cliff-wall" (bed 13). The top of the Birket Qarun succession, 15 m thick, consists, according to Beadnell, of two dark clay layers (beds 12 and 10), interbedded with yellow (bed 11) and dark brown ferruginous (bed 9) sandstones, the latter very rich in macroinvertebrates and nummulites.

Leaving aside differences in the thickness of the beds, the stratigraphic section just described is similar in almost every respect to that overlying the Gehannam Formation at Garet Gehannam in Wadi Hitan. The succession overlying the *Schizaster libycus* Sandstone at Garet Gehannam starts, as it does at the west end of Birket Qarun, with thick dark gypseous clays, mudstones and muddy sandstones. We regard these clays and mudstones as representing the base of the Birket Qarun Formation rather than including them, as Gingerich (1992) did, as part of the Gehannam Formation. The basal gypseous clays and mudstones are overlain by massive, poorly-bedded, clean sandstones, and the Birket Qarun Formation ends with dark clay layers interbedded with shelly sandstones. In the central and western parts of Wadi Hitan, the upper clay beds may be very thin locally or completely absent. The first appearance of the large anomiid bivalve *Carolia placunoides* marks the base of the Qasr El Sagha

Formation, as discussed below, and simultaneously defines the top of the Birket Qarun Formation.

Beadnell (1905, p. 48) wrote concerning the upper contact of the Birket Qarun Formation: "The exact junction between the Birket El Qurûn series and the overlying Qasr El Sagha beds is naturally perfectly arbitrary, many of the fossils being common to both groups. *Carolia placunoides*, which is perhaps the most abundant fossil in the Qasr El Sagha series, is sometimes very common in the upper beds of the underlying group, and… common enough in the still lower *Nummulites gizehensis* beds of Wadi Rayan." However, it has been shown repeatedly that the sudden, widespread occurrence of *Carolia placunoides*, when correctly identified, marks a very significant biostratigraphic event in many parts of Egypt (Strougo, 2008, and references therein). The large size (up to 13 cm) and abundance of *C. placunoides* (forming banks sometimes several decimeters thick) make it easy to recognize in the field. The first appearance of *C. placunoides* has been used to delineate the boundary between the Wadi Garawi and Wadi Hof formations in the greater Cairo area and in the Eastern Desert (Strougo, 1985a,b, 1988, 1992; Strougo and Abd-Allah, 1990), and also to delineate the boundary between the Birket Qarun and Qasr El Sagha formations elsewhere in the Western Desert (Strougo, 1979, 2008; Strougo and Hottinger, 1987; Adnet et al., 2011).

The so-called *Carolia placunoides* of the Wadi Rayan Group alluded to by Beadnell (1905) is a different genus and species called *Wakullina* (*Huyella*) *lefevrei* (Strougo, 1977, 1983). Beds bearing *C. placunoides* that Beadnell considered to be part of the Birket Qarun Formation are those at the base of the Qasr El Sagha Formation. Thus defined, the Birket Qarun Formation in Wadi Hitan is easy to recognize in the field. It is bounded by two prominent marker horizons: (1) a lower contact at the top of the *Schizaster libycus* Sandstone; and (2) an upper contact coinciding with the first occurrence of *Carolia placunoides*.

Qasr El Sagha Formation

In Wadi Hitan, as in the northern part of Fayum north of Birket Qarun, the full succession of the Qasr El Sagha Formation has to be pieced together from two superposed escarpments separated from each other by a plain several kilometers wide. The lower escarpment bounds the Wadi Hitan valley itself on the north. The upper escarpment is well exposed at Minqar Abyad, at the northwestern corner of the greater Wadi Hitan study area, where it is overlain by the continental Gebel Qatrani Formation.

The basal bed of the Qasr El Sagha Formation is invariably a calcareous sandstone or sandy limestone up to 20 cm thick, packed with *Carolia placunoides*. This is overlain by sediments typically arranged in coarsening upward parasequences. Individual parasequences start with dark shales at the base, transition gradually to siltstones and sandstones, and end with a shell bed at the top. The shell beds are commonly monospecific banks composed of large, thick-shelled oysters including *Ostrea* (*Turkostrea*) *strictiplicata* and *Nicaisolopha clotbeyi*, the anomiid bivalve *Carolia*, the gastropod *Turritella*, or, occasionally, nummulites. Other shell beds, however, contain a very rich and diverse macroinvertebrate assemblage including

FIGURE 4 — Southern face of Garet Gehannam showing the *Schizaster libycus* Sandstone of the uppermost Gehannam Formation (below the dashed line). The Birket Qarun Formation overlies the dashed line and the basal part of the Qasr El Sagha Formation caps the escarpment.

bivalves, gastropods, echinoids, crustaceans, serpulids, and bryozoans.

This package of parasequences is similar to the succession of facies displayed in the upper part of the Qasr El Sagha Formation at Qasr El Sagha itself, described by Vondra (1974), for which Bown and Kraus (1988) coined the terms Temple Member and Dir Abu Lifa Member. In Wadi Hitan, as at Qasr El Sagha, the upper part of the Qasr El Sagha Formation includes the Temple and Dir Abu Lifa members. The Dir Abu Lifa Member starts with giant foresets of cross-bedded sandstones, siltstones, and clays forming a prominent, vertical cliff-face, and ends in a highly indurated dolomitic sandstone or sandy limestone containing abundant echinoids and internal molds of molluscs — the so-called 'Bare Limestone' of Bowen and Vondra (1974) and subsequent authors.

Peters et al. (2009) recently described an incised valley fill complex in Wadi Hitan in the Umm Rigl Member of the lower Qasr El Sagha Formation. This was produced by an estimated 45 m drop in sea level, resulting in transient subaerial exposure of much of the area. Peters et al. interpreted this incised valley as a Type-1 sequence boundary, which they correlated to the Priabonian Pr-2 sequence boundary of Hardenbol et al. (1998). The base of the valley fill sediments is marked by a conglomeratic bed with abundant and highly diverse vertebrate remains, including isolated bones of *Basilosaurus*, *Dorudon*, dugongs, and the land-mammal proboscidians *Moeritherium* and *Barytherium*. Interestingly, the fossil content of this conglomeratic bed strongly recalls beds 16-17 described by Beadnell (1905, p. 51-52) from the type locality at Qasr El Sagha, where he wrote "…the beds 16 and 17 yielded a considerable number of land-animal remains, all of which occurred within a fairly confined space, suggesting that they had been carried out from the land to this point by a strong river current…"

CALCAREOUS PLANKTON BIOZONATION OF WADI HITAN

Calcareous plankton studied here came from four stratigraphic sections ('S') in Wadi Hitan. The sections were sampled at the localities shown on the map in Figure 2. Note that section S339 is a continuation upward of the section that starts at S338:

S329: Isolated hillock on the north side of the imposing hill-mass of Garet Gehannam. The section here is entirely Gehannam Formation, which overlies white nummulitic limestone of the El Gharaq Formation (seen nearby on the plain to the north). The stratigraphic distributions of planktonic foraminifera and
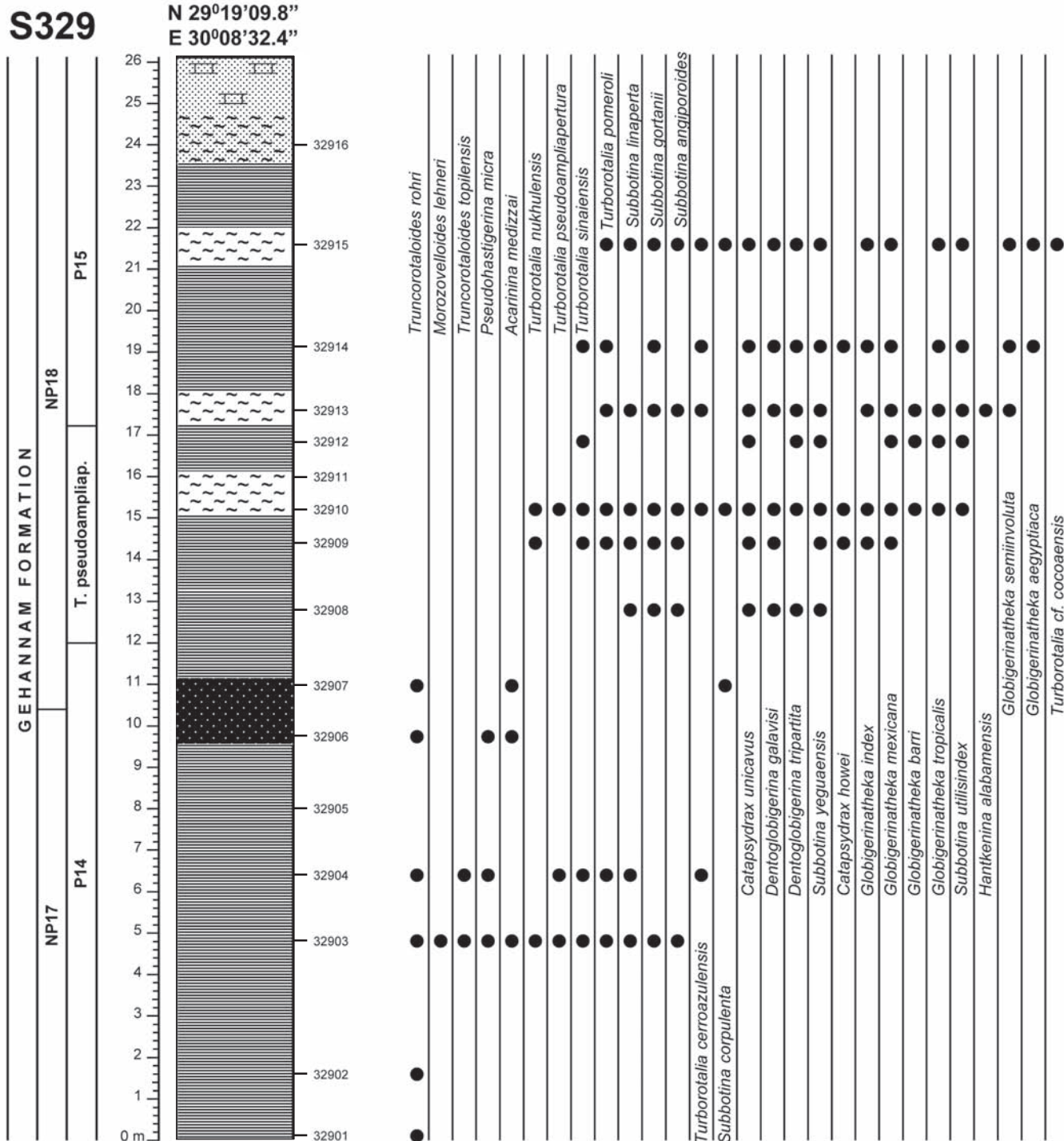
FIGURE 5 — Stratigraphic column for section S329 on the north side of Garet Gehannam (Fig. 2), showing the stratigraphic position of sampled intervals and corresponding occurrences of planktonic foraminifera. The legend for lithologies is included in Figure 9.

FIGURE 6 — General view of section S338 in Wadi Hitan (Fig. 2) showing the El Gharaq Formation. The floor of the plain is a white lime-stone packed with large nummulites. Arrow points to the Wadi Hitan Glauconite Layer.

calcareous nannofossils are tabulated in Figure 5 and Table 1, respectively.

S338: An elongated, low hillock situated a few kilometers southeast of the main entrance to Wadi Hitan. This exposes the oldest beds in the area, which belong to the El Gharaq Formation (Fig. 6). The stratigraphic distributions of planktonic foraminifera and calcareous nannofossils are tabulated in Figure 7 and Table 2.

S339: Minqar El Hut. This is a natural continuation upward of section S338. It includes the uppermost beds of Gehannam-like El Gharaq Formation at the base, followed by the Birket Qarun Formation and ends in the basal part of the Qasr El Sagha Formation (Fig. 8). The stratigraphic distributions of calcareous nannofossils are tabulated in Table 3.

S340: Tabular plateau south and east of Garet Gehannam. This includes a few meters of El Gharaq Formation at the base, overlain by Gehannam Formation (Fig. 10). The stratigraphic distributions of planktonic foraminifera and calcareous nannofossils are tabulated in Figure 11 and Table 4.

Planktonic foraminifera and calcareous nannofossils are the most widely used biotic taxa for long-distance biostratigraphic correlation of marine strata, at least within comparable climatic belts. Widely used standard zonations are available for planktonic foraminifera (Bolli, 1957; Blow, 1979; Berggren et al., 1995; and Berggren and Pearson, 2005, 2006), and for calcareous nannofossils (Martini, 1971; Okada and Bukry, 1980). Both are used together because sometimes foraminifera appear not to be as sensitive to environmental change in critical intervals of interest, like the transition from the Bartonian to Priabonian

or middle-to-late Eocene, as calcareous nannofossils are. The Bartonian-Priabonian boundary of Berggren and Pearson (2005, 2006) falls in or near the middle of their planktonic foraminiferal zones P15 and E14.

In discussing planktonic foraminifera we use the 'P' zones of Berggren et al. (1995) rather than the redefined 'E' zones of Berggren and Pearson (2005, 2006). We do this because the two systems of zonation reflect different ways of subdividing the same range distribution (Pearson et al, 2006), and our sections have yielded foraminifera enabling recognition of the 'P' zones but not the 'E' zones (we have not found *Morozovelloides crassatus*).

Planktonic Foraminiferal Zonation of Wadi Hitan

Planktonic foraminifera are rare in both the El Gharaq and Gehannam formations of Wadi Hitan, and preservation is moderate to fairly good. Selected taxa are illustrated in Figure 12. The overlying Birket Qarun and Qasr El Sagha Formations did not yield any identifiable planktonic foraminifera.

Three biostratigraphic intervals are recognized at Wadi Hitan. From base to top, these are as follows:

(1) Truncorotaloides rohri *or* Acarinina rohri *Zone (P14).— Turborotalia pseudoampliapertura* associated with *Truncorotaloides rohri* (or *Acarinina rohri*) and *T. topilensis* in the lower part of the Gehannam Formation in sections S329 and S340 indicate the presence of the *Truncorotaloides rohri* Zone (P14). Haggag and Luterbacher (1995) reported the occurrence of *T. pseudoampliapertura* s. l. in several parts of Egypt in an interval corresponding to Zones P13 and P14,
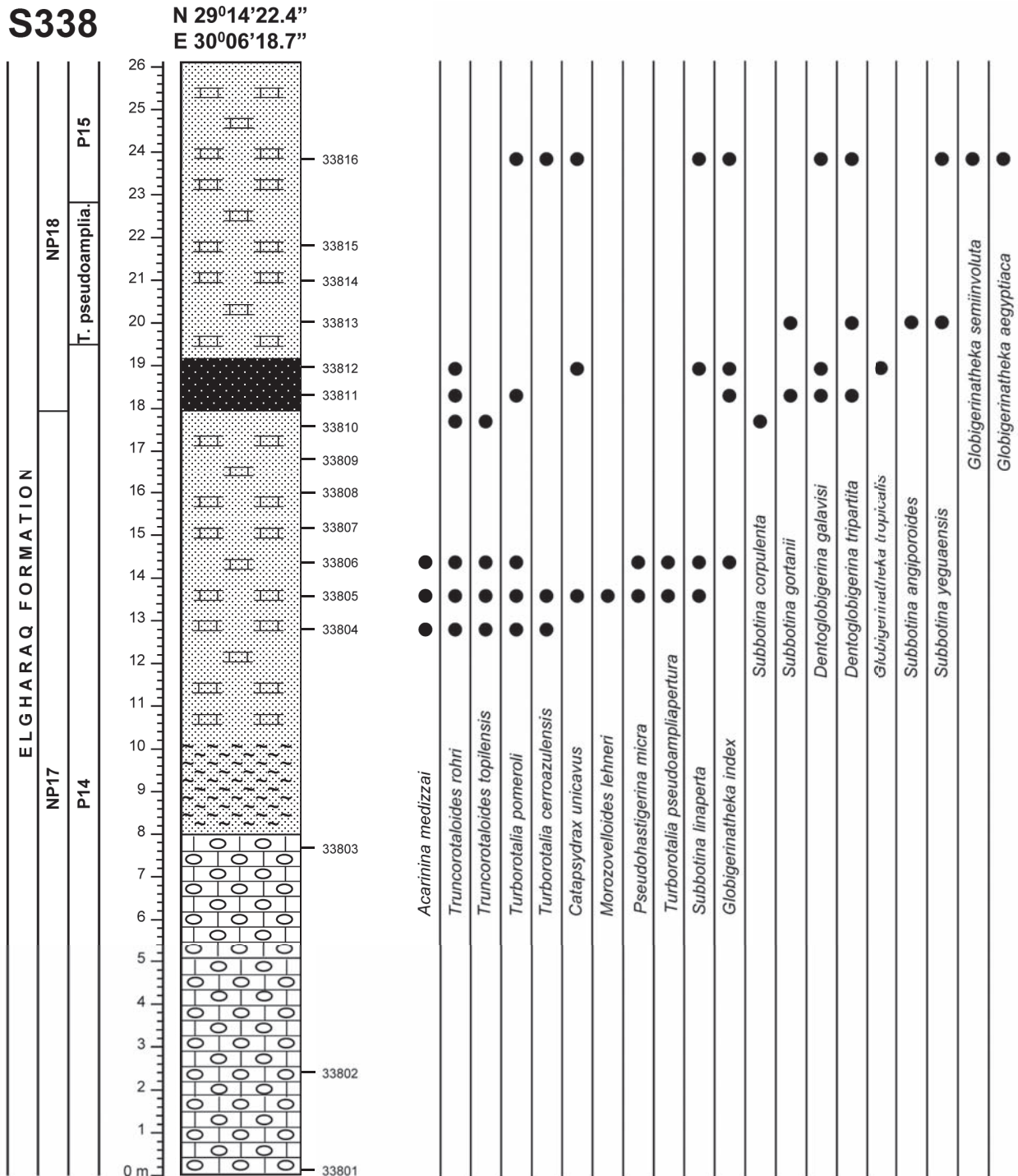
FIGURE 7 — Stratigraphic column for section S338 in Wadi Hitan (Fig. 2), showing the stratigraphic position of sampled intervals and corresponding occurrences of planktonic foraminifera. The legend for lithologies is included in Figure 9.
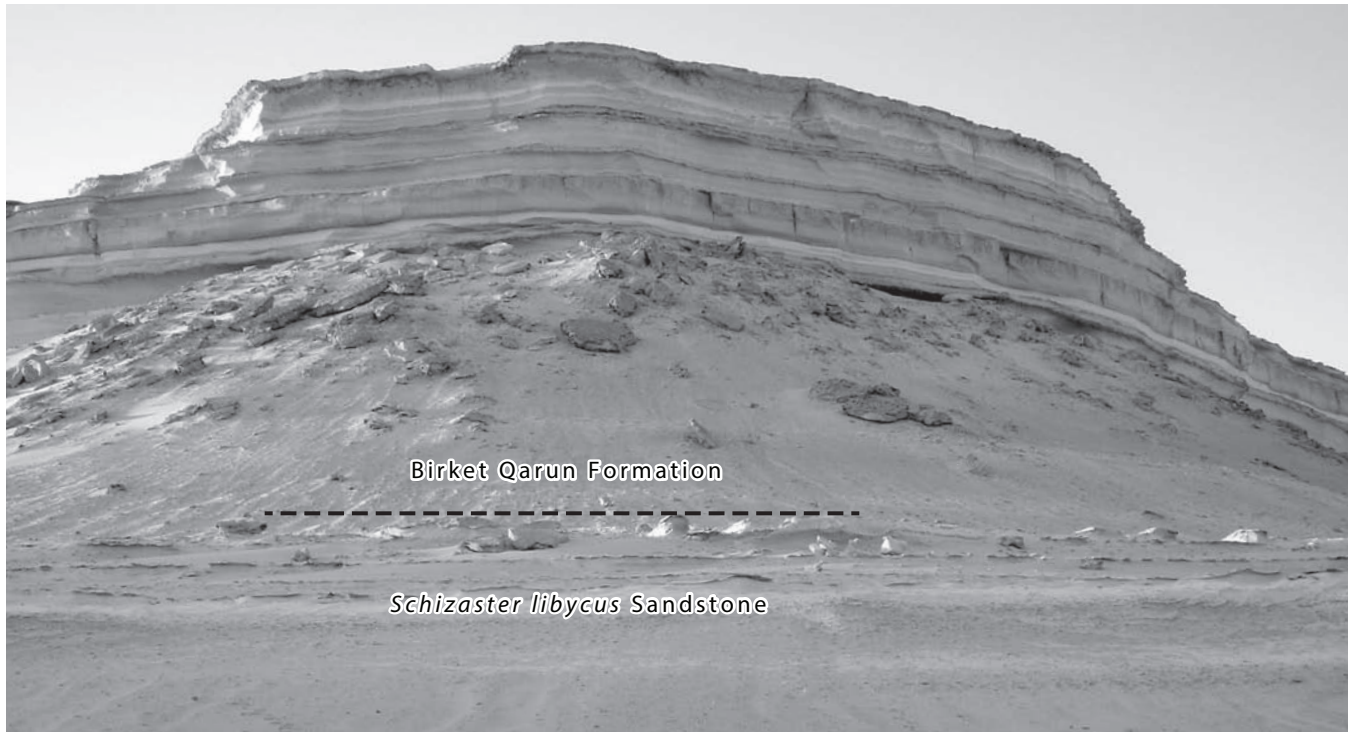
FIGURE 8 — Stratigraphic section at Mingar El Hut in Wadi Hitan (Fig. 2: S339). Successive ledges of *Schizaster libycus* Sandstone near the base of the section mark the top of the El Gharaq Formation. This is overlain by Birket Qarun Formation above the dashed line. The Qasr El Sagha Formation is present at the top of the escarpment here, but it does not appear in the photograph.

well below the level initially indicated for the species (Blow and Banner 1962). Similar reports of this early occurrence of *T. pseudoampliapertura* were previously given by Viotti and El Demerdash (1969) in Sinai, and by El Khoudary (1980) in Libya.

Haggag and Luterbacher (1995) distinguished three subspecies in the *T. pseudoampliapertura* lineage (herein treated as separate species): *T. p. nukhulensis* makes its initial appearance in Zone P13, succeeded upward by *T. p. pseudoampliapertura* at the base of Zone P14, with *T. p. sinaiensis* appearing in the upper part of Zone P14. It should be noted that there is a slight contradiction in Haggag and Luterbacher's paper. They stated in the text that *T. p. pseudoampliapertura* "has its first appearance at the base of the *Truncorotaloides rohri* Zone," whereas in their figure 2 the subspecies is mistakenly shown to range down into the upper part of the *Orbulinoides beckmanni* Zone. In Wadi Hitan, all three taxa of the *T. pseudoampliapertura* lineage occur together near the base of section S329 (in sample 32903; see Fig. 5), possibly suggesting a younger part of Zone P14. In section S340, *T. nukhulensis* and *T. pseudoampliapertura* co-occur at the very base of the succession, whereas *T. sinaiensis* first appears at the top of Zone P14 (Fig. 11). In the El Gharaq Formation (section S338) the lineage is very poorly represented (Fig. 7).

It seems, at least in Egypt, that the *T. pseudoampliapertura* lineage can be used either as an alternative to the *T. cerroazulensis* lineage (Toumarkine and Bolli, 1970) in the P13-P14 interval, or as an additional criterion for recognizing this time interval. Indeed, the abundance of representatives of the *T. pseudoampliapertura* lineage in the late middle Eocene and late Eocene of Egypt contrasts with the scarcity or absence of those of the *T. cerroazulensis* lineage (Haggag and Luterbacher 1995).

Pearson et al. (2006, p. 441-442) consider *Turborotalia pseudoampliapertura* to be a junior synonym of *T. ampliapertura,* characterizing the two species as contemporaneous. Pearson et al. (2006, p. 437) indicate that *T. ampliapertura* made its first appearance in zone P16. The type material of *T. pseudoampliapertura* from Tanzania may well be a synonym of *T. ampliapertura*, but we are using the name *T. pseudoampliapertura* to refer to specimens from Egypt that are older, P14-P15, and seemingly had a different evolutionary history (Haggag and Luterbacher (1995). We continue to use the name *T. pseudoampliapertura* for the older Egyptian material pending resolution of the taxonomic uncertainty.

(2) Turborotalia pseudoampliapertura *Zone (P15a).*— The interval from the extinction of *Truncorotaloides* spp. to the first appearance of *G. semiinvoluta* is confidently assigned to the *T. pseudoampliapertura* Zone of Haggag (1990). The final extinction of *Truncorotaloides* spp. occurs right above the highly glauconitic dark green bed (WHGL) intercalated within the lower part of both the Gehannam Formation and laterally equivalent upper El Gharaq Formation, thus indicating that this bed is a synchronous, stratigraphically useful field marker in the area. Haggag and Bolli (1995) described a new subspecies of *Globigerinatheka index* from the Guta section in Fayum, *G. i.*

S339

N 29⁰16'42.4"
E 30⁰04'59.8"

Shell beds alternating with clay, sandy mudstone and sandstone. Banks nearly monospecific, composed of very thick-shelled oysters, *Turritella, Carolia, Nummulites*

First *Carolia placunoides* Biohorizon

← Top of vertical cliff-face escarpment

Massive, unbedded to poorly bedded soft yellow sandstone, becoming harder and calcareous upward. Two thin beds, one in the middle and the other at the top, full of internal molds of a mactrid bivalve (*Crepispisula fourtaui*). Also thin, irregular stringers with clusters of small, thin-shelled oysters

Dark gray clay passing upward to mudstone and sandy mudstone. Frequent lucinid bivalves (*Pegophysema (Rawya)* gr. *pharaonis*)

S. libycus Sandstone. Fine grained calcareous sandstone, well-bedded, offwhite, contrasting with beds below and above, with abundant, remarkably well preserved echinoids (*Schizaster libycus*)

Covered interval

Frequent lucinid bivalves (*Pegophysema (Rawya)* gr. *pharaonis*)

Legend of Figures 2-5

|	
	Clay, mudstone & sandy mudstone
	Sandstone
	Calcareous sandstone
	Shell Bed
	Wadi Hitan Glauconite Layer (WHGL)
	Nummulitic limestone
	Marl

FIGURE 9 — Stratigraphic column for section S339 in Wadi Hitan (Fig. 2), showing the stratigraphic position of sampled intervals and corresponding occurrences of calcareous nannofossils.
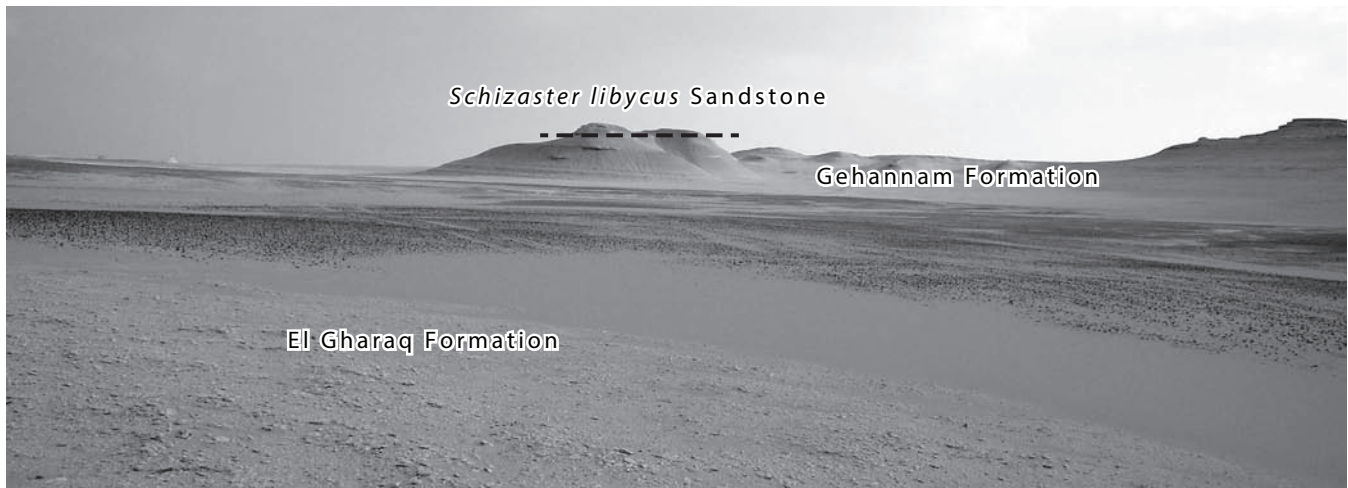
FIGURE 10 — Series of low hillocks lying south of Garet Gehannam in Wadi Hitan (Fig. 2: S340). Here the top of the El Gharaq Formation is the white limestone packed with large nummulites flooring the plain in the foreground. This is overlain by Gehannam Formation with a few meters of *Schizaster libycus* Sandstone at the top above the dashed line.

aegyptiaca, which first appears near the bottom of Zone P15. They derive it from *G. tropicalis* in the upper part of the *T. pseudoampliapertura* Zone, where transitional forms between the two taxa are observed. It became well established at the base of P15. Thus, typical forms of *G. i. aegyptiaca* can be used as an additional bioevent to approximate the lower boundary of Zone P15. In the Guta section (Haggag, 1985; Haggag and Bolli, 1995, 1996), as elsewhere in the world (Premoli Silva et al., 2006), the LO of *G. tropicalis* is in the upper part of P14; it is apparently somewhat delayed at Wadi Hitan as it first appears in the *T. pseudoampliapertura* Zone in sections S329 and S340 and in the topmost part of zone P14 in section S338. The extreme rarity of the species and its scattered presence in our samples may account for this retarded lowest occurrence.

(3) Globigerinatheka semiinvoluta *Zone (P15b).*— The LO of *G. semiinvoluta* in the upper part of the Gehannam and El Gharaq formations indicates the start of Zone P15, following the definition of Blow (1979) and Berggren et al. (1995) for the base of the zone. The abundance and diversity of planktonic foraminifera both drop sharply above the base of the zone. The *Schizaster libycus* Sandstone at the top of both the Gehannam Formation and laterally equivalent part of the El Gharaq Formation in the area, contains very rare and poorly preserved planktonic foraminifera.

<center>Calcareous Nannofossil Zonation of Wadi Hitan</center>

Reliable calcareous nannofossil associations were only observed in the lower part of the succession studied here, in the Gehannam Formation and equivalent part of the El Gharaq Formation, and in the lowermost part of the Birket Qarun Formation. A notable drop in species diversity is found at the Gehannam to Birket Qarun formational boundary. The samples generally contain common to abundant coccoliths, and the preservation is, in general, moderate to good. Representative forms are illustrated in Figures 13-15.

The abundance code used in Tables 1-4 translates as follows at 1250× magnification: A (abundant), more than ten specimens occurring per field of view; C (common), one to ten specimens per field of view; F (frequent), one specimen per one to ten fields of view; R (rare), one specimen per eleven to twenty fields of view; VR (very rare), one specimen per more than twenty fields of view.

The ranges of late middle Eocene and late Eocene calcareous nannofossil index taxa do not correlate well with established zonal schemes in many sections across the globe, as was discussed above. Most importantly, the LO of *Chiasmolithus oamaruensis* and *Isthmolithus recurvus*, used by Martini (1971) to define the bases of his Zones NP18 and NP19, respectively, appear not to be applicable in many sections. This becomes clear when nannofossil events are correlated to planktonic foraminifera zones. For example, in Egypt, *I. recurvus*, an unquestionable late Eocene taxon in standard zonations, has been found associated with an undisputed middle Eocene planktonic foraminiferal assemblage (Strougo and Faris, 2008); this observation is reconfirmed at Wadi Hitan. For this and other reasons, the NP17/NP18 zonal boundary recognized here must be regarded as tentative, while the boundary between NP18 and NP19-20 is impossible to clarify. Each concern will be considered in turn.

Concern 1.— The absence of *Chiasmolithus solitus* and *Chiasmolithus oamaruensis* in the basal part of the sections examined here indicates Zone NP17. However, the top of the zone is difficult to recognize because of the discontinuous distribution of *C. oamaruensis* in the basal part of its range (see below).

Concern 2.— The LO of *Chiasmolithus oamaruensis* occurs just above the extinction level of *Chiasmolithus grandis* in standard zonations. The two events have been shown to be problematic in many sections. At Wadi Hitan, *Chiasmolithus grandis* overlaps the lower range of *C. oamaruensis* in all the
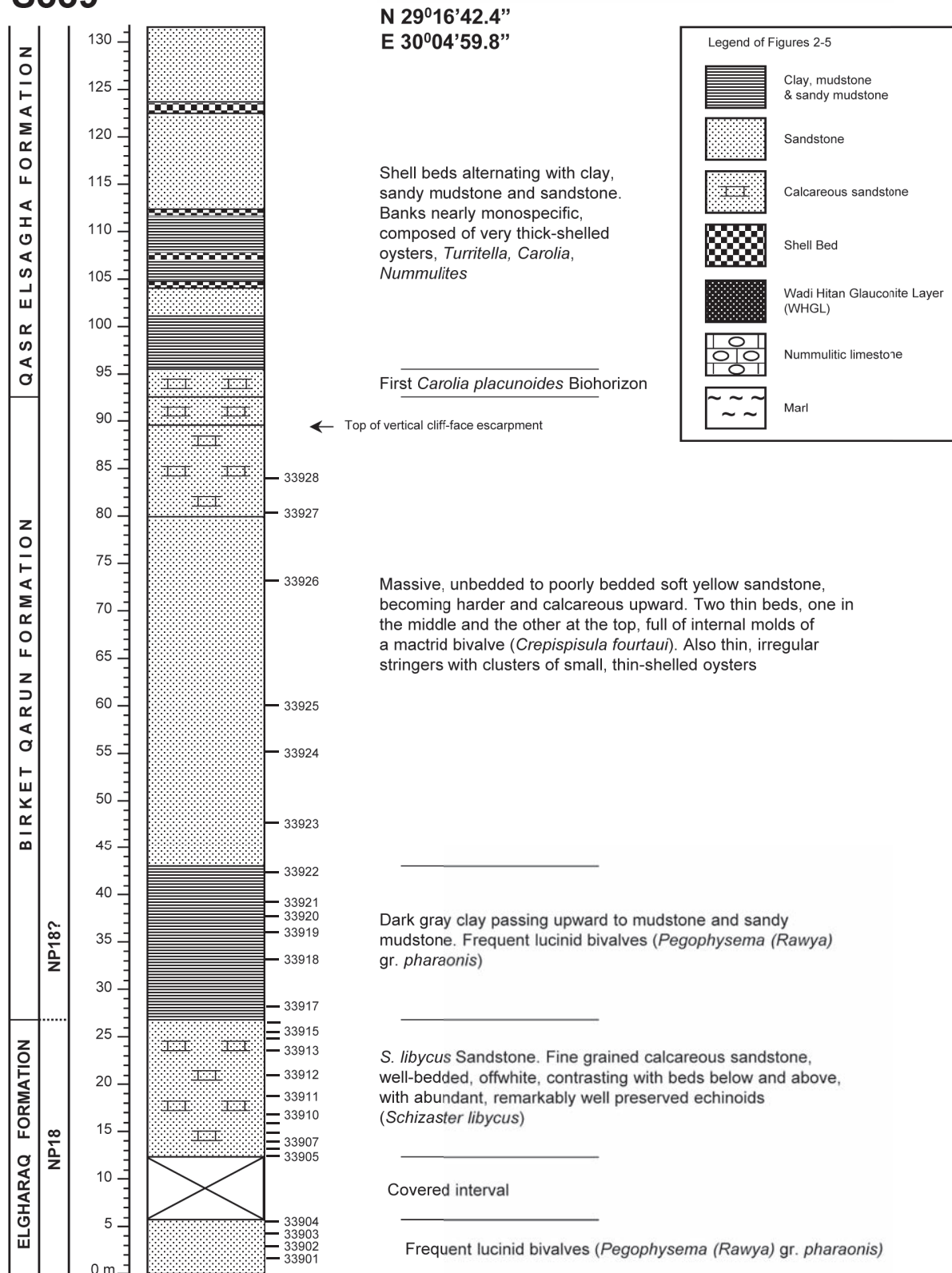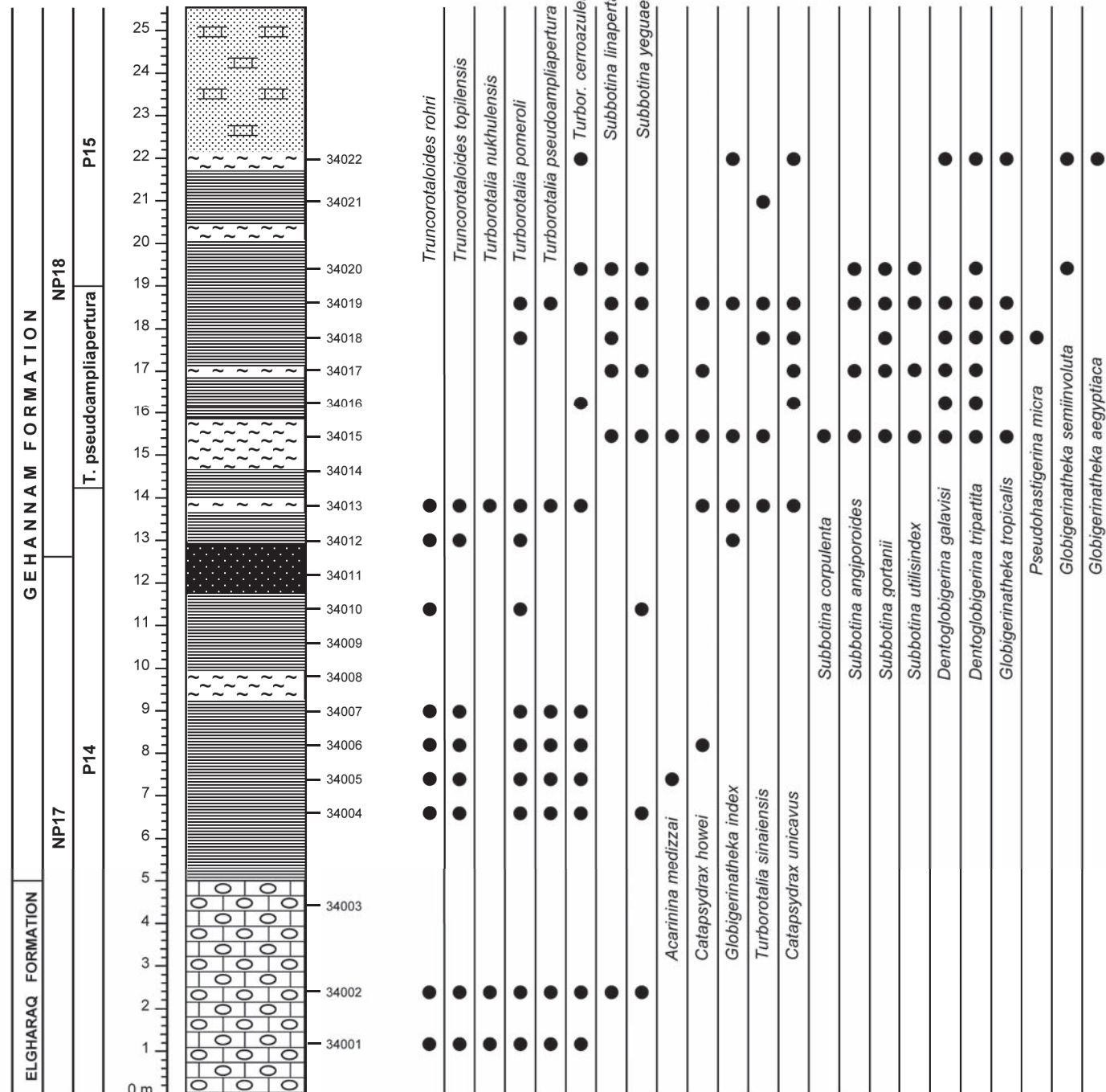
FIGURE 11 — Stratigraphic column for section S340 in Wadi Hitan (Fig. 2), showing the stratigraphic position of sampled intervals and corresponding occurrences of planktonic foraminifera. The legend for lithologies is included in Figure 9.

TABLE 1 — Distribution of calcareous nannofossils in the samples from section S329 (Fig. 2). Sample numbers are fourth and fifth digits added to the section number (e.g., 32901, etc.). Zone abbreviation: *T. p.*, *Turborotalia pseudoampliapertura* Zone. Abundance abbreviations: *A*, abundant; *C*, common; *F*, frequent; *R*, rare; *VR*, very rare. Preservation abbreviations: *G*, good; *M*, moderate. View abbreviations: *p.v.*, planar view; *s.v.*, side view.

Formation	GEHANNAM															
Planktonic foram zone	P14						T. p.					P15				
Nannofossil zone	NP17						NP18									
Sample number (329..)	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16
Abundance	A	F	C	C	A	A	C	A	A	A	A	A	C	A	A	A
Preservation	G	M	M	M	G	G	G	G	G	G	G	G	G	M	M	G
Braarudosphaera bigelowii	R	R	R	R	—	R	—	—	R	—	—	—	R	R	—	—
Chiasmolithus grandis	R	—	—	—	R	R	R	R	—	—	—	—	—	—	—	—
Coccolithus pelagicus	F	F	F	F	F	R	F	F	F	R	F	F	F	F	F	R
Cribrocentrum erbae	R	R	R	R	R	R	R	R	R	C	C	R	R	R	R	R
Cribrocentrum reticulatum	C	F	F	F	F	F	F	F	C	C	C	C	F	C	F	F
Dictyococcites bisectus	R	R	R	R	R	R	F	F	F	F	F	C	F	R	R	F
Discoaster saipanensis	R	R	R	R	R	R	R	R	R	R	R	R	—	F	F	F
Ericsonia formosa	R	R	R	R	F	R	R	R	F	F	R	F	R	R	R	F
Helicosphaera seminulum	R	—	R	—	R	R	R	R	R	R	R	R	R	R	R	R
Micrantholithus vesper	R	R	R	R	R	R	—	—	—	—	R	—	R	R	—	—
Pemma pasquensis	R	R	R	R	—	R	—	R	R	—	R	—	R	R	R	—
Pontosphaera multipora	R	R	R	—	R	R	—	F	F	R	R	R	F	R	R	R
Pontosphaera pectinata	R	—	R	—	R	R	—	R	R	R	R	R	R	R	R	—
Pontosphaera plana	R	—	R	—	R	R	—	R	R	R	R	—	R	R	R	R
Reticulofenestra hampdenensis	R	R	F	F	F	F	F	F	F	F	R	F	R	—	—	—
Reticulofenestra hillae	C	C	C	C	F	F	F	F	F	F	R	F	R	R	F	C
Reticulofenestra umbilica	R	R	R	F	R	R	R	R	F	F	F	F	R	R	R	R
Varolia cistula	R	R	R	R	R	R	R	R	R	R	R	—	—	—	—	—
Zygrhablithus bijugatus	F	R	R	R	R	F	R	F	R	R	R	—	F	F	R	R
Discoaster barbadiensis	—	R	—	—	—	R	R	—	—	R	—	R	R	—	R	—
Micrantholithus minutus	—	R	R	R	R	R	—	R	R	R	R	R	R	R	—	—
Scyphosphaera apsteinii	—	R	—	R	—	—	—	—	—	—	—	—	—	—	—	—
Coronocyclus nitescens	—	—	R	—	—	R	—	R	—	R	R	R	R	R	—	R
Sphenolithus moriformis	—	—	R	—	—	R	—	R	R	R	R	R	—	R	R	R
Varolia bloomeri	—	—	R	—	R	R	R	—	R	—	R	—	R	—	—	—
Discoaster tanii	—	—	—	R	—	R	R	R	R	—	R	R	R	R	R	R
Helicosphaera kamptneri	—	—	—	R	—	R	—	R	R	R	R	R	R	—	R	R
Discoaster deflandrei	—	—	—	—	R	R	—	—	R	—	—	—	—	—	—	—
Discoaster tani nodifer	—	—	—	—	R	R	—	—	R	R	R	R	R	—	R	—
Isthmolithus recurvus (s.v.)	—	—	—	—	R	R	R	R	R	R	R	R	R	R	R	R
Neococcolithes dubius	—	—	—	—	R	R	R	R	R	R	R	—	R	R	—	—
Neococcolithes minutus	—	—	—	—	R	R	R	R	R	R	R	—	R	R	—	—
Chiasmolithus oamaruensis	—	—	—	—	—	—	R	R	R	R	R	R	R	R	R	R
Cribrocentrum isabellae	—	—	—	—	—	—	R	R	R	—	—	R	R	F	F	R
Sphenolithus radians	—	—	—	—	—	—	—	—	—	—	R	R	R	R	—	—
Isthmolithus recurvus (p.v.)	—	—	—	—	—	—	—	—	—	—	—	—	—	R	R	R

TABLE 2 — Distribution of calcareous nannofossils in the samples from section S338 (Fig. 3). Sample numbers are fourth and fifth digits added to the section number (e.g., 33801, etc.). Zone abbreviation: *T. p.*, *Turborotalia pseudoampliapertura* Zone. Abundance abbreviations: *A*, abundant; *C*, common; *F*, frequent; *R*, rare; *VR*, very rare. Preservation abbreviations: *G*, good; *M*, moderate. View abbreviations: *p.v.*, planar view; *s.v.*, side view. Sample 33808 was barren.

Formation	EL GHARAQ															
Planktonic foram zone	P14												T. p.			P15
Nannofossil zone	NP17										NP18					
Sample number (338..)	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16
Abundance	F	F	F	C	F	C	C	—	F	C	A	A	A	A	C	A
Preservation	M	M	M	G	M	G	G	—	M	G	G	G	G	G	G	G
Braarudosphaera bigelowii	R	F	—	F	R	R	F	—	—	R	R	R	R	R	R	F
Coccolithus pelagicus	R	R	R	R	R	R	R	—	R	R	R	F	R	R	R	R
Coronocyclus nitescens	R	—	—	R	R	R	—	—	R	R	R	R	R	R	R	R
Cribrocentrum erbae	R	R	R	R	R	F	F	—	C	C	C	C	C	R	R	R
Cribrocentrum reticulatum	R	R	R	F	R	F	F	—	R	F	F	F	F	F	F	C
Dictyococcites bisectus	R	R	R	R	R	R	R	—	R	R	F	R	F	F	F	C
Discoaster barbadiensis	R	R	—	R	R	R	—	—	R	R	R	R	R	R	R	F
Discoaster deflandrei	R	R	—	R	—	—	—	—	—	R	R	R	R	R	R	R
Discoaster saipanensis	R	F	R	F	R	R	R	—	R	R	R	R	F	R	—	F
Discoaster tanii	R	R	—	R	—	R	—	—	R	R	R	R	R	R	R	R
Ericsonia formosa	R	R	R	R	R	R	R	—	R	R	R	R	R	R	R	F
Helicosphaera bramlettei	R	—	—	R	R	—	—	—	R	R	R	R	R	—	R	R
Isthmolithus recurvus (s.v.)	R	—	—	—	—	—	R	—	R	R	R	R	R	—	—	—
Micrantholithus vesper	R	R	—	R	R	R	R	—	—	R	R	R	—	R	R	R
Reticulofenestra dictyoda	F	R	R	F	F	F	R	—	F	F	F	F	R		F	R
Reticulofenestra hampdenensis	F	R	R	F	F	F	F	—	R	F	F	C	R	C	F	C
Reticulofenestra hillae	R	F	R	R	R	—	R	—	R	R	R	F	F	F	F	F
Reticulofenestra umbilica	R	R	R	R	R	—	—	—	R	R	F	F	R	F	R	F
Sphenolithus moriformis	R	R	R	R	R	R	R	—	—	R	R	R	R	R	R	—
Chiasmolithus grandis	—	R	—	R	—	—	—	—	—	—	—	R	R	R	—	—
Helicosphaera compacta	—	R	—	R	—	—	—	—	R	—	R	—	R	R	R	R
Helicosphaera lophota	—	R	—	R	—	R	—	—	R	—	R	R	R	—	R	—
Micrantholithus bramlettei	—	R	—	—	R	R	R	—	—	—	—	—	—	—	—	—
Micrantholithus discula	—	F	—	—	—	—	—	—	—	—	—	—	R	—	—	—
Neococcolithes minutus	—	R	—	R	—	R	—	—	—	R	R	R	R	R	—	R
Zygrhablithus bijugatus	—	R	R	R	F	R	R	—	—	R	R	F	F	F	F	F
Campylosphaera dela	—	—	—	R	R	—	—	—	—	—	—	—	—	—	—	—
Chiasmolithus oamaruensis	—	—	—	R	—	—	—	—	—	—	R	R	F	R	R	R
Discoaster tani nodifer	—	—	—	R	—	—	R	—	—	—	—	—	R	—	—	—
Neococcolithes dubius	—	—	—	R	R	—	—	—	—	R	R	F	R	R	—	R
Pontosphaera multipora	—	—	—	R	—	R	R	—	R	R	R	R	R	R	—	R
Pontosphaera pectinata	—	—	—	—	R	—	—	—	R	—	R	R	R	—	—	R
Pontosphaera plana	—	—	—	—	R	R	—	—	R	R	—	—	R	R	—	—
Cribrocentrum isabellae	—	—	—	—	—	R	—	—	—	R	R	—	—	R	R	R
Lanternithus minutus	—	—	—	—	—	—	R	—	—	—	—	—	R	—	R	R
Pontosphaera rimosa	—	—	—	—	—	—	—	—	R	—	—	—	R	R	—	—
Scyphosphaera apsteinii	—	—	—	—	—	—	—	—	—	—	R	—	—	—	—	—
Isthmolithus recurvus (p.v.)	—	—	—	—	—	—	—	—	—	—	VR	VR	VR	—	—	—
Pemma pasquensis	—	—	—	—	—	—	—	—	—	—	—	—	R	—	R	—
Sphenolithus radians	—	—	—	—	—	—	—	—	—	—	—	—	—	—	R	R

TABLE 3 — Distribution of calcareous nannofossils in the samples from section S339 (Fig. 4). Sample numbers are fourth and fifth digits added to the section number (e.g., 33901, etc.). Abundance abbreviations: *A*, abundant; *C*, common; *F*, frequent; *R*, rare; *VR*, very rare. Preservation abbreviations: *G*, good; *M*, moderate. View abbreviations: *p.v.*, planar view; *s.v.*, side view.

Formation	EL GHARAQ																BIRKET QARUN					
Nannofossil zone	NP18																NP18?					
Sample number (339..)	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22
Abundance	A	A	C	C	C	C	F	F	C	F	R	F	F	F	F	F	F	F	F	C	F	F
Preservation	G	G	G	G	G	G	M	M	M	M	M	G	G	G	M	G	M	M	G	G	G	G
Blackites spinosus	R	—	R	—	—	R	—	—	—	—	R	—	—	—	—	R	—	R	—	—	R	—
Blackites tenuis	R	R	R	R	—	R	R	R	R	R	R	R	R	R	—	R	—	R	R	—	—	—
Chiasmolithus oamaruensis	R	R	R	R	R	R	R	—	—	—	—	R	—	—	—	R	R	R	—	R	R	R
Coccolithus pelagicus	F	R	F	F	R	F	R	F	F	R	R	F	R	F	R	R	R	R	R	R	R	R
Coronocyclus nitescens	R	R	—	—	—	R	—	R	—	—	—	—	—	—	—	R	R	—	—	—	—	—
Cribrocentrum erbae	R	R	R	—	—	C	C	C	C	C	C	R	R	R	R	R	—	—	—	—	—	—
Cribrocentrum isabellae	R	R	—	R	—	R	—	—	R	—	—	R	R	R	R	R	R	R	R	R	R	—
Cribrocentrum reticulatum	F	F	R	R	—	F	R	R	F	R	F	R	R	R	R	R	R	R	R	R	R	—
Dictyococcites bisectus	R	F	R	—	R	R	F	R	R	R	R	—	R	R	R	R	R	R	R	R	R	—
Discoaster barbadiensis	R	R	R	R	R	F	—	R	R	—	R	—	R	R	—	—	—	R	R	R	R	R
Discoaster saipanensis	F	F	F	R	—	F	R	R	R	R	R	R	R	—	R	R	R	R	R	F	F	R
Discoaster tani nodifer	R	R	—	—	—	R	R	—	R	—	—	—	—	—	—	R	—	—	R	—	—	—
Discoaster tanii	R	R	R	R	R	F	R	R	R	—	—	—	—	—	—	—	R	R	R	R	—	—
Ericsonia formosa	R	R	R	—	—	F	R	—	R	R	—	R	R	—	F	F	—	R	F	R	F	R
Helicosphaera bramlettei	R	R	R	R	—	R	—	R	R	R	—	R	—	R	—	R	—	—	—	—	R	—
Isthmolithus recurvus (p.v.)	VR	VR	VR	—	VR	—	—	—	VR	—	—	—	VR	—	—	—	—	—	—	—	—	—
Isthmolithus recurvus (s.v.)	R	R	R	—	R	—	—	—	R	—	—	R	R	—	—	—	—	—	—	—	—	—
Pontosphaera formosa	R	R	R	—	—	R	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Pontosphaera multipora	F	F	R	—	—	R	R	R	R	R	—	R	—	—	—	R	—	R	—	—	—	—
Pontosphaera pectinata	F	R	R	—	—	R	—	—	R	—	—	—	—	—	—	—	—	—	—	—	—	—
Pontosphaera plana	R	R	R	—	—	R	R	R	—	—	R	R	—	—	R	—	—	—	—	—	—	—
Pontosphaera rimosa	R	R	—	—	—	—	—	—	—	—	—	—	—	—	—	R	—	—	—	R	—	—
Reticulofenestra dictyoda	R	R	R	R	R	R	R	R	R	F	R	R	F	F	F	R	F	R	R	R	F	R
Reticulofenestra hampdenensis	F	F	F	F	F	F	F	F	F	F	F	R	F	F	F	F	F	F	F	F	F	F
Reticulofenestra hillae	R	F	F	R	—	F	—	R	R	—	—	R	R	F	R	R	F	R	F	F	F	F
Reticulofenestra umbilica	F	F	F	R	—	R	R	R	R	—	R	R	R	R	R	R	R	R	F	R	R	R
Sphenolithus moriformis	R	R	—	—	R	R	R	—	—	—	—	R	—	R	—	R	—	R	R	—	—	—
Zygrhablithus bijugatus	R	F	R	—	R	R	R	—	R	R	R	—	—	—	—	—	—	—	—	R	—	—
Braarudosphaera bigelowii	—	R	—	—	—	—	—	—	R	—	—	R	—	R	—	—	—	—	R	—	—	—
Helicosphaera lophota	—	R	R	—	—	R	R	—	—	R	—	R	—	R	—	R	—	—	—	—	R	R
Neococcolithes minutus	—	—	R	—	R	—	—	—	R	—	—	—	R	—	—	—	—	R	—	—	—	—
Discoaster deflandrei	—	—	—	—	R	—	—	—	R	—	—	—	—	—	R	—	—	—	—	—	—	—
Helicosphaera compacta	—	—	—	—	R	—	R	—	R	—	R	—	R	—	—	—	—	—	—	—	—	—
Neococcolithes dubius	—	—	—	—	—	—	—	—	R	—	—	—	—	—	—	—	—	—	—	—	—	—

TABLE 4 — Distribution of calcareous nannofossils in the samples from section S340 (Fig. 5). Sample numbers are fourth and fifth digits added to the section number (e.g., 34001, etc.). Zone abbreviation: *T. p.*, *Turborotalia pseudoampliapertura* Zone. Abundance abbreviations: *A*, abundant; *C*, common; *F*, frequent; *R*, rare; *VR*, very rare. Preservation abbreviations: *G*, good; *M*, moderate. View abbreviations: *p.v.*, planar view; *s.v.*, side view.

	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22
Formation	EL GHARAQ		GEHANNAM																			
Planktonic foram zone	P14													T. p.						P15		
Nannofossil zone	NP17											NP18										
Abundance	C	C	A	A	C	C	F	F	C	A	A	A	F	F	A	A	A	A	A	A	F	F
Preservation	G	G	M	M	M	M	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
Blackites spinosus	R	—	R	R	R	R	R	R	R	R	R	R	R	—	R	R	R	R	R	R	R	R
Blackites tenuis	R	R	R	R	R	R	R	R	R	R	R	R	R	—	R	R	—	R	R	R	R	R
Campylosphaera dela	R	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Coccolithus pelagicus	R	F	R	R	R	R	R	R	F	R	F	R	R	R	F	R	F	R	R	R	R	R
Coronocyclus nitescens	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	—	—	—	—	—	—	—
Cribrocentrum erbae	R	—	F	R	R	R	—	—	—	—	—	R	R	R	R	R	R	R	R	R	R	R
Cribrocentrum reticulatum	R	—	F	F	R	F	R	F	R	F	R	F	F	R	F	F	F	F	F	F	R	F
Dictyococcites bisectus	R	R	F	R	F	R	R	R	F	R	R	F	F	F	C	F	F	F	R	R	F	F
Discoaster barbadiensis	R	R	F	F	R	R	—	—	R	R	R	R	R	R	R	R	R	R	R	R	R	R
Discoaster deflandrei	R	R	—	F	R	—	—	—	R	R	R	R	—	—	R	R	—	R	—	—	—	R
Discoaster saipanensis	F	F	F	F	R	R	R	R	F	F	R	F	R	—	R	R	R	R	F	R	R	R
Discoaster tani nodifer	R	R	R	R	—	—	—	—	R	R	—	R	R	—	R	R	R	R	—	R	—	—
Discoaster tanii	R	R	R	R	R	R	—	—	R	R	R	R	R	—	R	R	R	R	R	R	R	R
Ericsonia formosa	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	F	R	R	R	R	R
Helicosphaera bramlettei	R	R	—	—	R	—	—	—	R	R	R	R	R	—	—	R	R	R	—	R	—	—
Helicosphaera compacta	R	R	—	R	—	—	—	—	—	R	—	—	—	—	R	—	R	R	—	R	—	—
Helicosphaera lophota	R	R	R	R	R	—	—	—	R	R	R	—	—	—	—	R	—	—	R	R	R	R
Isthmolithus recurvus (s.v.)	R	—	—	R	—	—	R	—	R	R	—	—	—	—	R	R	R	R	—	—	—	R
Lanternithus minutus	R	R	R	R	R	R	—	R	R	R	R	R	R	R	—	R	R	R	R	R	—	R
Micrantholithus vesper	R	R	—	R	R	R	R	—	R	R	R	R	—	—	R	—	—	R	—	R	R	—
Neococcolithes minutus	R	R	R	R	R	—	—	—	R	R	R	R	R	R	—	—	R	R	R	—	R	R
Pontosphaera formosa	R	—	—	—	—	—	R	—	—	R	R	R	—	—	—	R	R	R	—	R	—	R
Pontosphaera plana	R	R	—	R	—	—	—	R	R	—	R	R	—	—	—	R	R	R	—	—	—	R
Reticulofenestra dictyoda	R	F	R	R	R	R	R	F	F	R	F	F	R	F	F	R	F	R	—	R	F	R
Reticulofenestra hampdenensis	F	R	F	F	F	R	F	F	F	R	F	R	F	R	F	R	F	R	F	F	F	R
Reticulofenestra hillae	F	C	F	F	F	F	R	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
Reticulofenestra umbilica	F	C	F	R	R	R	R	F	F	F	R	F	R	F	R	F	F	F	F	F	R	R
Zygrhablithus bijugatus	R	F	F	F	R	—	R	—	F	F	R	R	—	F	R	F	F	R	R	—	—	R
Braarudosphaera bigelowii	—	R	F	F	VR	R	R	R	—	R	R	R	—	—	R	R	R	R	R	R	—	—
Coronocyclus bramlettei	—	R	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	R	R	—
Neococcolithes dubius	—	R	R	R	R	—	—	—	R	R	R	R	R	R	—	R	R	R	R	R	—	R
Pemma pasquensis	—	R	—	—	—	—	—	—	—	—	—	R	R	—	—	—	—	R	R	F	—	—
Pontosphaera multipora	—	R	—	—	—	R	—	R	R	R	F	R	R	R	R	F	R	R	F	R	R	R
Pontosphaera pectinata	—	R	—	R	—	—	R	—	R	R	R	F	R	—	R	R	F	R	R	F	—	R
Scyphosphaera apsteinii	—	R	R	—	—	—	—	—	—	R	—	—	—	—	—	R	—	—	R	R	—	—
Sphenolithus moriformis	—	—	R	R	—	—	R	R	R	—	—	—	—	R	R	R	R	—	R	R	R	R
Micrantholithus bramlettei	—	—	—	R	R	F	R	R	—	R	R	—	—	—	—	—	—	—	—	—	—	—
Varolia bloomeri	—	—	—	R	R	R	—	—	—	R	R	R	—	—	R	—	—	—	—	—	—	—
Varolia cistula	—	—	—	R	—	R	R	—	—	R	R	R	—	—	R	—	—	—	—	—	—	—
Pema papillatum	—	—	—	—	—	—	R	—	—	—	R	—	—	—	—	—	—	—	—	—	—	—
Chiasmolithus grandis	—	—	—	—	—	—	—	—	R	R	—	R	—	—	R	R	R	R	—	R	R	—
Scyphosphaera columella	—	—	—	—	—	—	—	—	R	R	—	—	R	—	—	—	—	—	—	—	—	—
Chiasmolithus oamaruensis	—	—	—	—	—	—	—	—	—	—	—	R	—	—	F	F	R	R	F	R	R	R
Cribrocentrum isabellae	—	—	—	—	—	—	—	—	—	—	—	R	R	R	—	F	F	F	F	R	R	R
Pontosphaera rimosa	—	—	—	—	—	—	—	—	—	—	—	R	R	—	—	—	—	—	—	—	—	—
Isthmolithus recurvus (p.v.)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	R	—	R	R	—	—	—	—
Sphenolithus radians	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	R	—	—	R
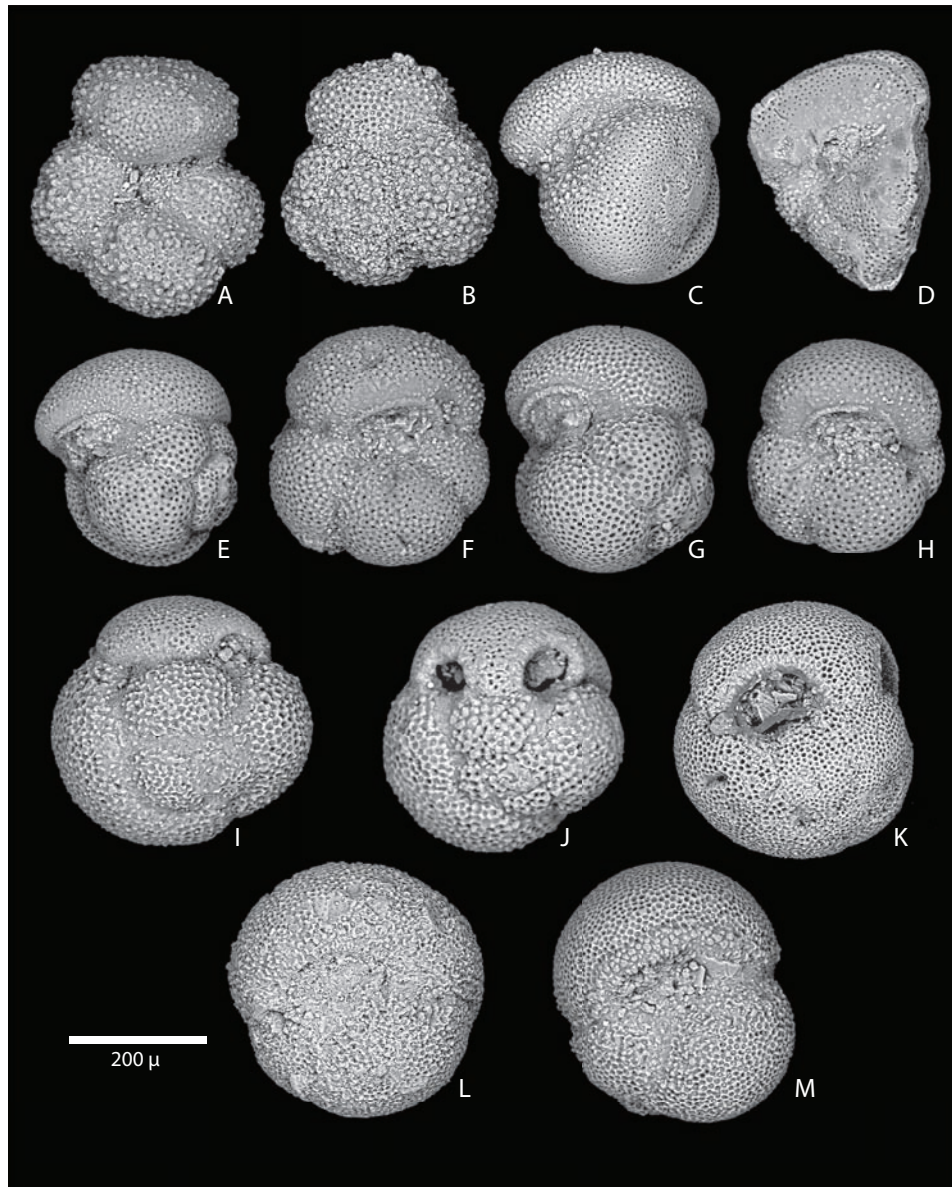
FIGURE 12 — **A-B,** *Truncorotaloides rohri* Brönnimann and Bermudez; sample 33806. **C,** *Turborotalia pomeroli* (Toumarkine and Bolli); sample 32910. **D,** *Turborotalia cerroazulensis* (Cole); sample 32913. **E,** *Turborotalia nukhulensis* Haggag and Luterbacher; sample 32910. **F-G,** *Turborotalia pseudoampliapertura* (Blow and Banner); F, sample 34007; G, sample 34019. **H,** *Turborotalia sinaiensis* Haggag and Luterbacher; sample 32903. **I,** *Globigerinatheka tropicalis* (Blow and Banner); sample 34019. **J,** Transitional form between *Globigerinatheka tropicalis* and *G. aegyptiaca*; sample 32912. **K,** *Globigerinatheka aegyptiaca* Haggag and Bolli; sample 33816. **L,** *Globigerinatheka index* (Finlay); sample 34019. **M,** *Globigerinatheka semiinvoluta* (Keijzer); sample 32913. Length of bar: 200 μ.

sections examined, which is consistent with observations previously made at Gebel Na'lun in the Nile-Fayum divide (Faris and Strougo, 1992) and outside of Egypt (Proto Decima et al., 1975; Shafik, 1983; Barbin, 1988; Fornaciari et al., 2010). Villa et al. (2008) have distinguished the LO from the LCO of *C. oamaruensis*, with only the latter, according to them, indicating the bottom of Zone NP18. We have attempted this distinction in our sections. In section S329, *C. oamaruensis* first appears in sample 32907 and continues uninterruptedly in all samples to the top;

i.e., the LO appears to coincide with the LCO. In section S338, the species has been found in rare frequencies in sample 33804, while its LCO is in sample 33811. In section S340, *C. oamaruensis* first appears in sample 34012, is absent over a very short interval in samples 34013 and 34014, and then reappears and extends continuously from sample S34015 to the top.

We have tentatively placed the lower boundary of Zone NP18 at the LO of *C. oamaruensis* in sections S329 (which, as said, is coincident with its LCO) and S340, and at the LCO of the
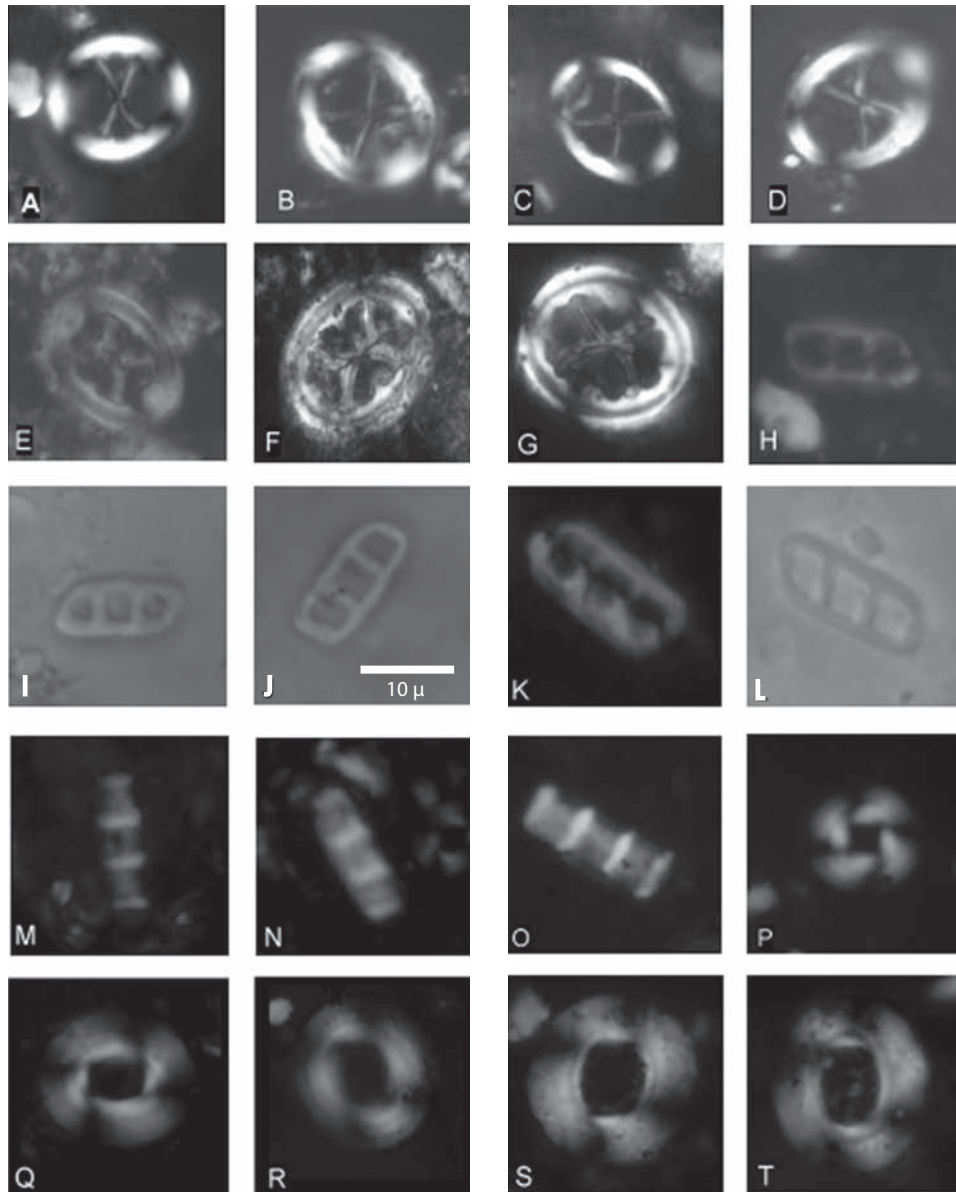
FIGURE 13 — **A-D,** *Chiasmolithus oamaruensis* (Deflandre, 1954); A, sample 33907; B, sample 33813; C, sample 32912; D, sample 34016. **E-G,** *Chiasmolithus grandis* (Bramlette and Riedel, 1954); E, sample 32908; F, sample 34015; G, sample 33804. **H-L,** *Isthmolithus recurvus* Deflandre, 1954, Planar views; H, sample 33905; I, sample 33813; J, sample 32916; K, sample 34016; L, sample 23913. **M-O,** *Isthmolithus recurvus* Deflandre, 1954, side views; M, sample 32909; N, sample 33912; O, sample 34004. **P,** *Reticulofenestra dictyoda* (Deflandre *in* Deflandre and Fert, 1954); sample 34017. **Q-R,** *Reticulofenestra hillae* Bukry and Percival, 1971; Q, sample 34002; R, sample 32904. **S-T,** *Reticulofenestra umbilica* (Levin, 1965); S, sample 33816; T, sample 33903. Length of bar: 10 μ.

species in section S338. With such an arrangement the bottom of Zone NP18 in all three sections has a fixed position relative to the planktonic foraminiferal zones: it correlates with the uppermost part of Zone P14. It also falls within the glauconite-rich horizon (WHGL) which, as we have seen, is a good datum in the area.

The top of Zone NP18 is difficult to recognize. All that can be said at present is that *Neococcolithes dubius*, whose upper range ends within the upper part of Zone NP18 (Perch-Nielsen 1985), has been found in the *Schizaster libycus* Sandstone that caps

the El Gharaq Formation in section S339 and the Gehannam Formation in section S340, suggesting that the NP18/NP19-20 zonal boundary lies above this horizon. There is some evidence in support of this assumption as we will now explain.

Concern 3.— The LO of *Isthmolithus recurvus* defines the NP18/NP19-NP20 zonal boundary in standard schemes. Data from several Egyptian sections indicate that the LO of *I. recurvus* is in fact much older than generally assumed in the literature (Strougo and Faris 2008), in agreement with other reports from
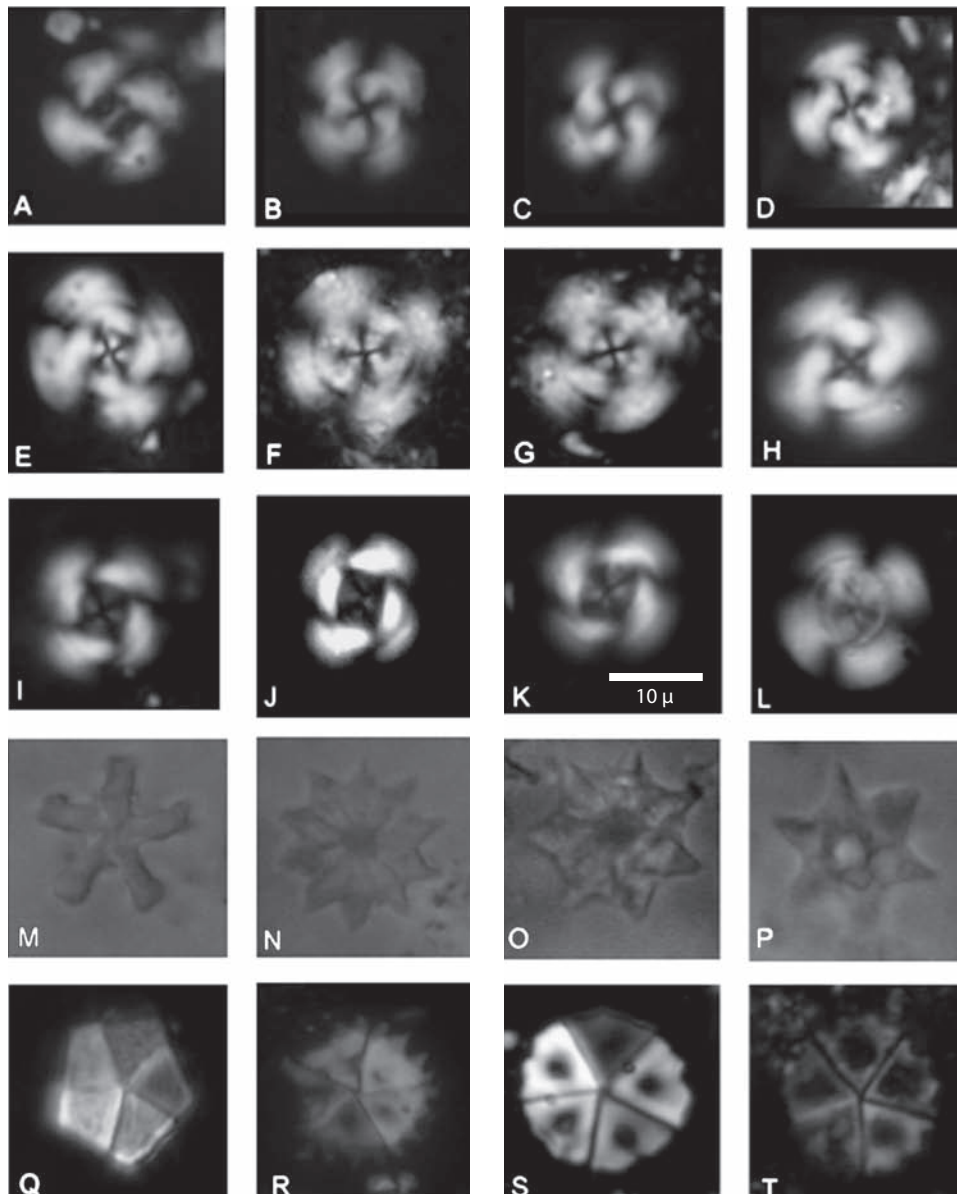
FIGURE 14 — **A,** *Reticulofenestra hampdenensis* Edwards, 1973; sample 32909. **B-D,** *Cribrocentrum erbae* Fornaciari et al., 2010; B, sample 34003; C, sample 32910; D, sample 33911. **E-H,** *Cribrocentrum isabellae* Fornaciari et al., 2010; E, sample 33914; F, sample 32912; G, sample 33814; H, sample 34019. **I-K,** *Cribrocentrum reticulatum* (Gartner and Smith, 1967); I, sample 34020; J, sample 33815; K, sample 32902. **L,** *Dictyococcites bisectus* Hay, 1966; sample 33814. **M,** *Discoaster tanii* Bramlette and Riedel, 1954; sample 32907. **N,** *Discoaster barbadiensis* Tan, 1927; sample 33816. **O-P,** *Discoaster saipanensis* Bramlette and Riedel, 1954; O, sample 33903; P, sample 34019. **Q,** *Braarudosphaera bigelowii* (Gran and Braarud, 1935); sample 32909. **R,** *Pemma papillatum* Martini, 1959; sample 34008. **S-T,** *Pemma pasquensis* (Martini, 1959); S, sample 33815; T, sample 32901. Length of bar: 10 μ.

outside of Egypt as well (Villa et al., 2008; Fornaciari et al., 2010). This has been confirmed at Wadi Hitan where *I. recurvus* is found from the base of the succession in sections S338 and S340, associated with planktonic foraminifera indicative of the Zone P14. The species occurs in rare frequencies throughout the succession with a very discontinuous distribution.

In section S229 *Isthmolithus recurvus* first appears in sample 22906 (again in Zone P14) and then it ranges continuously to

the top of the section, but it is rare throughout. One intriguing feature observed in all three sections is that only half pieces (or side views) of *I. recurvus* are observed in the lower range of the species, while typical whole specimens in planar views begin to appear higher up. The same observation was made by Strougo and Faris (2008), who remarked that in several sections in the Fayum whole specimens of *I. recurvus* only occur above the LO of *Globigerinatheka semiinvoluta* (P15). However, at Wadi
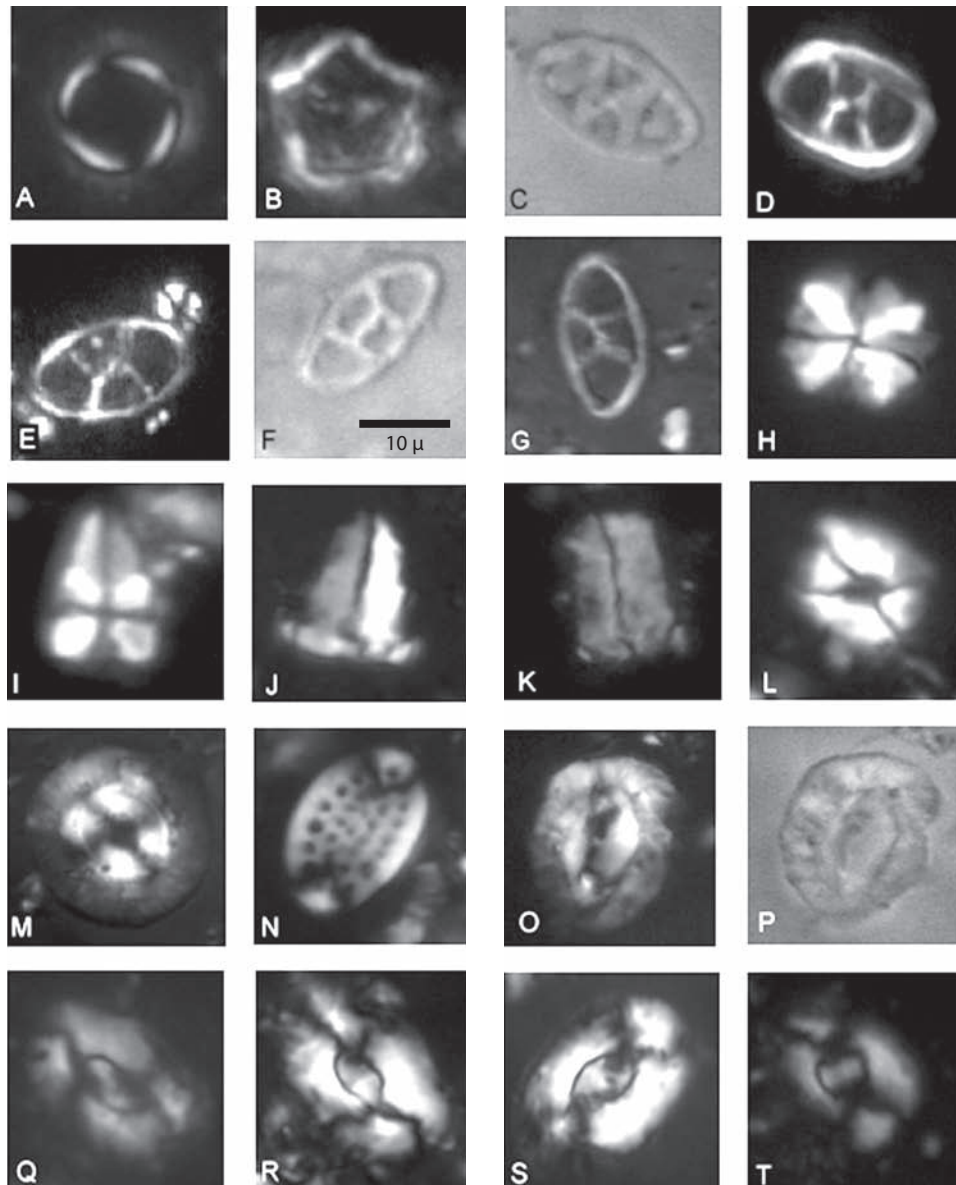
FIGURE 15 — **A,** *Coronocyclus nitescens* (Kamptner, 1963); sample 33902. **B,** *Varolia cistula* Bown, 2005; sample 32905. **C-E,** *Neococcolithes dubius* (Deflandre, 1954); C, sample 34020; D, sample 33909; E, sample 33816. **F-G,** *Neococcolithes minutus* Stradner, 1962; F, sample 34018; G, sample 33810. **H,** *Sphenolithus moriformis* (Brönnimann and Stradner, 1960); sample 32912. **I,** *Sphenolithus radians* Deflandre *in* Grasse (1952); sample 33816. **J-K,** *Zygrhablithus bijugatus* (Deflandre *in* Deflandre and Fert, 1954); J, sample 34017; K, sample 33902. **L,** *Lanternithus minutus* Stradner, 1962; sample 33813. **M,** *Ericsonia formosa* (Kamptner, 1963); sample 33816. **N,** *Pontosphaera multipora* (Kamptner, 1948); sample 34020. **O-P,** *Helicosphaera compacta* Bramlette and Wilcoxon, 1967; sample 33813. **Q,** *Helicosphaera bramlettei* Muller, 1970; sample 33810. **R-S,** *Helicosphaera lophota* Bramlette and Sullivan, 1961; R, sample 33921; S, sample 33815. **T,** *Helicosphaera seminulum* Bramlette and Sullivan, 1961; sample 32903. Length of bar: 10 μ.

Hitan this was found to be the case in section S329 only, planar views of whole specimens of *I. recurvus* occur with a Zone P14 planktonic foraminiferal assemblage in section S338 and with the *Turborotalia pseudoampliapertura* Zone in section S340.

In Tables 1-4 we have kept separate the half pieces (or side views) of *Isthmolithus recurvus* (indicated as s.v.) from whole specimens observed in planar view (indicated as p.v.) in order to show their respective ranges in the samples. The sporadic distribution of *I. recurvus* in sections S338 and S340 makes it impossible to recognize an LCO that, as suggested by Villa et al. (2008), would indicate the base of Zone NP19-20. In section S329, *I. recurvus* has a consistent distribution starting from sample S32906 and ranging to the top of the section, suggesting that the LCO of the species should be drawn right below this

sample. This, however, cannot indicate the base of Zone NP19-20 as it falls in Zone P14 and, additionally, it would lie at the top of Zone NP17.

Fornaciari et al. (2010) distinguished two new species in the genus *Cribrocentrum*, *C. erbae* and *C. isabellae*. We found them both in our material. Fornaciari et al. (2010) remarked that in northern Italy the LO of *C. isabellae* virtually coincides with LCO of *I. recurvus* and considered that it could be used as a supplementary bioevent for assessing the LCO of *I. recurvus*.

At Wadi Hitan, *C. isabellae* first appears toward the top of Zone P14, considerably lower than in northern Italy. Thus, although the LCO of *I. recurvus* and the LO of *C. isabellae* could be a useful tool for regional correlation, they do not seem to be applicable in long-range correlation across latitudes. Of course, it is possible that the difficulty of recognizing Zone NP19-20 in our study area is simply because the interval with calcareous nannofossils in the successions examined in this work ends below this zone. Peters et al. (2010) reported the occurrence of *I. recurvus* and *Neococcolithes minutus* in the marine sediments that enclose the incised valley fill reported one year before in the lower part of the Qasr El Sagha Formation at Wadi Hitan (Peters et al., 2009). The co-occurrence of these two taxa indicates that the incised valley fill formed in the basal part of Zone NP19-20 (Perch-Nielsen 1985), making the base of the Qasr El Sagha Formation here older than previously believed.

DISCUSSION

The utility and hence quality of any biostratigraphic zonation depends on the state of our understanding of the evidence being represented. Zonations depend on temporal successions and spatial distributions that are complex, and documentation grows with time. Hence it is not surprising that there are inconsistencies in standard zonations due to incomplete information. There are inconsistencies in zonations proposed at different times, there are inconsistencies between zonations based on different organisms, and there are inconsistencies in the temporal distributions of taxa sampled geographically. Index taxa are chosen to simplify complex patterns, and any zonation is contingent on the choice of index taxa.

Difficulties that preclude straightforward correlation using planktonic foraminifera and calcareous nannofossils include: (1) inconsistencies in the lowest stratigraphic occurrence ('LO') and highest stratigraphic occurrence ('HO') for index taxa in different sections; (2) inconsistencies in the definitions of some zones; (3) inconsistencies in the positions of planktonic foraminiferal zones relative to calcareous nannofossil zones; and (4) inconsistencies in the correlation of calcareous plankton zones to the global magnetostratigraphy (which has its own challenges due to sampling, etc.).

Fornaciari et al. (2010) and Agnini et al. (2011) have shown that many late middle Eocene to late Eocene index taxa in the genera *Discoaster*, *Chiasmolithus*, and *Isthmolithus* in the standard zonations of Martini (1971) and Okada and Bukry (1980) are very rare or absent in Tethyan sections. Fornaciari et al. (2010) and Agnini et al. (2011) then suggested alternative and additional biohorizons to refine the biostratigraphic classification for the late middle Eocene to late Eocene.

Here we review three uncertainties in standard biostratigraphic zonal schemes, and then focus on the middle Eocene to late Eocene boundary in Egypt.

Overview of Standard Biostratigraphic Zonal Schemes

According to most standard calcareous plankton zonal schemes, the planktonic foraminiferal assemblages around the middle Eocene-late Eocene boundary fall into two zones, *Truncorotaloides rohri* (or *Acarinina rohri*) Zone at the base and *Globigerinatheka semiinvoluta* Zone at the top, commonly codified as P14 and P15, respectively. Opinions diverge, however, as to the definition of the top of P14 and, hence, the bottom of P15: the last occurrence of *T. rohri* (Stainforth et al. 1975, Toumarkine and Luterbacher 1985), or the first occurrence of *G. semiinvoluta* (Berggren and Miller 1988, Berggren et al. 1995).

As long as using any one of these definitions seemed to make little difference in practice, there was no problem of adopting either of them. But Haggag (1990), examining the planktonic foraminiferal assemblages of the Gehannam Formation in four Fayum sections between Garet Gehannam and Guta, noted that the level at which *T. rohri* disappears is separated from the level at which *G. semiinvoluta* first appears by an interval up to 9 m thick. She placed this interval in a new zone, which she called the *Globigerina* (later changed to *Turborotalia*) *pseudoampliapertura* Zone. Haggag defined this zone as the interval above the last occurrence of *T. rohri* and below first occurrence of *G. semiinvoluta*. Two years later, the zone was identified at Jebel Hafit, UAE in the Arabian Peninsula (Anan et al. 1992).

An interval equivalent to the *T. pseudoampliapertura* Zone has been reported from the Spanish Pyrenees by Canudo and Molina (1992), but owing to the absence of the nominate species it was named the *Dentoglobigerina eocaena* Zone. More recently, Agnini et al. (2011) have shown that in the Venetian Alps the highest occurrence of large muricate forms (large *Acarinina* and *Morozovelloides*) occurs ca. 11 m below the lowest occurrence of *G. semiinvoluta*. Agnini et al. (2011) placed the intervening interval in the bottom part of Zone E14, which they show overlapping the base of Zone P14, the end of P14 being marked by the first appearance of *G. semiinvoluta* in P15 (Berggren et al., 1995). The end of P14 is generally regarded as preceding the beginning of E14 (Berggren and Pearson, 2005). Benjamini (1980) assigned a similar interval in the western Negev to the basal part of Zone P15 (below which *T. rohri* and genus *Morozovelloides* last occur).

The *T. pseudoampliapertura* Zone of Haggag (1990) allows a greater refinement of biostratigraphic correlation around the middle Eocene-late Eocene boundary and fills a gap between two highly significant events in low and middle latitudes: termination of morozovellids and *Truncorotaloides* at the bottom, and entry of *G. semiinvoluta* at the top (for more occurrences of this interval see Haggag, 1990; Agnini et al., 2011; and Wade et al., 2012).

Correlation of planktonic foraminiferal zones and calcareous nannofossil zones in the middle Eocene to late Eocene transition show numerous discrepancies. For example, the P14-P15 zonal boundary has been associated with the upper part of zone NP17 (Bolli et al., 1985; Luterbacher et al., 2004; Berggren and Pearson, 2005, 2006), with the NP17-NP18 zonal boundary (Hardenbol and Berggren, 1978), or with the lower part of zone NP18 (Cavelier and Pomerol, 1983, 1986). Recent studies have shown that biotic events used to define the NP17-NP18 (LO of *Chiasmolithus oamaruensis*) and NP18-NP19-20 (LO of *Isthmolithus recurvus*) zonal boundaries are poor biostratigraphic markers, unreliable in tropical areas (both are cool-water taxa) and even in extra-tropical areas (Backman, 1987; Persico and Villa, 2008; Villa et al., 2008; Strougo and Faris, 2008; Fornaciari et al., 2010; Agnini et al., 2011).

There are problems in positioning the first occurrences of two calcareous nannofossil index taxa, *C. oamaruensis* and *I. recurvus*. At ODP Site 748 in the Southern Indian Ocean (Kerguelen Plateau), Villa et al. (2008) distinguished two datums on the basis of abundance patterns: LO (lowest occurrence) and LCO (lowest common occurrence). Only the LCO for each species was considered to mark the base of the corresponding zone. However, Villa et al. (2008) found an interval containing rare specimens of the species below the LCO of *C. oamaruensis*, and consequently placed the LO of the species at the base of the interval of rare occurrence, in the upper part of Zone NP16. According to Fornaciari et al. (2010), the calibrations presently available for the LO of *C. oamaruensis* are highly contradictory, and diachrony between high and middle-to-low latitude areas has often been suggested. Fornaciari et al. found that the LCO of *C. oamaruensis* in some sections of northeastern Italy corresponds with the LO of the species in others, and they concluded that the LCO of *C. oamaruensis* is not a reliable event. Further, Persico and Villa (2008) found rare specimens of *I. recurvus* marking its LO below its LCO, which falls in the basal part of Zone NP18. Backman (1987) found a similar early occurrence of *I. recurvus* at Site 523 in the southern Atlantic Ocean, but interpreted this as downhole contamination. In Egypt *I. recurvus* was found to be associated with a typical middle Eocene planktonic foraminiferal assemblage, but here the distinction between its LO and LCO was not possible owing to the excessive rarity and sporadic distribution of the species throughout its range (Strougo and Faris 2008).

In conclusion, current planktonic foraminifera and calcareous nannofossil zonal schemes have inconsistencies that complicate interpretation of the middle and late Eocene in general, and the late middle Eocene to late Eocene transition in particular. Fornaciari et al. (2010), Agnini et al. (2011), and Wade et al. (2012) have proposed alternative or additional bioevents that, in their judgment, offer promise for refining the biostratigraphy of this interval and improving correlation over wide areas.

Middle-Late Eocene Boundary in Egypt

No global boundary stratotype section and point (GSSP) for the base of the Priabonian (middle Eocene-late Eocene boundary) has yet been designated. There have been many attempts in past decades to integrate radiometric dating and magnetic polarity time scales with more traditional biostratigraphic events to calibrate the numerical ages of stage boundaries, however at present the beginning of the Priabonian stage differs by as much as 1.5 m.y. among various authors (Agnini et al. 2011). The best chronostratigraphic control for the middle Eocene to late Eocene transition in Egypt is provided by planktonic foraminifera rather than calcareous nannofossils or larger foraminifera, even though the latter are useful biostratigraphically in many shallow water deposits across the country. Our discussion of the middle to late Eocene boundary here will be limited to biostratigraphic considerations because independent radiometric ages and integrated magnetostratigraphic data are lacking for the interval of interest in Egypt.

The Bartonian/Priabonian boundary is placed at the P14/P15 zonal boundary in many standard schemes, and virtually tied to the NP17/NP18 zonal boundary. In Egypt, however, the *Turborotalia pseudoampliapertura* Zone lies between P14 and P15. As discussed by Strougo (2008), the *Turborotalia pseudoampliapertura* Zone could be included in the top part of Zone P14, in the basal part of Zone P15, or it could constitute an independent entity, depending on the criteria used for definition of the zones. The boundary is thus elusive in chronostratigraphic terms. The *Turborotalia pseudoampliapertura* Zone could fall in the uppermost part of the Bartonian or in the lowermost part of the Priabonian. If, on the other hand, the LO of *Globigerinatheka semiinvoluta* is in the middle Eocene, as believed by some authors (Berggren and Miller, 1988; Berggren et al., 1995; Luterbacher et al., 2004; Premoli Silva et al., 2006), then the *T. pseudoampliapertura* Zone should definitely be assigned to the Bartonian.

Agnini et al. (2011) proposed the Alano section in the Veneto region (NE Italy) as a potential candidate for defining the base of the Priabonian Stage. They performed a detailed integrated magnetostratigraphic and biostratigraphic analysis of the section, the latter including planktonic foraminifera and calcareous nannofossils. Agnini et al. then suggested that the 'golden spike' defining the Bartonian-Priabonian boundary and the middle Eocene to late Eocene boundary should be placed at the base of what they called the Tiziano bed, a prominent crystal tuff layer, 14-16 cm thick. The Tiziano bed falls approximately halfway between the final extinction of large acarininas (and of the genus *Morozovelloides*) below, and the first occurrence of *Globigerinatheka semiinvoluta* above. The distance between the two events is approximately 11 m, covering a time span of nearly 330 ky. Wade et al. (2012) endorse this proposal, emphasizing the distinctive extinction of muricate planktonic foraminifera such as *Morozovelloides* but also a large turnover of radiolarians at the base of this interval. The planktonic foraminiferal events around the Bartonian-Priabonian boundary of the Alano section match nicely the situation observed at Wadi Hitan and in other parts of Egypt.

There is, on the other hand, a slight discrepancy with the calcareous nannofossils. At Alano, the LO of *Chiasmolithus oamaruensis* (Lowest Rare Occurrence, or LRO, of Agnini et al. 2011) is in the interval correlative with the *T. pseudoampliapertura*

Local Stage		Formation	Standard Stage	Main Event
Upper Mokattamian	MK12	Qasr El Sagha Fm.	Priabonian	
	MK11			
	MK10			↑ LO *Nummulites fabianii*
	MK9			↑ LO *Carolia placunoides*
Middle Mokattamian	MK8	Birket Qarun Fm.		↑ LO *Globigerinatheka semlinvoluta*
	MK7	El Gharaq/Gehannam Fm.	Bartonian	↓ HO *Truncorotaloides* spp.

FIGURE 16 — Important biostratigraphic events across the middle Eocene-late Eocene transition in Egypt. Mokattamian divisions and their corresponding formations in the Fayum follow Strougo (2008). Shaded band highlights the critical interval for drawing a Bartonian–Priabonian boundary. Abbreviations: *HO*, highest occurrence; *LO*, lowest occurrence.

Zone, whereas at Wadi Hitan it is associated with the upper part of Zone P14, consistent with data from elsewhere (Proto Decima, et al. 1975; Bigg, 1982; Cavelier and Pomerol, 1983, 1986; Strougo and Faris, 2008). Agnini et al. (2011) have cautioned not to rely too heavily on this event for age calibration. In other words, matching the NP17/NP18 zonal boundary with the Bartonian/Priabonian chronostratigraphic boundary must be discontinued.

Should the Alano section (and the Tiziano bed therein) be accepted in the future for delineating the GSSP of the Priabonian, then the *T. pseudoampliapertura* Zone of Egypt will have its base in the Bartonian and its top in the Priabonian.

Turning now to the shallow benthic foraminiferal zones (SBZ) of Serra-Kiel et al. (1998), the Bartonian-Priabonian boundary has been placed by these authors at the SBZ18/SBZ19 zonal boundary and correlated to upper zones P15 and NP18. *Nummulites ptukhiani*, in their scheme, encompasses zones SBZ17 and SBZ18 (Bartonian), correlated to upper Zone P12-lower Zone P15. Also, Schaub (1981) assigns *N. ptukhiani* to the uppermost part of the middle Eocene (Biarritzian). In Egypt, *N. ptukhiani* is confined to level MK8, corresponding to the Wadi Garawi Formation in the Nile Valley and to the Birket Qarun Formation in the Western Desert (Strougo, 2008). Its descendant, *N. fabianii* (Schaub, 1981), has been recorded in the Qasr El Sagha Formation (in MK10) on the northern plateau of the Bahariya oasis (Strougo and Hottinger, 1987). By general agreement, *N. fabianii* is characteristic of the Priabonian of the Tethyan realm (Cita, 1969; Blondeau, 1972; Herb and Hekel, 1975; Schaub, 1981; Strougo, 1992; Serra-Kiel et al., 1998). If one adopts the scheme of Serra-Kiel et al. (1998) and that of Schaub (1981), the Birket Qarun Formation could still fall in the Bartonian, and the middle Eocene-late Eocene boundary would be drawn somewhere around the Birket Qarun–Qasr El Sagha formational boundary; i.e., well above the top of the *T. pseudoampliapertura* Zone (Fig. 16).

Gingerich et al. (2012) mapped formational boundaries in Wadi Hitan with three-dimensional GPS coordinates of bed traces. Projection of the El Gharaq–Gehannam contact down dip indicates that there is topography developed on nummulite-rich carbonates of the El Gharaq Formation with overlying glauconite-rich beds (Gehannam Formation according to them) filling paleovalleys. This indicates a substantial unconformity between the two formations, which Gingerich et al. (2012) correlated to the Pr-1 sequence boundary of Hardenbol et al. (1998), a sequence boundary taken to mark the base of the Priabonian stage/age. In section S329, the erosional relief underlies the base of the succession; in sections S338 and S340 it falls between samples 33803–33804 and 34003–34004, respectively. Sea-level lowstands Pr-1 through Pr-4 are consistent with cooling events at or near the Bartonian-Priabonian boundary, within the Priabonian, and at the Priabonian-Rupelian boundary (Miller et al., 2005; Villa et al., 2008; Peters et al., 2010; Agnini et al., 2011: fig. 1). Sea level is important for late Eocene paleoclimate and global correlation, and it should be part of the conversation when defining a middle-to-late Eocene boundary.

CONCLUSIONS

Four stratigraphic sections were examined at Wadi Hitan for their planktonic foraminiferal and/or calcareous nannofossil content. Only the lower part of the succession, spanning the middle to late Eocene transition (El Gharaq Formation, Gehannam Formation, and basal part of the Birket Qarun Formation), contains a reliable record for these fossils. Owing to the many problems regarding the ranges of calcareous nannofossil marker taxa commonly used to construct standard zonal schemes, our chronostratigraphic interpretations are based mainly on planktonic foraminifera. But even the planktonic foraminiferal zones around the middle to late Eocene boundary need revision.

For example, the *Turborotalia pseudoampliapertura* Zone (or an equivalent interval), although today detected in numerous sections around the globe, has not received wide acceptance. It certainly occurs in the Alano section, proposed as a potential candidate for the GSSP of the base of the Priabonian Stage (Agnini et al. 2011). The *T. pseudoampliapertura* zone, lying above the final extinction of the genera *Truncorotaloides* and *Morozovelloides* (as well as all large acarininids) and below the initial occurrence of *Globigerinatheka semiinvoluta*, has been previously associated either with the *Truncorotaloides rohri* (or *Acarinina rohri*) Zone (P14) or the *Globigerinatheka semiinvoluta* Zone (P15).

The extinction of *Truncorotaloides* and *Morozovelloides* appears to be a crucial event at the middle Eocene-late Eocene transition, and we therefore advocate drawing the upper boundary of zone P14 at the top of this event and including the *T. pseudoampliapertura* zone at the base of zone P15. The latter zone should then be divided into two subzones: the *T. pseudoampliapertura* subzone (P15a) below, and the *G. semiinvoluta* subzone (P15b) above. The estimated duration of the interval between the HO of *Morozovelloides* and the LO of *G. semiinvoluta* at Alano is about 330 ky (37.996-37.665 Ma; Agnini et al. 2011), making it, together with the *Orbulinoides beckmanni* zone in the same section (estimated age: 40.253-39.922 Ma) the shortest recognized zones in the middle and late Eocene. If Wade (2004) is correct that the time between extinction of *Morozovelloides* and appearance of *Globigerinatheka semiinvoluta* at Site 1052 in the western North Atlantic is 20 kyr , then the *Turborotalia pseudoampliapertura* zone would be even shorter.

As concerns the calcareous nannofossils, it appears that the lowest occurrence of *Chiasmolithus oamaruensis*, the base of zone NP18 of standard schemes, correlates with the *Truncorotaloides rohri* zone, not with the *Globigerinatheka semiinvoluta* zone as indicated on some correlation charts (e.g., Berggren et al.,1995; Berggren and Pearson, 2005, 2006). At Wadi Hitan , the top of zone NP18 could not be properly defined, and it appears to be situated higher than the interval studied.

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