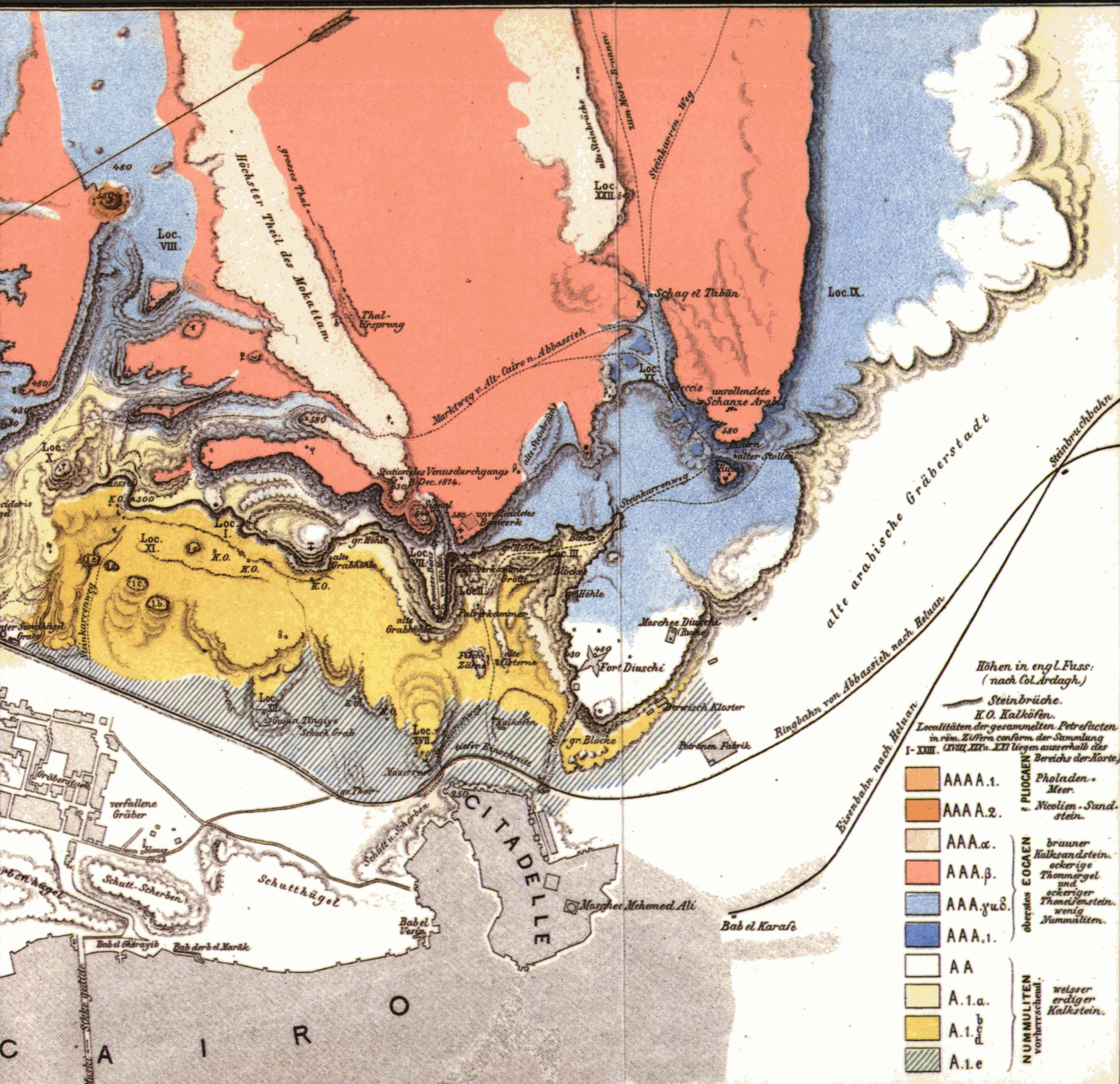
MARINE MAMMALS (CETACEA AND SIRENIA) FROM THE EOCENE OF GEBEL MOKATTAM AND FAYUM, EGYPT: STRATIGRAPHY, AGE, AND PALEOENVIRONMENTS

PHILIP D. GINGERICH



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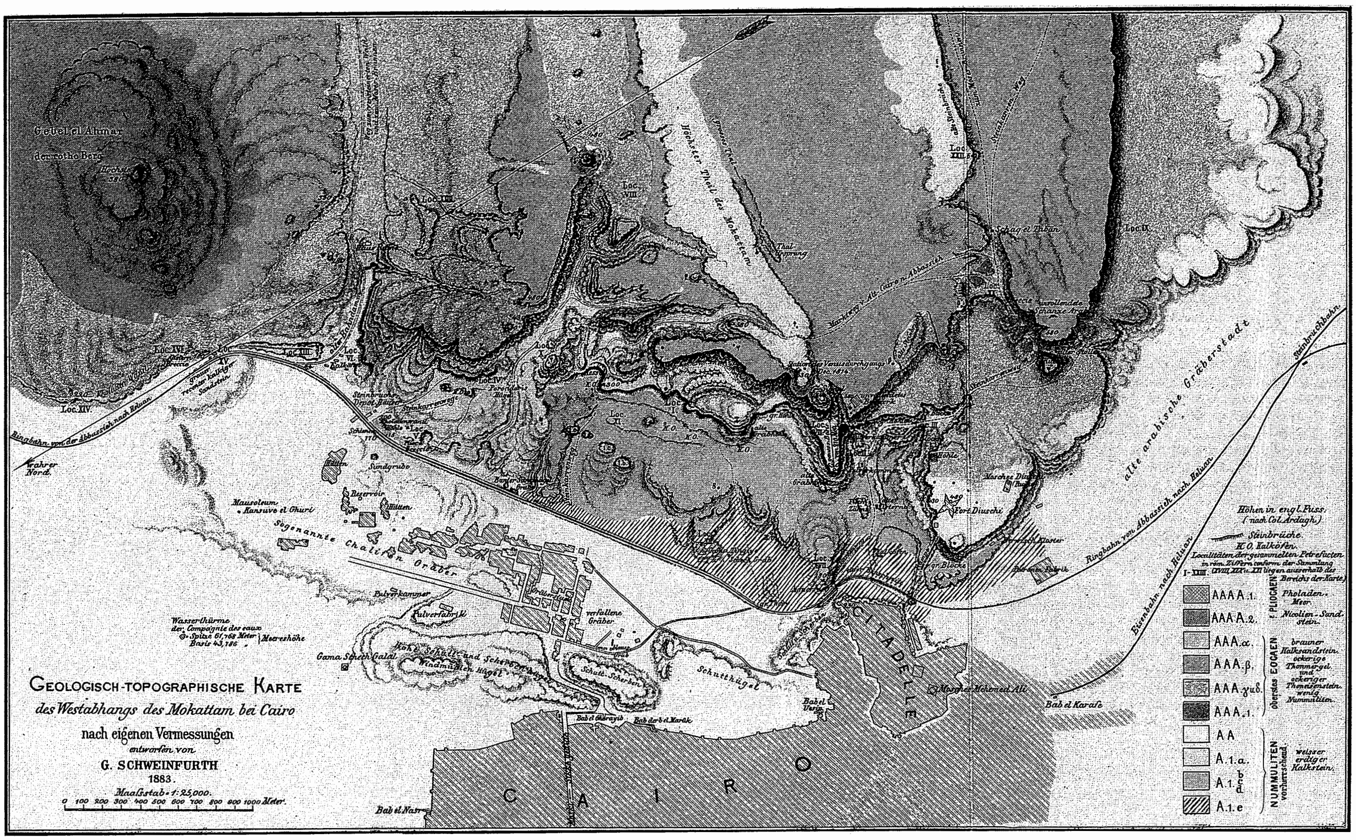

Frontispiece: Geological map of Eocene and Oligocene at Gebel Mokattam and Gebel Ahmar east of the great Citadel of Cairo, reproduced from Schweinfurth (1883). North is toward lower left of map. Schweinfurth's locality XII behind Tingiye Mosque (Gama Tingiye) in zone A1e has produced many fossil vertebrates.

MARINE MAMMALS (CETACEA AND SIRENIA) FROM THE EOCENE OF GEBEL MOKATTAM AND FAYUM, EGYPT: STRATIGRAPHY, AGE, AND PALEOENVIRONMENTS

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UNIVERSITY OF MICHIGAN
PAPERS ON PALEONTOLOGY NO. 30

1992

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Ann Arbor, Michigan 48109-1079

Philip D. Gingerich, Director

Published June 30, 1992

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ABSTRACT

Gebel Mokattam and Fayum are well known among vertebrate paleontologists for their rich and diverse faunas of Eocene marine mammals. Ten cetacean and seven sirenian species have been named from these two areas. The Eocene stratigraphy of each is reviewed here, and Fayum stratigraphy is supplemented with new observations.

The Mokattam Formation and most of the Giushi Formation at Gebel Mokattam are Lutetian and Bartonian (middle Eocene) in age, and these record deposition offshore in marine shelf and shallow shelf environments. The Maadi Formation at Gebel Mokattam is Priabonian (late Eocene) in age, and was deposited in nearshore and lagoonal environments.

The Wadi Rayan Formation and most of the Gehannam Formation in Fayum are Lutetian and Bartonian (middle Eocene) in age, and were deposited offshore in marine shelf and shallow shelf environments. The Birket Qarun Formation is earliest Priabonian (late Eocene) in age, and represents a long linear barrier bar complex buried during marine transgression. The Qasr el-Sagha Formation is Priabonian (late Eocene) in age, and most of it was deposited in lagoonal environments. The Qasr el-Sagha Formation is divided into four members: a shallow outer lagoonal Umm Rigl Member (new), a deeper central lagoonal Harab Member (new), a shallow inner lagoonal Temple Member, and, at the top, a non-lagoonal Dir Abu Lifa Member. The latter is interpreted to have been deposited on or near the fronts of submarine deltas and in interdeltaic nearshore marine environments. A dynamic stratigraphic model is developed relating sedimentary formations and facies in Fayum to sea level and sea level change. Middle and late Eocene formations at Gebel Mokattam and Fayum were deposited in similar environments, but Gebel Mokattam formations are thinner than their Fayum equivalents and Gebel Mokattam sediments accumulated farther offshore.

Comparisons to date indicate that six of the ten Eocene cetacean species described from Egypt are valid, and these represent at least five genera (*Dorudon osiris* is placed in the new genus *Saghacetus*). The cetaceans evolved rapidly and show no particular association with paleoenvironments. There are at least three valid species and possibly three genera of sirenians in the Eocene of Egypt. *Eotheroides* and *Protosiren* may have inhabited open shallow shelf environments while *Eosiren* inhabited lagoons, but interpretation is limited because here again genera are rarely known from the same environment at different times or different environments at the same time.

I

INTRODUCTION

Egypt has long been famous for its Eocene marine mammals, Sirenia and Cetacea, which have come principally from two areas: (1) Gebel Mokattam and nearby hills just east of Cairo, and (2) northwestern Fayum 100 km southwest of Cairo (see maps in Figs. 1 and 2). The first sirenian to be described was *Eotherium* [now *Eotheroides*] *aegyptiacum* named by Richard Owen in 1875 from Gebel Mokattam. The first cetaceans were found by G. Schweinfurth in 1879 on the island of Geziret el-Qarn in Fayum. In following years both areas yielded important specimens of Cetacea and Sirenia, and the named types are listed in Tables 1 and 2 at the end of this study. The taxonomic and morphological diversity of Eocene cetaceans and sirenians in Egypt cannot be evaluated without understanding their geological age and the diversity of environments they inhabited. This information is required too for proper comparison with Eocene Cetacea and Sirenia known elsewhere.

The Eocene of Egypt has been intensively studied for a long time (Blanckenhorn, 1921; Said, 1962, 1990), and the stratigraphy is unexpectedly complicated. This is due in part, ironically, to excellent exposures over a very broad area permitting sedimentary units to be studied in unusual detail. The literature is difficult because it is large and scattered, having been written in several languages and published on three continents over a period spanning more than 100 years. More serious, perhaps, is a long tradition of interpretation of geological formations as time slices accumulating like layers on an idealized country-wide stratigraphic cake. It is impossible to substitute a fully developed dynamic model for all the Eocene of Egypt, but it is clear that a dynamic model is required because sea level rose and fell while sedimentary formations in Egypt accumulated on the edge of a passively subsiding continental margin.

Two geological formations have yielded important marine mammals at Gebel Mokattam: the Mokattam Formation and the overlying Giushi Formation. Four formations have yielded marine mammals in Fayum: the marine Gehannam, Birket Qarun, and Qasr el-Sagha formations, and, in the case of one sirenian, the predominantly continental Gebel Qatrani Formation.

The history of study of these formations is presented in detail because earlier workers made many important geological observations and published stratigraphic sections that are essential for any comprehensive interpretation. The history of study of the Gebel Mokattam area is summarized first in Chapter II, followed by a summary for the Fayum area in Chapter III. New observations and new stratigraphic sections in Fayum are presented in Chapter IV.

Sea level sequence stratigraphy and implications for the geological age of the Gebel Mokattam and Fayum deposits are discussed in Chapter V. Paleoenvironmental interpretations of each of the Eocene formations at Gebel Mokattam and in Fayum are reviewed in Chapter VI. These formations have long been recognized as shallow marine deposits, but, to my knowledge, they have never been integrated into a single comprehensive stratigraphic model. After five seasons of field work in the Fayum, it has been possible to develop a dynamic model relating the Gehannam, Birket Qarun, and Qasr el-Sagha formations of Fayum to each other, and the model is extended to include formations at Gebel Mokattam. A review of the named species of Eocene Cetacea and Sirenia is included in Chapter VII. The species and their ranges are not yet as well known as one would like, and there is as yet only limited association of particular species with particular environments. Finally, Chapter VIII provides a summary of general conclusions and a brief prospectus for future work.

NOMENCLATURE OF INVERTEBRATE FOSSILS

The Eocene of Egypt is rich in invertebrate fossils, and these are important for interpretation of paleoenvironments. Mayer-Eymar (1883, 1898, 1900, etc.), Oppenheim (1903-1906), and Fourtau (1913) are among the many older authors who described Eocene invertebrates from Egypt. Many names used by early authors have been revised subsequently, and I have made some attempt to update these when possible (but invertebrate nomenclature is not a focus of this work).

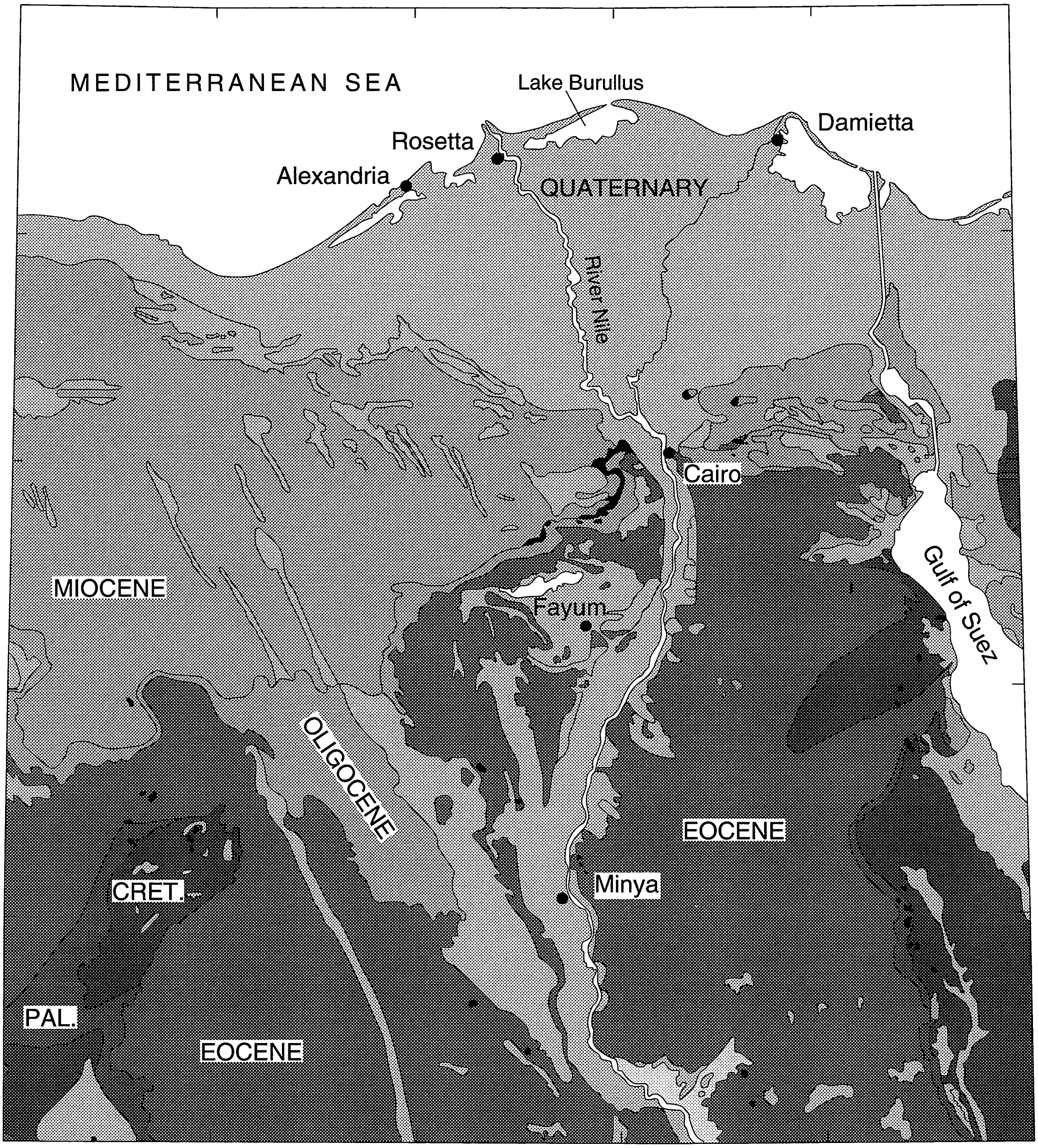


FIG. 1—Geological map of northeastern part of Egypt showing location of Fayum-Gebel Mokattam (Fayum-Cairo) area studied here (Fig. 2). Modern depositional settings in northern Egypt include open marine environments of the Mediterranean Sea, barrier-and-lagoon environments of Lake Burullus and other lagoons, active submarine delta fronts fed by the Rosetta and Damietta branches of the River Nile, and the fluvial continental coastal plain of the Nile Delta itself. Eocene sedimentary rocks (medium shading) were deposited in a similar north-south environmental sequence including open marine, barrier-and-lagoon or delta, backed by continental coastal plain. These transected an ancient coastline trending WSW-ENE like part of the present Egyptian coast. Note that lagoons and active delta fronts at river mouths alternate from east to west today, and the same was probably true in the Eocene. Abstracted from Geological Map of Egypt, scale 1:2000000 (Geological Survey of Egypt, 1981).

The standard work on Bivalvia is that of Oppenheim (1903-1906). Strougo (1988) published a very useful summary of current bivalve nomenclature, with ranges of the forms found at Gebel Mokattam and elsewhere near Cairo. Important taxa include *Carolia placunoides*, an isodont anomiacean bivalve (not an oyster) with large, thin, flat valves. The genus has a broader range, but Strougo limits the species *C. placunoides* to the late Mokattamian Stage (Priabonian). *Plicatula polymorpha* is an isodont pectinacean bivalve that ranges from early through late Mokattamian. Oysters are schizodont rather than isodont, and Egyptian Eocene oyster species placed in "*Ostrea*" or "*Gryphaea*" by earlier authors are now considered to represent *Crassostrea*, *Cubitostrea*, *Nicaisolopha*, *Ostrea (Turkostrea)*, or *Pycnodonte*. Many bivalves have narrow environmental tolerances, making them useful for paleoenvironmental interpretation but at the same time poor index fossils for correlation.

The standard work on Gastropoda is also Oppenheim (1903-1906), and I am not aware of any recent reviews.

Nummulites are benthic foraminifera that typically have rather localized geographic distributions and hence limited potential for correlation on a broad scale. Cuvillier (1930) wrote a major review, and he and others have supplemented this subsequently. *Nummulites gizehensis* is a conspicuously large middle Eocene nummulite several centimeters in diameter that is usually found in Lutetian sediments but may range upward into the Bartonian as well.

Roman and Strougo (1988) reviewed Eocene echinoids of greater Cairo.

The most widely studied Egyptian microfossils useful for worldwide correlation are planktonic foraminifera, which are not nearly as common as the larger benthic nummulites but evidently can be found when large enough samples of marine sediment are processed. These live in open marine waters but are less often found in nearshore or lagoonal environments. Bolli (1957) and Blow (1979) published the standard zonation widely used in Egypt and elsewhere (see also Toumarkine and Luterbacher, 1985). Important studies in Egypt include Krasheninnikov and Ponikarov (1965), Abdou and Abdel-Kireem (1975), Abdel-Kireem (1985), Haggag (1985, 1989, 1990), and Haggag and Luterbacher (1991).

ACKNOWLEDGMENTS

I thank Drs. D. C. Fisher and B. Wilkinson, University of Michigan, for discussion and literature on barrier bars and other shallow marine sedimentary environments and structures; Dr. Fisher for information on calcareous sponges, corals, and hardgrounds; Dr. C. E. Badgley, University of Michigan, for information on bone weathering; Dr. J. Kappelman, University of Texas, for showing me his preliminary interpretation of paleomagnetic stratigraphy; and Dr. A. Seilacher, Tübingen and Yale universities, for discussion of *Kerunia*. Drs. D. P. Domning, Howard University, and A. Miller, University of Cincinnati, provided information on callianassid shrimp and their association with seagrass beds. Dr. R. Feldmann, Kent State University, identified the *Lobocarcinus*. Research on Eocene Cetacea has been carried out jointly with Dr. B. H. Smith of the University of Michigan. Dr. Domning reviewed the sirenian systematics included in Table 2.

Dr. T. M. Bown, U. S. Geological Survey, generously provided maps and other information when this project started, and he was the first to identify mangrove in Wadi Hitan when we worked there together in 1985.

Drs. D. C. Fisher and G. F. Gunnell read and improved the entire text. Drs. T. M. Bown, J. Kappelman, D. T. Rasmussen, J. Van Couvering, and Messrs. W. Clyde, W. Sanders, and M. Uhen reviewed a draft of Chapter V.

I thank Drs. B. el-Khashab, Cairo Geological Museum, Cairo; K. Fischer and H. Jaeger, Museum für Naturkunde der Humboldt-Universität, Berlin; J. Hooker, Natural History Museum, London; E. Heizmann, Staatliches Museum für Naturkunde, Stuttgart; V. Fahlbusch and K. Heissig, Universitäts-Institut und Staatssammlung für Paläontologie und Historische Geologie, Munich, for access to collections in their care.

Mr. Ali Barakat, Dr. T. M. Bown, Dr. G. F. Gunnell, Messrs. M. Hilal, A. A. Abdul Latif, A. Van Nievelt, W. J. Sanders, El-Said Hashem Sherif, and Dr. B. Holly Smith worked with me in Fayum one or more seasons in 1983, 1985, 1987, 1989, and 1991.

Specimens illustrated here were prepared by W. J. Sanders. Figures 1-3, 43-45, and 55-56 were drawn or redrawn by B. Miljour.

This project was carried out in cooperation with Mme. Dr. Ferial El Bedewi of the Cairo Geological Museum and Geological Survey of Egypt, and with Dr. E. L. Simons and P. Chatrath of Duke University. It is a special pleasure to acknowledge Dr. Simons' encouragement and interest in this research.

Financial support in 1987, 1989, and 1991 was provided by the Committee for Research and Exploration of the National Geographic Society, Washington (grants numbered 3424-86, 4154-89, and 4624-91).

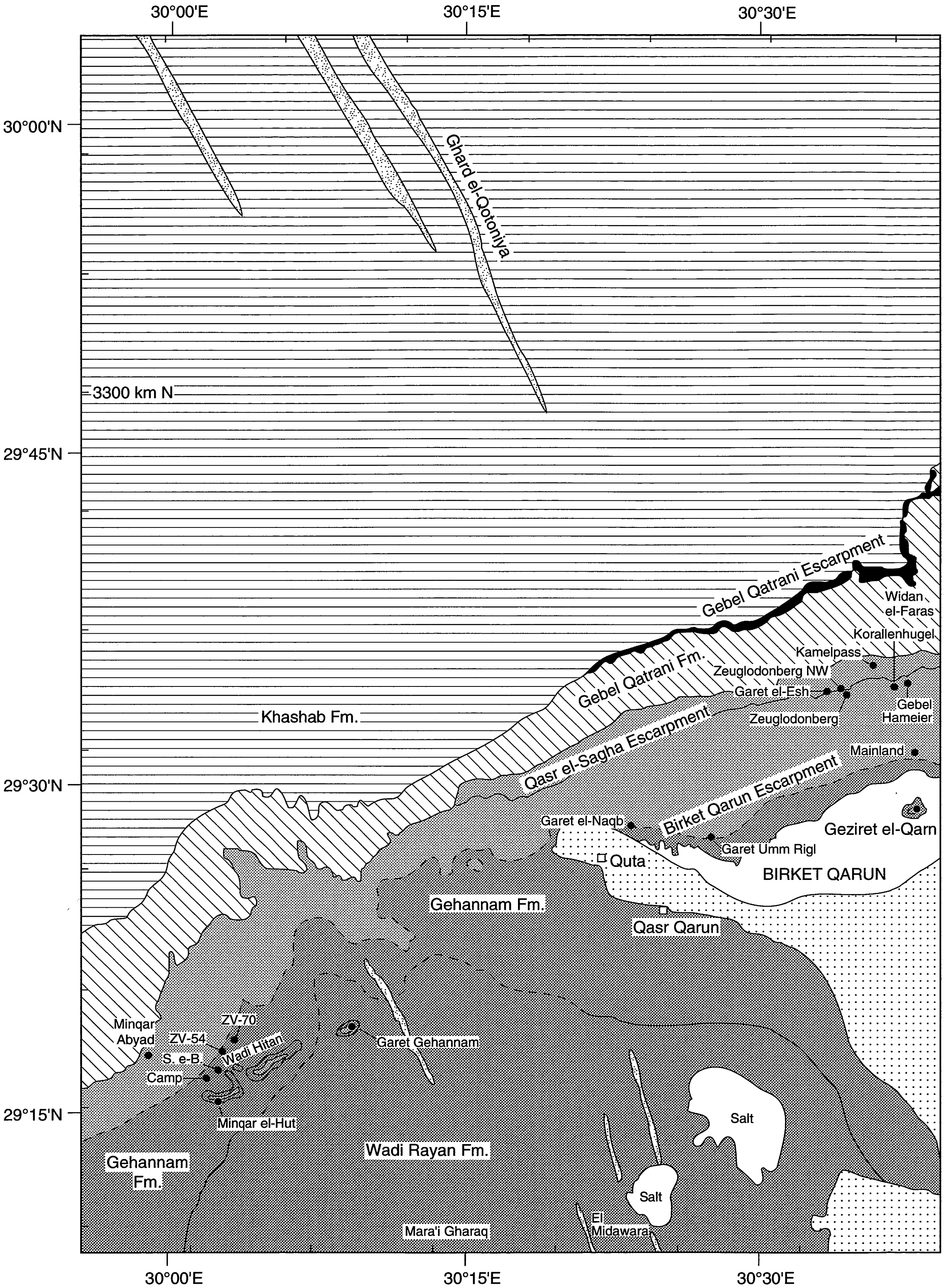
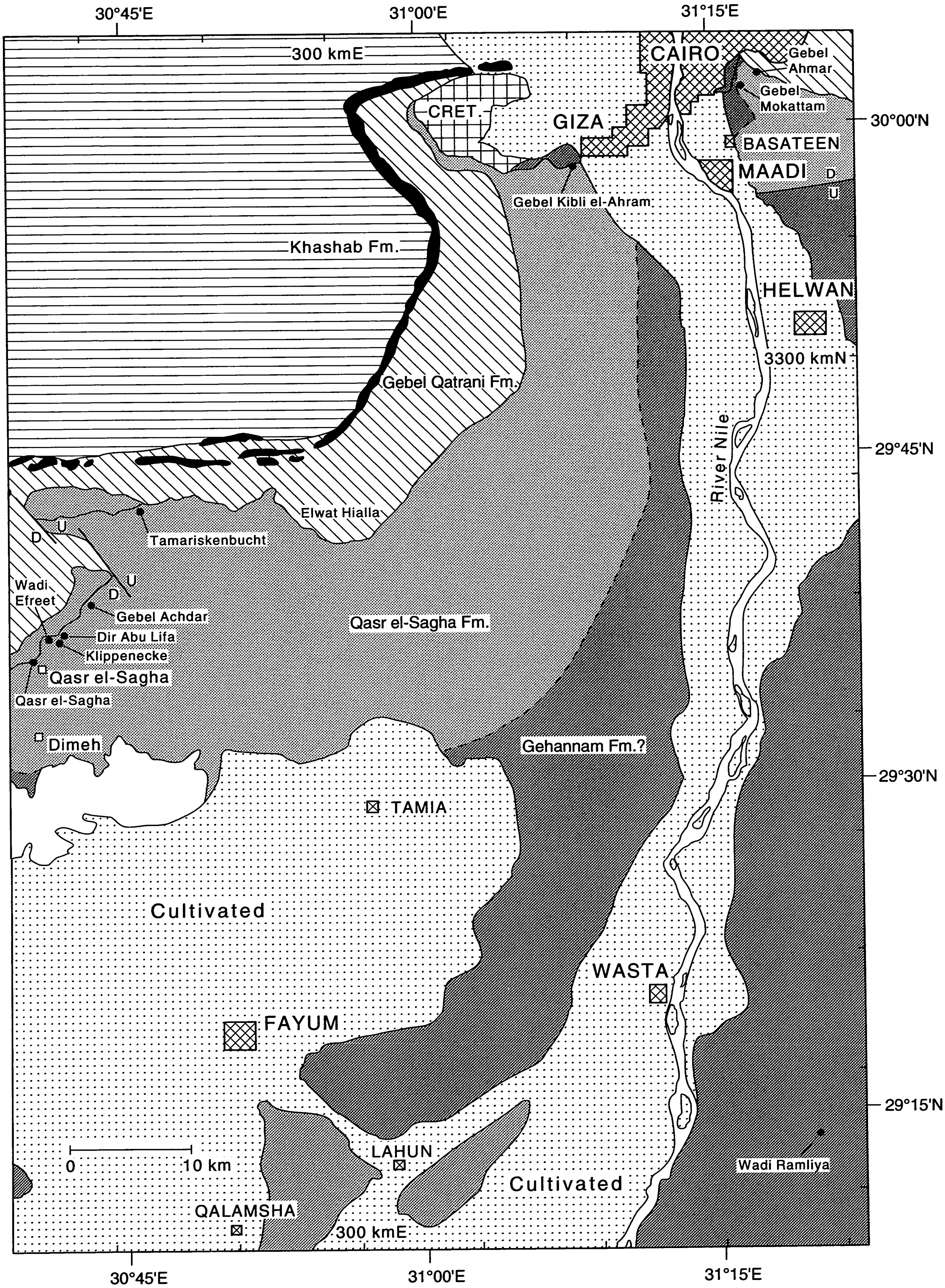


FIG. 2—Geological map of Gebel Mokattam and Fayum showing localities and formations discussed in the text. Solid circles mark location of stratigraphic sections in following figures. North is at



top of map. Marks on inside of border are 10 km UTM hatchures. Solid black is basalt. Geology from Beadnell (1905) and Geological Survey of Egypt (1981, 1983).

II

HISTORY OF STUDY: GEBEL MOKATTAM

The Eocene of Egypt was first studied at Gebel Mokattam. This mountain has always been a conspicuous landmark in Cairo, rising east of the Old City and providing a ready source of stone for building construction. The building stone is Eocene in age, some of it is richly fossiliferous, and as a result Gebel Mokattam and its quarries were seemingly studied by every nineteenth century geologist and paleontologist to visit the city. Contributions by nineteenth and twentieth century authors are summarized in the following pages.

Fraas

Otto Fraas (1867) divided the Gebel Mokattam Eocene into four units: (1) a lower *Callianassa* bank and nummulite beds; (2) a building stone interval with endocasts of the gastropod *Cerithium giganteum* and crabs including *Lobocarcinus*; (3) a 25 m interval with the echinoid *Conoclypus*, large nummulites identified as *Nummulites gizehensis*, and clay; and (4) an upper interval rich in oysters and *Turritella*. These units appear to correspond approximately to what are now called the Lower Building Stone Member of the Mokattam Formation, the Upper Building Stone Member, the Giushi Formation, and the Maadi Formation.

Fraas visited a place on the north side of Gebel Mokattam called Moses' Spring (Aïn Musa), where he reported sirenian bones (never described) and described the uppermost limestone as containing echinoids. He mentioned this bed as being overlain by the red sands of Gebel Ahmar. Aïn Musa is important because the "Ain Musa" echinoid bed can be traced 100 km southwestward to the Fayum and 100 km eastward to the Gulf of Suez.

Bauerman and Le Neve Foster

The following year Bauerman and Le Neve Foster (1868) published a more detailed section of the Gebel Mokattam Eocene, dividing a part of the sequence into lower "white beds" 36 m thick and upper "brown beds" 17 m thick. Bauerman and Le Neve Foster were particularly interested in a unit 1 m or so thick at the top of the brown beds that is unusually rich in celestite ("celestine" [strontium sulphate]), which they postulated to reflect precipitation from sea water concentrated by evaporation. This unit is in what is today called Giushi Formation.

Zittel

Two important works appeared in 1883, one by Karl von Zittel and the other by Georg Schweinfurth. Zittel's monograph was his report on geological investigations undertaken during the Rohlfs Expedition of 1873-74 exploring much of the eastern and western deserts of Egypt. Zittel (1883) divided the Eocene into three stages, the "*Libysche Stufe*" (early Eocene), "*Mokattam Stufe*" (middle and late Eocene), and "*Ober Eocaen*" (Oligocene). He divided 95 m of section at Gebel Mokattam into 35 m of white limestone overlain by about 60 m of dark brown or reddish strata. He subdivided the *Mokattam Stufe* into (1) building stone with celestite, 10 m; (2) porous limestone with large *Nummulites gizehensis* in the lowest bed and clay, gypsum, and celestite nodules at the top, 25 m; and (3) brown clay shale lacking large nummulites, but with *Ostrea*, *Carolia*, and other bivalves. These are approximately the Mokattam, Giushi, and Maadi formations of later authors.

Zittel published a colored map summarizing his geological observations and those of earlier explorers. This covered Egypt from Siwa in the west to the Gulf of Suez in the east, and from Cairo in the north to Dakhla and Kharga in the south. Surprisingly, the northern and western Fayum remained largely uncolored as a "*geologisch unbekanntes Gebiet*" [geologically unknown region] in spite of its proximity to Cairo. Those of us working in a mechanized age must be grateful for Zittel's note with the scale of the map: "*Kamelstunden 3½ bis 4½ Kilometer*"—one camel-hour of travel time corresponds to about 4 km of distance, providing the factor necessary to relocate fossil sites specified by early authors in terms of bearing and camel-hour travel time from some prominent landmark (Osborn, 1907a,b, also mentioned such a conversion).

Schweinfurth

The most comprehensive early study of Gebel Mokattam stratigraphy was published in 1883 by Georg Sch-

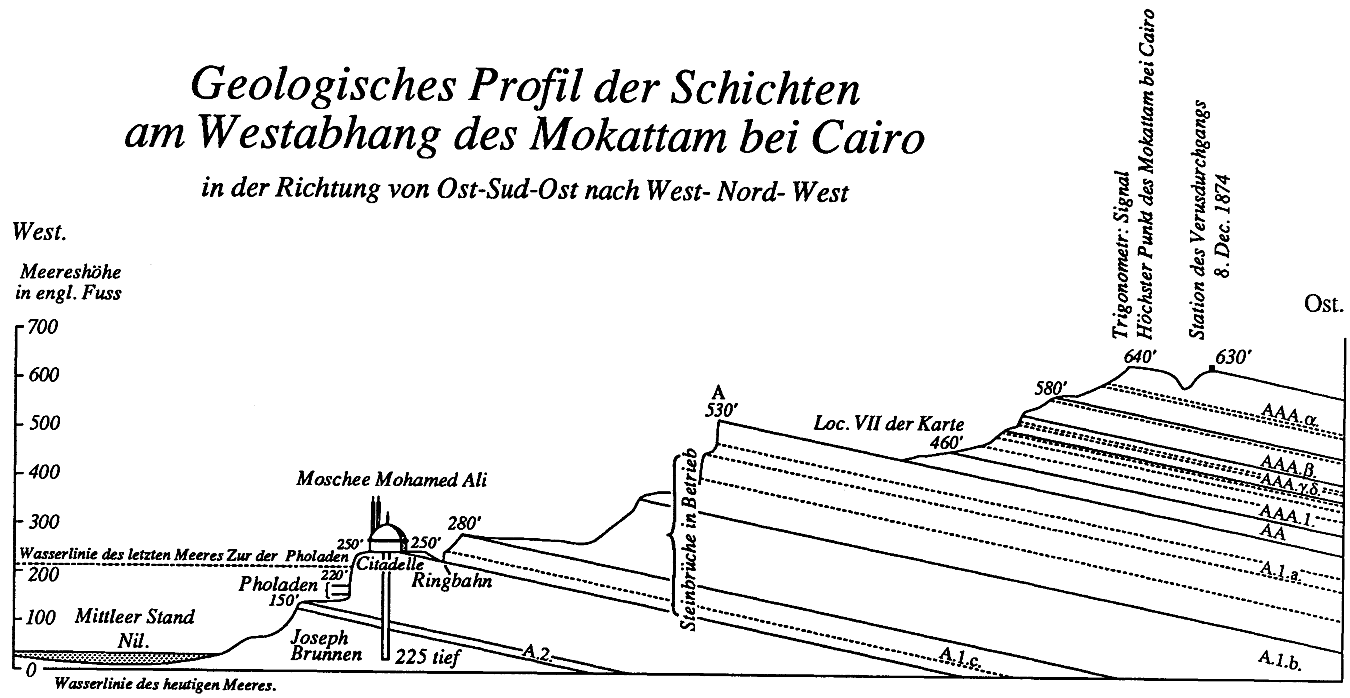


FIG. 3—Schweinfurth's (1883) geological cross section of the west face of Gebel Mokattam near Cairo. Section was constructed east of the Mohammed Ali Mosque and the Citadell of Cairo using landmarks located by triangulation and elevations determined by barometer. Principal stratigraphic subdivisions are lettered A2 through AAAα, following Schweinfurth (see section in Fig. 4). Redrawn from Schweinfurth (1883, Plate XXI). "Pholaden" are mollusks that bore holes in rock, here indicating high Plio-Pleistocene sea stands.

weinfurth, who was already famous by this time as an East African explorer. Schweinfurth's paper was illustrated by a colored geological map of Gebel Mokattam (reproduced here on the cover and frontispiece), two colored cross sections, and a colored perspective drawing. One of the cross sections is reproduced in Figure 3. Current interpretation of the Gebel Mokattam section is shown in Figure 4, taken from Strougo (see below). Schweinfurth (1883) adopted a system for labelling strata that worked first from bottom up, starting with A at the base and proceeding through AAAA at the top. However, Schweinfurth then discussed and numbered or lettered beds within each of these units from top down, which is inexplicably confusing. Schweinfurth's stratigraphic section and his system for lettering and numbering beds are shown in Figure 5. Like others before him, Schweinfurth divided the Mokattam section into a lower "white" section (A in his scheme) and an upper "brown" or "dark" section (AAA), separated by a relatively thin transitional interval (AA). These divisions (with different names) and Schweinfurth's thicknesses are approximately those recognized today by the Geological Survey of Egypt (1983).

Mayer-Eymar

Karl Mayer-Eymar (1886) was the next to study the Gebel Mokattam section. He was Swiss and following two weeks of observation in the field attempted to subdivide the Mokattam section into units corresponding to those recognized in Europe. He correlated all of the Mokattam section with beds exposed in the Paris Basin and thus considered the section to be "Parisian" ("Lutetian" or "middle Eocene") as opposed to "Londinian" ("early Eocene") or "Bartonian" ("late Eocene"). Mayer-Eymar provided no measurements of lithological sections, nor any illustrations.

Fourtau

René Fourtau (1897) published a brief summary description of the stratigraphy of Gebel Mokattam, including a schematic stratigraphic section similar to Schweinfurth's but with a total thickness only about one-half that reported by Schweinfurth. Fourtau's section is redrawn here in Figure 6. It was originally published to introduce paleontological work of Priem (1897a,b), and Fourtau did not bother to compare his thicknesses with those of Schweinfurth nor to explain how these were determined. Fourtau's section is included to show how different the same section can appear when described by different authors. This is true for thickness, and it is also true in terms of lithology and recorded fossils.

Fourtau (1897), like Mayer-Eymar (1886), regarded the entire Gebel Mokattam section as Lutetian ("Parisian" or "middle Eocene"). He compared beds in the Gebel Mokattam section to the *Calcaire grossier inférieur* (beds N-L), *Calcaire grossier moyen* (beds K-H), and upper Lutetian (*Calcaire grossier supérieur*, beds G-A) of the Paris Basin. In his 1897 paper, Bed K, the *Nummulites gizehensis* member of the Mokattam, was regarded as estuarine following notice of a possible palm seed and anecdotal reports of palm leaves being found in this bed. Later Fourtau (1900) developed a rather limited dynamic model involving sea level change. In the later study, the bed K palm was forgotten in favor of Fraas' (1867, p. 128) report of palms ("*Apeibopsis gigantea*") from the "building stone" interval. This led Fourtau to regard building stone as a local shallow or regressive facies, limestone with *Lobocarcinus* crabs as a littoral facies, and nummulitic limestone as an open-ocean facies (*faciès de haute mer*). He then interpreted the sequence from (1) nummulitic limestone, to (2) building stone, to (3) *Lobocarcinus* limestone, and back to (1) nummulitic limestone in the Gebel Mokattam section as a full cycle of sea level change. Fourtau deserves credit for being the first to propose a dynamic stratigraphic model to explain this distribution of facies, but the model was interpreted backwards. Building stone is the deeper open-ocean facies.

Blanckenhorn

Max Blanckenhorn was employed as a Geological Survey of Egypt geologist from 1897 until 1899, during which time he made a thorough study of Paleogene stratigraphy in the vicinity of Cairo (Blanckenhorn, 1900; published after he moved to Pankow near Berlin). Blanckenhorn (1900) divided the "*Mokattamstufe*" into a lower "light" Mokattam consisting of about 120-180 m of white or yellow-white limestone with siliceous flint beds and also clays, marls, and glauconitic marls, and an upper "dark" Mokattam consisting of 60-70 m of yellow and blue gypsum and celestite clays, marls, dirty limestones, sandy limestones, and sandstones. The "light" Mokattam was also referred to as *Gizehensis*-Stufe, and the "dark" Mokattam as *Carolia*-Stufe. The Gebel Mokattam section described by Blanckenhorn (1903, p. 370) is redrawn in Figure 7. Like Mayer-Eymar and Fourtau before him, Blanckenhorn regarded the entire Mokattam sequence as being equivalent to the *Calcaire grossier* and thus of Parisian or Lutetian age.

Blanckenhorn measured a stratigraphic section of the lower Mokattam in Wadi el-Sheikh in the Eastern Desert near Maghagha 150 km south of Cairo. This section, shown graphically in Figure 8, was subdivided into five units (I-1 through I-5). While the Wadi el-Sheikh section was not measured anywhere near Gebel Mokattam, it yielded five subdivisions that were later applied to the lower Mokattam in Cairo (Blanckenhorn, 1903).

Much of Blanckenhorn's (1900) report was devoted to the upper or "dark" Mokattam, for which he developed an eight-fold subdivision (II-1 through II-8). Unlike the five-part division of the lower Mokattam, Blanckenhorn's eight-part division of the upper Mokattam was developed at Gebel Mokattam itself. The eight subdivisions were as follows:

- II-8 4-20 m, hard limestone with *Cardium*, *Lucina*, and *Turritella*, no *Carolia* and few *Plicatula*
- II-7 6-8 m, variegated clay
- II-6 3-6 m, sandy limestone with *Carolia*, *Turritella* (upper *Carolia* horizon)
- II-5 2-3 m, oyster banks and gypsiferous calcareous shale (carbonaceous shale and oyster horizon)
- II-4 ~3 m, *Plicatula* horizon
- II-3 2-3 m, *Carolia* (lower *Carolia* horizon, cliff-forming)
- II-2 5-6 m, small nummulites and gastropods
- II-1 9 m, gypsiferous clay shale and hard shale ("Tafle" or Tafla) with celestite. [*Tafla* is an Arabic name for a particular kind of clay or claystone.]

These units differ slightly from those recognized by Schweinfurth (1883). Blanckenhorn (1900) constructed the sequence at Gebel Mokattam (Fig. 7), but tested it in Fayum before it was published (see Figs. 16 and 17).

Blanckenhorn (1900, p. 430) contradicted Fourtau's description of building stone as a local facies, reporting it from many localities in addition to Gebel Mokattam, and he contradicted Fourtau's interpretation of building stone as an estuarine facies, arguing instead that it must represent a more open pelagic marine facies.

Blanckenhorn returned to Fayum with Ernst Stromer von Reichenbach in January, 1902, as part of an expedition to collect vertebrate fossils (Stromer, 1903a). Blanckenhorn (1903) described "middle Eocene" stratigraphic sections from Gebel Mokattam, Gebel Ahmar, and Gebel Kibli el-Ahram in the vicinity of Cairo. Blanckenhorn was particularly interested in the transition from lower to upper Mokattam and this shows in his Gebel Mokattam section (Figure 7). Blanckenhorn omitted zones I-1 and I-2, what are today called the Lower Building Stone and Gizehensis members, to focus on the sequence from I-3 (Upper Building Stone) through II-8 (Ain Musa bed). Important markers are the tafla in zone II-1, abundance of nummulites through II-1 and II-2, appearance of *Carolia placunoides* in II-3, abundance of *Plicatula* in II-4, *Turritella*-rich "hard beds" and bone beds in II-5 (few at Gebel Mokattam, but numerous in Fayum), hard ledge-forming sandy limestone or *Carolia* limestone in II-6, variegated clays in II-7, and

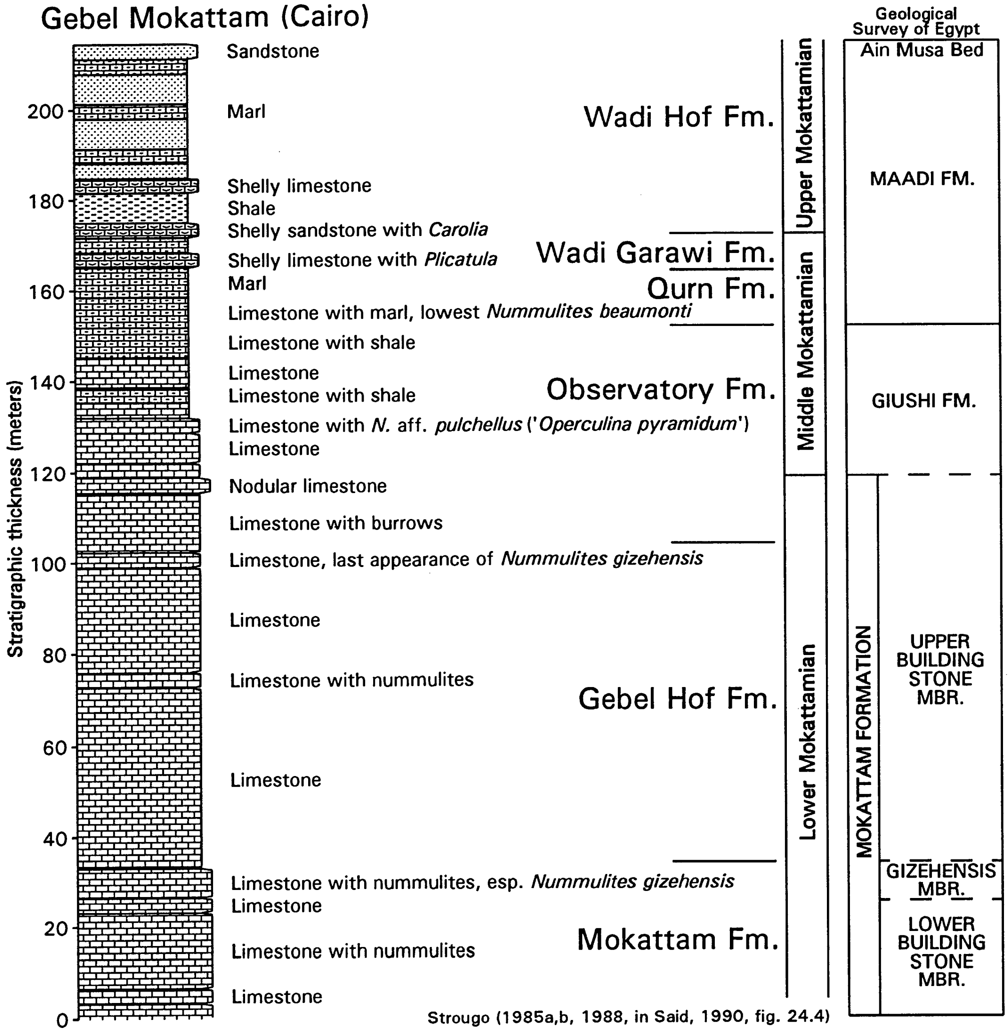


FIG. 4—Modern description and interpretation of Eocene stratigraphic section at Gebel Mokattam, based on thicknesses in Strougo (1985a,b, 1986), as illustrated in Said (1990, fig. 24.4). Vertical scale is the same as Fig. 5, but half that in subsequent figures. Lithologies are shown diagrammatically in left column and described in center. Strougo's (1988) correlation of Helwan formations and subdivisions of the Mokattamian Stage are also shown in center. Column at the right shows conventional stratigraphic subdivision into formations and members recognized by Geological Survey of Egypt (1983). Strougo (op. cit.) regarded the middle Mokattamian as Bartonian and upper Mokattamian as Priabonian, whereas Abdel-Kireem (1985) regarded much of the middle Mokattamian (including part of Giushi Fm.) as Priabonian. This and following localities are in Universal Transverse Mercator [UTM] grid zone 36R; kilometer coordinates of the locality within the grid zone are approximately 333.500E × 3323.000N.

limey sandstone or sandy limestone with *Echinolampas crameri* in II-8 (Ain Musa bed).

The section at Gebel Ahmar (now Gebel Akhdar under Nasr City) northwest of Gebel Mokattam is similar to that at Gebel Mokattam but thinner, with zones II-1 and II-2 being much condensed (Fig. 9). The transition from lower to upper Mokattam stage is preserved at Gebel Kibli el-Ahram in Giza (Fig. 10), where Blanckenhorn interpreted zones as being of comparable thickness to those at Gebel Mokattam. Alternatively, it is possible that zones I-2, I-3, I-4, I-5 or II-1 through II-5 or II-6 are missing and the uppermost bed here is II-8 (it is a hard limey sandstone with *Echinolampas crameri*; Strougo's correlations, in Said, 1990, p. 461, suggest that zones I-2 through I-5 are missing along with the lower part of the upper Mokattam).

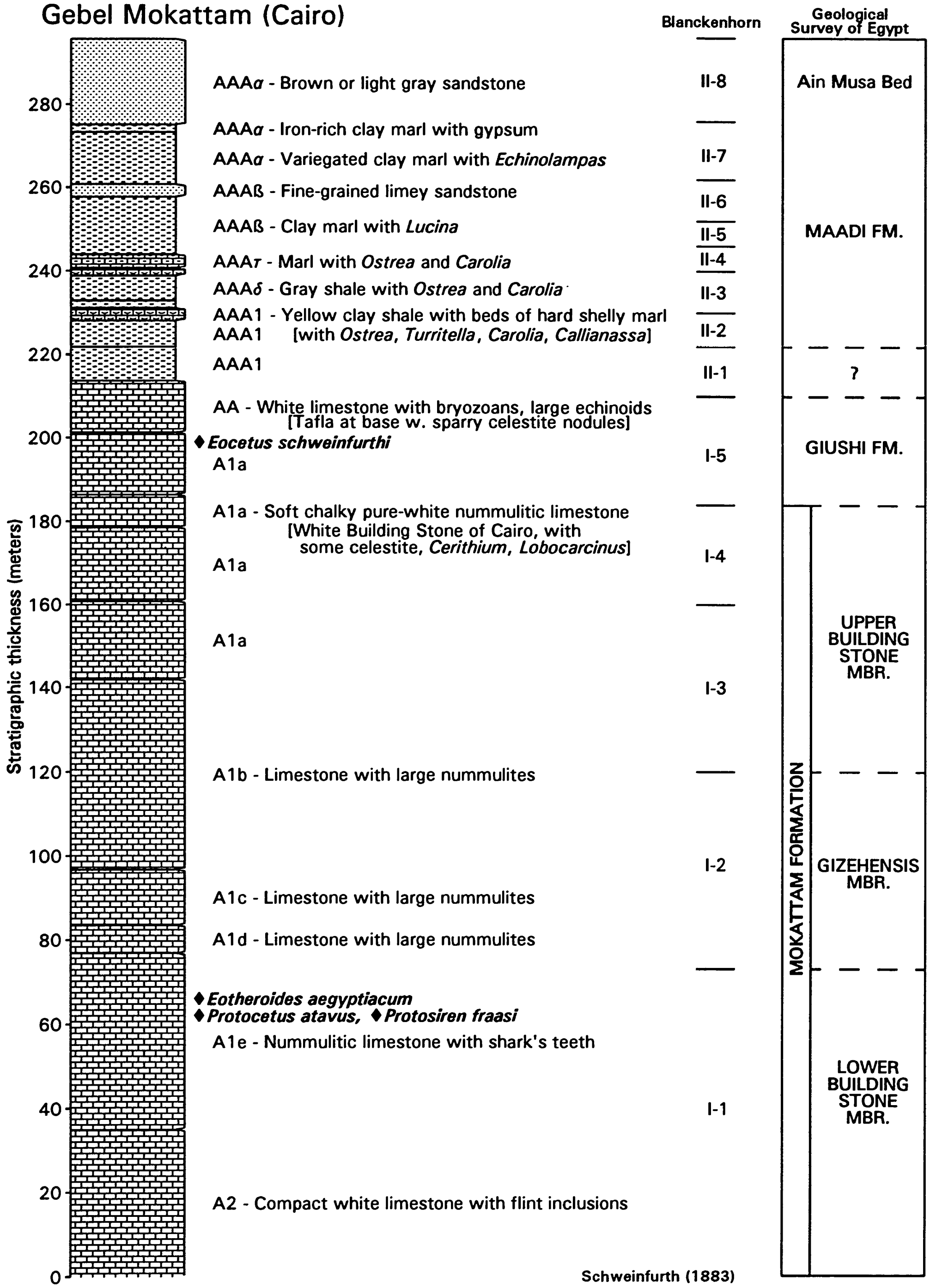


FIG. 5—Eocene stratigraphic section at Gebel Mokattam based on thicknesses scaled from Schweinfurth's (1883) Plate XXI and descriptions in his text. Subdivisions from A2 through AAAα are system developed by Schweinfurth. Subdivisions from I-1 through II-8 are parallel system developed by Blanckenhorn (1900, 1903). Column at the right shows formations and members recognized by Geological Survey of Egypt (1983). Note that vertical scale here is the same as Fig. 4 but half that in following figures. Diamonds mark probable levels where the type specimens of *Eocetus schweinfurthi*, *Eotheroides aegyptiacum*, *Protocetus atavus*, and *Protosiren fraasi* were found (according to Fraas, 1904a, pp. 200-201). UTM coordinates of the locality are approximately 333.500E × 3323.000N.

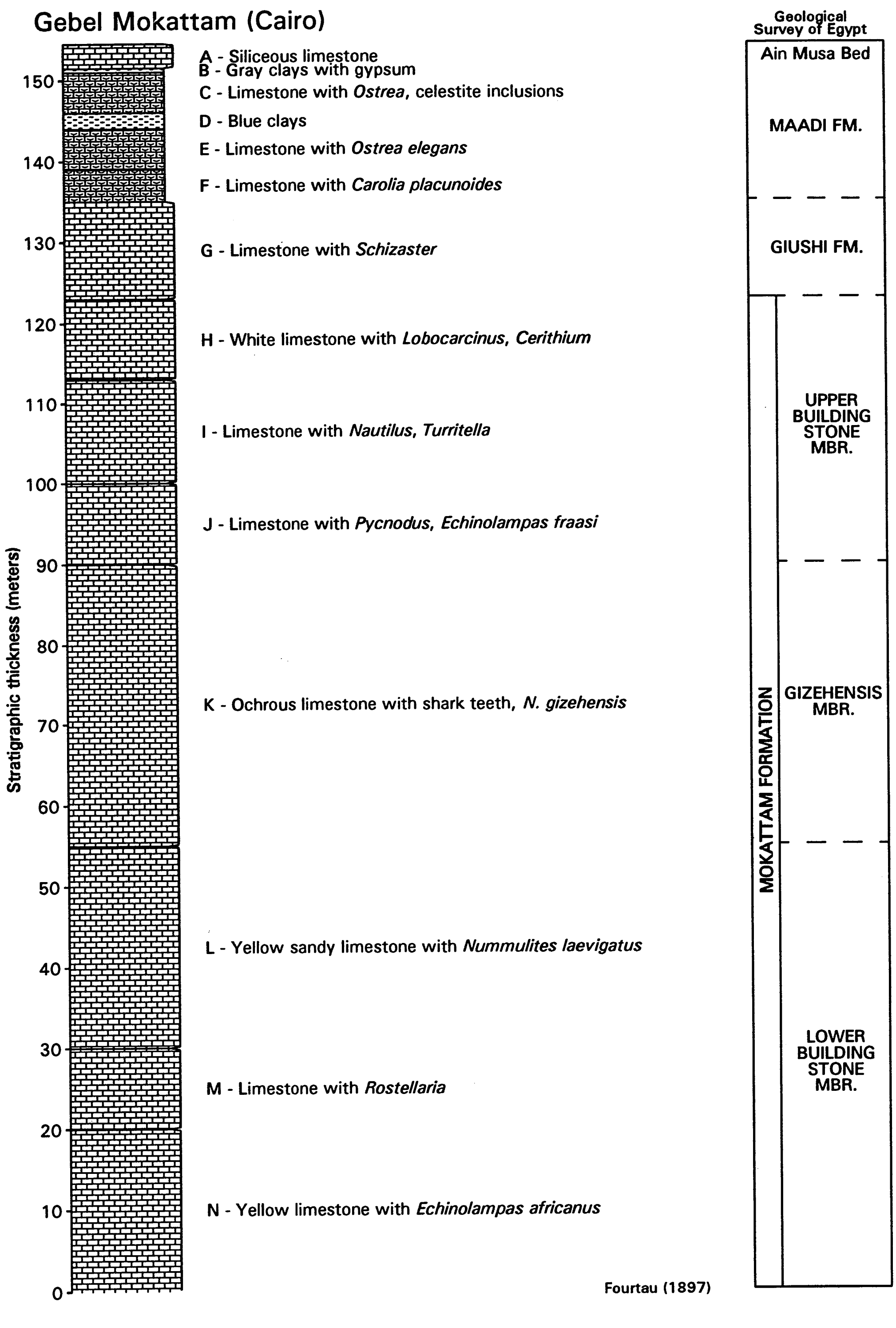


FIG. 6—Stratigraphic section of Eocene at Gebel Mokattam, based on thicknesses scaled from Fourtau's (1897) figure 2 and descriptions in his text. Column at the right shows stratigraphic subdivision into formations and members recognized by Geological Survey of Egypt (1983). Fourtau's thicknesses are about one-half those of Schweinfurth (Fig. 3). Note that vertical scale here is double that in Figure 3. UTM coordinates of the locality are approximately 333.500E × 3323.000N.

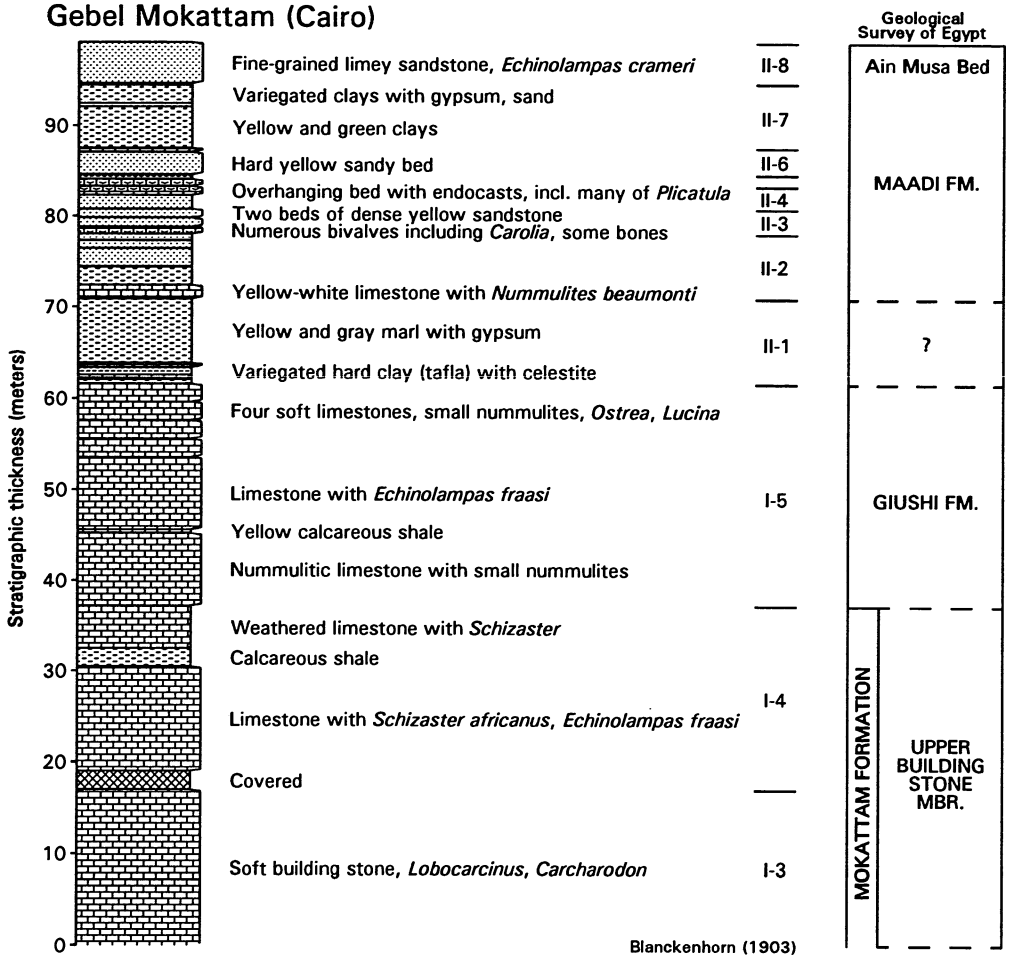


FIG. 7—Stratigraphic section of Eocene at Gebel Mokattam, based on thickness and descriptions published by Blanckenhorn (1903, p. 370). Column at the right shows stratigraphic subdivision into formations and members recognized by Geological Survey of Egypt (1983). UTM coordinates of the locality are approximately 333.500E × 3323.000N.

Barron

T. Barron's (1907) study, published posthumously, is important because he focused on a bed, the Ain Musa bed mentioned above (Blanckenhorn's bed II-8, uppermost member of Maadi Formation at Gebel Mokattam), that can be traced from Gebel Mokattam across the Eastern Desert to the Gulf of Suez. On the north side of Gebel Mokattam this bed is overlain by red sands of the Gebel Ahmar Formation (Schweinfurth, 1883), while at Gebel Awebed 80 km east of Gebel Mokattam these beds are separated by 70 m of upper Mokattam marine deposits (Barron, 1907). At Gebel Anqabia, 25 km east of Gebel Mokattam, the Ain Musa bed and the Ahmar Formation are separated by 65 m of *Ostrea* and *Carolia*-rich marine limestones and shales of the Anqabia Formation (Shukri and Akmal, 1953). Barron (1907, p. 87-92) inferred that 70 m of marine upper Mokattam was removed by erosion before deposition of the Ahmar Formation, meaning that a major unconformity separates the Oligocene Gebel Ahmar Formation from the Eocene upper Mokattam (Maadi Formation). As illustrated below, this is important for understanding the stratigraphy and age of these deposits.

Krasheninnikov and Ponikarov

V. A. Krasheninnikov and V. P. Ponikarov (1965) were the first to study planktonic foraminifera from Gebel Mokattam. Two zones were recognized. The first, the *Truncorotaloides rohri* zone of latest middle Eocene age (now Paleogene planktonic foraminiferal zone P14, Bartonian), included the Gizehensis and Upper Building Stone members. The second, the *Globigerina*

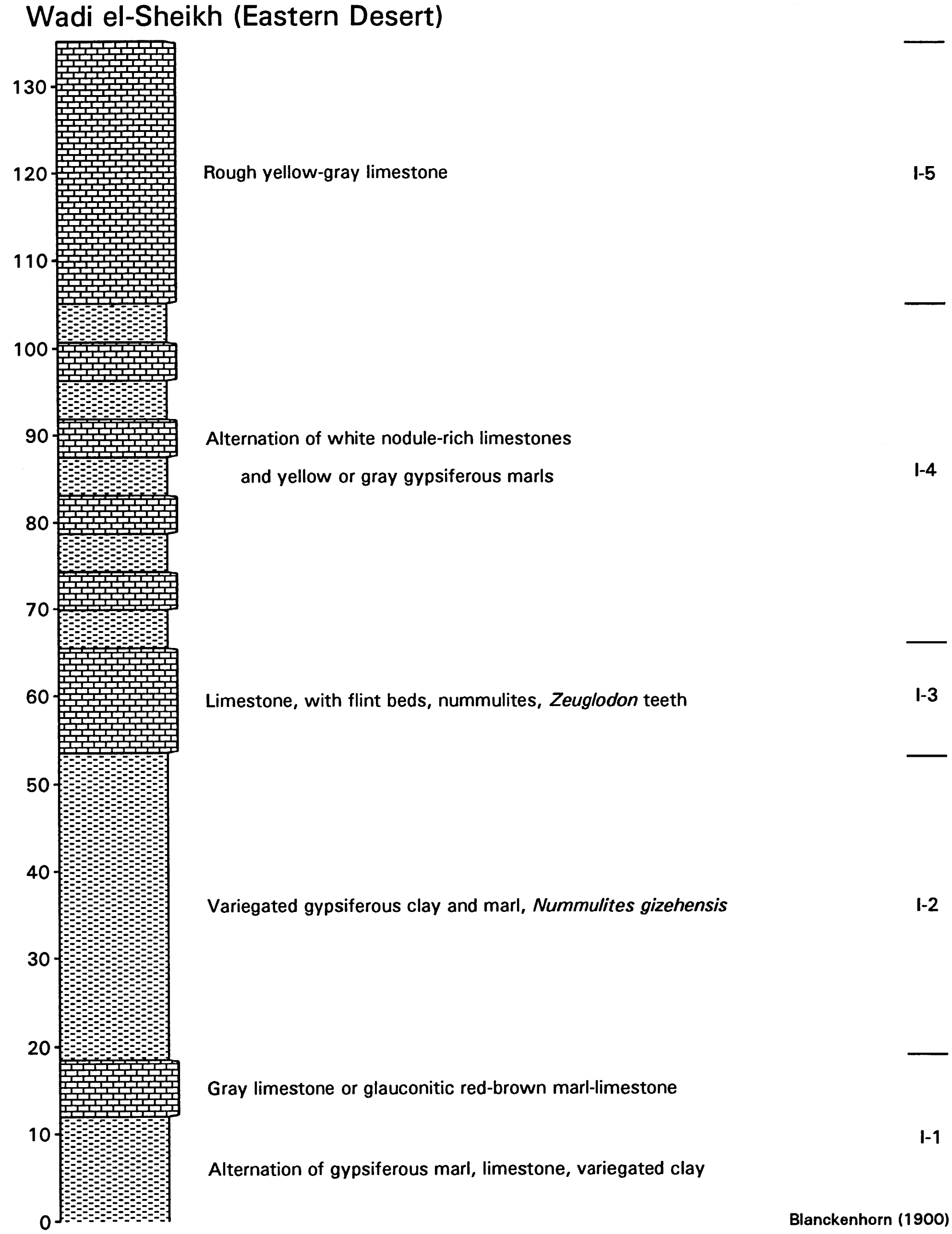


FIG. 8—Stratigraphic section of Eocene at Wadi el-Sheikh in the Eastern Desert of Egypt, based on measurements and lithological descriptions of Blanckenhorn (1900). Blanckenhorn divided this section into five units, I-1 through I-5, and extended these zones to describe the lower Mokattam at Gebel Mokattam. Blanckenhorn noted that *Nummulites gizehensis* is found through this entire section (Blanckenhorn, 1903, p. 364) though interval I-2 has the greatest concentration (see Fig. 4). UTM coordinates of the locality are approximately 310.000E × 3175.000N.

corpulenta zone of late Eocene age (now P16, Priabonian), included the Giushi Member/Formation and the Maadi Formation. Raising the Gizehensis and Upper Building Stone members of the Mokattam Formation to latest middle Eocene (Bartonian) contradicted previous (and current) assessments, but Krasheninnikov and Poni-

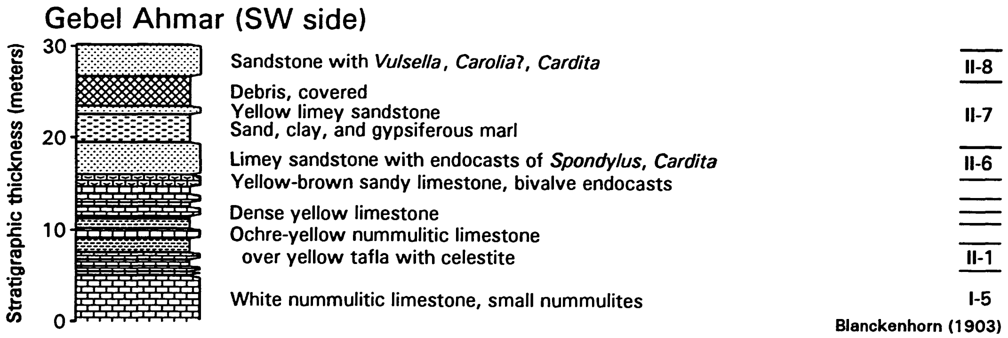


FIG. 9—Stratigraphic section of Eocene on the southwest side of Gebel Ahmar 2-3 km northeast of Gebel Mokattam, based on measurements and lithological descriptions of Blanckenhorn (1903, p. 373). Blanckenhorn divided the section into units I-5 through II-8 developed at Gebel Mokattam. If correctly correlated (note that diagnostic fossils characteristic of zones II-6 and II-8 are lacking), this section is much thinner than that at Gebel Mokattam (Fig. 7). UTM coordinates of the locality are approximately 335.500E × 3324.000N.

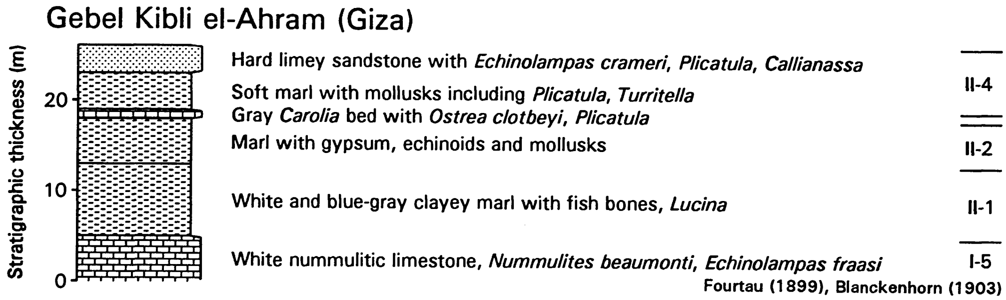


FIG. 10—Stratigraphic section of Eocene at Gebel Kibli el-Ahram east of the pyramid of Menkara or Mycerinus in Giza, based on measurements and lithological descriptions of Fourtau (1899) and Blanckenhorn (1903, p. 375). Blanckenhorn divided the section into units I-5 through II-4 developed at Gebel Mokattam (Fig. 7). Upper and lower Mokattam appear to be present, but more precise correlations are suspect. UTM coordinates of the locality are approximately 320.500E × 3317.000N.

karov's results corroborated a late Eocene age for the upper part of the Gebel Mokattam section.

Strougo

Amin Strougo (1976a) studied the Ain Musa bed at Gebel Mokattam and described temporal equivalents elsewhere. Strougo (1976b) documented a hiatus, with beds between the *Plicatula* bed and Ain Musa bed of the Maadi Formation missing east of Kait Bey on the northwest side of Gebel Mokattam. He attributed this 20 m discontinuity to local syndepositional tectonic movements. Strougo (1979; see also Strougo et al., 1982; Strougo and Boukhary, 1987) regarded the upper Mokattam as Priabonian (late Eocene), citing *Carolia placunoides* as evidence, while including the whole middle Mokattam (possibly including Maadi Formation beds below those bearing *Carolia placunoides*) in the Bartonian (Biarritzian, middle Eocene). Strougo et al. (1982) described a section at Darb el-Fayum in Giza where the middle Eocene ends with an erosion surface and is directly overlain by a *Carolia placunoides* bed marking the beginning of the late Eocene.

Strougo's synthesis of the stratigraphy and macro-invertebrate biostratigraphy of Gebel Mokattam and surrounding areas is the most comprehensive available (Strougo, 1985a,b, 1988; also Strougo in Said, 1990, fig. 24.4). Strougo extended stratigraphic nomenclature developed by Farag and Ismail (1955, 1959) to Gebel

Mokattam (Fig. 4), substituting this for the Mokattam, Giushi, Maadi sequence of Said (1962) and of Awad and Said (1966). Strougo (1988) interpreted molluscan stratigraphy to favor a middle-to-late Eocene boundary between the middle and late Mokattamian at the base of the Wadi Hof Formation.

Abdel-Kireem

M. R. Abdel-Kireem (1985) made a second study of planktonic foraminifera at Gebel Mokattam, following up on the work of Krasheninnikov and Ponikarov. Abdel-Kireem recognized three biostratigraphic zones: (1) the late middle Eocene *Truncorotaloides rohri* zone [P14] for the Gizehensis and Upper Building Stone members of the Mokattam Formation and for part of the Giushi Formation, (2) the earliest late Eocene *Globigerinatheka semiinvoluta* zone [P15] for the upper Giushi and lower Maadi formations, and (3) the late Eocene *Globigerina corpulenta* zone [P16] for the middle and upper Maadi Formation. Abdel-Kireem regarded *Carolia placunoides* as a facies fossil rather than an index to the Priabonian. He regarded the Giushi Formation as entirely synchronous with the Gehannam marl member (Ismail and Abdel-Kireem, 1975) of the Gehannam Formation. Both units were considered to straddle the middle-late Eocene boundary. Strougo and Boukhary (1987) responded by citing nummulite and calcareous nannofossil evidence indicating that the Gizehensis and Upper Building Stone members must be older than the *Truncorotaloides rohri* zone [P14], and they questioned whether any of the Giushi Formation could be late Eocene.

Other authors

Cuvillier (1930) provided several stratigraphic sections of Gebel Mokattam, interpreted in the context of a general review of Eocene stratigraphy in Egypt. A very useful map with accompanying text was published by the Geological Survey of Egypt (1983). Hassaan et al. (1990) compared microfacies at Kait Bey and Basateen on the northwest and southeast sides of Gebel Mokattam.

Summary

The Gebel Mokattam stratigraphic section includes three or six Eocene formations, depending on nomenclature employed (Fig. 4). The Mokattam and Gebel Hof formations are middle Eocene in age (Lutetian), and were deposited on a shallowing marine shelf. The Giushi Formation equivalent to the upper Observatory Formation has concentrations of celestite, was deposited in shallow marine waters, and may straddle the middle-late Eocene boundary (being mainly Bartonian but also, possibly, in part Priabonian). The Qurn, Wadi Garawi, and Wadi Hof formations, also called the Maadi Group or Maadi Formation, are middle to late Eocene in age (mainly Priabonian), and these were deposited in shallow nearshore to lagoonal marine environments. Mollusks favor a middle-to-late Eocene boundary between the middle and late Mokattamian (at the base of the Wadi Hof Formation; Strougo, 1988). Planktonic foraminifera favor a middle-to-late Eocene boundary within the middle Mokattamian and within the Giushi Formation (Abdel-Kireem, 1985). No significant unconformities have been identified within the Giushi Formation, but abundant celestite may indicate a low sea stand. There is an unconformity between the middle and late Eocene at Darb el-Fayum in Giza. Late Eocene marine Maadi and Wadi Hof formations are separated from overlying Oligocene continental beds of the Gebel Ahmar Formation by a major unconformity.

III

HISTORY OF STUDY: FAYUM

The Fayum, like Gebel Mokattam, has a long and complex history of study, with early authors establishing the basic stratigraphic framework. Topography is important for understanding this framework and its development.

The cultivated oasis and lake Birket Qarun together occupy a broad valley floor dipping slightly to the northwest (NNW). A prominent escarpment, the Birket Qarun escarpment, rises above the northwest side of the lake (Fig. 2). This escarpment trends WSW-ENE and its top forms a broad plain, the plain of Dimeh, some 5-8 km wide. Strata exposed in the Birket Qarun escarpment were the basis for Schweinfurth's (1886) "*zweite Stufe*" and Beadnell's (1901) "Birket el Qurun Series" discussed in following sections of this chapter. Lithologically, the top of the first escarpment and all of the plain of Dimeh above it belong to the Qasr el-Sagha Formation.

A second parallel escarpment, the Qasr el-Sagha escarpment, rises above the plain of Dimeh, and the top of the second escarpment forms a second narrower plain 4-5 km wide. Strata exposed in the Qasr el-Sagha escarpment were the basis for Schweinfurth's "*dritten Stufe*" or "*dritten Fayumstufe*" and Beadnell's "Qasr el Sagha Series." Much of the second or narrow plain is Gebel Qatrani Formation.

A third parallel escarpment, the Gebel Qatrani escarpment with basalt flows, rises above the second plain, and a third high plain dips gently away to the northwest for a great distance. Strata exposed in the Gebel Qatrani escarpment were the basis for Schweinfurth's "*vierten Fayumstufe*" and Beadnell's "fluvio-marine series" or "Jebel el Qatrani beds" (now Gebel Qatrani Formation). The third or highest plain is now usually placed in the Miocene Khashab Formation.

The topography of northern Fayum is clearly stratigraphically controlled, but, as we shall see, the topography is not itself the stratigraphy. Study of Fayum stratigraphy developed in parallel with investigation of Gebel Mokattam, and these developments are summarized by author in the following pages.

Schweinfurth

Georg Schweinfurth made several visits to Fayum during and after his work at Gebel Mokattam. He travelled to Wadi Muela in western Fayum in 1876, and he visited the island of Geziret el-Qarn in Birket Qarun in 1879. Schweinfurth found vertebrae of Eocene whales, teeth of selachians, and remains of other fishes on the latter trip. These discoveries were described by Dames (1883a,b, 1894). Schweinfurth worked north of Birket Qarun in 1884, which may be the year he discovered the ancient stone building or "*qasr*" now known as Qasr el-Sagha (also called "Schweinfurth's Temple"). Exploration of Zittel's "*geologisch unbekanntes Gebiet*" came in January 1886 when Schweinfurth made a month-long traverse of the western and northern deserts of the Fayum depression. His report (Schweinfurth, 1886) included a good topographic map of Fayum. The expedition started near Qalamsha and travelled in a large circle through the desert first southwest to Wadi Muela, then northwest to Wadi Rayan and Minqar el-Rayan (Schweinfurth's "*Cap Rajan*"), and then farther northwest to Garet Gehannam (Schweinfurth's "*Haram Meduret el-Barhl*"). Eocene invertebrates were found all along the traverse.

Schweinfurth clearly wanted to explore valleys and escarpments visible in the desert west of Garet Gehannam, but wrote that he was deterred by poor camels and assistants he did not trust. To the west are Minqar el-Hut and Wadi Hitan (Zeuglodon Valley) where hundreds of archaeocete cetacean skeletons lie exposed at the surface over a large area of desert. Unaware of these and unable to proceed westward, Schweinfurth turned northeast toward Birket Qarun. Teeth of a sawtooth shark were found west of the lake (the type of *Amblypristis cheops* described by Dames, 1888). Remaining days of the expedition were spent exploring north of Birket Qarun where Schweinfurth found one good dentary of an archaeocete (the type of *Zeuglodon osiris* described by Dames, 1894).

Schweinfurth's (1886) description of the geological section north of Birket Qarun is confusing and disappointing, especially in comparison to the clear geological sections and maps he prepared for his Gebel Mokattam study. Schweinfurth divided Fayum strata into four "stages" (*Stufe*) or intervals, corresponding to successive escarpments above Birket Qarun. For simplicity these can be referred to as I (basal interval near the lake), II

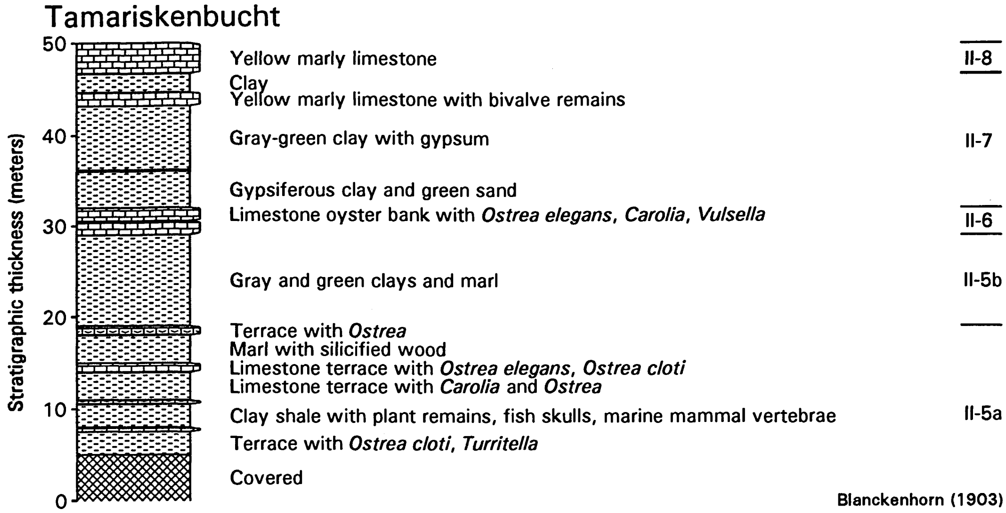


FIG. 11—Stratigraphic section of Eocene at Tamariskenbucht about 12-15 km (half-day's travel) NNE of the temple building at Qasr el-Sagha, based on measurements and lithological descriptions of Blanckenhorn (1903, p. 381). Blanckenhorn divided the section into units II-5a through II-8 developed at Gebel Mokattam (Fig. 7). UTM coordinates of the locality are approximately 284.000E × 3289.000N.

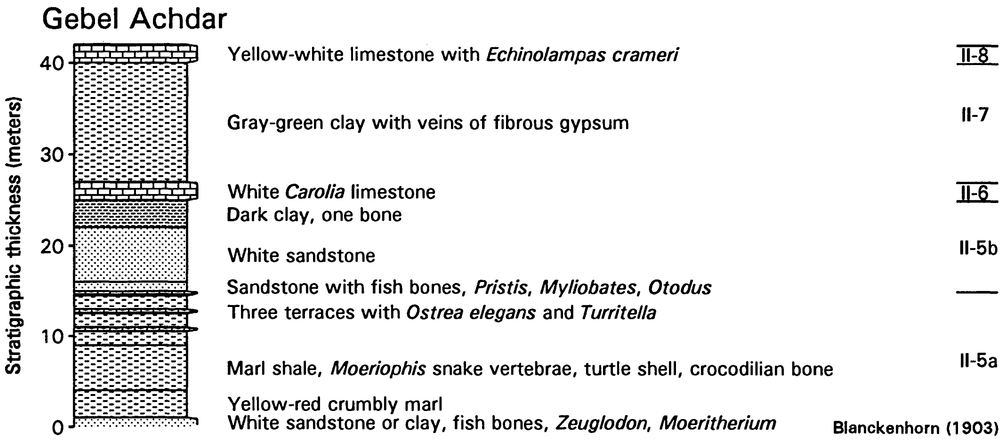


FIG. 12—Stratigraphic section of Eocene at Gebel Achdar about 6 km (1.5 hours) NNE of the temple building at Qasr el-Sagha, based on measurements and lithological descriptions of Blanckenhorn (1903, p. 382). Blanckenhorn divided the section into units II-5a through II-8 developed at Gebel Mokattam (Fig. 7). UTM coordinates of the locality are approximately 279.500E × 3281.000N.

(Birket Qarun escarpment), III (Qasr el-Sagha escarpment), and IV (Gebel Qatrani escarpment). Schweinfurth's stages are simple enough, but these are numbered inconsistently in his text. He gave thicknesses for each interval, but some were reported in terms of elevation above lake level while others were reported relative to their elevation above sea level (Birket Qarun lake level is about 40 m *below* sea level). Schweinfurth's thicknesses, as reported, are much less than thicknesses determined by subsequent investigators. Thus I think Schweinfurth may have meant to call the 40 m interval from lake level to sea level his first interval, the next 60 m his second interval, the next 90 m his third interval, and a final 160 m his fourth interval. These values are at least roughly proportional to measurements reported by later authors.

Schweinfurth (1886, p. 135) first described the lowest interval as including a conspicuous red shell bed and being capped by an oyster conglomerate. Later (p. 136) he described the first unit as unfossiliferous gray and

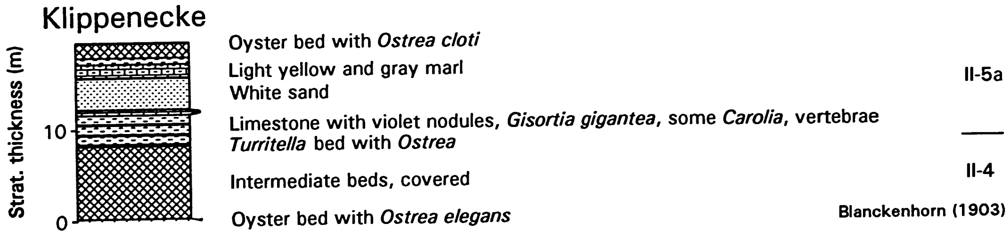


FIG. 13—Stratigraphic section of Eocene at Klippenecke about 2 km (0.5 hours) NNE of the temple building at Qasr el-Sagha, based on measurements and lithological descriptions of Blanckenhorn (1903, p. 383). This section must have been measured very near the Wadi Efreet section of Bown and Kraus (1988; Fig. 31). Blanckenhorn divided the section into units II-4 through II-5a developed at Gebel Mokattam (Fig. 7). UTM coordinates of the locality are approximately 277.000E × 3278.000N.

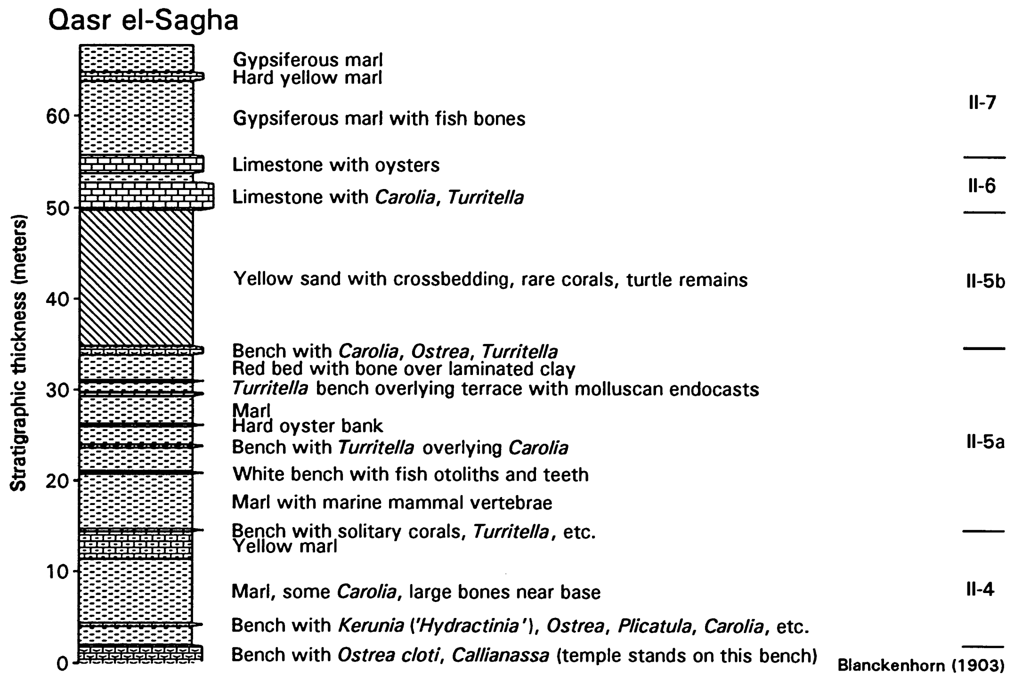


FIG. 14—Stratigraphic section of Eocene immediately behind the temple building at Qasr el-Sagha, based on measurements and lithological descriptions of Blanckenhorn (1903, p. 384). Blanckenhorn divided the section into units II-3 through II-7 developed at Gebel Mokattam (Fig. 7). UTM coordinates of the locality are approximately 274.800E × 3276.500N.

ash-gray marls overlain by fossiliferous beds with *Ostrea clotbeyi*, *Carolia placunoides*, etc., capped by a conspicuous hard oyster bank more than a meter thick. From context (p. 137), and my own knowledge of the stratigraphy, it appears that only the unfossiliferous gray and ash-gray marls are in interval I, and the rest of the section is in interval II. Schweinfurth mentioned chalk-white mollusk shells in a sandy ocherous yellow or dark blood-red clay in this interval, and a "best" fossiliferous locality 3 km west of the west end of the lake (Beadnell, 1905, p. 46, included this bed in the upper part of his Birket Qarun Series). Schweinfurth considered this interval to be the same as that producing the mollusks he collected in 1879 on Geziret el-Qarn, described and identified as "upper Parisian" by Mayer-Eymar (1883). Schweinfurth regarded the upper part of Fayum interval II as equivalent to part of his interval AAA1, the lowest upper Mokattam stage at Gebel Mokattam.

Schweinfurth (1886) started a paragraph on p. 138 by mentioning the "*zweite Stufe*," but it seems clear that this and subsequent paragraphs are actually about his third interval. Schweinfurth regarded the escarpment by the

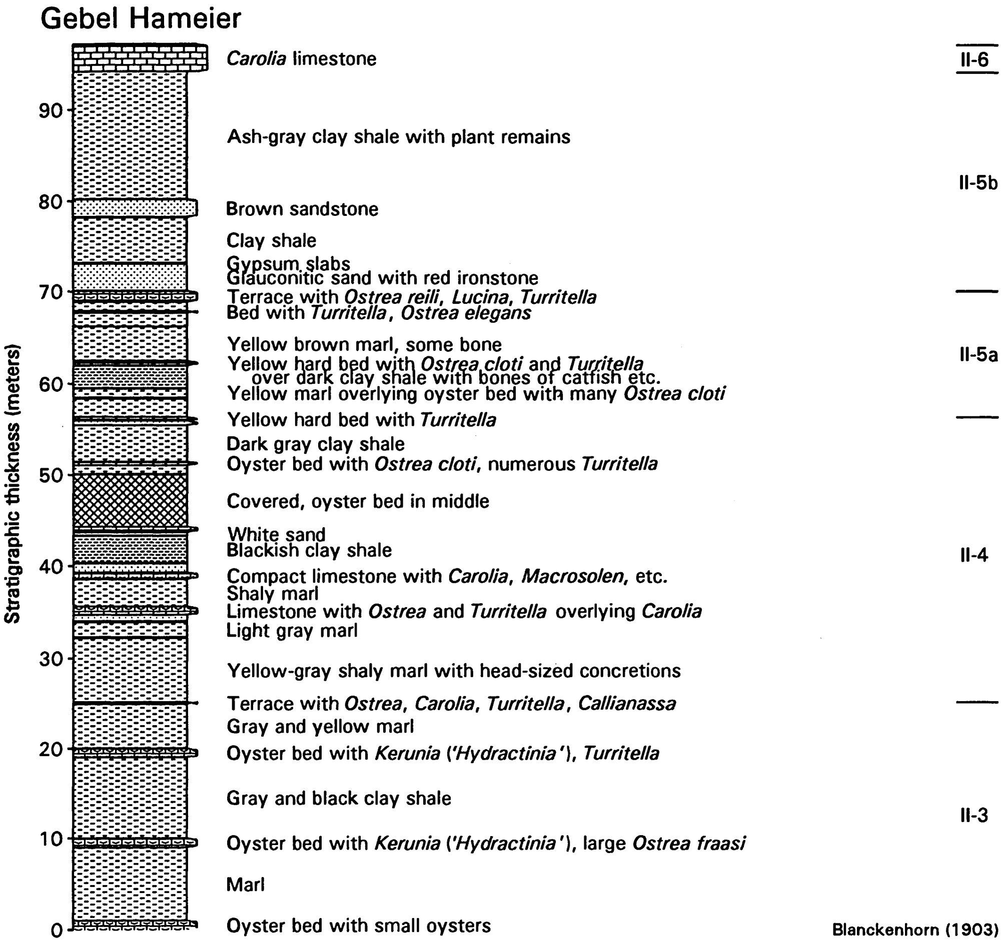


FIG. 15—Stratigraphic section of Eocene at Gebel Hameier about 6 km (1.5 hours) WSW from the temple building at Qasr el-Sagha, based on measurements and lithological descriptions of Blanckenhorn (1903, p. 386). This section appears to have been measured a kilometer or so east of Blanckenhorn's Korallenhügel section (Fig. 16). Blanckenhorn divided the section into units II-3 through II-6 developed at Gebel Mokattam (Fig. 7). UTM coordinates of the locality are approximately 270.500E × 3275.500N.

alten Tempel [Qasr el-Sagha] as a characteristic example of interval III, and further divided it into twenty subunits. He correlated the whole with beds AAA1 through AAAα at Gebel Mokattam.

Most interesting from our point of view was discovery of a lower jaw of "*Zeuglodon*" with five teeth, and also two associated lower jaws of "*Schwein oder Tapir erinnernden Geschöpfes*" [pig or tapir-like creatures] at a locality in interval III. The former specimen is the holotype of *Zeuglodon osiris* described by Dames (1894). The latter specimen was never identified or illustrated, but Schweinfurth's comparison to a pig or tapir suggests that it was *Eosiren* or *Moeritherium*. Schweinfurth (1886, p. 139) described the locality as follows:

An dem von mir 12½ km im Westen vom alten Tempelbau ausgebeuteten ☿ Berge (wie benennt man solche unbekannte Grössen?), der als Vorwerk der Abfallslinie der dritten Stufe ein isoliertes Stück derselben ausmacht, das sich von allen Seiten um so bequemer untersuchen liess, machte ich in derselben Schicht zwei wichtige Knochenfunde.

[In the ☿ hills (how does one refer to such unnamed masses?) 12½ km west of the old temple, which constitute an isolated parcel in the foreground of the third-stage scarp, easily located from all sides, I made two important finds of bones in the same bed.]

These hills at the front of the Qasr el-Sagha escarpment must have been near Garet el-Esh (flat-topped "hill of the

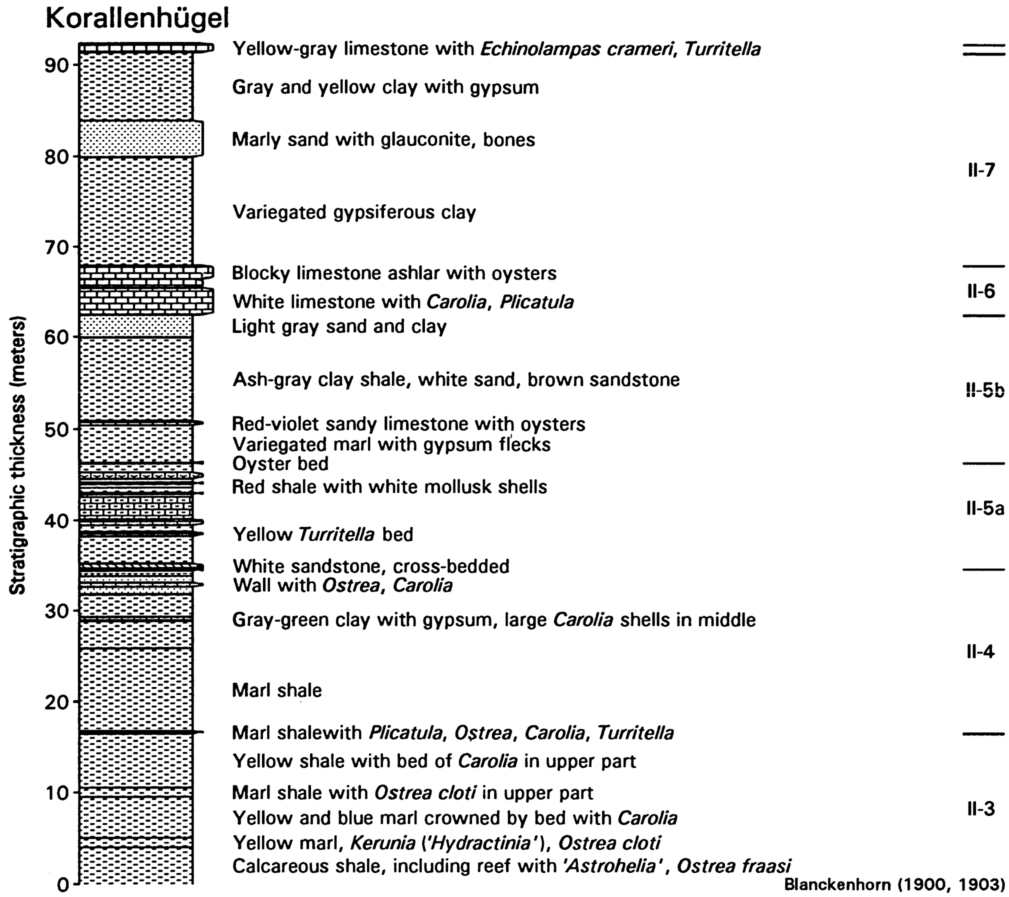


FIG. 16—Stratigraphic section of Eocene at Korallenhügel 7 km northwest of Dimeh in Fayum, based on measurements and lithological descriptions of Blanckenhorn (1900, p. 448; 1903, p. 388). Blanckenhorn first divided the section into units II-1 and II-3 through II-8. Later he included beds referred to II-1 in II-3 and subdivided II-5 into two parts. These are the same zones of the upper Mokattam that Blanckenhorn recognized at Gebel Mokattam (Figs. 5 and 7). UTM coordinates of this locality are approximately 269.000E × 3274.000N.

nest"), which is shown as being 12 km west of the Qasr el-Sagha temple on Beadnell's (1905) geological map of the Fayum depression. "*Zeuglodon*" *osiris*, *Eosiren*, and *Moeritherium* are all found at this place. The calcareous shales [*Mergeln*] yielding the *Zeuglodon osiris* type at the ☿-Berge are overlain by beds with *Ovula*, *Strombus*, *Solen*, and *Nautilus* that Schweinfurth (p. 140) correlated with his AAAβ interval at Gebel Mokattam. Many bivalves here are preserved as compact masses of leather-brown colored steinkerns, overlain by *Carolia* and *Ostrea clotbeyi*.

The top of the cliffs behind the Qasr el-Sagha temple building are capped by a 2 m light brown, dense, hard, calcareous sandstone packed with shell casts and serving as the top of a conspicuous 15 m cliff of gray marl shale (walls of the Qasr el-Sagha temple building were constructed from fallen pieces of the calcareous sandstone). According to Schweinfurth (p. 140), the whole Qasr el-Sagha escarpment sequence (interval III) ends with yellow gypsum-rich shales with *Carolia*, *Echinolampas crameri*, *Micropsis*, and every widely distributed species of upper Eocene oyster in Egypt, capped by an irregular hard white limestone [*Kalkbreccie*]. This "Kalkbreccie" forms a hard plateau surface 1½ km wide. Heat and haste prevented Schweinfurth from making a thorough study of the rest of the second plain and the Gebel Qatrani escarpment (interval IV), but he was able to report brightly colored white, ocher-yellow, and brick-red shales and sandstones like those at Gebel Ahmar near Gebel Mokattam, and wood of fossil forests like those known from the vicinity of Cairo. Schweinfurth recognized that fossil forests in interval IV meant retreat of the sea between interval III time and interval IV time.

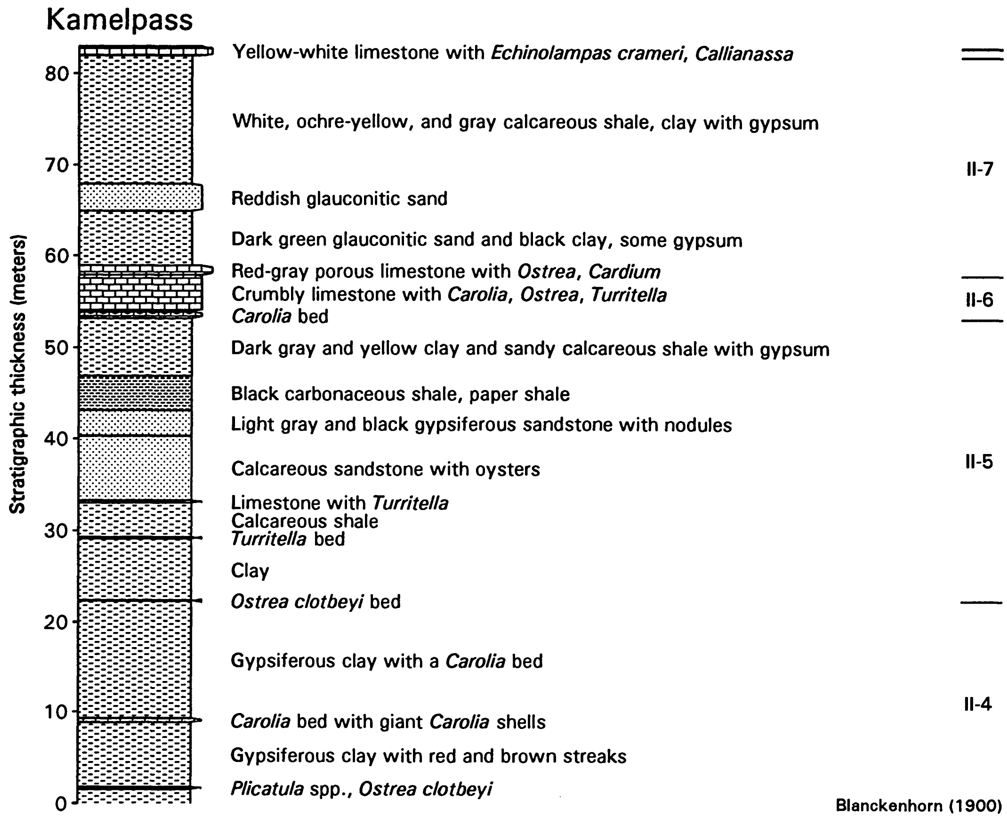


FIG. 17—Stratigraphic section of Eocene at Kamelpass about 9-10 km northwest of Dimeh in Fayum, based on measurements and lithological descriptions of Blanckenhorn (1900, p. 449). Blanckenhorn divided the section into units II-4 through II-8. These are the same zones of the upper Mokattam that Blanckenhorn recognized at Gebel Mokattam (Figs. 5 and 7). UTM coordinates of this locality are approximately 267.000E × 3276.000N.

Mayer-Eymar

Karl Mayer-Eymar's first work on Egyptian faunas was a study of invertebrate fossils from Geziret el-Qarn in the Fayum. These were collected by Schweinfurth in 1879, and published by Mayer-Eymar (1883) as a part of Zittel's *Beträge zur Geologie und Palaeontologie der Libyschen Wüste*. Mayer-Eymar's first visit to Egypt, discussed above, was brief and limited to the vicinity of Cairo (Mayer-Eymar, 1886). Mayer-Eymar's study of the Fayum started with a paper interpreting Schweinfurth's 1886 observations (Mayer-Eymar, 1893). He made a two-day excursion to Fayum in 1894, when he worked north of Dimeh. The report on this was entitled "*Quelques mots ...*" (Mayer-Eymar, 1895). True to the title, it was brief. Observations on the "Ligurian" [Priabonian, late Eocene] were very limited, and Mayer-Eymar's sole conclusion was that there was evidence of a late Eocene sea in Fayum. Mayer-Eymar observed the "Tongrian" [Lattorfian or Rupelian, early Oligocene] fossil forests and basalt, attributing discovery of these to Schweinfurth. The following year, in 1895, Mayer-Eymar made a 7-day trek from Fayum to Kom Aushim, to Dimeh, then northward to climb the Fayum escarpments, and finally eastward to return to Cairo (Mayer-Eymar, 1896). Observations on both of these trips were made haphazardly, with little documentation of distance or thickness, and they consequently retain little value. Further, Mayer-Eymar appears to have had a poor sense of direction, and it is disconcerting to read that Dimeh is west of Birket Qarun (it is north of the lake) or that Mayer-Eymar thought he worked 4 km south of the Qasr el-Sagha section studied by Schweinfurth (1886) when he must have worked 4 km west of it.

Blanckenhorn

Max Blanckenhorn's (1900) discussion of Gebel Mokattam is reviewed above. He also published two Fayum stratigraphic sections of the uppermost marine Eocene "*Carolia*-Stufe" in his 1900 paper. The sections are shown graphically in Figures 16 and 17.

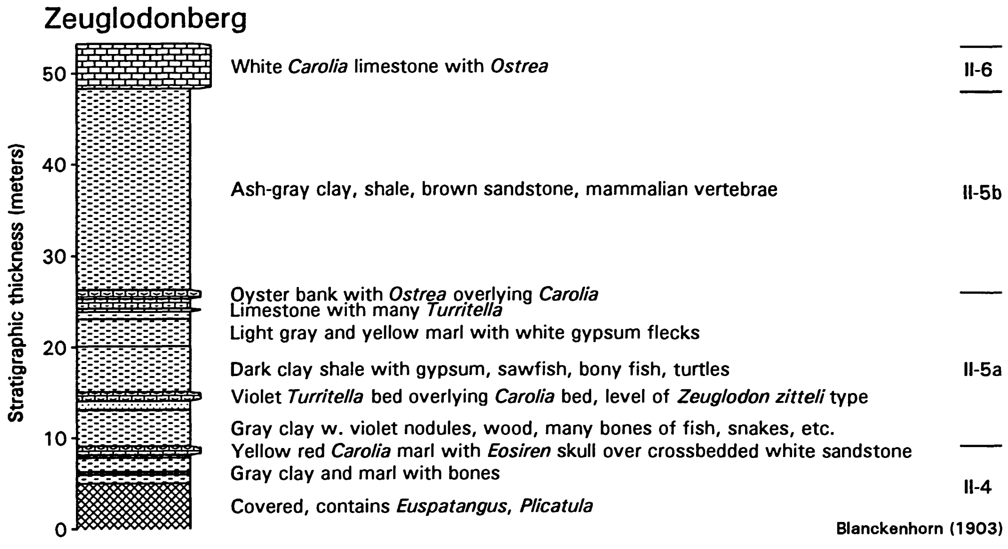


FIG. 18—Stratigraphic section of Eocene at "Zeuglodonberge" about 12½ km west of Qasr el-Sagha (Schweinfurth, 1886, p. 139). Blanckenhorn (1903, p. 390, see Fig. 19) refers to this as a single hill, Zeuglodonberg (Fig. 19), 3 hours WSW of Qasr el-Sagha. In either case, this section must have been measured close to Garet el-Esh. Measurements and lithological descriptions are from Blanckenhorn (1903, p. 390). Blanckenhorn divided the section into units II-4 through II-6 developed at Gebel Mokattam (Fig. 7). UTM coordinates of the locality are approximately 265.000E × 3274.000N.

The first section was measured at a place Blanckenhorn acknowledged Mayer-Eymar for calling "*Korallenhügel*" (possibly in conversation, because I have found no reference to this in Mayer-Eymar's published papers). Blanckenhorn adopted this name as well. According to Blanckenhorn (1900, p. 447), the hill is 5½ km on an exactly northwest bearing from the temple ruin at Dimeh. Later Blanckenhorn (1903, p. 388) indicated that Korallenhügel is "2 *Stunden*" northwest of Dimeh. The latter, applying Zittel's *Kamelstunden* conversion factor, corresponds to a distance of about 7-9 km. A northwest bearing intersects the Qasr el-Sagha escarpment at a distance of just over 7 km [on the 1:100,000 Gebel Qatrani topographical map (Survey of Egypt, 1956)].

The second or "*Kamelpass*" section was measured farther to the northwest along a route Blanckenhorn (1900, p. 448) described as the only one by which camels can easily ascend the escarpment in the west. This pass is shown clearly on the Gebel Qatrani topographical map. The two localities lie 3-4 km east and northeast of Garet el-Esh (Fig. 2).

Comparing the Korallenhügel and Kamelpass sections, the boundaries between Blanckenhorn's zones II-3 and II-4 and between his zones II-4 and II-5 appear arbitrary. By contrast, zone II-6 is well defined as a prominent ledge-forming limestone sequence rich in *Carolia*, II-7 is well defined as a thick section of sands and shales, and II-8 is well defined as another prominent ledge and plateau-forming limestone bearing the small echinoid *Echinolampas crameri*. These are among the most widely traceable units in the Fayum *Carolia* beds.

Blanckenhorn (1900) did not discuss Fayum formations underlying his *Carolia* beds, but noted (p. 452) that overlying "Bartonian" or "upper Eocene" strata could be divided into two stages, a lower stage of fresh and brackish water sediments, and a higher stage of predominantly marine sediments alternating with fresh water beds up to the capping basalt.

As noted above, Blanckenhorn returned to Fayum with Ernst Stromer von Reichenbach in January, 1902, as part of a vertebrate paleontological expedition (Stromer, 1903a). The Stromer expedition of 1902 made two traverses through Fayum beds west and north of Birket Qarun (Stromer, 1903a, p. 342). The first traverse took eleven days (January 17-27) and went from the temple ruin at Qasr Qarun west and north around the west end of Birket Qarun, then east on the north side of the lake to Dimeh and Qasr el-Sagha, and then to Tamia in the Fayum oasis. The second traverse took thirteen days (February 6-18) and went directly overland from Cairo to the northern Fayum, providing access to bone beds of the "upper Eocene" not reached from below. This trek also ended at Tamia.

Stromer and Blanckenhorn made a trip to Wadi Natrun, looked for fossils and measured sections in Wadi Ramliya southeast of Wasta in the Eastern Desert, and then

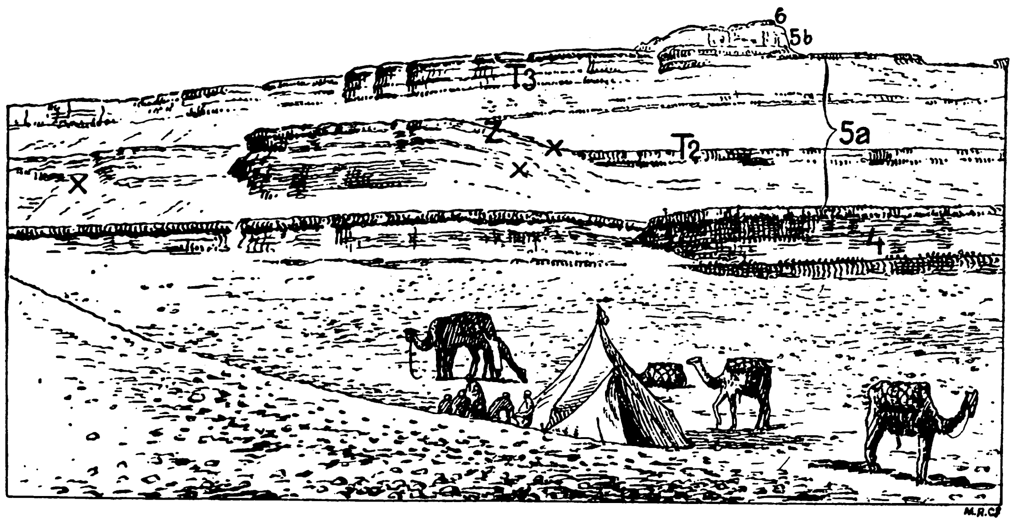


FIG. 19—Sketch of "Zeuglodonberg" locality as shown in figure 12a of Blanckenhorn (1903, p. 391). Note developmentof ridges correspondingto fossil-rich "*harte Bank*" or hard bed deposits at top of zone II-4 and within II-5a. This locality is within the Zeuglodonberge hills of Schweinfurth (1886, p. 139), type locality of *Saghacetus osiris* (Dames 1894), and must be somewhere near Garet el-Esh. Numerals 4, 5a, 5b, and 6 refer to zones II-4, II-5a, II-5b, and II-6, respectively. T2 and T3 label *Turritella*-rich horizons. Z is interval with *Zeuglodon*, and individual finds are marked with an x.

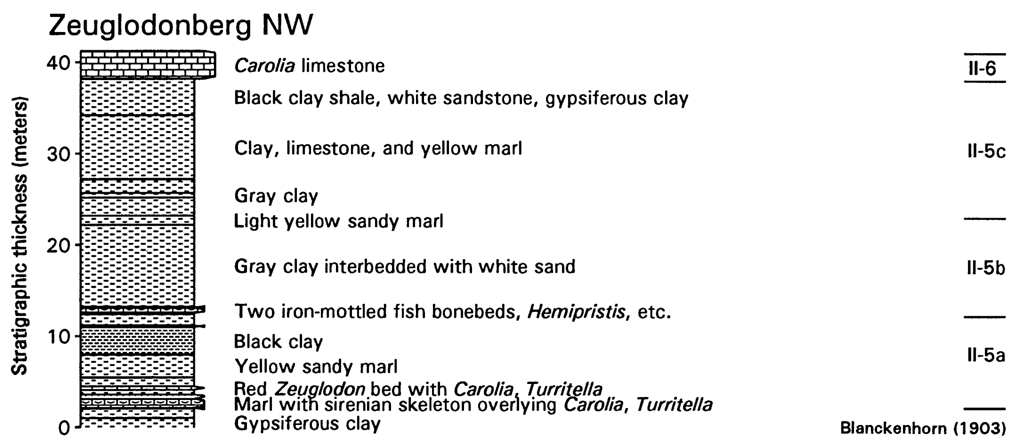


FIG. 20—Stratigraphic section of Eocene at Zeuglodonberg NW about 1.5 km (0.5 hours) northwest of Zeuglodonberge, based on measurements and lithological descriptions of Blanckenhorn (1903, p. 392). Blanckenhorn divided the section into units II-4 through II-6 developed at Gebel Mokattam (Fig. 7). UTM coordinates of the locality are approximately 263.200E × 3274.000N.

accompanied Schweinfurth to Qena and Luxor. Stromer (1903a) expressed some disappointment in the paleontological results of his expedition, attributing poor collecting to the fact that the fossiliferous beds had already been examined by others, but he also took some satisfaction from Blanckenhorn's geological observations. Stromer (1903a) was able to describe one new skull of *Zeuglodon osiris* (now *Saghacetus osiris*).

Blanckenhorn's (1903) report following the Stromer expedition covered a wide range of geological problems in Egypt, with parts of the report devoted to the boundary between the Cretaceous and Eocene, to the *Mokat-*

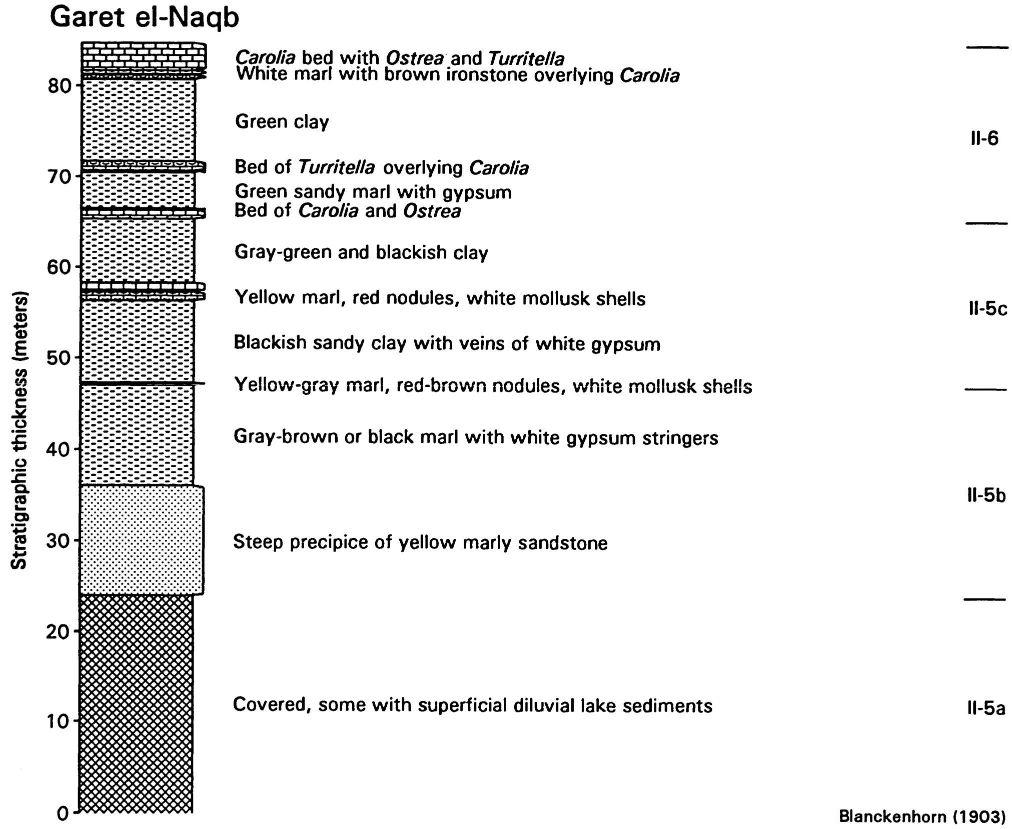


FIG. 21—Stratigraphic section of Eocene at Garet el-Naqb just north of the west end of Birket Qarun (⁜ on Schweinfurth's, 1886, map; Gebel d'Archaic of Mayer-Eymar), based on measurements and lithological descriptions of Blanckenhorn (1903, p. 393). Blanckenhorn divided the section into units II-5a through II-6 developed at Gebel Mokattam (Fig. 7), but this interpretation is certainly in error. Blanckenhorn's "steep precipice of yellow marly sandstone" is Birket Qarun Formation as this formation is understood here. Overlying beds belong to the lower part of the Qasr el-Sagha Formation and are probably older than Blanckenhorn's zone II-1 at Gebel Mokattam. UTM coordinates of the locality are approximately 247.500E × 3262.800N.

tamstufe or "middle Eocene," to the upper Eocene and Oligocene, and to basalt in the Libyan or Western Desert. The only part of the report that concerns us here is the section on the "middle Eocene." Blanckenhorn reviewed his earlier work on the Mokattam Eocene in which the lower Mokattam was divided into five units I-1 through I-5, and the upper Mokattam was divided into eight units II-1 through II-8. He reaffirmed that Gebel Mokattam is not the most representative section for either the lower or upper Mokattam. Advantages of the Wadi el-Sheikh section in the Eastern Desert over the lower Mokattam section at Gebel Mokattam are exposure in four distinct terraces instead of one cliff section, greater thickness, and richer fossil production (Blanckenhorn, 1903, p. 364). Advantages of the Fayum section in the Western Desert over the upper Mokattam section at Gebel Mokattam are its three-fold greater thickness, richer fossil production, better fossil preservation, and greater accessibility.

Blanckenhorn (1903) described ten "middle Eocene" stratigraphic sections from Fayum, and one from Wadi Ramliya in the Eastern Desert east of Fayum and Wasta. These are logically described from northeast to southwest, that is, from the northeastern Fayum to Wadi Ramliya to the southwest. Nine of Blanckenhorn's sections describe upper Mokattam beds along a 30 km length of the Qasr el-Sagha escarpment in northern Fayum. These are, from east to west: Tamariskenbucht (Fig. 11), Gebel Achdar (Fig. 12), Klippenecke (Fig. 13), Qasr el-Sagha (Fig. 14), Gebel Hameier (Fig. 15),

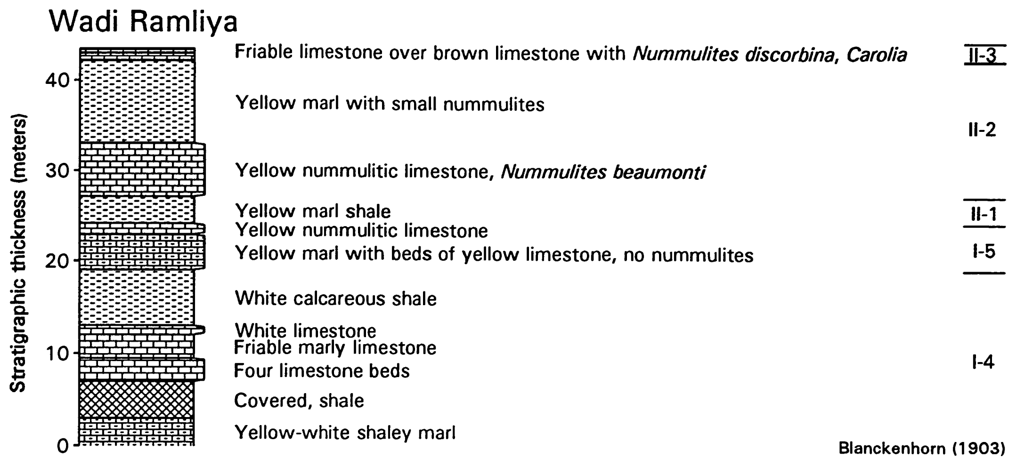


FIG. 22—Stratigraphic section of Eocene at Wadi Ramliya in the Eastern Desert east of Fayum, based on measurements and lithological descriptions of Blanckenhorn (1903, p. 367). Blanckenhorn divided the section into units I-4 through II-3 developed at Gebel Mokattam (Fig. 7), but this is questionable because there is so little basis for comparison in terms of fauna. This section is isolated from all others, and the locality should represent depositional environments much farther onshore. UTM coordinates of the locality are approximately 338.000E × 3235.000N.

Korallenhügel (Fig. 16), Kamelpass (Fig. 17), Zeuglodonberg (Figs. 18, 19), and Zeuglodonberg NW (Fig. 20).

The sections Blanckenhorn studied generally preserve his Gebel Mokattam zones II-3 through II-8. Lower beds are not exposed in the Qasr el-Sagha escarpment. Zones II-6 and II-8 both form prominent ledges and these are often separated by a wide terrace developed on the top of II-6, which explains why some of Blanckenhorn's sections stop at II-6. All of these sections are very similar, and there is considerable lithological continuity and uniformity in the zones. Prominent markers like II-6 are easily traced from one section to the next. Within zones, especially II-3 through II-5 and II-7, there is variability in facies representing local environments on a shelf floor influenced by factors like clastic influx and distribution.

The thickest interval in Blanckenhorn's Fayum sections is usually II-5, which is very different from the situation at Gebel Mokattam. II-5 includes numerous benches labelled "*harte Bank*" [hard bed], and Blanckenhorn sometimes noted that these tend to have *Carolia* at the base and *Turritella* or *Ostrea* at the top. Fossils identified by Blanckenhorn are all marine except for occasional drifted wood and possibly some lower vertebrate remains, and Blanckenhorn interpreted the entire sequence as representing marine deposition.

Blanckenhorn's (1903) last Fayum section, at Garet el-Naqb (Fig. 21) is interesting because it was measured along a lower escarpment, the Birket Qarun escarpment, near the west end of lake Birket Qarun. The Garet el-Naqb section spans a much lower stratigraphic interval, but Blanckenhorn appears not to have realized this and erroneously identified the same sequence of zones II-5 through II-6 recognized elsewhere in Fayum. This mistake demonstrates the importance of lithological continuity and/or abundant faunas in well studied strata when making lateral correlations.

Blanckenhorn's final section, at Wadi Ramliya east of Fayum (Fig. 22) is isolated from all the others, the section is relatively short, and it is southeast of the others and hence farther onshore, making interpretation difficult and questionable. Even the presence of *Carolia* at the top of a sequence of nummulite-rich limestones and shales is difficult to interpret because these sometimes occur together in the Wadi Rayan Formation as well as in the Qasr el-Sagha Formation (see below).

Blanckenhorn (1903, p. 399) was the first to recognize an unconformity between the marine upper Eocene [Qasr el-Sagha Formation] and overlying "fluvio-marine" beds [Gebel Qatrani Formation]:

> *Obwohl eine Diskordanz nicht direkt zu beobachten ist, könnte man doch speziell im NO. an eine Lücke oder Unterbrechnung der Sedimentation zu Beginn des Obereocäns (Bartonien) denken und geneigt sein, den ganzen fluviomarinen Komplex ins Oligocän zu stellen.*

> [Although an unconformity cannot be observed directly, one can still recall, especially in the northeast, a gap or interruption of sedimentation at the beginning of the upper Eocene due to erosion, thus placing the whole Gebel Qatrani fluviomarine complex in the Oligocene].

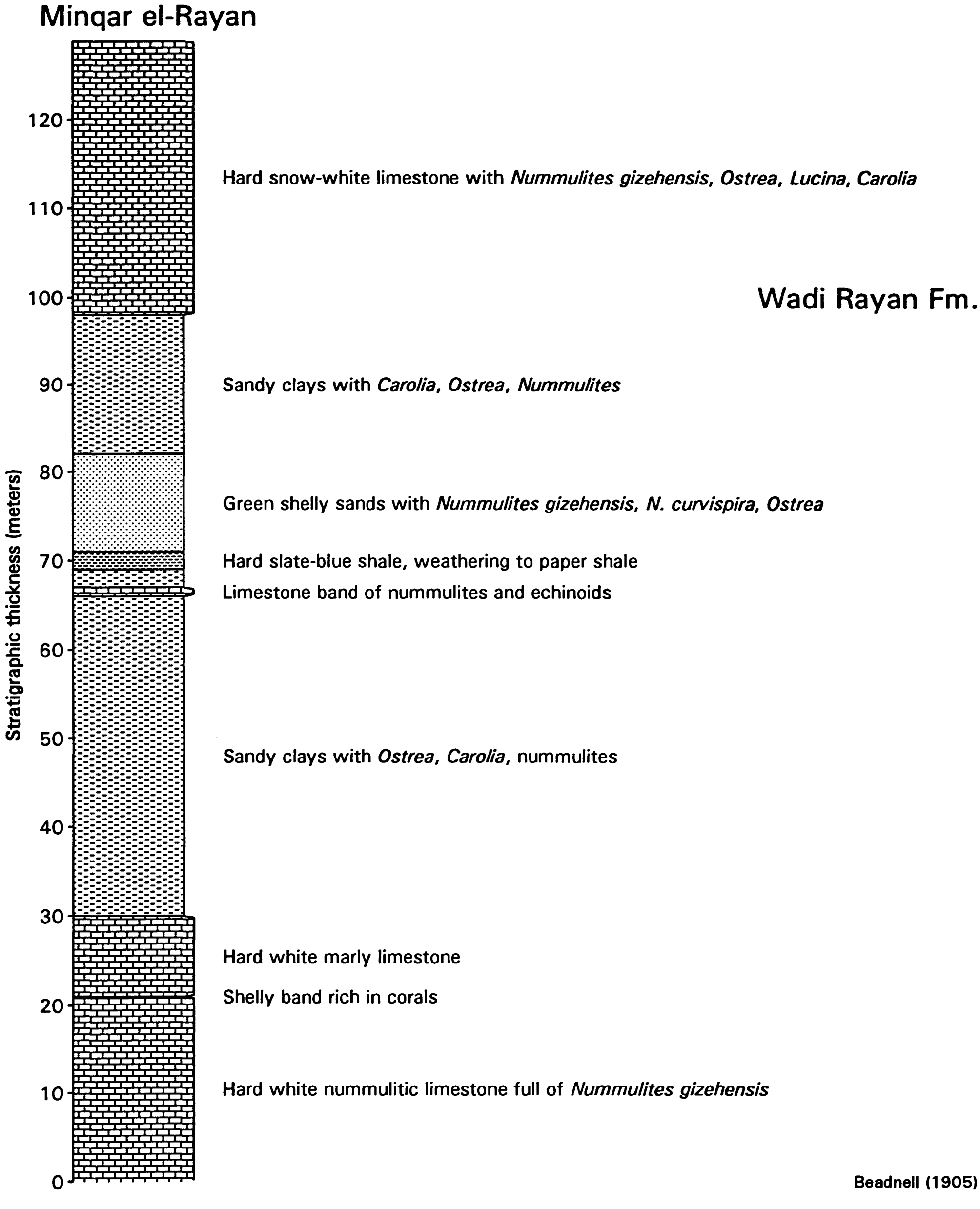


FIG. 23—Stratigraphic section of Eocene at Minqar el-Rayan in the western Fayum depression, based on measurements and lithological descriptions of Beadnell (1905, p. 36). Beadnell included all of this section in his Wadi Rayan series (Wadi Rayan Formation), but it has subsequently been subdivided into Muela, Midawara, Sath el-Hadid, and Gharaq formations by Iskander (1943). UTM coordinates of the locality are approximately 238.000E × 3223.000N.

This observation, communicated via Stromer (1907) and Osborn (1908), probably explains how the Gebel Qatrani Formation in Fayum came to be regarded as Oligocene in age. It has been called Oligocene by virtually all authors since Osborn (1908).

Blanckenhorn (1921) is a very useful review of the geology of Egypt as it was understood by early investigators. Much of the discussion of Fayum stratigraphy repeats work published earlier, but a new north-south cross section of the entire Fayum stratigraphic sequence

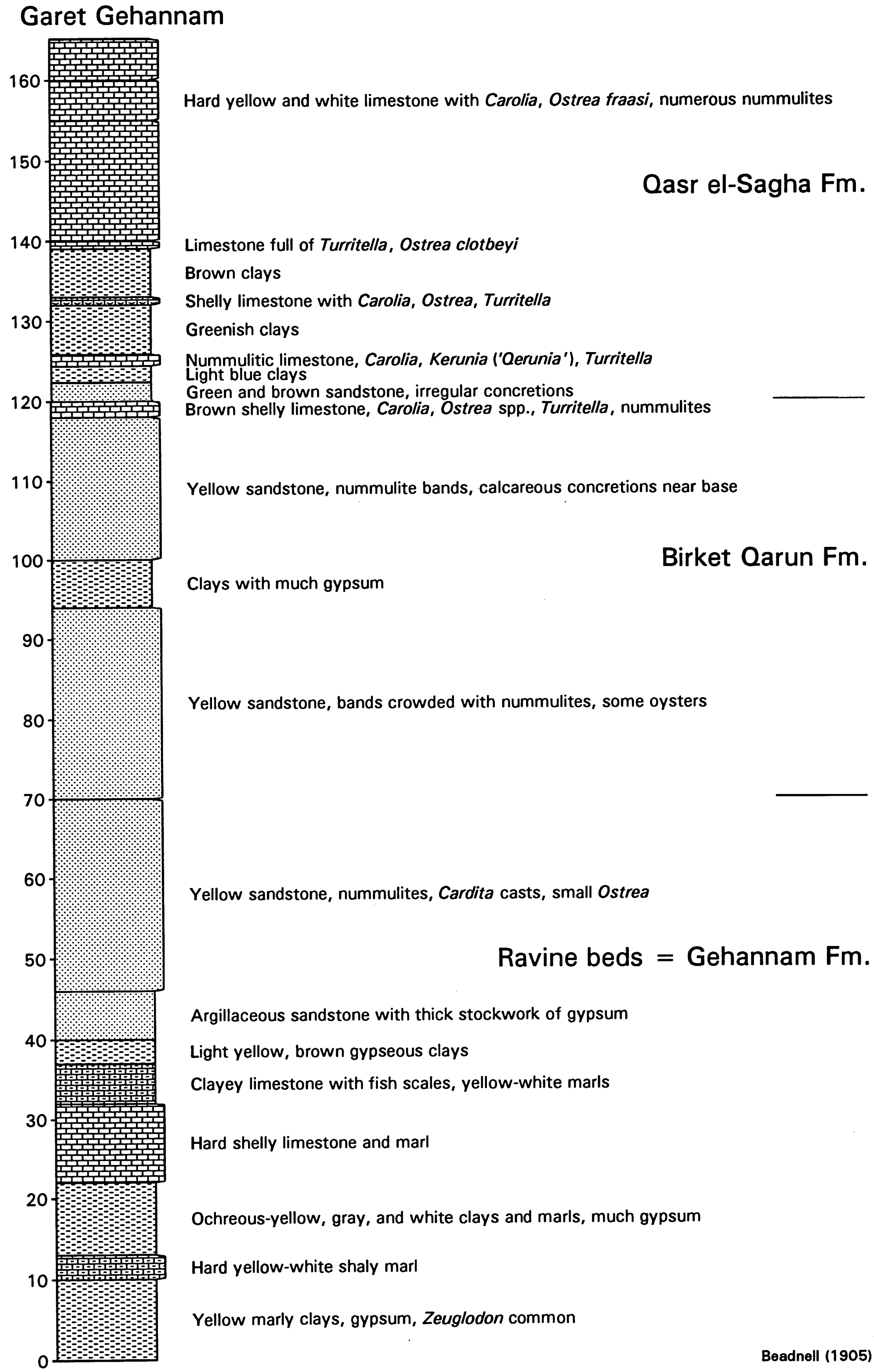


FIG. 24—Stratigraphic section of Eocene at Garet Gehannam in the northwestern Fayum depression, based on measurements and lithological descriptions of Beadnell, 1905, p. 38). Beadnell recognized three formations here: Ravine beds (Gehannam Formation, 70 m), Birket Qarun series (50 m), and Qasr el-Sagha series (45 m). Upper 24 m sandstone of Beadnell's Ravine beds is lithologically indistinguishable from overlying sandstones and is now included in the Birket Qarun Formation. ⇒

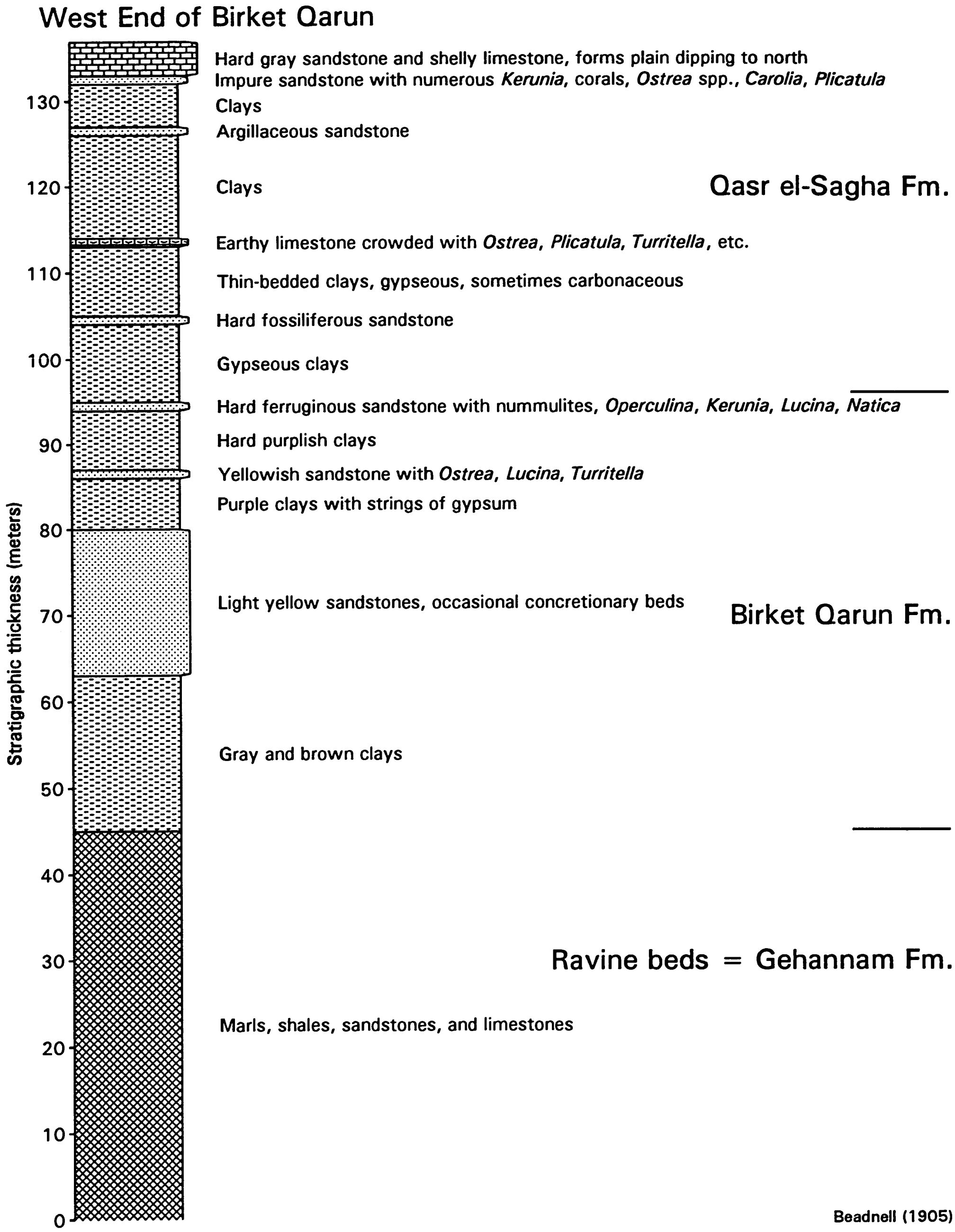


FIG. 25—Stratigraphic section of Eocene at west end of Birket Qarun in the northwestern Fayum depression (see Fig. 26), based on measurements and lithological descriptions of Beadnell (1905, p. 46). This is near Garet el-Naqb (compare section by Blanckenhorn in Fig. 21). Beadnell recognized three formations here: Ravine beds (Gehannam Formation, 45+ m), Birket Qarun series (50 m), and Qasr el-Sagha series (42+ m). Lower 18 m of gray and brown clays and upper 15 m of clays and thin sandstones of Beadnell's Ravine beds are lithologically indistinguishable from overlying and underlying formations, respectively, and are now included in them, making the Birket Qarun Formation 17 m thick at its type locality (see text). UTM coordinates of the locality are approximately 247.500E × 3262.800N.

Upper 2 m of Beadnell's Birket Qarun Formation is lithologically indistinguishable from overlying shelly limestones and is here included in the Qasr el-Sagha Formation. With these changes, the Gehannam Formation is 46 m thick, the Birket Qarun Formation is 72 m thick, and the Qasr el-Sagha Formation is 47 m thick at Garet Gehannam (see text). UTM coordinates of the locality are approximately 224.000E × 3246.500N.

FIG. 26—Photograph of Birket Qarun escarpment north of west end of lake Birket Qarun in vicinity of Beadnell's type section of the Birket Qarun Formation (compare with Fig. 25). Lower slope is upper part of Gehannam Formation. Vertical cliffs of sandstone in middle of section are Birket Qarun Formation. Upper cliffs and slopes are lower part of Qasr el-Sagha Formation (Umm Rigl Member). View is to east, and lake is in distance at right side of photograph.

was included, drawn through Geziret el-Qarn, Korallenhügel, and Gebel Hameier.

Beadnell

Hugh J. L. Beadnell was a geologist employed by the Geological Survey of Egypt to conduct the first thorough survey of Fayum geology. This was motivated in part by the need to store river water from the Nile for irrigation, and it was carried out contemporaneously with Blanckenhorn's stratigraphic investigations. In his final report, Beadnell (1905, p. 9) stated that the purpose of the survey was "to construct as rapidly as possible a general map of the depression, at the same time laying down in broad outline the chief geological formations and trusting to future opportunity to examine in more detail places of special interest."

Beadnell had several advantages over Schweinfurth, Mayer-Eymar, and Blanckenhorn in his investigation of Fayum geology, including full government logistical support for field work, a staff for drafting of maps and sections, and a sponsor for publication of results. More importantly, he had the advantage of a project of wide scope that placed observations in a broader context than that available to earlier authors.

Beadnell's field party began work in October 1898 in the eastern part of Fayum, progressed to the northern escarpments, and extended mapping as far westward as Garet Gehannam and Wadi Rayan during the spring of 1899. Evidently no field work was done during the winter of 1899-1900. Field work in 1901 was limited to soil and water surveys in the Fayum oasis. Bone beds discovered in 1898 were revisited with C. W. Andrews in April 1901, and again later the same year (Andrews, 1901). Field study was concentrated in continental beds in the upper part of the Fayum sequence during the winter of 1901-1902, and some collecting continued there for two more winters. A second phase of mapping was carried out in the winter of 1902-1903, when a traverse was carried from Garet Gehannam southwestward (with discovery of Wadi Hitan or Zeuglodon Valley) and then eastward back to Wadi Rayan. The neighborhood of Garet Gehannam was further explored in the winter of 1903-1904. In addition to preliminary technical papers, this field work resulted in two classic monographs, the

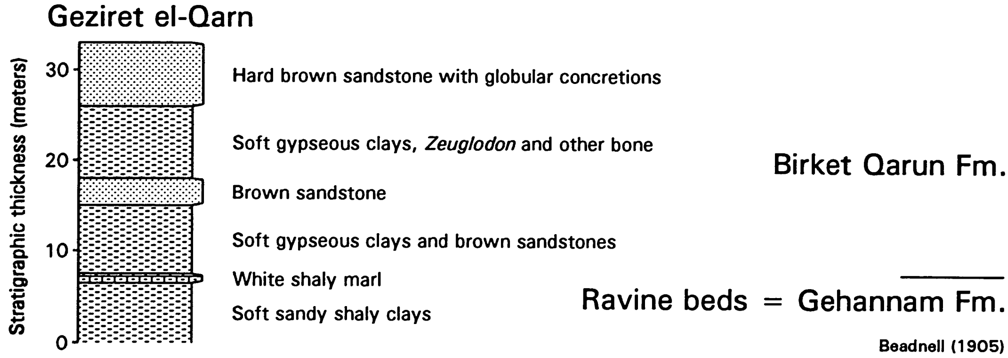


FIG. 27—Stratigraphic section of Eocene on the island of Geziret el-Qarn in Birket Qarun in the northern Fayum depression, based on measurements and lithological descriptions of Beadnell (1905, p. 44). Beadnell included the lower 8 m of this section in his Ravine beds (Gehannam Formation) and the upper 25 m in his Birket Qarun series, and considered the top bed here to underlie his section measured on the mainland opposite this island (Fig. 28). Lithologically the only bed that should be included in the Birket Qarun Formation is the top 7 m sandstone (see text). UTM coordinates of the locality are approximately 270.500E × 3264.000N.

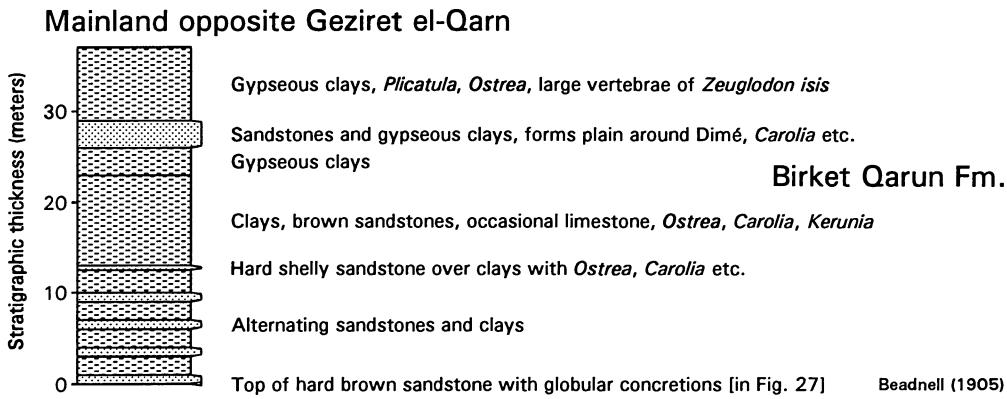


FIG. 28—Stratigraphic section of Eocene on the north shore of Birket Qarun opposite the island of Geziret el-Qarn in the northern Fayum depression, based on measurements and lithological descriptions of Beadnell (1905, p. 45). Beadnell included all of this section in his Birket Qarun series, but lithologically and paleontologically it belongs in the Qasr el-Sagha Formation (see text). UTM coordinates of the locality are approximately 270.500E × 3268.500N.

first by Beadnell (1905) on the topography and geology of Fayum Province, and the second by Andrews (1906) on Tertiary Vertebrata of the Fayum.

Beadnell (1901) provided a summary of Fayum stratigraphy that has guided most subsequent work. He divided the marine Eocene into four formations or "series," overlain by a fifth "fluvio-marine" formation. These are as follows:

5. Fluvio-marine Series (Gebel el Qatrani beds), variegated sands and sandstones, clays, and marls, divided near the summit by one or more thick intercalated lava sheets, upper Eocene to lower Oligocene, 250 m thick [now divided into Khashab Formation, Widan el-Faras Basalt, and Gebel Qatrani Formation]

4. Qasr el Sara Series (*Carolia* beds), group of alternating clays, sandstones, and limestones, middle Eocene, equivalent to the upper Mokattam beds of Cairo, 175 m thick [now called Qasr el-Sagha Formation]

3. Birket el Qurun Series (*Operculina*-Nummulite beds), clays, sandstones, and calcareous grits, middle Eocene, 60 m thick [now called Birket Qarun Formation]

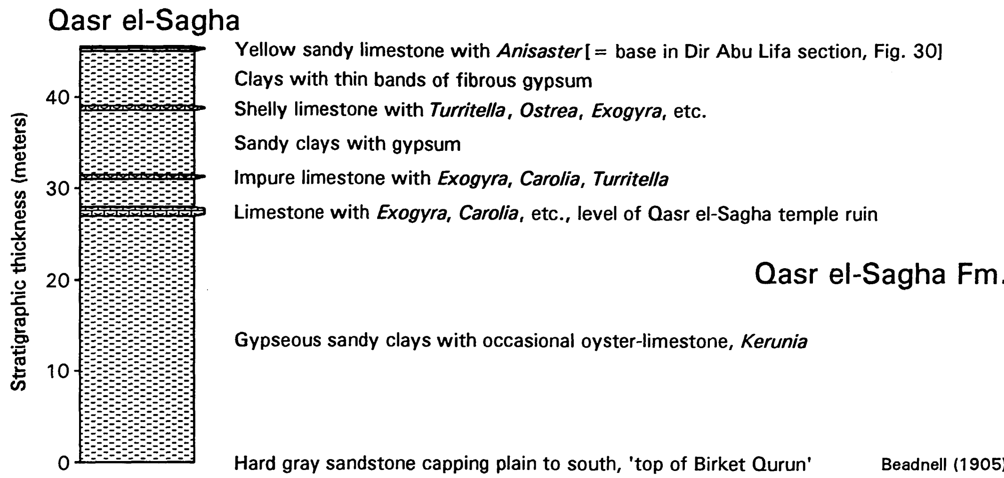


FIG. 29—Stratigraphic section of Eocene at the Qasr el-Sagha temple ruin in the northern Fayum depression, based on measurements and lithological descriptions of Beadnell (1905, p. 52). Beadnell included all of this section in his Qasr el-Sagha series (Qasr el-Sagha Formation). Eighteen meters of section above level of Qasr el-Sagha temple ruin overlap Blanckenhorn's section here (Fig. 14). UTM coordinates of the locality are approximately 274.800E × 3276.500N.

2. Ravine Beds (fish-scale marls), white marly limestones and gypseous clays, middle Eocene, 25 m thick [now called Gehannam Formation]

1. Wadi Rayan Series (*Nummulites gizehensis* beds), clays, marls, and limestones, middle Eocene, undetermined thickness [now called Wadi Rayan Formation or subdivided into Muela, Midawara, Sath el-Hadid, and Gharaq formations]

The Wadi Rayan Formation forms the valley floor over much of the western part of the Fayum depression, but it is breached and exposed in the southwest at Wadi Rayan and vicinity. The Gehannam Formation borders Birket Qarun and forms the floor of much of the cultivated oasis. The Birket Qarun, Qasr el-Sagha, and Gebel Qatrani formations appear from Beadnell's (1901) descriptions to have corresponded largely to sedimentary rocks exposed in the Birket Qarun, Qasr el-Sagha, and Gebel Qatrani escarpments, respectively, irrespective of lithology.

Beadnell (1905) published good stratigraphic sections for all of his marine formations. The type locality of the Wadi Rayan Formation is at Minqar el-Rayan (Fig. 23), where there is a section of limestones, clays, and sands 129 m thick. The top unit is a thick bed of hard snow-white limestone with *Nummulites gizehensis* that floors much of the western Fayum depression. This bed can be traced northward from Minqar el-Rayan to Garet Gehannam where the Gehannam Formation ("Ravine beds") rests on top of it.

The type locality of the Gehannam Formation is at Garet Gehannam, where Beadnell reported it as being 70 m thick (Fig. 24). However the upper 24 m of this is a thick sandstone Beadnell noted resembles overlying sandstones of the Birket Qarun Formation, and there is no lithological or other reason to include this sandstone in the Gehannam Formation. Removing the upper sandstone, the Gehannam Formation is 46 m thick at its type locality (which is closer to Beadnell's original, 1901, report of a 25 m thickness for the "Ravine beds"). The upper 2 m of Beadnell's Birket Qarun Formation at Garet Gehannam is lithologically indistinguishable from overlying shelly limestones and these are here included in the Qasr el-Sagha Formation. Beadnell (1905) reported the Birket Qarun Formation as being 50 m thick at Garet Gehannam (Fig. 24), but addition of 24 m of sandstones removed from the Gehannam Formation and subtraction of 2 m of shelly limestone moved to the Qasr el-Sagha Formation makes the Birket Qarun Formation 72 m thick here. Finally, the upper part of the section at Garet Gehannam (Fig. 24) is a 45 m unit of nummulitic *Carolia*, *Ostrea*, and *Turritella*-rich limestones and clay shales that Beadnell placed in the Qasr el-Sagha Formation. Addition of 2 m makes this 47 m thick at Garet Gehannam.

The type locality of the Birket Qarun Formation is north of the west end of Birket Qarun (Figs. 25, 26). Beadnell (1905, p. 46-47) included 50 m from the middle of this section in the Birket Qarun Formation, but here

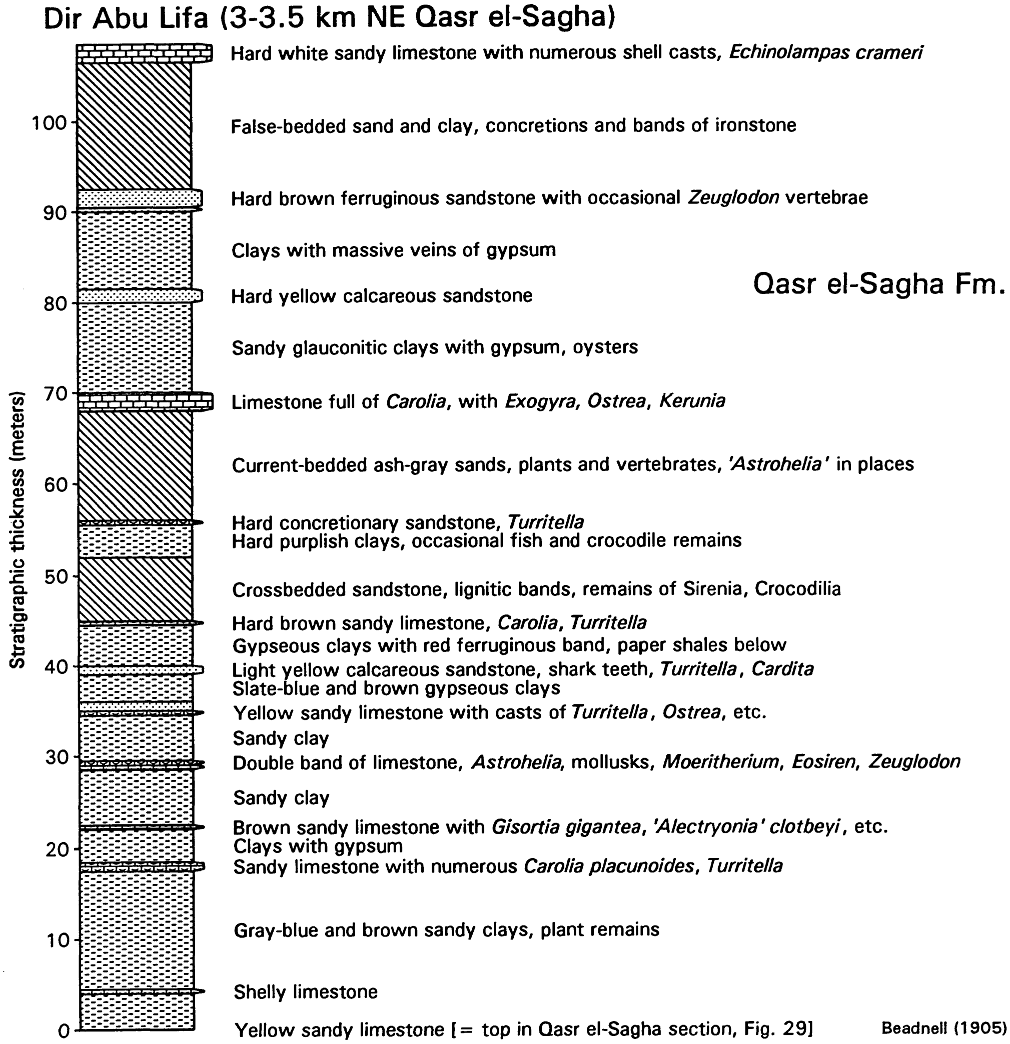


FIG. 30—Stratigraphic section of Eocene at or near Dir Abu Lifa 3-3.5 km northeast of Qasr el-Sagha temple ruin in the northern Fayum depression, based on measurements and lithological descriptions of Beadnell (1905, p. 50). Beadnell included all of this section in his Qasr el-Sagha series (Qasr el-Sagha Formation). Blanckenhorn's short Klippenecke section (Fig. 15) was measured near here and the *Gisortia* bed shown here is probably the same in both sections. Bown and Kraus's Wadi Efreet section (Fig. 31) was measured just west of here, where crossbedded sandstone beds occupy even more of the section. UTM coordinates of the locality are approximately 277.100E × 3278.800N.

again this makes little sense lithologically. The lower 18 m are gray and brown clays more like the underlying Gehannam Formation, and the upper 15 m are alternating clay shales and sandy limestones more like the overlying Qasr el-Sagha Formation. The distinctive lithology justifying recognition of a separate formation is the 17 m sequence of soft light-yellow sandstones that forms vertical cliff walls. These sandstones weather to produce clusters of spherical sand bodies in places, but the underlying Gehannam Formation produces these too (and the overlying Qasr el-Sagha formation includes what appear to be spherical bioherms that Beadnell confused with Birket Qarun spherical sandstone bodies elsewhere, see Chapter VI). The Birket Qarun Formation, as restricted here to a lithologically defined sandstone unit, is 72 m thick at Garet Gehannam but only 17 m thick at its type locality.

Beadnell (1905, p. 44) visited the island Geziret el-Qarn in Birket Qarun and published a 33 m thick section that he regarded as 7.5 m of "Ravine beds" at the bottom, overlain by 25.5 m of gypseous clays and sandstones of the Birket Qarun Formation (Fig. 27). The top 7 m bed is the only Birket Qarun-like sandstone, and I regard the lower 26 m as Gehannam Formation. Beadnell (1905, p. 45) published a 37 m "Mainland" section measured just north of Birket Qarun on the mainland opposite the island of Geziret el-Qarn (Fig. 28). He regarded all of this section as Birket Qarun Formation, but it is full of *Ostrea*, *Carolia*, and *Kerunia* ("*Qerunia*"), which are more typical of the Qasr el-Sagha Formation, making it more likely that this section is really part of the Qasr el-Sagha Formation. Thus the Birket Qarun Formation is probably only 7 m or so thick in the vicinity of Geziret el-Qarn.

Beadnell's (1905, p. 50-52) Qasr el-Sagha Formation section was measured in two parts at two places. The first part was measured at the type locality, the Qasr el-Sagha temple ruin (Fig. 29; where Blanckenhorn measured the Qasr el-Sagha section shown in Fig. 14). Beadnell's Qasr el-Sagha section is 45 m thick, but only the upper 18 meters overlap Blanckenhorn's section. The main part of Beadnell's Qasr el-Sagha Formation section was measured 3 to 3.5 km northeast of Qasr el-Sagha in the vicinity of the Coptic cliff-dwelling at Dir Abu Lifa (Fig. 30). This contributes an additional 109 m to the whole, and shows, in the lower part, the alternation of clay shales with limestone "hard beds" described by Blanckenhorn (1903). Beadnell was more impressed than Blanckenhorn by massive cliff exposures of cross-bedded sandstones and clays. Beadnell, like Blanckenhorn, noted the plateau-forming limestone full of *Carolia* (68-70 m interval in Fig. 30), and the hard white sandy limestone with *Echinolampas crameri* at the top of the section (106-109 m interval in Fig. 30). Beadnell's Qasr el-Sagha Formation section was 154 m thick (45 m at Qasr el-Sagha and 109 m at Dir Abu Lifa), which he thought included the whole formation. Eight meters of the Mainland section discussed above overlap this, but the remaining 29 m must be added at the base of the Qasr el-Sagha Formation, which makes its total thickness 183 m.

Beadnell (1905) measured sections including what he called Birket Qarun series sandstones near Tamia, Lahun, and Qalamsha on the east and south sides of the Fayum depression but these, like Blanckenhorn's Wadi Ramliya section, are isolated, relatively short, and farther southeast (and hence farther onshore) than other localities, making interpretation difficult and questionable. Sandstones in these sections may be unusually thick sandstone beds within the Gehannam Formation.

Simple correspondence of the Gebel Qatrani Formation and the Gebel Qatrani escarpment proved unsatisfactory lithologically, and Said (1960) and Bowen and Vondra (1974) subdivided the Gebel Qatrani escarpment, restricting the Gebel Qatrani Formation to beds below the basalt, naming the Widan el-Faras Basalt, and extending the Khashab Formation to include beds above the basalt. The Qasr el-Sagha escarpment is sometimes divided into two parallel escarpments, but even so all beds in the escarpment(s) belong to the Qasr el-Sagha Formation. The Birket Qarun escarpment includes three distinct lithological units, a lower marly shale unit (Gehannam Formation), an intermediate cliff-forming sandstone (Birket Qarun Formation), and an upper alternating sandy limestone and shale unit (lower part of Qasr el-Sagha Formation).

Beadnell (1901) interpreted the transition from the Qasr el-Sagha Formation to the Gebel Qatrani Formation as "conformable," although these formations are now known to be separated by an unconformity. This null hypothesis of conformity weakened when Blanckenhorn (1903, p. 399) described the "*Lücke oder Unterbrechnung*" [gap or interruption] between the Gebel Qatrani and Qasr el-Sagha formations (discussed above). Beadnell (1905, p. 55) clarified this further, but interpreted missing upper beds of the Qasr el-Sagha as indicating facies change rather than erosion:

> From an examination of the [Gebel Qatrani] series in the field, there is no doubt that, in at least the centre of the area, the deposition of the lowest beds was continuous with those of the Qasr el Sagha ... series below. Followed away from the centre ... the series gradually thins out, and eastwards, at Elwat Hialla, some 23 kilometres north of Tamia, has a thickness of only 40 metres, the basal beds being apparently laid on to a bed of limestone of the Qasr el Sagha series about the horizon of Bed 12 in Section XXIII. The junction here is apparently one of perfect conformity as far as the individual beds go, and the peculiar sequence does not seem to be due to ordinary overlap; it appears as if the change from marine to estuarine conditions had set in earlier here than further to the west, with the result that the upper Qasr el Sagha beds are wanting. Moreover, the accumulation of estuarine beds went on so slowly in this locality that the series does not attain to nearly its normal thickness, while further east it dies out altogether. The slight dip to the north is identical in both series, their lithological characters being, however, very different.

Barron (1907) favored Blanckenhorn's interpretation over Beadnell's (as did Blanckenhorn, 1921, p. 109; Strougo, 1976a, p. 1139; and Bown and Kraus, 1988, p. 23).

Vondra

Carl Vondra (1974) studied the Eocene Qasr el-Sagha Formation in connection with research on the overlying Oligocene Gebel Qatrani Formation (Bowen and Vondra, 1974). Vondra gave the thickness of the Qasr el-Sagha Formation as 200 m, although he did not publish any sections himself nor explain how this round number was determined. Vondra (1974) divided the Qasr el-Sagha Formation into four distinct facies (paraphrased here):

1. *Arenaceous bioclastic carbonate facies*. Basal unit of yellow-orange glauconitic and limonitic, calcareous, silty, fine-grained quartz sandstone, gradational with underlying siltstone or claystone, with abundant sand-filled vertical burrows 2-3 cm in diameter attributed to *Callianassa*.

   Basal unit grades upward into 0.5 to 2 m of poorly sorted bioclastic carbonate with admixture of fine quartz sand in matrix of micrite (original lime mud). Very fossiliferous, packed with complete as well as disarticulated and comminuted remains of shelly marine invertebrates, including bivalves, gastropods, echinoids, and coelenterates (corals). Assemblages are usually dominated by *Turkostrea*, *Carolia*, *Crassostrea*, or *Turritella*, or by a mixture of *Turkostrea* and *Turritella*. Abraded bones or teeth of transitional marine and marine vertebrates are present, and these occasionally include a skull or partially articulated skeleton of a moerithere or sirenian. Carbonized fossil wood fragments are also found. Shelly fossils are recrystallized and selectively dissolved. Orange color is due to oxidized glauconite grains.

   Bioclastic carbonates grade upward into a 1-2 m unit of sparsely fossiliferous yellow-orange calcareous fine-grained quartz sandstone. Sedimentary structures, when present, include horizontal stratification or gently (5°) northwest dipping and more steeply (17-23°) southeast dipping large scale planar cross-stratification occurring in isolated sets.

   Uppermost unit composed of up to 1 m white to yellow-orange, very fine-grained, structureless quartz sandstone.

   Faunal assemblages indicate a firm to mobile sand-silt substrate, and suggest well circulated, moderate to high energy, warm, normal salinity marine coast or bar front environments to more brackish estuarine mouth environments, with water depths generally less than 20 m (E. G. Kauffman in Vondra, 1974). Vondra considered that the four sedimentary units within this facies corresponded to lower shoreface, middle shoreface, beach-upper shoreface, and eolian environments, respectively, and suggested that the arenaceous bioclastic carbonate facies was deposited by shoreward migrating "megaripples" like those found in shallow water of the Bahamas Bank and Recent beaches.

2. *Gypsiferous and carbonaceous laminated claystone and siltstone facies*. Interbedded with above facies. Pale yellow-brown to dark gray laminated claystone, silty claystone, and argillaceous siltstone ranging in thickness from 1 to 6 m. Sandy in lower portion and fines upward into siltstone and claystone. Fibrous and massive gypsum common. Veinlets of halite also present. Facies is very carbonaceous and contains small fragments of carbonized wood and leaves throughout. Complete carbonized leaves and leaf impressions common in claystones. These may form beds up to 0.5 m in thickness, and occur as interbedded lignitic paper shales. Invertebrate fossils are very rare. Sedimentary structures are lacking except for lamination and horizontal sand-filled callianassid burrows in the upper 10-20 cm.

   Facies interpreted to have been deposited in open and restricted shallow lagoons on the lee side of barrier islands. Lignitic paper shales represent leaf accumulations under very low energy conditions on the landward side of lagoons where abundant broad-leafed plants must have lined the shore. Impeded circulation yielded hypersalinity and deposition of calcium sulfate rich muds, later mobilized and redeposited as gypsum in diagenetic shrinkage fractures.

3. *Interbedded claystone, siltstone, and quartz sandstone facies*. Interfingers with both of above facies. Well exposed in prominent cliffs behind Qasr el-Sagha temple ruin. Interbedded units of 10-35 cm thickness fining upward from fine white quartz sandstone to dark gray siltstone and claystone. Each unit constitutes a foreset bed of a large-scale planar cross-stratification set. Foresets dip at 5° to northwest and are from 100-200 m in length. Sandstones within each foreset display steeply dipping cross-stratification of planar-delta type.

   Invertebrate fossils are very rare. Disarticulated and abraded remains of transitional marine and continental vertebrates occur. Finely comminuted plant debris is abundant in siltstones and claystones. Bioturbation structures and burrows are absent. Facies ranges up to 35 m in thickness and can be traced laterally for up to 15 km.

   This facies was deposited on a rapidly prograding delta front invading shallow brackish marine waters. Fining upward foresets and smaller scale planar-delta type cross-stratification indicate periodic influx of sediment introduced into a quiet lagoon by flood waters of a stream. Deposition was rapid and inhibited bioturbation and development of an invertebrate fauna.

4. *Quartz sandstone facies*. This is cut into the interbedded claystone, siltstone, and quartz sandstone facies (facies 3). Its basal contact is erosional, and a 1-2 m unit of channel lag intraformational conglomerate overlies this surface. The lag includes siltstone and claystone clasts, abraded bones, and reworked shells in a quartz sandstone matrix. This grades into white fine to medium-grained quartz sandstone with occasional thin interlaminations of carbonaceous siltstone and claystone. Large scale trough and planar crossbeds generally indicate northward paleocurrents.

   Invertebrate fossils are rare. Vertebrate fossils are locally abundant, including marine fish and aquatic marine to transitional-marine reptiles and mammals. All are at least partially disarticulated and many are abraded.

Facies is lenticular, with a concave upward basal contact. It ranges up to 35 m in thickness and 1 km in width. Lithology, basal contact, lateral relationship to other facies, primary structures, and mixed vertebrate fossil fauna suggest this facies is a distributary channel deposit.

Three of Vondra's facies are easily recognized in Blanckenhorn's (1903) section at Qasr el-Sagha (Fig. 14) and Beadnell's (1905) sections at Qasr el-Sagha (Fig. 29) and Dir Abu Lifa (Fig. 30), and the fourth is probably present as well. Facies 1, the arenaceous bioclastic carbonate facies, includes most of the bench-forming "hard beds" with *Carolia*, *Ostrea*, and *Turritella*. Facies 2, the gypsiferous and carbonaceous laminated claystone and siltstone facies, includes most of the interbeds between facies 1 hard beds. Facies 3, the interbedded claystone, siltstone, and quartz sandstone facies, includes the thick conspicuously crossbedded units near the top of the sequence labelled as being cross-bedded, current-bedded, or false-bedded. Facies 4 is less common, but the "hard brown ferruginous sandstone with occasional *Zeuglodon* vertebrae" near the top of the Dir Abu Lifa section (Fig. 30) fits this description, and the "hard yellow calcareous sandstone" below it might be a distributary channel deposit too.

Vondra's environmental interpretations for the Qasr el-Sagha Formation yield a coherent lagoonal mosaic of harder substrates densely inhabited by bivalves and other invertebrates (facies 1) separated by softer less-habitable clay and mud floors (facies 2), with this lagoonal mosaic invaded by prograding delta front (facies 3) and delta distributary (facies 4) deposits. Vondra did not mention either of the two prominent ledge-forming limestones or sandy limestones corresponding to Blanckenhorn's zones II-6 and II-8, and these do not appear to fit any of Vondra's Qasr el-Sagha facies.

Bowen and Vondra (1974, p. 118) introduced the term "Bare Limestone" for the top-most bed of the Qasr el-Sagha Formation exposed in Fayum, and described the contact between this and the overlying Gebel Qatrani Formation as "paraconformable," noting that the base of the latter is a persistent, 15-20 m thick, nonresistant, conglomeratic quartz sandstone. Bowen and Vondra's work was important in changing interpretation of the Gebel Qatrani Formation depositional environment from estuarine or fluviomarine with a coastline [i.e., land] not far distant to the south (Beadnell, 1905, p. 53) to "a low, featureless deltaic plain with a loosely sinuous to meandering stream. Gallery forests existed on alluvial ridges (levees) associated with the stream while savannahs may have existed in the interstream areas" (Bowen and Vondra, 1974, p. 135). In Bowen and Vondra's interpretation the coastline was not far distant to the *north*, and rivers formed the deposits on the planar top of a delta.

Strougo

Amin Strougo's first contribution to Fayum stratigraphy was a note in which he argued that the Qasr el-Sagha Formation in Fayum begins with a faunal zone he called the "*Cossmannella fajumensis* horizon," corresponding to Blanckenhorn's (1903) zone II-2 (Strougo, 1974). Later Strougo (1976a) correlated the Ain Musa bed from Gebel Mokattam to the Qasr el-Sagha Formation in Fayum, but another important aspect of this contribution was review of earlier literature on the Qasr el-Sagha - Gebel Qatrani formational contact and discontinuity of sedimentation marking the Eocene-Oligocene boundary in Fayum (Strougo, 1976a, p. 1139):

> *Au Fayoum, une discontinuité de sédimentation marque la limite de l'Éocène et de l'Oligocène comme le prouve le développement suivant.*
>
> *Blanckenhorn (1900) a assimilé à son niveau II-8 du Gébel Mokattam (équivalent du Membre Ain Musa) la couche terminale de la Formation Qasr el Sagha, puissante de 1 m seulement et renfermant de nombreux* Echinolampas crameri *et* Anisaster gibberulus. *Ce synchronism amena Barron (1907) à constater que plus de 70 m de roches reconnues par lui dans le district Le Caire-Suez, au-dessus du Membre d'Ain Musa, et appartenant encore à l'Éocène supérieur, n'avaient pas d'équivalents au Fayoum où le banc à* E. crameri *et* A. gibberulus *est directement subordonné à la Formation Qatrani, d'âge oligocène; il conclut qu'une profonde discontinuité de sédimentation sépara l'Éocène supérieur de l'Oligocène au Fayoum. ...*
>
> *Nous venons de voir que les couches du Mokattam et de Qasr el Sagha pouvaient être considérées comme homologues sans difficulté. Seuls les 10 m du sommet de ce dernier gisement semblent appartenir à une tranche de temps un peu plus récente que celle ayant présidé au dépôt de la Formation Maadi, à l'est du Caire. Il n'en demeure pas moins qu'une grande partie des couches affleurant dans le district Le Caire-Suez, au dessus du Membre Ain Musa, fait encore défaut au Fayoum, ce qui implique l'existence d'une discontinuité de sédimentation à la limite Éocène-Oligocène dans cette dernière région.*

[In Fayum, a discontinuity of sedimentation marks the limit of the Eocene and Oligocene, as the following proves.

Blanckenhorn (1900) included the uppermost bed of the Qasr el-Sagha Formation, only 1 m thick and containing numerous *Echinolampas crameri* and *Anisaster gibberulus*, as his Gebel Mokattam level II-8 (equivalent to the Ain Musa member). This synchrony led Barron (1907) to conclude that more than 70 m of rocks he recognized in the Cairo-Suez district, above the Ain Musa member and belonging to the upper Eocene, had no equivalents in Fayum where the *E. crameri* and *A. gibberulus* bed is directly beneath the Qatrani Formation of Oligocene age. He concluded that a profound discontinuity of sedimentation separated the upper Eocene from the Oligocene in Fayum ...

We come to see that the Mokattam and Qasr el-Sagha beds may be considered as homologs without difficulty. Only the uppermost 10 m of the latter deposit appear to represent a slice of time a little more recent than that at the top of the Maadi Formation east of Cairo. Little remains there of a great part of the beds deposited in the Cairo-Suez district above the Ain Musa member, missing also in Fayum, implying the existence of a discontinuity of sedimentation at the Eocene-Oligocene boundary in the latter region.]

Strougo regarded Bowen and Vondra's report of conglomeratic sandstone at the base of the Gebel Qatrani Formation as consistent with this discontinuity.

Abdou and Abdel-Kireem

Abdou and Abdel-Kireem (1975) were the first to propose a planktonic foraminiferal zonation of middle and upper Eocene rocks in Fayum. They found *Globigerinatheka semiinvoluta* [P15] in the Gehannam Formation and concluded that it is late Eocene in age.

Haggag

Abdou and Abdel-Kireem's study was followed by further work by Strougo and Haggag (1984) and by Haggag (1985, 1990). Strougo and Haggag (1984) studied the Gehannam Formation at Quta near the west end of Birket Qarun, found *Globorotalia lehneri* and *Truncorotaloides rohri*, and concluded, first, that the Gehannam Formation is a Fayum correlative of the Giushi Member (Giushi Formation) at Gebel Mokattam, and, second, that both formations are middle Eocene in age. The lower 10 m of the Gehannam Formation at Quta produced foraminifera of the *Globorotalia lehneri* zone [P12], and the overlying 50 m were considered equivalent to the *Orbulinoides beckmanni* zone [P13] or *Truncorotaloides rohri* zone [P14]. The Birket Qarun Formation lacks planktonic foraminifera, but Strougo and Haggag suggested that this formation might be middle Eocene also. One problem is recognition of formational boundaries: it is clear from Strougo and Haggag's (1984) section that what they recognize as Birket Qarun Formation includes shales that would here be placed in the Gehannam Formation.

With further investigation, Haggag (1990) determined that the upper part of the Gehannam Formation at Garet Gehannam and at Quta includes *Globigerinatheka semiinvoluta* [P15] and is thus late Eocene in age (as Abdou and Abdel-Kireem, 1975, proposed earlier). Spinose planktonic foraminifera characteristic of the middle Eocene end at the top of the *T. rohri* zone [P14], before *G. semiinvoluta* appears, and Haggag proposed a new late Eocene *Globigerina pseudoampliapertura* zone to fill this gap. As a result, a significant part of the Gehannam Formation is again recognized as being late Eocene in age on the basis of planktonic foraminifera.

Bown and Kraus

Thomas Bown and Mary Kraus (1988) included a substantial discussion of the upper Qasr el-Sagha Formation and two important observations on the Birket Qarun Formation in their monograph on the Gebel Qatrani Formation and adjacent rocks in Fayum. Observations on the Birket Qarun Formation will be mentioned first. Bown and Kraus (1988, p. 48) wrote:

> The earliest appearance of the coast in the immediate Fayum area during the Eocene was in Birket Qarun and (or) Temple Member time with the development of mangrove swamps and offshore subaqueous dunes in much of the region west of Garet Gehannam.

Bown first identified mangrove west of Garet Gehannam when we worked together in Wadi Hitan in 1985. At that time we both regarded the mangrove bed as part of the Birket Qarun Formation, but after several more seasons of field work it is clear that mangrove is confined to one narrow zone and the mangrove zone is in the Gehannam Formation underlying "subaqueous dunes" of the Birket Qarun Formation (see Chapter V).

Bown and Kraus (1988) adopted Vondra's (1974) thickness estimate of 200 m for the Qasr el-Sagha Formation, but divided the formation into two members rather than four facies. Their upper or Dir Abu Lifa Member measured 77 m thick at its type locality (Wadi Efreet, Fig. 31). Their lower or Temple Member was thus, by subtraction, thought to be 123 m thick (Vondra's 200 m total, minus 77 m placed in the Dir Abu Lifa Member).

The dominant lithology of the Dir Abu Lifa Member is crossbedded sandstone, and the Dir Abu Lifa Member appears to be composed of Vondra's facies 3, the interbedded claystone, siltstone, and quartz sandstone facies (delta front), and Vondra's facies 4, the quartz sandstone facies (delta distributary facies). The Temple Member appears to be composed predominantly of Vondra's facies 1, the arenaceous bioclastic carbonate facies, and facies 2, the gypsiferous and carbonaceous laminated claystone and siltstone facies (both shallow lagoonal facies). Grouping into members indicates that different facies associations characterize different parts of the Qasr el-Sagha Formation stratigraphic section.

Bown and Kraus (1988, p. 47) interpreted "conglomeratic coquina" beds in the Temple and Dir Abu Lifa members of the Qasr el-Sagha Formation as "strandline lag deposits" that are "overlain by deposits of more alluvial aspect." I understand each of Bown and Kraus' "strandline lag deposits" to be what Blanckenhorn called a "*harte Bank*" [hard bed] and Vondra called an "arenaceous bioclastic carbonate facies" (facies 2). I understand Bown and Kraus' overlying deposits of "alluvial aspect" to be Vondra's "gypsiferous and carbonaceous laminated claystone and siltstone facies" (facies 2). Previous authors interpreted both facies as marine and, from faunal evidence, these can hardly be anything but marine (see Chapter VI).

Bown and Kraus (1988, p. 11) described the Qasr el-Sagha Formation as "conformably overlying" the Birket Qarun Formation, and noted that 15 km west of Garet-Gehannam and on the northwest shore of Birket Qarun it seems likely that the Temple Member of the Qasr el-Sagha Formation is actually a facies correlative of at least part of the supposedly older Birket Qarun Formation. The latter observation is clarified by restriction of the Birket Qarun Formation to distinctive cliff-forming sandstones, and inclusion of overlying lagoonal facies in the Qasr el-Sagha Formation (see following chapters).

In their abstract, Bown and Kraus (1988, p. 1) characterized the Gebel Qatrani Formation as "conformably overlying" the Qasr el-Sagha Formation. However, in their text they described this boundary as a "conformable to minor erosional unconformity" (fig. 3, p. 9); "no ... major unconformity" (p. 20); or "at least locally marked by a minor erosional unconformity" (p. 20). Bown and Kraus later wrote that "The Gebel Qatrani Formation overlies the upper part of the Qasr el-Sagha Formation with apparent erosional unconformity everywhere the base of the formation is exposed in the Fayum Depression" (p. 22), while in the western Fayum "the lowest beds of the Gebel Qatrani ... lie with apparent conformity on the bare limestone sequence" (p. 22). Finally (p. 23), they cited Beadnell's observation that the Gebel Qatrani contact with the Qasr el-Sagha at Elwat Hialla "though 'conformable,' is with beds lower in the Qasr el-Sagha section than in the type area," interpreting this as having "resulted from the absence of deposition of the Dir Abu Lifa Member of the upper Qasr el-Sagha Formation. In the Eastern Desert, the Gebel Ahmar beds (= Gebel Qatrani Formation equivalents) lie unconformably on all older rocks."

Some of these statements appear contradictory, but they are not contradictory if "conformable" is understood as an adjective meaning *formation-scale bedding is parallel*, while "conformity" is understood to mean that *no erosional surface separates formations*. "Apparent conformity" describes a cryptic erosion surface. Thus the Gebel Qatrani and Qasr el-Sagha formations are *conformable* because formation-scale bedding is parallel, but the formations are clearly separated by an erosional *unconformity*. Rasmussen et al. (1992, p. 560) characterize this as a "major" unconformity. The Gebel Qatrani/Qasr el-Sagha unconformity is not conspicuously angular anywhere in Fayum, but is rather, technically, a disconformity in the northeastern Fayum and a paraconformity farther west.

Other authors

Other authors contributing to Fayum stratigraphy include Osborn (1907a,b). Osborn (1908) cited Stromer (1907) to justify considering the "Fluvio-Marine Beds" (Gebel Qatrani Formation) as Oligocene rather than upper Eocene. Iskander (1943), in an obscure report, introduced formational names Muela, Midawara, Sath el-Hadid, and Gharaq as subdivisions of what is here called Wadi Rayan Formation in Fayum. Benthonic and other foraminifera in Fayum have been studied by Shamah and Blondeau (1979), Shamah et al. (1982), and Abdel-Kireem et al. (1985). Shamah and Blondeau considered the upper part of the Midawara Formation to belong in the *Truncorotaloides rohri* zone [P14], but this, like inclusion of the Gizehensis and Upper Building Stone members of the Mokattam Formation in the Bartonian (Chapter II), appears questionable.

Khashab (1974) included a good general map and composite stratigraphic chart for the Fayum. Moustafa (1974, p. 49) called the lower part of the Qasr el-Sagha Formation the "*Prozeuglodon* zone," which is surely a misnomer considering that *Prozeuglodon* comes from the Gehannam and Birket Qarun formations but not the Qasr el-Sagha Formation.

Ismail and Abdel-Kireem (1975) discussed Fayum stratigraphy. Kappelman (1991) published a preliminary interpretation of paleomagnetic stratigraphy in Fayum, retaining virtually all of the Gebel Qatrani Formation in the Oligocene.

Summary

Four Eocene formations are found in Fayum. All are marine. The Wadi Rayan Formation is at least 129 m thick, it is mainly Lutetian (middle Eocene) in age, and it was deposited on an open marine continental shelf. The Gehannam Formation is about 46 m thick, of middle to late Eocene age (Bartonian through early Priabonian) on the basis of planktonic foraminifera, and was deposited on a shallow shelf. The Birket Qarun Formation, where it is found, ranges from 7 to 72 m thick, and it is late Eocene in age (early Priabonian). A new environmental interpretation is outlined in Chapter VI. The Qasr el-Sagha Formation is about 183 m thick north of lake Birket Qarun, is late Eocene in age (Priabonian), and was evidently deposited in lagoons and embayments and on the fronts of advancing deltas. Finally, the Gebel Qatrani Formation overlying the marine Eocene Qasr el-Sagha Formation is continental, it is Oligocene in age, and it is separated from the Qasr el-Sagha Formation by a major unconformity.

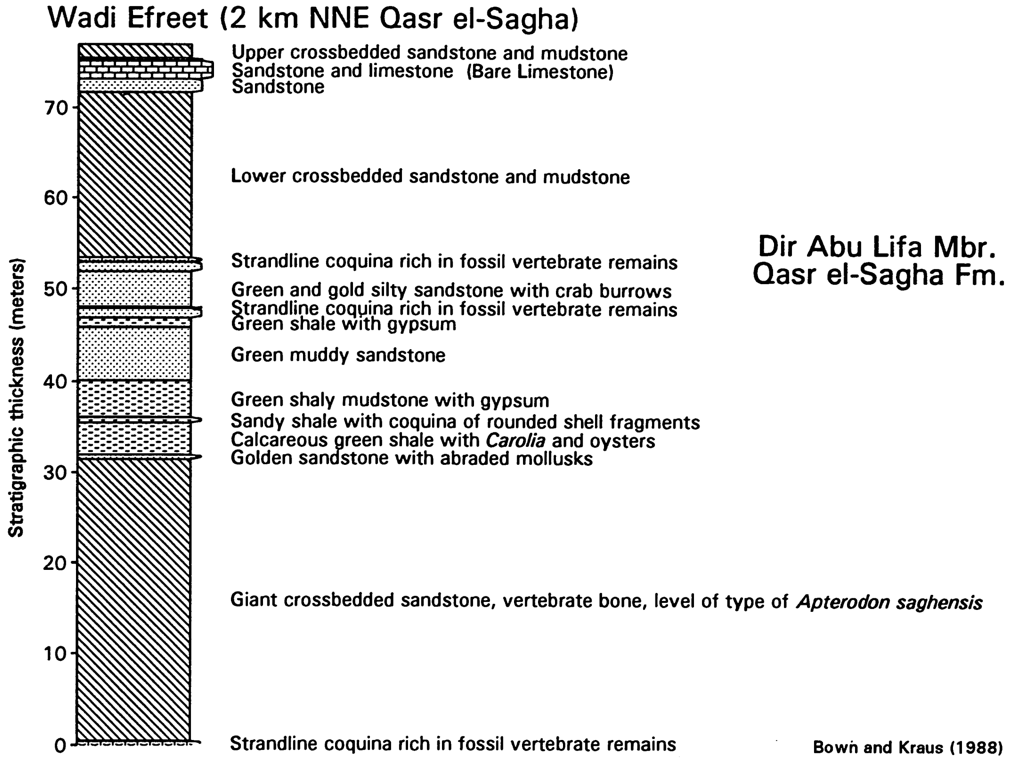


FIG. 31—Stratigraphic section of Eocene at Wadi Efreet 2 km NNE of Qasr el-Sagha temple ruin in the northern Fayum depression, based on measurements and lithological descriptions of Bown and Kraus (1988, p. 13). Bown and Kraus made this the type section of their Dir Abu Lifa Member of the Qasr el-Sagha Formation. Note predominance of crossbedded sandstone and mudstone units, including upper crossbedded sandstone and mudstone above the Bare Limestone [or Ain Musa bed] at the top of the section. UTM coordinates of the locality are approximately 276.000E × 3278.500N.

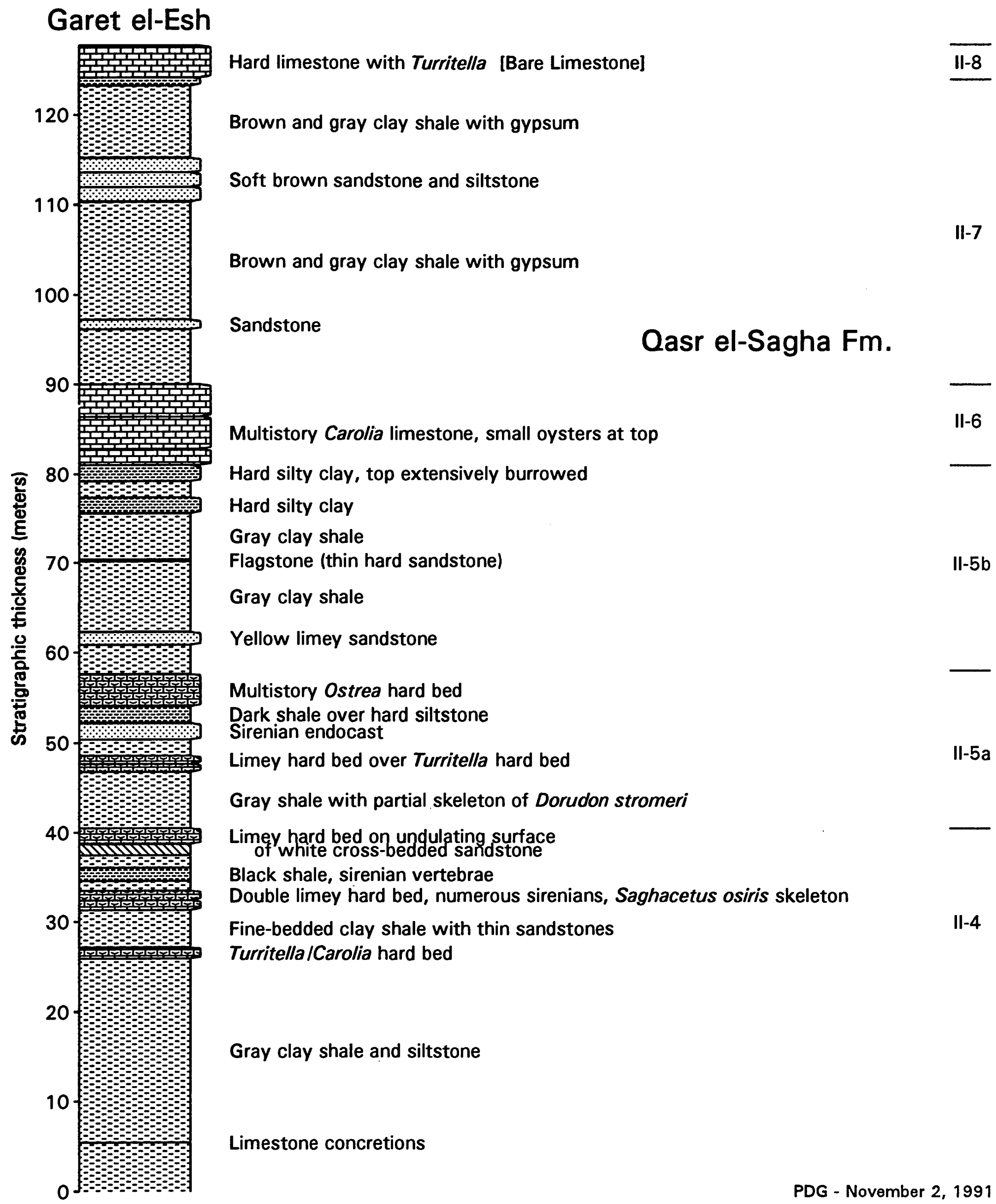


FIG. 32—New stratigraphic section of Eocene Qasr el-Sagha Formation at Garet el-Esh in the northern Fayum depression. Base of section is not exposed. Garet el-Esh is near the localities Schweinfurth and Blanckenhorn called Zeuglodonberge or Zeuglodonberg (Figs. 18-19) and Zeuglodonberg NW (Fig. 20). Blanckenhorn's zones (1903) are shown at right. UTM coordinates of the locality are approximately 264.500E × 3274.200N.

IV

NEW OBSERVATIONS IN FAYUM

New stratigraphic sections were measured in Fayum in 1991 to document the levels and relative ages of cetacean and sirenian skeletal remains collected during past field seasons, and to develop a better understanding of Eocene depositional environments and sedimentary facies relationships. These sections were measured through the upper Qasr el-Sagha Formation in the Qasr el-Sagha escarpment at Garet el-Esh; through the Birket Qarun and lower Qasr el-Sagha formations in the Birket Qarun escarpment at Garet Umm Rigl; and through the upper Gehannam, Birket Qarun, Qasr el-Sagha, and lower Gebel Qatrani formations in and near Wadi Hitan (Zeuglodon Valley). Sections in each area are described in turn. These clarify the geometry of the Birket Qarun Formation. Two new members are added to the Qasr el-Sagha Formation. Finally, geographic trends across northern Fayum are described on the basis of previously published sections illustrated in Chapters II and III and new sections presented here.

GARET EL-ESH

Garet el-Esh is a distinctive flat-topped hill on the Qasr el-Sagha escarpment about 12 km west of the Qasr el-Sagha temple ruin. Garet el-Esh is somewhere near Schweinfurth's Zeuglodonberge and Blanckenhorn's Zeuglodonberg locality (Fig. 18), which is the type locality of *Zeuglodon osiris* [*Saghacetus osiris*]. This area has been prospected in recent years to collect additional material and clarify which of several archaeocetes the type specimen represents. In the process, the Garet el-Esh section has yielded several important new partial skeletons of cetaceans and sirenians.

The stratigraphic section at Garet el-Esh is about 130 m thick (Fig. 32), and, by comparison with Blanckenhorn's Zeuglodonberg section, the Garet el-Esh section includes Blanckenhorn's biostratigraphic zones II-4 through II-8. Blanckenhorn (1903, p. 390-392) placed the II-4\II-5a boundary at the top of a yellow and red *Carolia-Ostrea* "marl" with *Myliobates* and a skull of *Eosiren libyca*. This hard bed overlies a thin (25 cm) white false-bedded sand. A similar unit is found at the 40.5 m level in the Garet el-Esh section. Blanckenhorn placed the II-5a\II-5b boundary at the top of a distinctive terrace-forming oyster bed, and this is found at the 58 m level in the Garet el-Esh section. Blanckenhorn placed the II-5b\II-6 boundary at the base of the *Carolia* bed with *Ostrea* that forms the top of Zeuglodonberg (Fig. 19), and this is clearly at the 81 m level in the Garet el-Esh section. Blanckenhorn's bed II-6 is the multistory *Carolia* limestone with small oysters at the top occupying the interval from 81 to 90 m in the Garet el-Esh section. The interval of gypsiferous clay shales from 90 to 124 m corresponds to Blanckenhorn's zone II-7. Finally, the top of Garet el-Esh is a hard, 4 m thick, wind-sculpted limestone (Bare Limestone of Bowen and Vondra, 1974) occupying the interval from 124 to 128 m at Garet el-Esh. The lower part of the Garet el-Esh section is monotonous gray clay shale, the middle part includes numerous *Carolia-Ostrea* and *Carolia-Turritella* hard beds, and the upper part has coarser clastics and thicker limestone units (see section on members of the Qasr el-Sagha Formation below and also Chapter VI).

GARET UMM RIGL

Garet Umm Rigl is a hill on the north shore of lake Birket Qarun 16.5 km southwest of Garet el-Esh. This is in the Birket Qarun escarpment, stratigraphically and topographically below the Qasr el-Sagha escarpment. Garet Umm Rigl is east of Garet el-Naqb (Fig. 21) and east of the type section of the Birket Qarun Formation at the west end of Birket Qarun (Figs. 25-26). Vertebrate fossils are rare, but several fragmentary skeletons of interesting archaeocetes were found here in 1985 and 1991.

The stratigraphic section at Garet Umm Rigl (Fig. 33) was studied to clarify transitions from the Gehannam Formation to the Birket Qarun Formation, and from the Birket Qarun Formation to the Qasr el-Sagha Formation, as distinguished lithologically. The uppermost 10 m of Gehannam Formation at Garet Umm Rigl is gray clay shale with gypsum. The Birket Qarun Formation is 27 m of yellow sandstone that forms cliffs along much of the

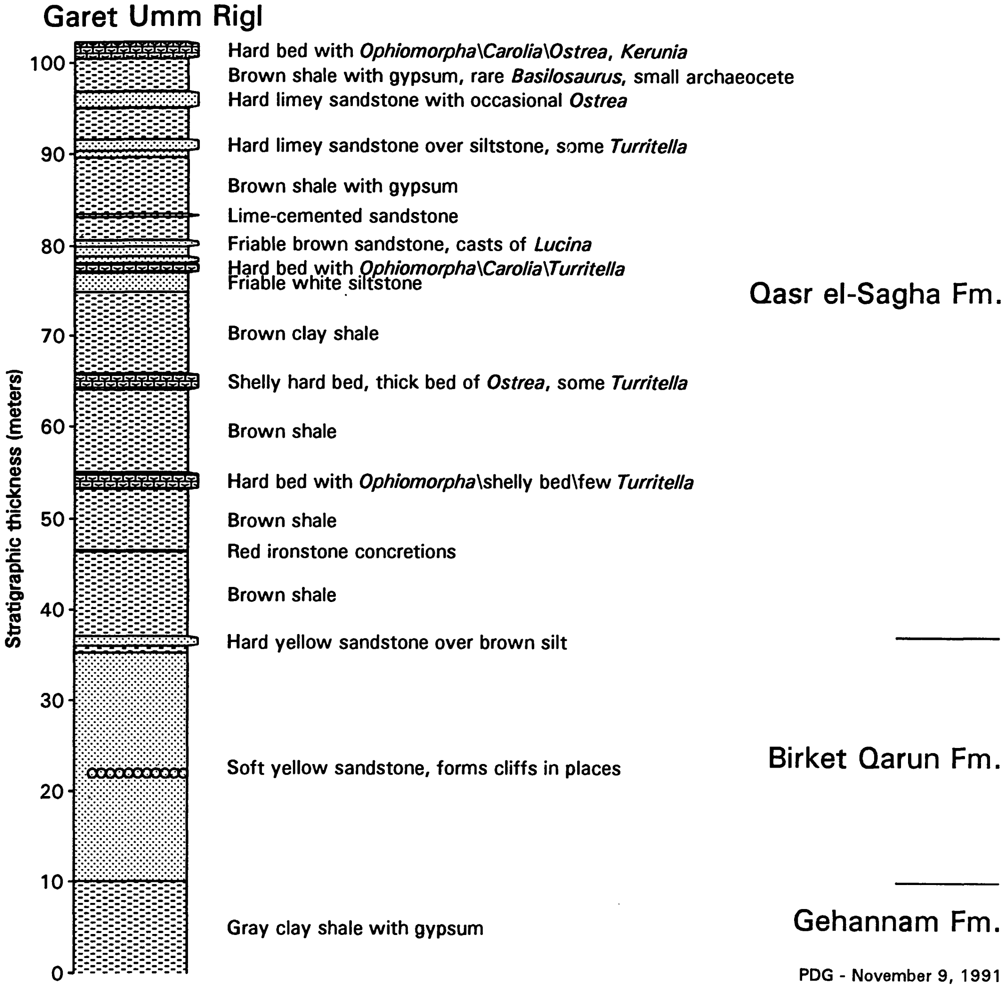


FIG. 33—New stratigraphic section of Eocene Gehannam, Birket Qarun, and Qasr el-Sagha formations at Garet Umm Rigl in the northern Fayum depression. Base of section is not exposed. Garet Umm Rigl is between Geziret el-Qarn (Fig. 27) and the mainland opposite Geziret el-Qarn (Fig. 28) in the east and Garet el-Naqb (Fig. 21) and the west end of Birket Qarun (Fig. 25) in the west. UTM coordinates of the locality are approximately 253.500E × 3261.800N.

escarpment. There is a zone in the middle that weathers into the large spherical masses mentioned by Beadnell (1905) as being characteristic of the formation. The lower 65 m of the Qasr el-Sagha Formation exposed at Garet Umm Rigl has a succession of hard beds reminiscent of those in the middle part of the upper Qasr el-Sagha section at Garet el-Esh. The significance of these is discussed in the section on members of the Qasr el-Sagha Formation below and in Chapter VI.

WADI HITAN

Six sections were studied in Wadi Hitan (Zeuglodon Valley). The first three are short. At locality ZV-54NW (Fig. 34) there is a 35 m succession of gray clay shales and thin terrace-forming marls of the Gehannam Formation, overlain by a distinctive green shale with white gypsum and then sandstone. Traced laterally, the gray clay shales include many skulls and partial skeletons of

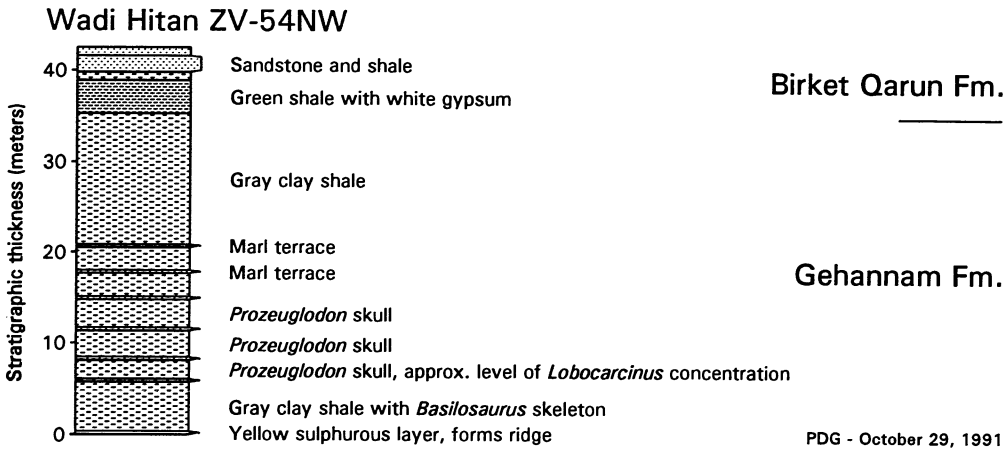


FIG. 34—New stratigraphic section of Eocene Gehannam and Birket Qarun formations 100 m northwest of locality ZV-54 in Wadi Hitan (Zeuglodon Valley) in the northwestern Fayum depression. Yellow sulphurous layer at base of this section can be traced to middle of ZV-54 section (Fig. 35). UTM coordinates of the locality are approximately 212.400E × 3245.300N.

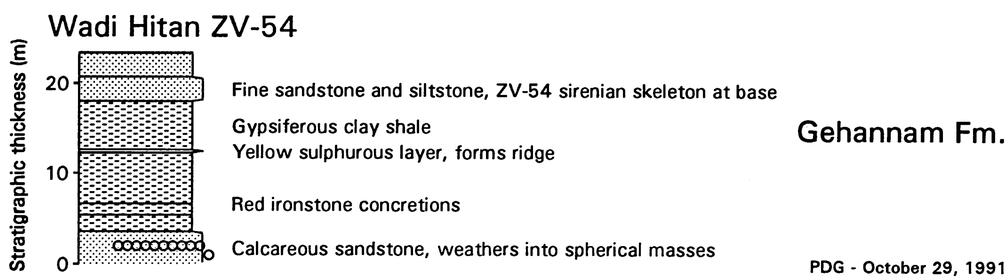


FIG. 35—New stratigraphic section of Eocene Gehannam Formation at locality ZV-54 in Wadi Hitan (Zeuglodon Valley) in the northwestern Fayum depression. Sandstone at top of section represents a local distributary channel deposit. Note spherical masses weathering from sandstone at base of section. This can be traced to top of ZV-70 section (Fig. 36). UTM coordinates of the locality are approximately 213.100E × 3244.600N.

the archaeocetes *Basilosaurus* and *Prozeuglodon*. The green shale with white gypsum thins to the south and southwest, but it can be traced, within a few kilometers, into the middle of the Birket Qarun Formation (forming the "Black Layer" marker bed, as at Sandouk el-Borneta; see Figs. 37 and 43). The base of the ZV-54NW section is a low ridge-forming yellow sulphurous layer that can be traced to the middle of the section at locality ZV-54 (Fig. 35). All of this 23 m section is Gehannam Formation. The top bed at ZV-54 is a multistory channel sandstone (with a sirenian skeleton weathering from the base) that probably represents a local distributary channel deposit. The bottom bed at ZV-54 is a calcareous sandstone that weathers into spherical masses. This bed can be traced for a kilometer or so to the northeast where, at locality ZV-70 (Fig. 36), it caps a section of Gehannam Formation clay shales with white marl, silt, and sandstone bands. Here again, the shales are rich in archaeocete and other vertebrate remains. These three short sections taken together form one composite section of 74 m of Gehannam Formation below the "Black Layer" green shale with gypsum. The upper part of the Gehannam Formation clays here can be traced into Birket Qarun Formation sandstones within a few kilometers to the south.

The Sandouk el-Borneta section (Fig. 37) has 26 m of Gehannam Formation light clay shales with some marl at the base. This is overlain by 57 m of yellow cliff-forming sandstones with the "Black Layer" of gray-to-black shale in the middle. There is a bed packed with

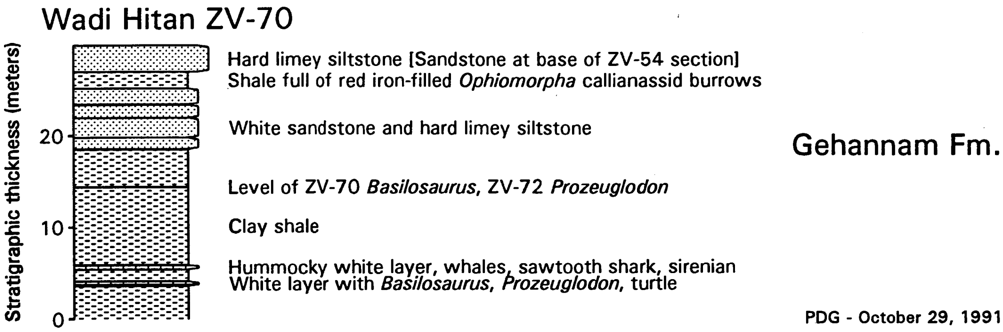


FIG. 36—New stratigraphic section of Eocene Gehannam Formation at locality ZV-70 in Wadi Hitan (Zeuglodon Valley) in the northwestern Fayum depression. Base of section is not exposed. Birket Qarun Formation here is about 57 m thick. UTM coordinates of the locality are approximately 214.100E × 3245.600N.

Carolia nine meters from the top of the Birket Qarun Formation. Two meters of Qasr el-Sagha Formation overlie the Birket Qarun Formation. This capping unit has a bed packed with two species of oysters at the base (including one with valves up to 15 cm in diameter) and a densely packed, well cemented bed of nummulites overlying this (Fig. 38). The oysters appear to have been swept together before they were deposited on a scoured surface, and they are now buried under 1-2 m of packed and cemented nummulite tests. The high concentration of oysters, deposition on a scoured surface, and burial under packed nummulite tests suggest that this is probably a storm deposit or "tempestite" like others described from the Eocene of Egypt by Aigner (1982, 1983).

At Minqar el-Hut, south of Sandouk el-Borneta, the Birket Qarun Formation is very thick (Fig. 39). The Minqar el-Hut section (Fig. 40) has 37 m of Gehannam Formation at the base. This is largely brown shale with gypsum (forming cliffs in places), but there is a complex of hard sandstones and marls near the base that is rich in the large echinoid *Schizaster* and rich in archaeocete remains (both *Basilosaurus* and *Prozeuglodon*). In the interval 33 to 36 m above the base, there is a thick limey hard bed with vertical mangrove pneumatophores weathering from it. This mangrove bed, because of its uniqueness and its position at the top of the Gehannam Formation where overlying Birket Qarun sandstones are thickest, is almost certainly the same mangrove-rich bed (the "Camp White Layer") found a kilometer or so to the north in Wadi Hitan (see Chapter V).

The final stratigraphic section measured in Wadi Hitan is the Minqar Abyad section (Fig. 41), which is 269 m thick. It was measured from the hard white marl bed ("Camp White Layer") at our camp (Fig. 42) to the top of the white escarpment at Minqar Abyad 5 km to the northwest. It starts at the top of the Gehannam Formation, includes a full section of Birket Qarun Formation, a full section of Qasr el-Sagha Formation, and ends in Gebel Qatrani Formation. The Camp White Layer at the base of the section can be traced for a kilometer or so to the east, southeast, and southwest of camp. East and southwest of camp the white layer includes areas rich in mangrove pneumatophores and anchor roots. The Camp White Layer has many skeletons of *Basilosaurus* and *Prozeuglodon* weathering from it or from beds within a few meters above and below it. Hind limbs found with skeletons of *Basilosaurus* described by Gingerich et al. (1990) came from this Camp White Layer at the top of the Gehannam Formation.

The Birket Qarun Formation is 50 m thick in the Minqar Abyad section, and it has much the same character as observed at Sandouk el-Borneta. The Qasr el-Sagha Formation has 35 m of interbedded shales and hard beds at the base, like those observed at Garet Umm Rigl. These are overlain by 40 m of brown shale, much of it covered by blown sand and desert serir, forming a broad featureless plain. Then there is another 37 m unit of interbedded shales and hard beds corresponding to the Temple Member of Bown and Kraus (1988). This is followed by 66 m of brown sandstone, siltstone, and shale, some crossbedded like the interbedded claystone, siltstone, and quartz sandstone facies (Vondra, 1974) characteristic of the Dir Abu Lifa Member of Bown and Kraus (1988). This unit is capped by a shelf-forming shelly limestone that is interpreted as the Bare Limestone of Bowen and Vondra (1974).

The uppermost 30 m of the Minqar Abyad section is red and yellow sandstone and siltstone with white bone and white coprolites that is clearly part of the continental Gebel Qatrani Formation. Much of the Gebel Qatrani Formation here is covered by slope wash and inaccessible. The top of the Minqar Abyad section is a 10-18 m thick crossbedded calcareous sandstone that fills paleo-

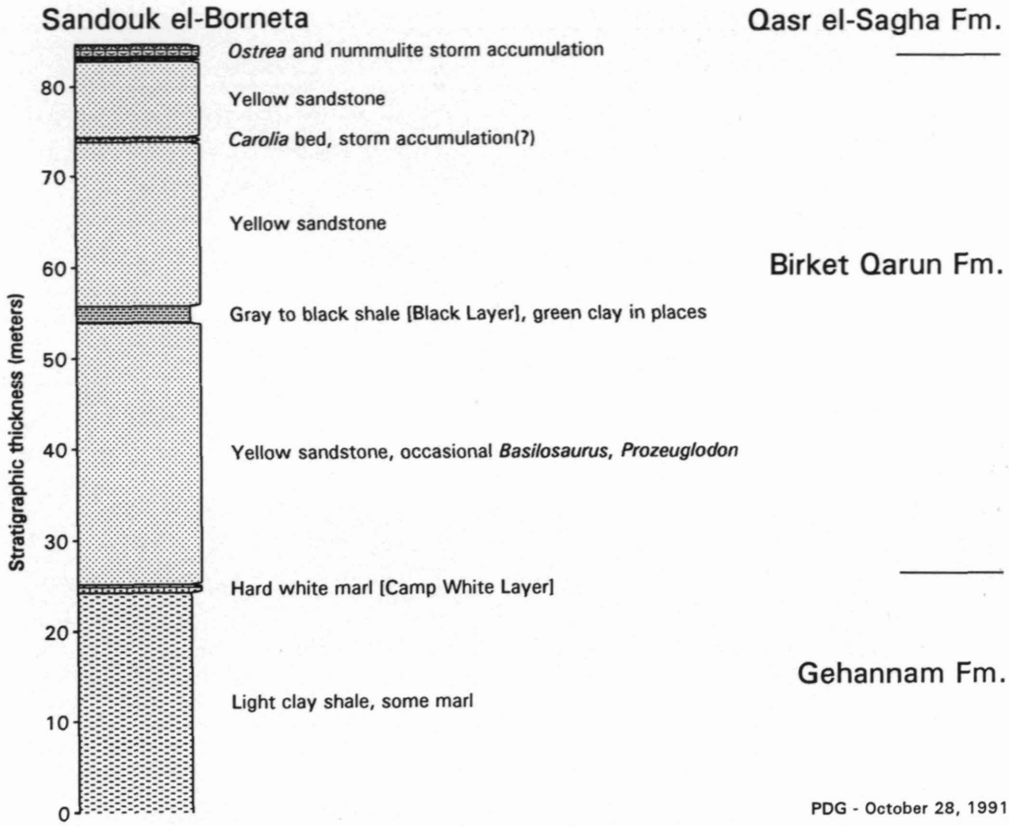


FIG. 37—New stratigraphic section of Eocene Gehannam, Birket Qarun, and Qasr el-Sagha formations at Sandouk el-Borneta in Wadi Hitan (Zeuglodon Valley) in the northwestern Fayum depression. Base of section is not exposed. Birket Qarun Formation here is about 65 m thick. UTM coordinates of the locality are approximately 212.600E × 3243.000N.

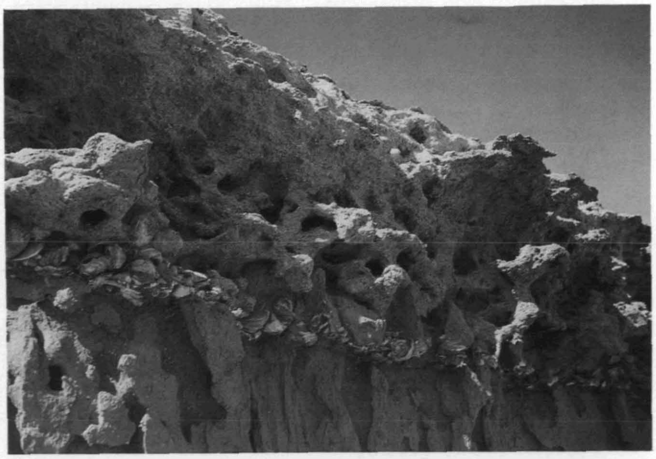


FIG. 38—Photograph of nummulite and oyster beds capping Birket Qarun sandstone at Sandouk el-Borneta (see section in Fig. 37). Largest oysters have heavy round valves on the order of 15 cm in diameter. Density of oysters, deposition on a scoured surface, and burial under 1-2 m of packed nummulite tests suggest storm deposition.

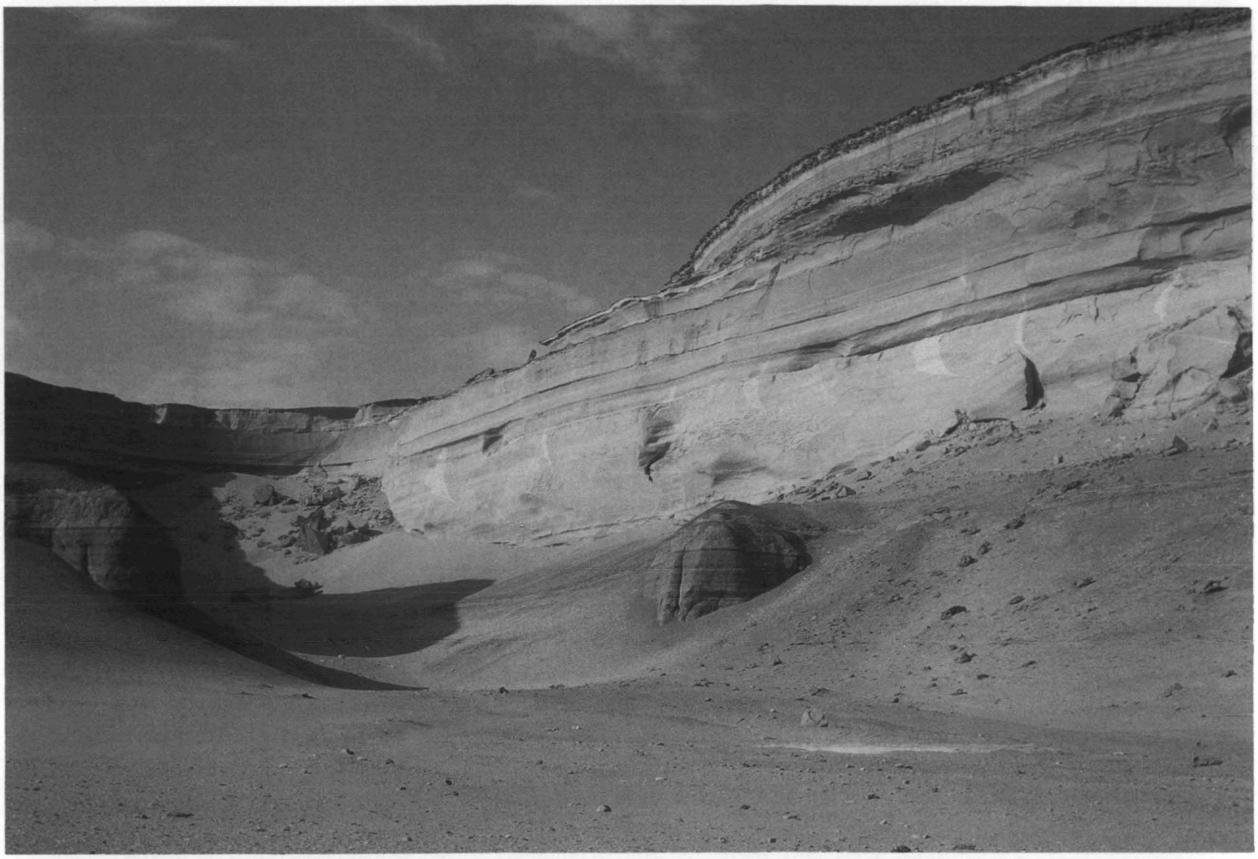


FIG. 39—Photograph of Birket Qarun Formation where it forms steep cliffs along the southern escarpment of Minqar el-Hut. Stratigraphic section is shown in Fig. 40. View is to north. White stripe in valley floor at lower right of photograph is white marl bed that contains numerous skeletons of *Basilosaurus* farther to the east. Lower prominences at left and right center are brown shale with gypsum of Gehannam Formation. Brown shale is overlain by a hard marl with vertical mangrove pneumatophores (not visible at this scale) interpreted as the Camp White Layer (see Figs. 42, 46, and 47) marking the top of the Gehannam Formation in Wadi Hitan north of Minqar el-Hut. Steep cliffs 60-65 m high are entirely Birket Qarun Formation sandstone. Note thick horizontal bedding in otherwise massive linear sandstone body that indicate deposition of a succession of barrier sands. Gray to black shale marker bed found in more northern sections is not found here. Capping bed marks the base of the Qasr el-Sagha Formation locally.

valleys conspicuously scoured as much as 8 m into the underlying red and yellow sand and siltstone. The name Minqar Abyad refers to the gleaming white color this calcareous sandstone gives the whole escarpment. It is filled with rhizoliths like those in the Barite Sandstone illustrated by Bown and Kraus (1988, fig. 27c; possibly this *is* the Barite Sandstone). Bown and Kraus (1988, p. 19) stated that the Bare Limestone is "very thick (exceeding 10 m)" at Madwar el-Bighal in the western Fayum Depression (Madwar el-Bighal is the plain south of Minqar Abyad), but the Bare Limestone is only 2.5 m thick here. It would be easy to mistake the capping white rhizolith-rich sandstone of the Gebel Qatrani Formation here for the Bare Limestone of the Qasr el-Sagha Formation when viewing these from a distance, but the two are very different and easily distinguishable when studied in outcrop or hand specimen.

GEOMETRY OF BIRKET QARUN FORMATION

Two formations, the Birket Qarun Formation and the Qasr el-Sagha Formation, were studied in the field. The Birket Qarun Formation of Beadnell (1905) is restricted

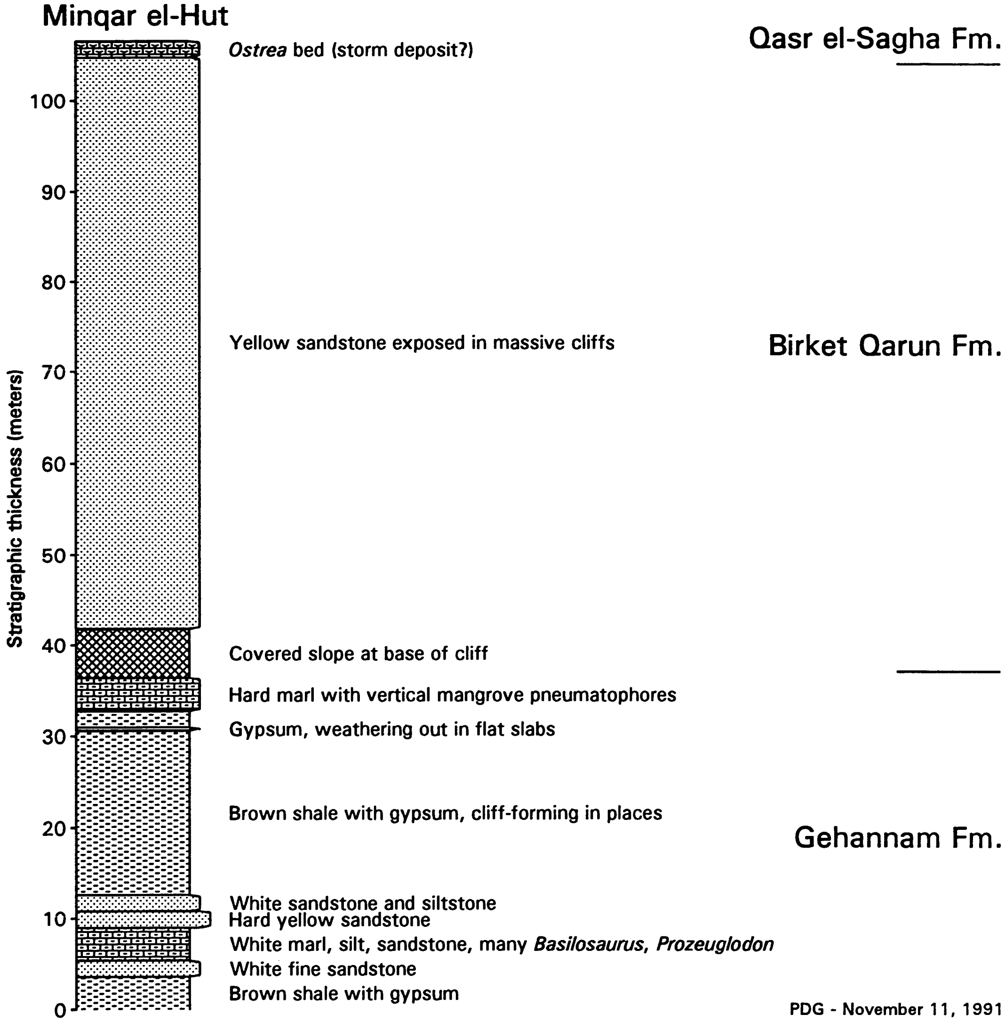


FIG. 40—New stratigraphic section of Eocene Gehannam, Birket Qarun, and Qasr el-Sagha formations at Minqar el-Hut south of Wadi Hitan (Zeuglodon Valley) in the northwestern Fayum depression. Base of section is not exposed. UTM coordinates of the locality are approximately 212.000E × 3240.500N.

to the cliff-forming yellow sandstones that are so conspicuous above the northwest shore of Birket Qarun, at Garet Gehannam, in Wadi Hitan, and at Minqar el-Hut. The Birket Qarun Formation can be traced along strike in a WSW-ENE direction for 60 km or so, but it is only in Wadi Hitan and at Minqar el-Hut that the Birket Qarun Formation can be studied perpendicular to strike. Lateral variation perpendicular to strike can be illustrated by comparing stratigraphic sections measured at three places: at ZV-54 on the north side of Wadi Hitan (Figs. 34-35), at Sandouk el-Borneta on the south side of Wadi Hitan (Fig. 37), and in the cliffs on the south side of Minqar el-Hut (Fig. 40).

Stratigraphic sections of the Birket Qarun Formation at ZV-54, Sandouk el-Borneta, and Minqar el-Hut are compared and correlated in Figure 43. ZV-54 and Sandouk el-Borneta are about 1.5 km apart, and Sandouk el-Borneta and Minqar el-Hut are about 2 km apart in a north-south transect. This is nearly perpendicular to strike, and it is approximately an offshore-onshore transect. Vertical exaggeration in Figure 43 is about 30×. Principal features to be explained are (1) thickening of lower and upper sandstone units of the Birket Qarun Formation southward from ZV-54, while the distinctive "Black Layer" marker bed becomes thinner southward, (2) change from a 30 m section of Gehannam

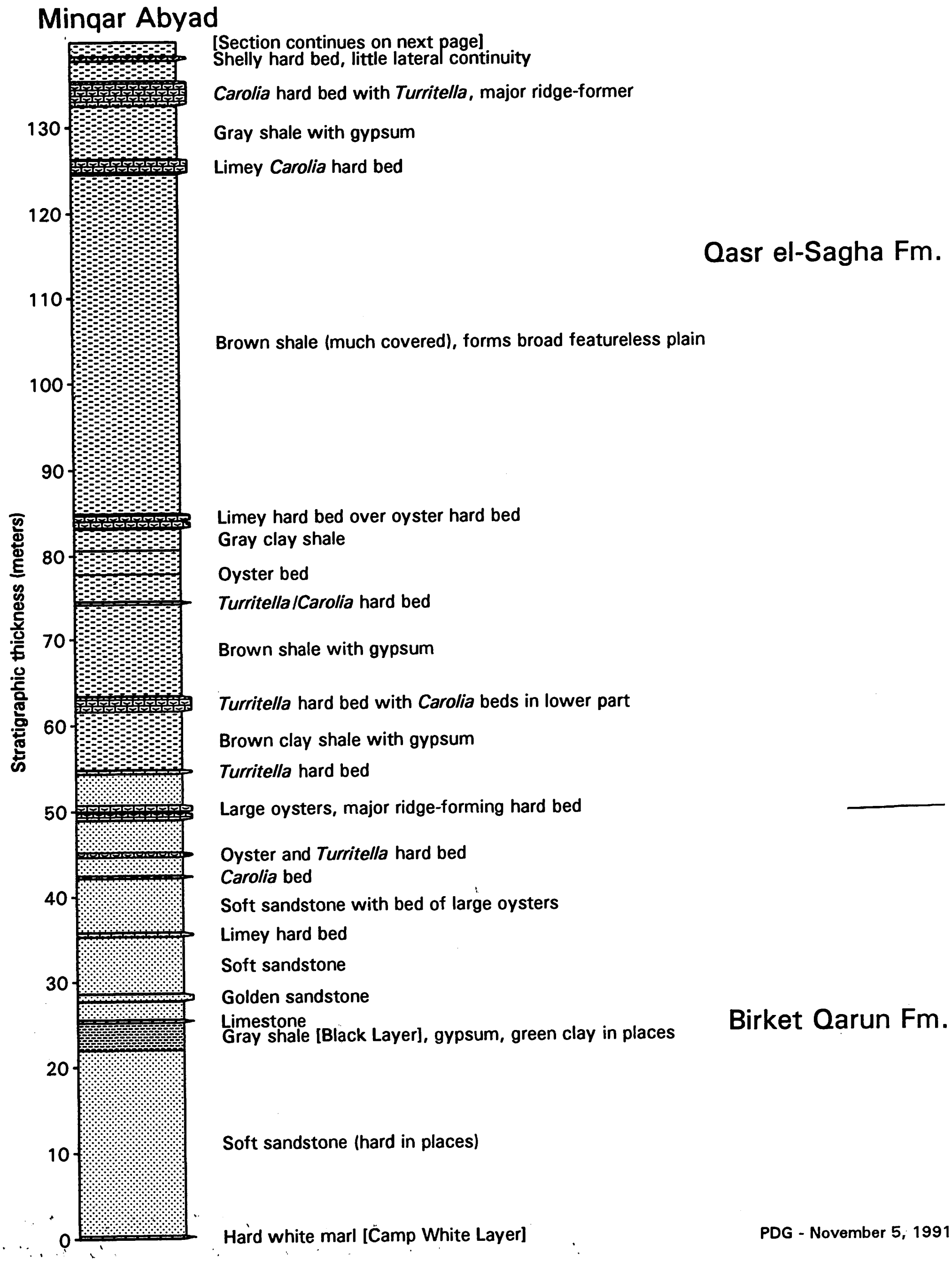


FIG. 41—New stratigraphic section of Eocene Gehannam, Birket Qarun, and Qasr el-Sagha formations measured in a transect from the University of Michigan camp in Wadi Hitan (Zeuglodon Valley) to Minqar Abyad 5 km to the northwest in the northwestern Fayum depression. Base of section is top of Gehannam Formation. Birket Qarun Formation is 50 m thick. Qasr el-Sagha Formation is 178 m thick. UTM coordinates of the University of Michigan camp are approximately 211.600E × 3242.100N, and UTM coordinates of Minqar Abyad are approximately 207.200E × 3244.300N.

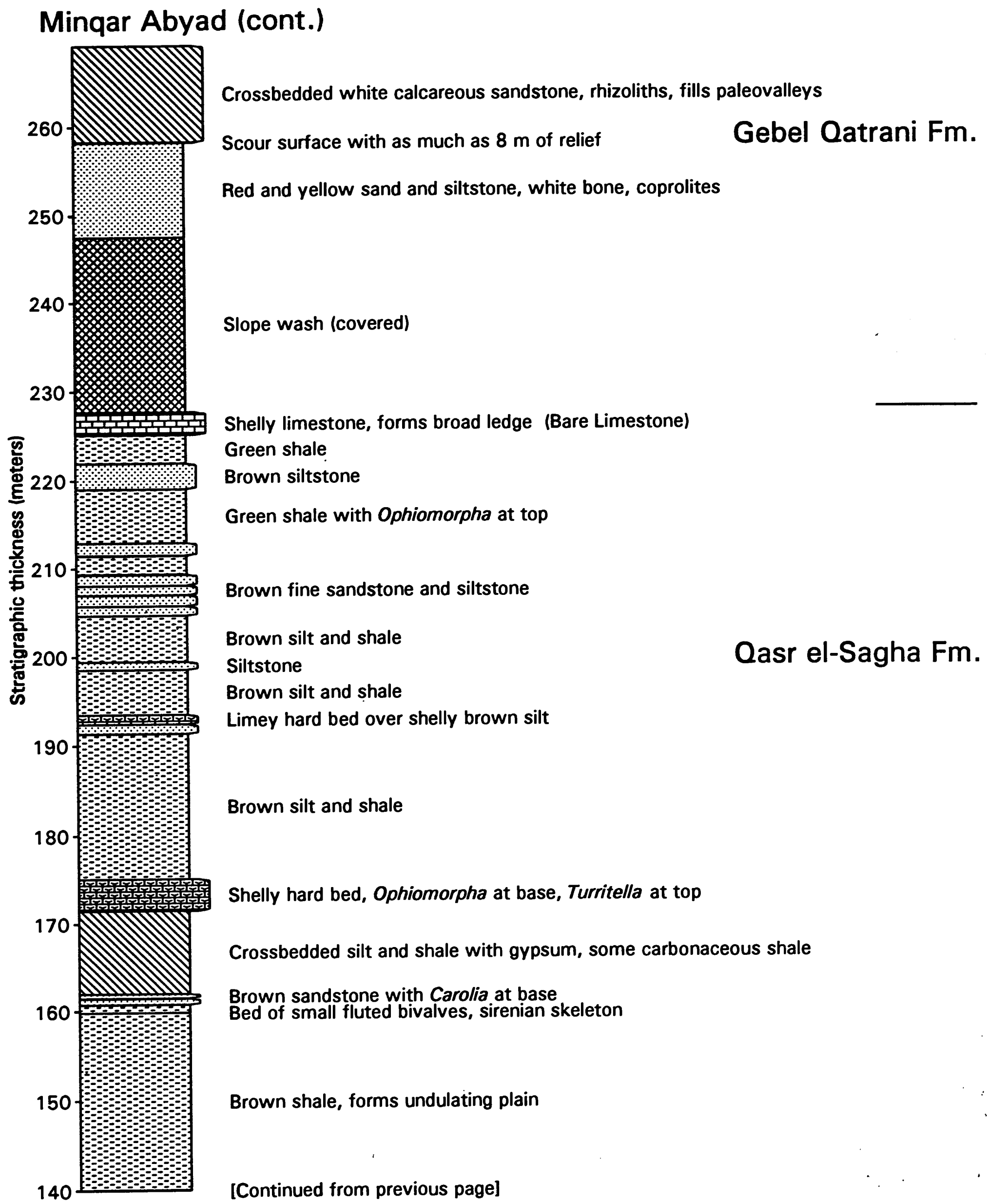


FIG. 41—Continued from previous page.

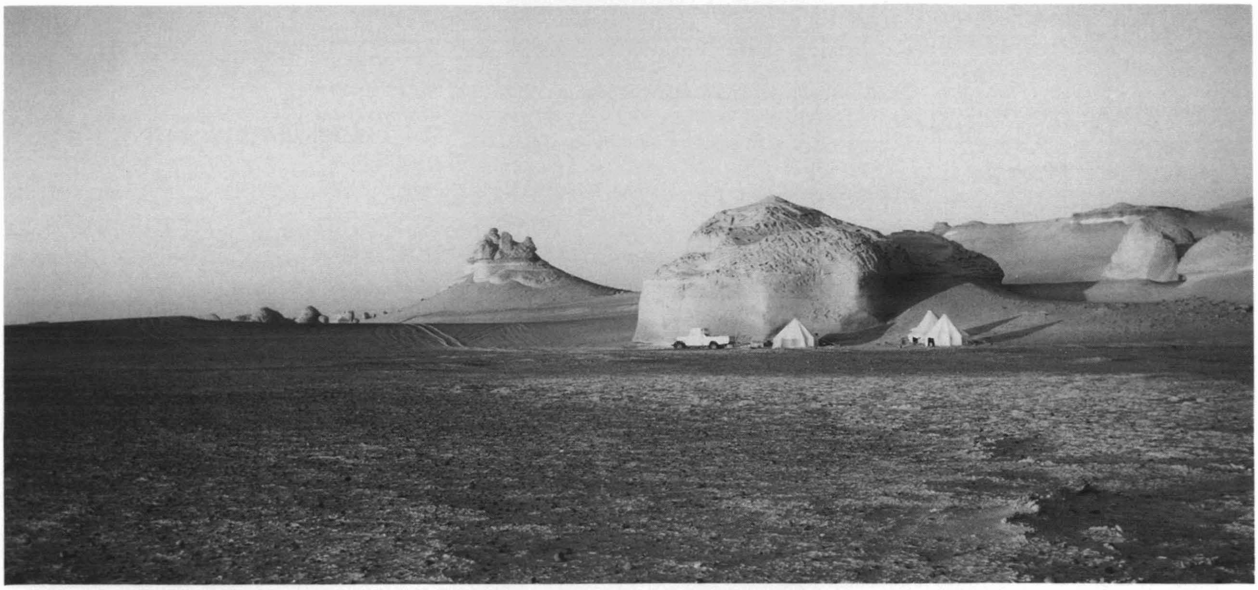


FIG. 42—University of Michigan camp in Wadi Hitan (Zeuglodon Valley). Dip surface in foreground is hard top of Camp White Layer marking the top of the Gehannam Formation and also the Bartonian-Priabonian lowstand of Tethys. Massive sand bodies are erosional remnants of Birket Qarun Formation. Landmark on skyline at left center is Salâs Awahât (Three Sisters). View is to southwest.

gray clay shale below the green marker bed ("Black Layer") at ZV-54 to a 30 m section of Birket Qarun sandstone below the Black Layer at Sandouk el-Borneta within a distance of 1.5 km, and (3) absence of Birket Qarun Formation south and east of Minqar el-Hut.

Clear differences in thickness of the same bed, and thickening of some units while others thin in the same direction both indicate that a static layer-cake stratigraphic model is inadequate. Change from 30 m of Gehannam shale to 30 m of Birket Qarun sandstone laterally within a distance of 1.5 km suggests that one or the other formation is a more local facies. Coarser grain size makes it likely that the Birket Qarun Formation is the more local facies, and it does have a more limited geographic distribution. This may explain why the Birket Qarun Formation is not found south and southeast of Minqar el-Hut: it seems unlikely that all Birket Qarun Formation south of Minqar el-Hut would have been eroded leaving the present linear belt of sandstone if, in former times, the formation continued to thicken southward of Minqar el-Hut. Parts of the Birket Qarun Formation are less well consolidated than others, but there is no clear pattern to this. Consequently, the present distribution of the Birket Qarun Formation is likely to approximate its original distribution, and the Formation is reconstructed in Figure 43 as having had a narrow width of about 3-5 km in spite of its demonstrably much greater length.

The main body of the Birket Qarun Formation is presently distributed discontinuously in a linear belt about 60 km long and 5 km wide, and the formation reaches a maximum thickness on the order of 70 m at Garet Gehannam and Minqar el-Hut. This linear geometry, by itself, is suggestive of an offshore barrier bar, or possibly an offshore tidal-current sand body or sand ridge. Intertonguing of sand and shale units north of ZV-54, and conspicuous thick horizontal bedding like that shown in Figure 39 indicate that the Birket Qarun Formation is probably a barrier bar *complex* rather than a single bar or ridge. This helps to explain the discontinuous distribution and uneven thickness of sandstones in the formation.

Barrier bars are found on linear shorelines where there is a supply of terrigenous clastic sediment and a longshore marine current competent to redistribute this. Tidal current sand bodies are found on shallow shelves with a supply of terrigenous sediment and strong tidal currents. These are not always easy to distinguish (Selley, 1978), and for our purposes it is not absolutely necessary to distinguish them. Both are reworked and removed continuously during normal progradation and regression on a passive continental margin. Barrier bars and tidal ridges are buried and preserved during episodes of marine transgression, and both are thus transgressive systems tracts. Invertebrates including benthic foraminifera (Abdou and Abdel-Kireem, 1975) and fairly abun-

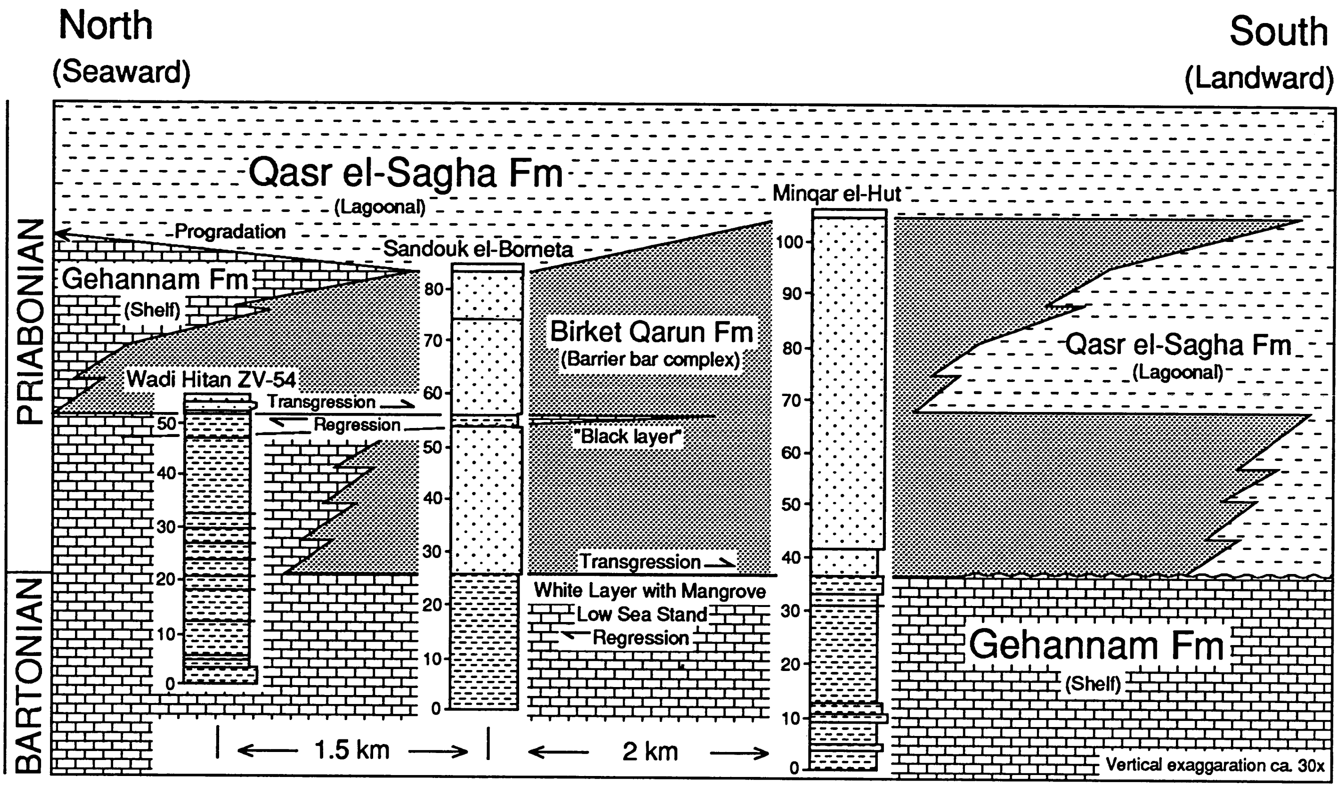


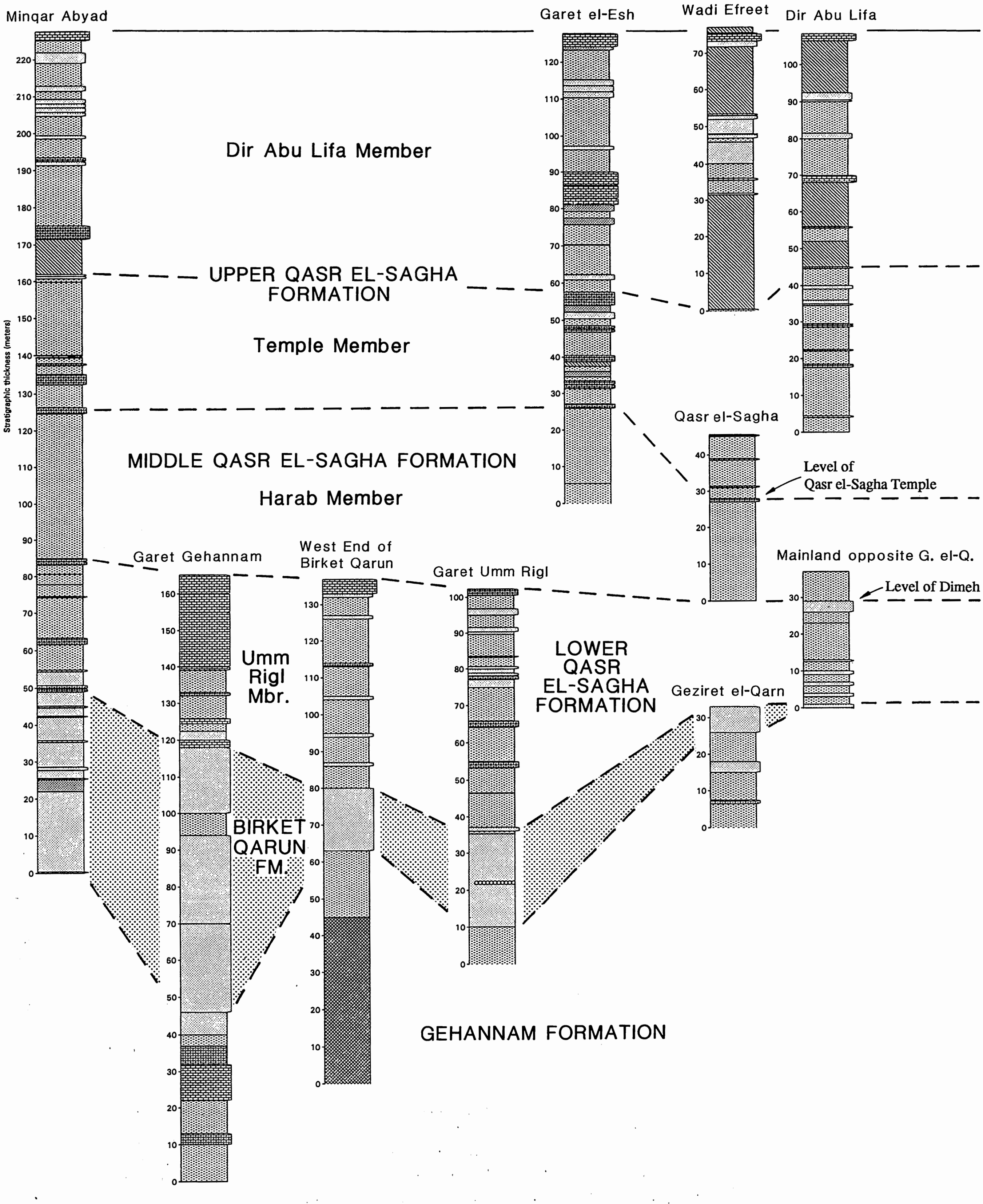
FIG. 43—Interpretative north-south (seaward-landward) cross-section of Birket Qarun Formation sandstone barrier bar complex in Wadi Hitan, reconstructed from stratigraphic sections in Figs. 34-35, 37, and 40). Note narrow breadth of Birket Qarun Formation shown here (about 5 km) in comparison to an outcrop length of 60 km or more. Gehannam Formation shelf sediments (limestone and dense shale patterns) and Qasr el-Sagha Formation lagoonal sediments (open shale pattern) were evidently deposited contemporaneouslyon opposite sides of the Birket Qarun sandstone barrier bar complex (stippled shading). Vertical exaggeration is about 30×. Compare with larger-scale stratigraphic model in Figs. 55 and 56.

dant planktonic foraminifera (Strougo and Haggag, 1984; Haggag, 1990) indicate that the Gehannam Formation was deposited in an open marine setting; this lies under and seaward from the Birket Qarun Formation. Foraminifera are rare and oysters common in the Qasr el-Sagha Formation, and this is commonly interpreted as representing estuarine or lagoonal environments (Beadnell, 1905; Cuvillier, 1930; Vondra, 1974; Bown and Kraus, 1988); this lies landward and above the Birket Qarun Formation. Paleoenvironmental interpretation of contiguous formations suggests that the Birket Qarun Formation is probably a barrier bar complex rather than a tidal current sand complex.

MEMBERS OF QASR EL-SAGHA FORMATION

The uppermost Qasr el-Sagha Formation was studied by Bown and Kraus (1988), who recognized and named the Dir Abu Lifa Member composed of Vondra's interbedded and crossbedded claystone, siltstone, and quartz sandstone facies and Vondra's quartz sandstone facies. Bown and Kraus included the rest of the Qasr el-Sagha Formation in their Temple Member, composed of Vondra's arenaceous bioclastic carbonate facies with hard beds (see below) and Vondra's gypsiferous and carbonaceous laminated claystone and siltstone facies. Study of the middle and lower Qasr el-Sagha Formation west and south of Qasr el-Sagha, at Garet Umm Rigl, and at Minqar Abyad indicate that two additional members should be recognized. These are here called the Harab Member and the Umm Rigl Member.

Ḫarâb is an Arabic word referring to a desolate or featureless place. The Harab Member of the Qasr el-Sagha Formation is a 30-40 m barren interval of brown shale with few or no hard beds of any kind. It forms broad featureless plains, and separates the Umm Rigl Member below from the Temple Member above. The


Minqar Abyad
Garet el-Esh
Wadi Efreet
Dir Abu Lifa
Stratigraphic thickness (meters)
Dir Abu Lifa Member
UPPER QASR EL-SAGHA FORMATION
Temple Member
MIDDLE QASR EL-SAGHA FORMATION
Harab Member
Qasr el-Sagha
Level of Qasr el-Sagha Temple
Garet Gehannam
West End of Birket Qarun
Garet Umm Rigl
Mainland opposite G. el-Q.
Level of Dimeh
Umm Rigl Mbr.
LOWER QASR EL-SAGHA FORMATION
Geziret el-Qarn
BIRKET QARUN FM.
GEHANNAM FORMATION

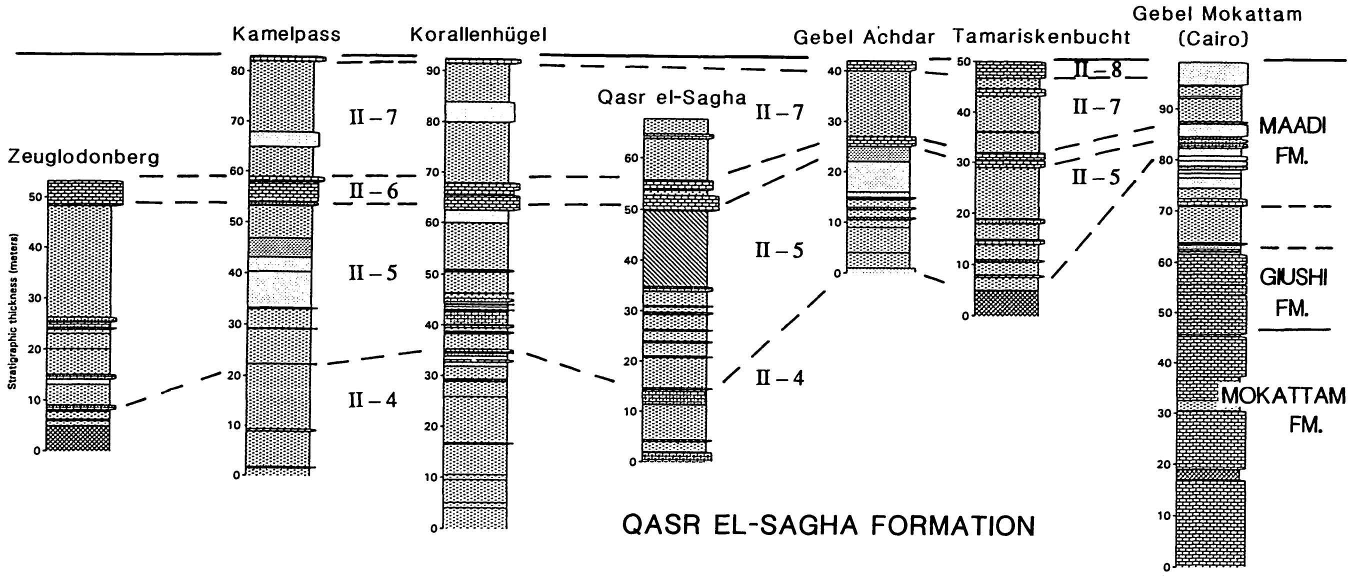


FIG. 45—Sections measured by Blanckenhorn (1900, 1903) in Fayum (six sections at left) compared with Gebel Mokattam (one section at right). Sections are aligned on Blanckenhorn's zone II-8, where present, at top, and zones II-7, II-6, and II-5 are traced with dashed lines. Note thickening of upper Qasr el-Sagha Formation from Cairo to Fayum, and generally uniform thickness across northern Fayum. Blanckenhorn's sections are not integrated into Fig. 44 because they are consistently less thick than comparable sections measured by others.

type section of the Harab Member is the interval from 85 to 125 m in the Minqar Abyad section (Fig. 41), 2-3 km northwest of Wadi Hitan. This member also forms much of the broad featureless plain of Dimeh between the top of the Birket Qarun escarpment and the base of the Qasr el-Sagha escarpment north of lake Birket Qarun.

The Umm Rigl Member is a 30-65 m interval at the base of the Qasr el-Sagha Formation. It is named for Garet Umm Rigl in the Birket Qarun escarpment north of Birket Qarun, and the type section of this member is the Qasr el-Sagha Formation part of the Garet Umm Rigl section (Fig. 33). The Umm Rigl Member consists of an alternation of Vondra's arenaceous bioclastic carbonate facies (hard beds) and Vondra's gypsiferous and carbonaceous laminated claystone and siltstone facies, similar to that found in the Temple Member (but separated by the intervening Harab Member).

FIG. 44 (facing page)—Distribution of Birket Qarun and Qasr el-Sagha formations and facies in the northwestern and northern Fayum, based on stratigraphic sections of Beadnell (1905) and Bown and Kraus (1988), and new sections in Figures 32, 33, and 41. Sections reaching the top of the formation were aligned on top of the Bare Limestone bed. Minqar Abyad section spans both formations in west. Qasr el-Sagha section is a continuation of Dir Abu Lifa section, lower 29 m of Mainland section and Geziret el-Qarn section extend this farther, and together the four span both formations in east. Interposed lower Qasr el-Sagha Formation sections were aligned on their resistant tops. Thickness of Qasr el-Sagha Formation at Minqar Abyad in western Fayum (178 m) is very close to that reconstructed by adding parts of the formation documented in Beadnell's Mainland (29 m, Fig. 28), Qasr el-Sagha (45 m, Fig. 29), and Dir Abu Lifa sections (109 m, Fig. 30) in northern Fayum (183 m total).

GEOGRAPHIC TRENDS

The distribution of Birket Qarun and Qasr el-Sagha formations and facies in the northwestern and northern Fayum is compared in Figure 44. This figure shows a general uniformity of thickness of the middle and upper Qasr el-Sagha Formation (Harab, Temple, and Dir Abu Lifa members) across northwestern and northern Fayum, while the lower Qasr el-Sagha Formation (Umm Rigl Member) is thicker in the middle of this transect. The Birket Qarun Formation is thicker in the west and generally appears to thin to the east (which may also be due to an otherwise negligible difference in the trend of the outcrop belt relative to the trend of the linear formation itself).

Stratigraphic sections measured by Blanckenhorn (1900, 1903) are compared in Figure 45. These are not integrated with sections in Figure 44 because Blanckenhorn's sections are consistently less thick than the same or comparable sections measured by Beadnell (1905), by Bown and Kraus (1988), or by me. However, Blanckenhorn's thicknesses appear to be internally consistent and they show a general thickening from the upper Maadi Formation or Wadi Hof Formation at Gebel Mokattam to the upper Qasr el-Sagha Formation in Fayum. The Ain Musa bed at the top (II-8) appears to thin westward. Zones II-7, II-6, and II-5, comprising most of the comparable sections, thicken between Gebel Mokattam and Qasr el-Sagha and then remain approximately uniform across northern Fayum as far as Zeuglodonberg near Garet el-Esh. For comparison across figures, the Temple Member in Figure 44 corresponds closely to Blanckenhorn's zone II-4 and the lower part of II-5 (II-5a) in Figure 45. The Dir Abu Lifa Member in Figure 44 corresponds closely to Blanckenhorn's zones II-5b, II-6, II-7, and II-8 in Figure 45.

Bown and Kraus (1988, their fig. 40) showed that activation of deep structures ("buried anticlines") influenced the relative thicknesses of Gebel Qatrani Formation that accumulated at different places in northern Fayum during the Oligocene. Figures 44 and 45 here indicate that a greater thickness of Qasr el-Sagha Formation accumulated in Fayum than at Gebel Mokattam, but there is little variation in thickness of the Qasr el-Sagha Formation across northern Fayum. This suggests that the deeper structures were not activated (or reactivated) until the early Oligocene, which may mean activation was associated with opening of the Gulf of Suez. Subsequent outpouring of late Oligocene basalts is usually attributed to opening of the Gulf of Suez.

V

SEA LEVEL SEQUENCE STRATIGRAPHY

Sea level sequence stratigraphy recognizes that many sedimentary formations and groups of formations (depositional *sequences* or *sequence tracts*) are bounded by unconformities, and that unconformities on passive continental margins are often caused by rapid falls in global sea level, giving them considerable value for worldwide correlation and chronostratigraphy (Pitman, 1978; Vail et al., 1977; Vail and Hardenbol, 1979; Haq et al., 1987). Most marine stages are sequence tracts or groups of tracts, and sequence stratigraphy provides a natural context for their study.

There are major unconformities or other evidence of sea level change at Gebel Mokattam, in Fayum, and elsewhere in Egypt. These are discussed for five areas: Western Desert, Cairo-Giza, Eastern Desert, northwestern Fayum, and western Sinai. The succession of formations in each area is outlined and compared in Figure 52 at the end of this chapter. WSW-ENE orientation of the Eocene Tethyan shoreline in Egypt means that the five areas represent a transect of environments from west to east along the ancient shoreline, but a west-to-east transect is also to some extent an offshore-onshore transect.

The age of Fayum formations is reviewed at the end of this chapter, taking account of refinement provided by sea level sequence stratigraphy. Depositional environments are reviewed in Chapter VI, which provides a model for similar consideration of Gebel Mokattam and Eastern Desert formations in the future when these are restudied in the context of major changes in sea level.

WESTERN DESERT

Sheikh and Faris (1985) described Eocene-Oligocene sections in three oil wells in the Western Desert of Egypt. The first well, North Ghazalat-1, is 500 km west of Cairo and has a continuous sequence of pelagic sediment with no noticeable gap at the Eocene-Oligocene boundary. Eocene and Oligocene parts of the Dabaa Formation here are apparently perfectly conformable. The second well, Dabaa-1, is 300 km west-northwest of Cairo and is reported to have the top part of planktonic foraminiferal zone P17 missing, indicating a gap at the Eocene-Oligocene boundary. The third well, East Mubarak-3, is 150 km west-southwest of Cairo. It has a sharp break in lithology where the Dabaa Formation overlies the Appolonia Formation, and several planktonic foraminiferal zones (P15-lower P21) are missing. This suggests that erosion associated with the Rupelian-Chattian low sea stand removed whatever was deposited of Priabonian and Rupelian sequence tracts, and the break is now a very large unconformity.

CAIRO-GIZA

The Eocene-Oligocene section in Cairo is well exposed east of the Nile at Gebel Mokattam, and a partial Eocene section is exposed west of the Nile in Giza and elsewhere. These have been studied by generations of geologists (reviewed in Chapter II). The Mokattam Formation at Gebel Mokattam is all or mostly Lutetian in age, the Giushi Formation is Bartonian and Priabonian, and the Maadi Formation is Priabonian. Precise age ranges of the Mokattam and Giushi formations need not concern us here; however, it is worthy of note that the celestite and tafla beds of Gebel Mokattam lie within the Giushi Formation (Bauerman and Le Neve Foster, 1869; Blanckenhorn, 1900—Blanckenhorn's zone II-1 includes the upper Giushi; see Fig. 5). This interval is correlative with an interval rich in celestite in Fayum (see below). If celestite deposition reflects chemical precipitation in a restricted shallow sea as Bauerman and Le Neve Foster (1869) first proposed, this suggests a significantly restricted low sea stand during Giushi time.

Blanckenhorn (1921, p. 92) noted the following regarding his zone II-1 at Gebel Mokattam (Fig. 5):

> *Charakteristisch is das Vorkommen knollenfaserigen Cölestins und einzelner schöner Kristalle aus demselben Mineral sowie die Armut an Fossilien (vereinzelt* Taonurus*). Beide Umstände hängen wohl mit der Entstehung der Gipsmergel und des Cölestin-tafles unter abnormen ozeanographischen Verhältnissen in vom offenem Meere abgeschlossenen flachen Lagunen zusammen, wo eine partielle Eindampfung des Meerwassers und Konzentration der Kalk- und Strontiumsulfate stattfand.*

[Characteristic are the presence of fibrous nodules of celestite and beautiful single crystals of the same mineral, as well as a paucity of fossils (isolated *Taonurus* [a trace fossil]). Both circumstances agree well with an origin of the gypsum marl and celestite tafla under abnormal oceanographic conditions in which open sea closes to a shallow lagoon, where a partial evaporation of sea water and concentration of lime and strontium sulfate take place.]

The Giushi low sea stand mentioned by Bauerman and Le Neve Foster and by Blanckenhorn probably corresponds to the Bartonian-Priabonian [B-P] sequence boundary shown in the right column of Figure 52.

Strougo et al. (1982) described a section at Darb el-Fayum in Giza where the equivalent interval is marked by an erosion surface indicating disconformity. Faunal constraints suggest that this disconformity also corresponds to the Bartonian-Priabonian [B-P] sequence boundary.

The Maadi Formation is similar to the Qasr el-Sagha Formation in lithology and fauna, with abundant oysters, *Carolia*, etc., but few nummulites. The Gebel Ahmar Formation lies directly on top of the Maadi Formation on the north side of Gebel Mokattam and at Gebel Ahmar (Gebel Akhdar) just north of Gebel Mokattam. The Gebel Ahmar Formation is overlain in turn by basalt a few kilometers east of Gebel Ahmar. The Gebel Ahmar Formation is similar to the Gebel Qatrani Formation, with variegated sediments (*Ahmar* means red in Arabic) and abundant silicified wood, and it has been considered Oligocene going back at least to Barron (1907). Contact between the marine Maadi Formation and the overlying continental Gebel Ahmar Formation has long been known to lie along an erosional unconformity (Schweinfurth, 1883, p. 719; Barron, 1907; Shukri and Akmal, 1953).

The highest bed of the Maadi Formation at Gebel Mokattam is the Ain Musa bed of Barron (1907) described in Chapter II. This is a bed of hard brown limestone several meters thick that is rich in *Anisaster* (*A. gibberulus*) and a small *Echinolampas* (*E. crameri*). The Ain Musa bed is important because it can be recognized 25 km east of Gebel Mokattam at Gebel Anqabia, it can be recognized 80 km east of Gebel Mokattam at Gebel Ataqa (see below), and it can be recognized 80 km southwest of Gebel Mokattam in Fayum. At Gebel Anqabia, 65 m of brown *Ostrea* and *Carolia*-rich marine limestone and shale separate the Ain Musa bed from the overlying Gebel Ahmar Formation. This 65 m unit, named the Anqabia Formation by Shukri and Akmal (1953), demonstrates that the erosional surface separating the Maadi Formation and the Gebel Ahmar Formation is a major unconformity, and this is almost certainly the Priabonian-Rupelian [P-R] sequence boundary.

Said (1990, p. 465) indicated that the Gebel Ahmar Formation is 40-100 m thick in the Cairo-Suez district. Basaltic lava flows overlie this near Gebel Anqabia and elsewhere (Barron, 1907), but I am not aware of any radiometric age determinations on the Gebel Anqabia basalts (Meneisy, 1990).

EASTERN DESERT

The geology of the desert east of Cairo and Gebel Mokattam was described by Barron (1907). Later Farag and Ismail (1955, 1959) carried out a more detailed investigation in Wadi Hof east of Helwan and 20 km southeast of Gebel Mokattam. Farag and Ismail named five new formations: Gebel Hof, Observatory, Qurn, Wadi Garawi, and Wadi Hof, spanning much of middle and late Eocene time. These cover the same time range as formations exposed at Gebel Mokattam, but lie 20 km or so farther landward and represent slightly different depositional environments. Correlation with Gebel Mokattam is illustrated by Said (1990, figure 24.4 not table 24.3), based on work of Strougo (1985a,b, 1986; see Fig. 4 here).

At places in the Eastern Desert, as at Gebel Genefe north of Suez and 100 km east of Gebel Mokattam (Barron, 1907, p. 83 and section I), there is an angular erosional unconformity between limestones of the "lower Mokattam" (Observatory Formation of Farag and Ismail) and *Ostrea-Carolia* bearing beds of the "upper Mokattam" (Wadi Hof Formation of Farag and Ismail). This is probably the Bartonian-Priabonian [B-P] sequence boundary.

Barron (1907, p. 64 and section V) also described an erosional unconformity between the "upper Mokattam" (Wadi Hof Formation) and the Oligocene (Gebel Ahmar Formation) at Gebel Awebed 80 km east of Gebel Mokattam. Barron (1907, p. 85) recorded the presence of 70 m of "upper Mokattam" (Wadi Hof Formation) lying above the Ain Musa bed at Gebel Ataqa just west of Suez and 100 km east of Gebel Mokattam. Removal of the upper Wadi Hof Formation by erosion before deposition of the Gebel Ahmar Formation indicates that a major unconformity separates the two formations in the Eastern Desert. This is almost certainly the Priabonian-Rupelian [P-R] sequence boundary. Barron (1907, pp. 87-92) argued that the full 70 m of "upper Mokattam" was removed by erosion from the top of the Mokattam sequence (top of the Maadi Formation) in Cairo and from the top of the Qasr el-Sagha Formation in Fayum.

Basaltic lava flows overly the Gebel Ahmar Formation in the Eastern Desert, and a basaltic neck cuts through Eocene limestones at Gebel Gafra (Barron, 1907). Three age determinations for Eastern Desert basalts range from 23.0 ± 1.0 to 22.0 ± 2.0 Ma (Meneisy, 1990).

FIG. 46—Camp White Layer at top of Gehannam Formation (foreground) in Wadi Hitan. Sandstones in background are remnants of overlying Birket Qarun Formation. Rod-like structures 1 cm or so in diameter projecting from hard surface or weathering down slope in foreground are mangrove pneumatophores. Handle of hammer in foreground is about 30 cm long. Salâs Awahât landmark is on skyline at right center (compare with Fig. 42). View is to northeast.

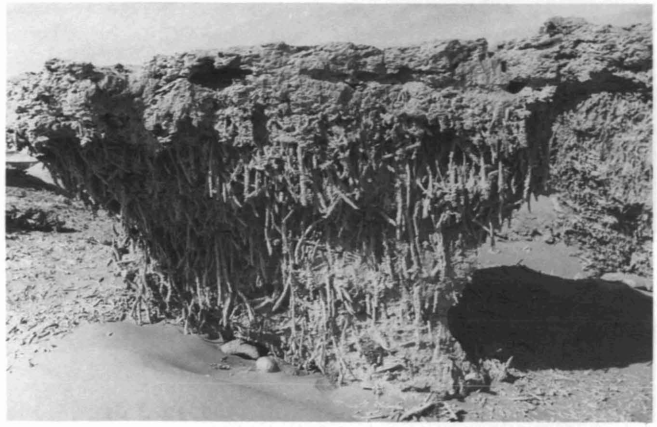


FIG. 47—Broken block of Camp White Layer in Wadi Hitan showing hard limestone top in cross-section. This top bed forms an extensive dip slope resistant to erosion. Succession of vertical mangrove pneumatophores dissected by wind erosion are visible below. Block stands about 1.5 m high.

FAYUM

The stratigraphy of the northwestern part of the Fayum depression has been studied by many investigators (reviewed in Chapter III). The Eocene section begins with the Wadi Rayan Formation of Lutetian or possibly Lutetian and Bartonian age. This is overlain by the Gehannam Formation of Bartonian and Priabonian age (Haggag, 1990), and by the Birket Qarun and Qasr el-Sagha formations of Priabonian age. The Oligocene section includes the continental Gebel Qatrani Formation and the Widan el-Faras Basalt, and these are overlain by Miocene Khashab Formation.

No major break in sedimentation has been described within the Wadi Rayan Formation or at the transition from Wadi Rayan Formation to Gehannam Formation. However, there is conspicuous evidence of a well marked low sea stand in the middle of the Gehannam Formation (the top of the formation where it is overlain by Birket Qarun Formation). This includes:

1. Abundant mangrove pneumatophores and anchor roots (Figs. 46 and 47) eroding from the Camp White Layer at the top of the Gehannam Formation over a broad area in Wadi Hitan. Pneumatophores are related to aerobic respiration in mangroves, and grow upward out of waterlogged substrates to reach air (Hutchings and Saenger, 1987; they indicate, if not subaerial exposure, that air was within reach of growth). The stratigraphic interval containing mangrove is only at most a few meters thick, suggesting that the time interval of low sea stand was relatively short.

2. Discovery of ribs, vertebrae, and both pelves of the estuarine proboscidean *Moeritherium* (Fig. 48) a few meters below the Camp White Layer at ZV-165 in Wadi Hitan. *Moeritherium* is not found elsewhere in Fayum except in the upper Qasr el-Sagha Formation.

3. Celestite filling many mollusks, including *Nautilus*, *Lucina*, and *Teredo* at the Gehannam-Birket Qarun transition. There is a large tree trunk 18 m long and about 1 m in diameter resting about 4 m below the top of the Camp White Layer (Fig. 49). It is riddled with 'ship worm' (bivalve *Teredo*) burrows, and must have been sunk or beached as driftwood. Tubes formed as calcareous linings of ship worm borings are filled with celestite (Fig. 50).

All of this evidence taken together indicates a marked interval of low sea stand, possibly with limited subaerial exposure.

Patterned cracking of the surface of a femur (Fig. 51) found with a nearly complete skeleton of *Basilosaurus* in mangrove at Wadi Hitan locality ZV-191 suggests stage 1 subaerial weathering of Behrensmeyer (1978), but this pattern of cracking can also be observed on bone submerged in ponds and never exposed subaerially (D. C. Fisher, pers. comm.).

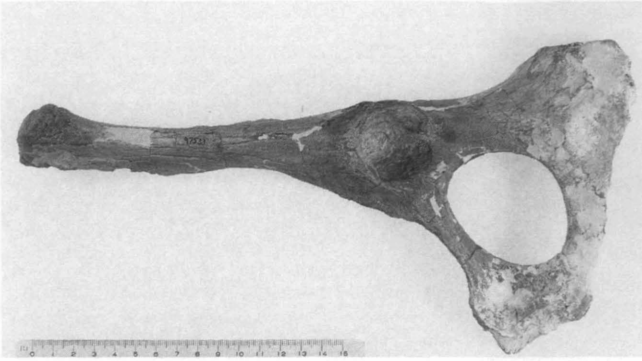


FIG. 48—Left innominate of *Moeritherium* sp. from ZV-165 in Wadi Hitan, in lateral view. This compares closely in size and form to the innominate of *Moeritherium* illustrated by Andrews (1906, p. 214) and differs from Wadi Hitan Cetacea and Sirenia in having an obturator foramen much larger than the acetabulum. Scale is in cm.

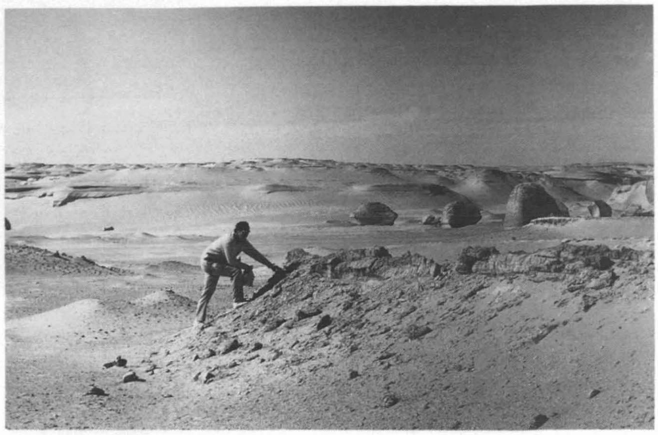


FIG. 49—Tree trunk 18 m long and about 1 m in diameter resting some 4 m below the top of the Camp White Layer in Wadi Hitan. This trunk is riddled with 'ship worm' (*Teredo*) burrows (Fig. 50). View is to northwest, with sandstone remnants of Birket Qarun formation in background.

This evidence of low sea stand is unlike any found lower or higher in the Gehannam Formation, higher in the Birket Qarun Formation, or higher in the Qasr el-Sagha Formation (*Moeritherium* is known from the upper Qasr el-Sagha Formation, but mangrove has not been reported). The Gehannam Formation was deposited on a shallow shelf in open marine waters, and a part of that deposition occurred during an interval of low sea stand, but there is no evidence of an erosional unconformity of any kind in the area studied.

This low sea stand during Gehannam Formation time may help to explain why so many archaeocete skeletons are preserved in Wadi Hitan. Some may have been beached on shallow shoals by retreating tides (although nothing is known of possible tidal ranges here in the Eocene). Alternatively, shallows may have attracted archaeocetes for other reasons: possibly calving in the case of *Prozeuglodon* and feeding in the case of *Basilosaurus* (which may not have been totally independent—skulls of immature *Prozeuglodon* are common, and these often bear impressed tooth marks made by a large predator).

The upper Gehannam Formation and lower Birket Qarun Formation have long been known to be unusually rich in celestite (strontium sulfate; Beadnell, 1905), interpreted above to reflect unusually restricted oceanographic conditions where partial evaporation of sea water concentrated lime and strontium sulfate. Interpretation of the Birket Qarun Formation as a barrier bar complex (Chapter IV) is consistent the idea of a low sea stand at its base because barrier bars, as a rule, are only preserved in the stratigraphic record when buried during subsequent transgression. The Birket Qarun Formation is a "transgressive systems tract" in the language of sequence stratigraphy. Evidence of a low sea stand at the top of the Gehannam Formation where it is overlain by Birket Qarun Formation corroborates placement of these formations in sequence tracts TA3.6 and TA4.1, respectively (see Fig. 52), straddling the Bartonian-Priabonian [B-P] low sea stand.

Standard interpretation places the Qasr el-Sagha Formation in the upper Eocene and the Gebel Qatrani Formation in the lower Oligocene (Osborn, 1908; Schlosser, 1911; Said, 1962; Simons, 1968; Fleagle et al., 1986a,b; Bown and Kraus, 1988; Simons and Rasmussen, 1990). These formations are separated by a major unconformity first detected by Blanckenhorn (1903, p. 399) and Beadnell (1905, p. 55), and discussed by Barron (1907, p. 68), Strougo (1976a, p. 1139), and Bown and Kraus (1988, p. 23; see Chapter III). A minimum of 76 m of erosional relief is associated with the Qasr el-Sagha - Gebel Qatrani formational boundary in parts of Fayum. This is attributed to erosion, or erosion and non-deposition, during marine regression.

The 76 m minimum includes 68 m below the Ain Musa bed present at Dir Abu Lifa (Fig. 30) but missing at Elwat Hialla (Beadnell, 1905, p. 55; Barron, 1907, p. 68), and the lesser of 10 m above the Ain Musa bed present at Qasr el-Sagha (Strougo, 1976a, p. 1139) or 8 m of the "upper crossbedded sandstone and mudstone" above the Ain Musa bed at Wadi Efreet (Bown and Kraus, 1988, p. 20).

One would hope that erosional scouring responsible for 76 m or more of missing section would leave obvious evidence in the form of an angular unconformity, especially on a continually subsiding continental margin. However, the distance from Qasr el-Sagha or Dir Abu Lifa to Elwat Hialla is on the order of 20 km. Geometri-

FIG. 50—Detail of 'ship worm' (*Teredo*) borings that have completely replaced wood in tree trunk of Fig. 49. Borings are filled with celestite. Pencil is about 7 mm in diameter.

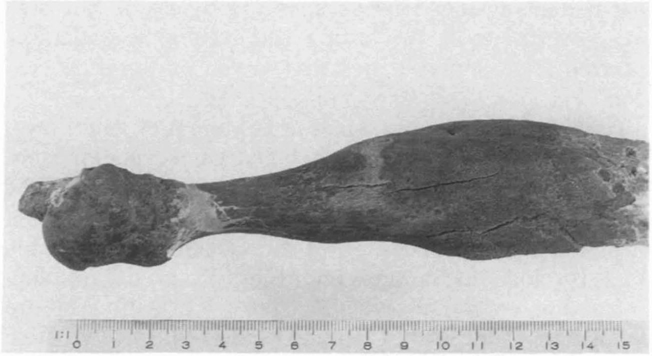


FIG. 51—Caput and midshaft of left femur of *Basilosaurus isis* from ZV-191 in Wadi Hitan. Caput is at left, and specimen is shown in dorsal view. Midshaft exhibits pathological hyperostosis in response to breakage during life. Large post-mortem cracks developed parallel to midshaft and cancellous texture of bone appear to be desiccation cracks of some kind. Scale is in cm.

cally, loss of 76 m of sediment over a distance of 20 km requires an angular relationship between beds averaging only about 0.2° (arcsin of 76/20000), which could not possibly be detected in the field. The unconformity probably would be perceptibly angular if it could be viewed perpendicular to the hinge axis of subsidence, but available outcrops all lie parallel to this axis. Removal of 76 m or more of stratigraphic section is clear evidence of a major unconformity and this is almost certainly the Priabonian-Rupelian [P-R] sequence boundary.

Other unconformities with evidence of up to 20 m of section missing also occur within the Gebel Qatrani Formation (Bown and Kraus, 1988). Terrestrial fossil mammals come mainly from six levels in the Gebel Qatrani Formation. These are labelled in Figure 52: L-41, quarries A and B, Quarry E, Quarry V, Quarry G, and quarries I and M.

The Gebel Qatrani Formation is overlain by the Widan el-Faras Basalt. Radiometric dates on the basalt are 24.7 ± 0.4, 27.0 ± 3.0, and 31.0 ± 1.0 m.y. (Fleagle et al., 1986a,b). The Gebel Qatrani - Widan el-Faras contact was considered "continuous" by Beadnell (1901), "disconformable" by Bowen and Vondra (1974), and a "pronounced erosional unconformity" by Bown and Kraus (1988), illustrating how interpretation of boundaries sometimes changes as the boundaries become better known. Parts of the Widan el-Faras Basalt were deposited in erosional scours indicating 40 m or more of regional relief at this unconformity (Bown and Kraus; 1988, p. 44).

SINAI

Eocene and Oligocene stratigraphy in western Sinai on the east side of the Gulf of Suez is described by Hume et al. (1920), Boukhary and Abdelmalik (1983), Said (1990), and Haggag and Luterbacher (1991). The succession includes the marine Thebes, Darat, and Khaboba formations deposited in deep water, overlain by Tanka Formation shelf sediments. These are overlain by 35 m of red continental Tayiba Formation and then basalt. The Tayiba is separated above and below by unconformities. Radiometric ages of basalt dikes at Gebel Araba include 31.0 ± 2.0 and 18.0 ± 1.0 Ma, while age determinations on basalt dikes from Wadi Nakhul and Wadi Tayiba are 22.0 ± 1.0 and 21.0 Ma, respectively (Meneisy, 1990). Meneisy (1990, p. 167) considered basalts in the age range 26-22 Ma to reflect vulcanicity related to opening of the Red Sea, but independent age determinations of 31 Ma for basalts in Fayum and Sinai suggest that Gulf of Suez and Red Sea opening started earlier in the Oligocene.

AGE OF FAYUM FORMATIONS

The preceding observations are summarized in Figure 52. Low sea stands and unconformities by themselves obviously tell nothing of age, but they begin to be informative when they separate formations or parts of formations correlated with the global time scale on the basis of fossils or other evidence. Sea level sequence stratigraphy is similar to paleomagnetic stratigraphy in that neither system tells us anything by itself, but both are powerful tools for testing and refining correlations inferred from superposition and faunal or floral succession.

The logic of this refinement in Fayum goes as follows. The Qasr el-Sagha and Gebel Qatrani formations are separated by an unconformity in the Fayum that involved erosion of a minimum of 76 m of Qasr el-Sagha sediment in places before deposition of the Gebel Qatrani. This total is close to the minimum of 65 m of Anqabia Formation eroded above the Maadi Formation before deposition of the Gebel Ahmar Formation in the Cairo-Giza area, and this total is close to the minimum of 70 m eroded from the top of the Wadi Hof Formation before deposition of the Gebel Ahmar Formation in the Eastern Desert. The great thickness of sediment removed by erosion at the Qasr el-Sagha - Gebel Qatrani boundary and the consistency of measurements of erosion separating correlative formations across northern Egypt, taken together, provide clear evidence of a major unconformity. A rapid fall in sea level of 76 m (or more) is required to remove 76 m of shallow marine sediment on a passive continental margin. This happened three times in the middle to late Eocene and Oligocene (Haq et al., 1987): at the Bartonian-Priabonian [B-P], the Priabonian-Rupelian [P-R], and the Rupelian-Chattian [R-C] sequence boundaries shown in Figure 52. These involved rapid sea level falls of about -100 m, -90 m, and -140 m, respectively.

Sea level falls at any one of the Bartonian-Priabonian [B-P], Priabonian-Rupelian [P-R], or Rupelian-Chattian [R-C] sequence boundaries would be sufficient to explain removal of 76 m of sediment between deposition of the Qasr el-Sagha and Gebel Qatrani formations. However, radiometric ages on the overlying Widan el-Faras Basalt, taken together, demonstrate that the Gebel Qatrani Formation is older than the Rupelian-Chattian [R-C] sequence boundary. Planktonic foraminiferal biostratigraphy of the underlying Gehannam Formation demonstrates that the Qasr el-Sagha Formation is younger than the Bartonian-Priabonian [B-P] sequence boundary. Consequently, the Priabonian-Rupelian [P-R] boundary is the only major 'type-1' sequence boundary that can separate the Gebel Qatrani and Qasr el-Sagha formations consistent with constraints on the ages of the two formations. Matching the Gebel Qatrani - Qasr el-Sagha boundary with the Priabonian-Rupelian [P-R] sequence boundary makes it likely that the unconformity at the top of the Gebel Qatrani Formation coincides with the Rupelian-Chattian [R-C] sequence boundary. There is no unconformity at the base of the Qasr el-Sagha Formation, but the low sea stand in the Gehannam Formation at the base of the Birket Qarun Formation coincides with the Bartonian-Priabonian [B-P] boundary.

In a recent study, Van Couvering and Harris (1991) claimed that there is no major unconformity between the Qasr el-Sagha and Gebel Qatrani formations. They then proposed that *both* formations lie beneath the Priabonian-Rupelian [P-R] sequence boundary and are thus Priabonian late Eocene in age. A profound change from marine to continental deposition at this boundary has been noted by virtually all geologists and paleontologists who have worked in the field in Fayum, and broader regional evidence summarized here and in Chapter III from literature covering the past ninety years makes it clear that a major unconformity separates the Qasr el-Sagha and Gebel Qatrani formations. Consequently it is very unlikely that the Gebel Qatrani Formation is Priabonian in age, and this formation cannot be Eocene according to any current concept of the epoch.

Rasmussen et al. (1992) interpreted the lower 157 m of the Gebel Qatrani Formation (including all of the 'lower fossil wood zone' with Duke Quarry L-41, American Museum quarries A and B, and Yale Quarry E) as late Eocene. Rasmussen et al. (1992, p. 560) justified this by correlation of mammals from Fayum Quarry E with mammals from Oman localities (Thomas et al., 1989) that Rasmussen et al. characterized as having "paleomagnetic dates" older than the 34 Ma Eocene-Oligocene boundary. However, the Eocene-Oligocene boundary is not defined radiometrically, paleomagnetic correlations are not "dates," and Thomas et al. (1989) themselves regarded the Oman localities as Oligocene. Fossil mammals found at the Oman Thaytiniti locality lie within a normal-polarity magnetic anomaly in association with the Oligocene nummulite *Nummulites fichteli*. The anomaly is interpreted as 13N (Thomas et al., 1989), which is Oligocene whatever its radiometric age (Berggren et al., 1985; Haq et al., 1987; Odin and Montanari, 1989; Swisher and Prothero, 1990). If Fayum Quarry E is correlative with Thaytiniti in Oman, then the lower part of the Gebel Qatrani Formation is Oligocene rather than Eocene.

Radiometric calibration in Figure 52 requires some comment. The geological time scale is constructed from observation of the superpositional and cross-cutting relationships of strata and formations in the field. Fossils are observed to change in successive strata, which is, on one hand, the material evidence for organic evolution and, on the other hand, the basis for the most complex and informative succession used to correlate and integrate strata worldwide. As discussed above, the position of paleomagnetic stripes ('bar code') and the position of high or low sea stands can be used to test and refine correlations based on fossils and faunal succession, but paleomagnetic stripes and high or low sea stands, by themselves, are meaningless chronologically.

Radiometric ages calibrate the result and give us a numerical value for how far back in time events in the Eocene happened, but there are relatively few dated strata, these are often dated using different radiogenic elements and calibration constants, and the derived ages

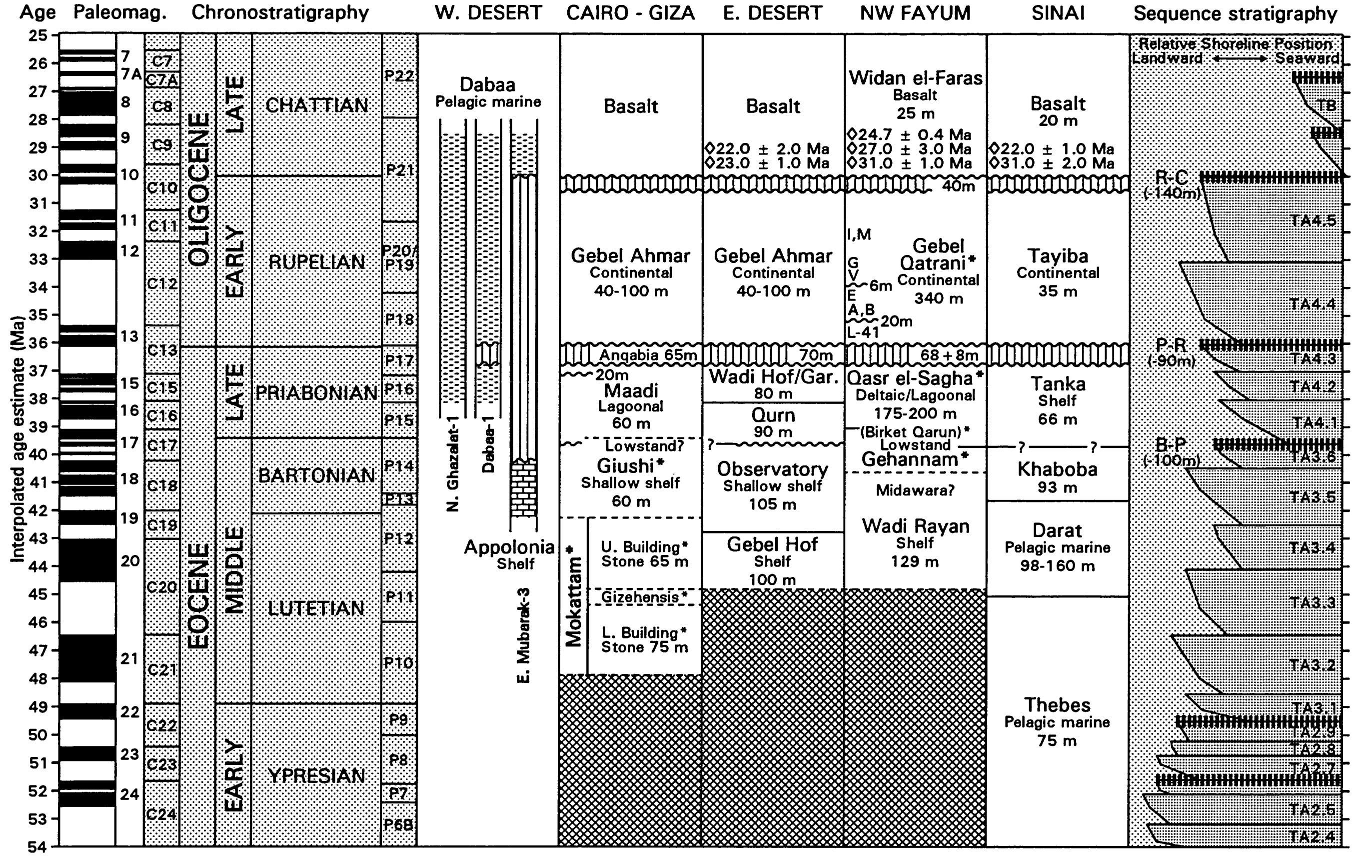


FIG. 52—Eocene and Oligocene stratigraphy of northern Egypt. Succession of geological formations is shown for five areas: the Western Desert, Gebel Mokattam and vicinity near Cairo and Giza, the Eastern Desert east of Cairo, northwestern Fayum, and western Sinai. Formations are shown with environment of deposition and thickness when space permits. Asterisks identify important marine and continental mammal-bearing formations. Wavy lines represent unconformities (vertical lines separating pairs of wavy lines depict major unconformities); all are shown with an estimate of minimum thickness of missing section when known. Interpolated age estimates based on radiometric calibration (age) and paleomagnetic reversal stratigraphy are shown at left, Eocene-Oligocene chronostratigraphy including magnetochrons and Paleogene planktonic foraminiferal zones (P6B-P22) is shaded at left, and sea level sequence stratigraphy is shaded at right (all taken from Haq et al., 1987). Diamonds depict radiometric ages of Widan el-Faras and other basalts. Letters I, M, G, etc., show positions of land-mammal localities in Gebel Qatrani Formation. Crosshatching represents strata covered or missing in the area studied. Sequence tracts (TA2.4, TA2.5, etc.) separated by heavy broken lines separate important 'type-1' sequence boundaries corresponding to major sedimentary unconformities caused by rapid sea level fall moving shoreline seaward. Type-1 boundaries near the Bartonian-Priabonian transition (B-P), Priabonian-Rupelian transition (P-R), and Rupelian-Chattian (R-C) are shown with approximate magnitude of sea level change in parentheses (estimated as difference between long term maximum and short term minimum for transition). All measures of thickness, missing section, and sea level change are in meters.

are inherently imprecise in comparison to the resolution of paleomagnetic polarity reversals and many sea level changes.

Figure 52 illustrates all three points. There are relatively few dated strata: the only relevant radiometric ages are from the Widan el-Faras and correlative basalts at the top of the sections of interest. These are dated using different methods: the Widan el-Faras and correlative basalts were all dated using the decay of radiogenic potassium to argon, but we necessarily compare these to potassium-argon, argon-argon, rubidium-strontium, and uranium-lead ages elsewhere determined from whole rock or single-crystal samples using a variety of minerals and analytical instruments. Radiometric ages are inherently imprecise: the Widan el-Faras ages range from 24.7 ± 0.4 to 31.0 ± 1.0 Ma, and correlative basalts elsewhere in Egypt have ages ranging from 22.0 ± 2.0 to 31.0 ± 2.0. Radiometric ages are not available for enough strata, are not measured with sufficient uniformity, and do not have the precision to constitute an independent time scale. Radiometric ages are important for calibration of the geological time scale, but radiometric ages do not now (and probably never will) constitute a Phanerozoic time scale independent of superposition and faunal succession.

I have reviewed the differing roles different evidence plays in constructing the geological time scale to emphasize the primacy of fossils (here planktonic foraminifera), the secondary refinement offered by paleomagnetic reversals and sea level stratigraphy, and the tertiary importance of radiometric calibration. It really makes little difference for the time scale in Figure 52 whether the Eocene-Oligocene boundary is interpolated as being at about 36 Ma (Haq et al., 1987) or at about 34 Ma (Odin and Montanari, 1989; Swisher and Prothero, 1990). Radiometric recalibration would compress some formations slightly and stretch others slightly, but the sequences and correlations of formations and their ages and epochs in relation to stratal stages and series remain the same.

VI

INTERPRETATION OF PALEOENVIRONMENTS

One goal of this study is a better understanding of paleoenvironments inhabited by Eocene Cetacea and Sirenia in Egypt. Each Fayum formation yielding marine mammals is reviewed here, and this review is followed by discussion of a general model to explain the succession and progradation of environments observed in Fayum.

GEHANNAM FORMATION

The middle and upper parts of the Gehannam Formation were studied over a broad area in Wadi Hitan (e.g., Figs. 34-37) and at Minqar el-Hut (Fig. 40). This formation, like the lower part of the overlying Birket Qarun Formation, is of particular interest in yielding many skeletons of the marine archaeocetes *Basilosaurus isis* and *Prozeuglodon atrox*. Archaeocete specimens are rarely found together in any concentration, but rather seem to be distributed almost randomly throughout the area studied. Archaeocetes are commonly found as partially articulated skeletons with the axial skeleton more or less complete and articulated, while fore and hind limbs are usually disarticulated and scattered. Skulls are sometimes found separately too. Large *Basilosaurus* are often more completely articulated than smaller *Prozeuglodon*, and disarticulation is attributed to the action of sharks and other scavengers. Sirenians are rare in the Gehannam Formation, but they are present and occasionally well preserved. In addition, there is a diverse fauna of sharks, represented by ubiquitous shed teeth. Pristid sawtooth sharks are common, represented by rostra and rostral fragments. Large sea turtles specialized for swimming are present, as are smaller turtles. Crocodilians are present but rare.

The macroinvertebrate fauna of the Gehannam Formation includes *Nuculana*, *Lucina*, *Pegophysema*, *Paraglans*, and "*Tellina*" (Strougo and Haggag, 1984), but it has not, to my knowledge, been studied from an environmental point of view. There are abundant echinoids of the genus *Schizaster* in the white marl units near the base of the Minqar el-Hut section (Fig. 40). The macroinvertebrates are mostly infaunal, and they are typical of shallow rather than deep sea bottoms. Epifaunal elements include crabs of the genus *Lobocarcinus*, which is abundant in the Wadi Hitan ZV-54NW section (Fig. 34). Barnacles (*Balanus*) sometimes encrust whale bones. The Gehannam Formation has yielded diverse nummulites (Abdel-Kireem et al., 1985) and planktonic foraminifera (Abdou and Abdel-Kireem, 1975; Strougo and Haggag, 1984; Haggag, 1990), and these indicate open marine conditions. Consequently we can be confident that much of the Gehannam Formation was deposited on a shallow but open marine shelf.

BIRKET QARUN FORMATION

The Birket Qarun Formation has a distinctive geometry, with an outcrop belt as much as 60 km long but never more than about 5 km wide. The Birket Qarun Formation is on the order of 70 m thick at maximum (e.g., at Garet Gehannam, Fig. 24, and Minqar el-Hut, Fig. 40), but thins rapidly perpendicular to the long axis of outcrop. This linear lenticular geometry by itself suggests deposition as an offshore barrier bar complex paralleling the shore line of ancient Tethys (something like the barrier bars or beaches enclosing Lake Burullus and other lagoons shown in Fig. 1). In some places, where the Birket Qarun Formation is thick (as at Minqar el-Hut, Fig. 40, and elsewhere in Wadi Hitan), the barrier complex rests on low sea stand deposits with mangrove (Camp White Layer and equivalents) of the Gehannam Formation. Barrier bars are normally reworked and destroyed during regression, and regression is the common situation on prograding passively-subsiding continental margins like the Egyptian Eocene continental margin studied here. Transgression flooding a shelf is required to bury bars or beaches and thus preserve them (Hoyt, 1967; Selley, 1978). Barrier bar complexes like the Birket Qarun Formation are transgressive systems tracts (Haq et al., 1987), and it is no accident that the Birket Qarun Formation overlies low sea stand deposits of the Gehannam Formation: a barrier bar complex is unlikely to have been preserved in any other setting.

The invertebrate and vertebrate faunas of the lower Birket Qarun Formation appear similar to those of the underlying Gehannam Formation, indicating that both were deposited on a shallow marine shelf. The upper Birket Qarun Formation at Sandouk el-Borneta (Fig. 37) has a bed packed with *Carolia* that is interpreted as a possible storm deposit (tempestite), and the basal bed of the Qasr el-Sagha Formation there is an *Ostrea* and nummulite bed interpreted as a storm accumulation like others described from Egypt by Aigner (1982, 1983).

Mangrove and estuarine or land mammals like *Moeritherium* have not been found in the Birket Qarun Formation (except, of course, at its base where this formation lies directly on low sea stand deposits of the Gehannam Formation). Taken together, this negative evidence suggests that the Birket Qarun Formation was a submerged barrier bar rather than beach complex, which is consistent with Bown and Kraus' (1988, p. 48) reference to Birket Qarun "offshore subaqueous dunes."

QASR EL-SAGHA FORMATION

Four members of the Qasr el-Sagha Formation are recognized here (see Chapter IV), and the sedimentary structures and fauna characteristic of each suggest deposition in distinct environments. Hard beds are important in two of the four members and these will be described first. The two members described by Bown and Kraus (1988) will be discussed next, followed by interpretation of the two new members described in Chapter IV.

Hard beds

Blanckenhorn (1903) used the term "*harte Bank*" for some of the beds he described in Fayum. Five of the ridge-forming sandy limestone or limey sandstone units in the lower part of the Garet el-Esh section (Fig. 32) are interpreted as single- or multiple-story "hard beds" (Fig. 53), and these are present in the Garet Umm Rigl section (Fig. 33) as well. The term "hard bed" is appropriate because each bed is hard and resistant to erosion, and the term is appropriate also because it is general and noncommittal, reflecting a need for more detailed study.

Each bed described as a hard bed here may be a hardground (a sea floor deposit formed by synsedimentary lithification), but there is as yet no clear evidence that lithification took place as the sediments accumulated. Hardgrounds reflect specific complex interactions between depositional, biological, and diagenetic processes, and typically preserve part of their fauna in place (Fürsich, 1979). The hard beds reported here have some of the general characteristics of hardgrounds, but more study will be required to determine if they were lithified as they were deposited. If these do prove to represent hardgrounds, they appear to conform to hardgrounds of Fürsich's (1979) genetic sequence I.

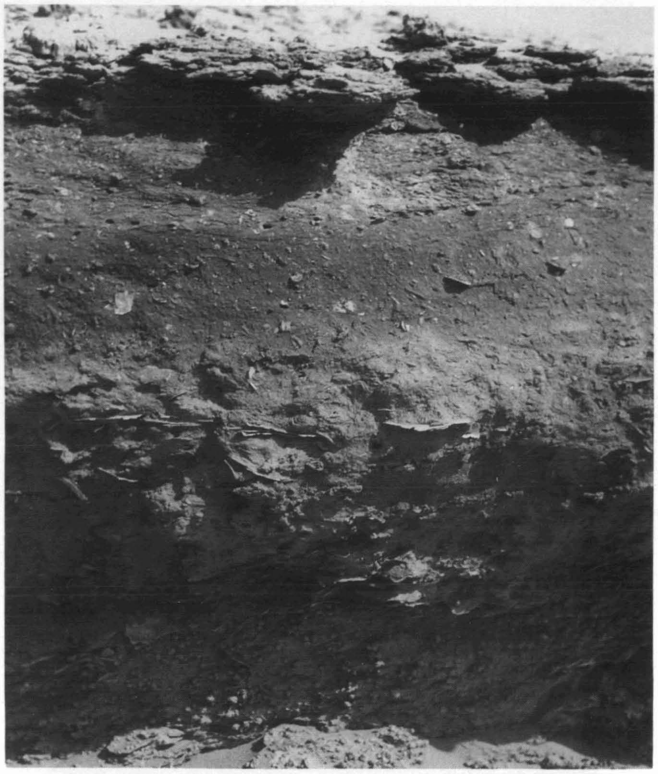


FIG. 53—Hard bed at 27 m level in Garet el-Esh stratigraphic section (Fig. 32). This is in the Temple Member of the Qasr el-Sagha Formation. Photograph shows thin flat valves of *Carolia placunoides* near the base, red to yellow intermediate zone with mollusk shells and shell fragments, and upper zone rich in *Turritella*. Section shown here is about 1.5 m thick. Red and yellow color may come from iron hydroxide mineralization, which is characteristic of shallow shelf hardgrounds (Fürsich, 1979).

Two characteristics of hard beds stand out: (1) they are rich in molluscan remains, and (2) there is a definite succession of bivalves preserved in each hard bed. The richness of mollusks must be due to conditions favorable for growth. Schäfer (1972) identified water currents and clastic sediment contamination as probably the two most important determinants of biotope development. Currents provide oxygen for organismal respiration and growth, but currents may also carry terrigenous sediment that interferes with respiration and growth. Qasr el-Sagha hard beds are shell beds that appear to have developed in areas of sea floor where organisms flourished because they were well oxygenated and because the influx of terrigenous clastic sediment was low.

The idea of succession in these beds is not new. Blanckenhorn (1903) mentioned banks or benches with *Turritella* overlying *Carolia* (Figs. 14, 15), and *Ostrea* overlying *Carolia* (Figs. 15, 18), and both are present in the Garet el-Esh section (Fig. 32). *Ophiomorpha* or

Callianassa burrows are usually found at the base. These are usually overlain by an interval with *Carolia*. There is then, optionally, an interval of small to medium-sized bivalves. Finally at the top there is an interval rich in *Ostrea*, *Turritella*, or *Kerunia* (or all three). Hard beds are invariably well cemented, which is why they form ridges in the field.

Callianassa, the brine shrimp, is an infaunal suspension-feeding crustacean often associated with seagrass meadows (Brasier, 1975). *Carolia* is an anomiid bivalve that, like living *Anomia* but unlike oysters, was an epibyssate suspension feeder. Aberhan and Fürsich (1991) characterize *Anomia* as living on hard substrates, but *Carolia* had large flat paper-thin valves up to 20 cm in diameter that give an appearance of having been able to virtually "float" on soft mud sea bottoms. *Ostrea* is a cemented epifaunal suspension feeder living on hard substrates (Aberhan and Fürsich, 1991). *Turritella* is a shallow infaunal suspension feeder living on soft substrates. Putting all of this together, it is easy to visualize each hard bed as representing the following succession (from bottom to top):

6. Return to a "normal" influx of clay and silt choking and burying organisms still living on what has now become a cohesive shell bed.
5. Invasion of *Turritella* as influx of clastic sediment increased.
4. Attachment and growth of one or more generations of *Ostrea* cemented to this substrate, sometimes with commensal or symbiotic *Kerunia* and its host present as well.
3. Colonization by one or more generations of other mollusks, whose shells contribute to buildup of a firm substrate.
2. Establishment and growth of one or many generations of epibyssate *Carolia*.
1. Initial establishment of a seagrass meadow with *Callianassa* in areas of lagoon floor where the influx of clastics (clay and silt) was unusually low.

There is considerable variation in individual successions, but all share enough of a pattern, with *Callianassa* below, *Carolia* grading to other mollusks in the middle, and *Ostrea* and/or *Turritella* above, to indicate that some repetitive process was at work.

Vondra (1974) described the beds in question as an arenaceous bioclastic carbonate facies, without mentioning succession within them and without elaborating on sources of bioclastic carbonate. Bown and Kraus (1988, p. 47) interpreted "conglomeratic coquina" beds in the Temple and Dir Abu Lifa members as "reworked shoreline lags." While some conglomeratic coquina beds in the upper Qasr el-Sagha Formation may be shoreline deposits, the mollusks in most are too well preserved (even as steinkerns with shell material leached away) to represent reworked shoreline lags. Also, a shoreline lag interpretation does not explain the repeated succession from *Ophiomorpha-Callianassa* to *Carolia* to *Ostrea* or *Turritella* and other mollusks, and most of the arenaceous bioclastic carbonate beds probably represent sea floor living surfaces rather than shoreline strands.

Temple Member

The Temple Member of the Qasr el-Sagha Formation is dominated by two of Vondra's (1974) Qasr el-Sagha facies (see Chapter III): the arenaceous bioclastic carbonate facies (facies 1), and the gypsiferous and carbonaceous laminated claystone and siltstone facies (facies 2). As mentioned above, hard beds developed in areas of sea floor where currents were sufficient to provide oxygen enhancing biological productivity but the influx of terrigenous sediment was low. This is where bioclastic carbonates accumulated. Corals abound along many horizons (Beadnell, 1905, p. 53). These are hermatypic scleractinians that require light, clear water, shallow depths (less than 50 m), normal marine salinity, and a firm substrate (Wells, 1967). Oysters are often abundant and these indicate shallow marine to intertidal water depths. Organisms do poorly where the influx of silt and clay is high, and this is where laminated claystones and siltstones accumulated. The two facies alternate in vertical succession in the Temple Member, demonstrating that the influx of silt and clay was localized and spatially variable while the member was being deposited.

Dir Abu Lifa Member

The dominant lithology of the Dir Abu Lifa Member is crossbedded sandstone of Vondra's facies 3, the interbedded claystone, siltstone, and quartz sandstone facies, which Vondra interpreted as forming on a delta front. A delta front is as far downstream as a river-sourced submarine current transports terrigenous clastics, and this is where most of its sediment load is dropped. Vondra's facies 4, the quartz sandstone facies, is also part of the Dir Abu Lifa Member and Vondra interpreted this as a delta distributary facies. Delta distributary channels are found less far downstream where river-sourced submarine currents of higher energy continue transportation of most terrigenous sediment and leave only the coarsest fraction behind.

Bown and Kraus introduced a novel fluvial interpretation of the Qasr el-Sagha Formation, meaning that they considered much of it to have been deposited by rivers. Bown and Kraus (1988, p. 46-47) reinterpreted Vondra's (1974) interbedded claystone, siltstone, and quartz sandstone facies (facies 3 above) and his quartz sandstone facies (facies 4) as having been deposited by rivers rather than prograding deltas, writing:

These data are indeed consistent with a delta debouching into a bay developed more or less to the north, as suggested by Vondra. However, the contrasting dip directions (185°, 229°, 345°, and 355°) recorded by us at localities east and west of the Qasr el-Sagha Temple, our recognition of west- or west-northwest-oriented channels within this sequence, and internal (intraset) stratification showing flow directions of 255° to 310° (45° to 100° different from the flow direction suggested by Vondra's 'sloping surface of the delta front') indicate a somewhat different, nondeltaic origin. ... In the Qasr el-Sagha Formation, there is a 45° to 100° disparity between the dip directions of the giant foresets and the large-scale intrasets. This suggests that the giant cross sets in the bottom of the Dir Abu Lifa Member represent lateral accretion deposits that formed within stream channels.

Vondra (1974, p. 86) stated that the foresets dip "to the northwest" (i.e., at a bearing averaging about 315°, or say, 295° to 335°), so it is not clear where the "45° to 100° disparity" comes from. Neither Vondra nor Bown and Kraus indicated the number or values of their measurements, and "sloping surfaces of delta fronts" are bound to be curved in any case (or even lobed), weakening this as an argument for fluvial rather than delta front deposition.

The Temple Member appears to be composed predominantly of Vondra's (1974) Qasr el-Sagha facies 1, the arenaceous bioclastic carbonate facies, and facies 2, the gypsiferous and carbonaceous laminated claystone and siltstone facies (both shallow lagoonal facies). The Dir Abu Lifa Member is dominated by a different pair of Vondra's Qasr el-Sagha facies: the interbedded claystone, siltstone, and quartz sandstone facies (facies 3), and the quartz sandstone facies (facies 4). These are interpreted as prograding delta front and delta distributary deposits, with terrigenous sediment predominating. Grouping into members indicates that different facies associations characterize different parts of the Qasr el-Sagha Formation stratigraphic section.

Hermatypic scleractinian corals (including "*Astrohelia*" of Mayer-Eymar) are reported from the giant cross-bedded sandstone sequence of Bown and Kraus (1988, p. 14; see Figs. 14, 30; Blanckenhorn, 1903; Beadnell, 1905), making it very unlikely that this is a river deposit.

Umm Rigl Member

The Umm Rigl Member of the Qasr el-Sagha Formation (Chapter IV), like the Temple Member, is dominated by two of Vondra's (1974) Qasr el-Sagha facies: the arenaceous bioclastic carbonate facies (facies 1), and the gypsiferous and carbonaceous laminated claystone and siltstone facies (facies 2). Here again, the two facies alternate in vertical succession. Hard beds developed in areas of sea floor where currents of clear water provided oxygen, enhancing biological productivity, while silt and clay were deposited in other areas by currents clouded with terrigenous sediment.

The Umm Rigl and Temple members are separated stratigraphically, but they are similar lithologically. One faunal difference may be significant. *Kerunia cornuta* Mayer-Eymar 1899 (1900) is a distinctive problematical fossil currently interpreted, questionably, as composed of calcareous mats of periderm of hydractinians colonizing the external surfaces of gastropod shells inhabited by hermit crabs and living symbiotically with the crabs (Hill and Wells, 1956). The type specimen of *K. cornuta* came from the Umm Rigl Member near Dimeh, and this fossil is much more common in the Umm Rigl Member of the Qasr el-Sagha Formation than it is in the Temple Member. A better understanding of the form and function of *Kerunia* (currently under study by A. Seilacher) may clarify paleoecological differences between the Umm Rigl and Temple members.

East of Dimeh, the Umm Rigl Member includes a succession of beds above the north shore of Birket Qarun weathering to reveal circular or oval masses that Beadnell (1905, p. 71) confused with spherical Birket Qarun sandstone bodies found elsewhere. These oval masses (Fig. 54) appear to be calcareous bioherms of some kind. They are reminiscent of stromatolitic bioherms described by Whybrow et al. (1987) from Saudi Arabia, but their origin is unknown (they may, for example, have been constructed by calcareous marine sponges rather than stromatolites). Interpretation is complicated because the undersides of these are often bored (Beadnell, 1905, fig. 7) by Pliocene mollusks (Schweinfurth's "*Pholaden*"), and some fish bones and other vertebrate fossils found here may have been reworked by a Pliocene sea from overlying members of the Qasr el-Sagha Formation.

Harab Member

The Harab Member (Chapter IV) is so-named because it is composed of shales that weather as featureless plains. This member is also featureless in terms of sedimentary structures and in terms of fossils, by comparison with other members of the Qasr el-Sagha Formation. It is a monotonous sequence of Vondra's gypsiferous and carbonaceous laminated claystone and siltstone facies (facies 2) without the siltstone. Sedimentary structures and fossils are not available to aid interpretation, which is tentatively attributed to deposition in deeper less-aerated water without the currents needed to provide oxygen or distribute silt and sand.

GEBEL QATRANI FORMATION

Paleoenvironments of the Gebel Qatrani Formation have recently been studied and reviewed by Bown et al. (1982) and Bown and Kraus (1988). Most of the Gebel

FIG. 54—Circular or oval masses weathering from the Umm Rigl Member of the Qasr el-Sagha Formation north of Birket Qarun and east of Dimeh in the northern Fayum. Beadnell (1905, p. 71-72) confused these with spherical sandstone concretions of the Birket Qarun Formation found elsewhere. These oval masses appear to be calcareous bioherms of some kind. They show borings described by Beadnell on the underside of lateral projections, and appear to have been bored by marine mollusks when they were exposed and inundated during a Pliocene high sea stand. Fish and other vertebrate bones and teeth found here may be of Pliocene age or may be reworked from younger members of the Qasr el-Sagha formation (or both). View is to southeast.

Qatrani Formation is continental and it was deposited on a tropical to subtropical lowland coastal plain. Mangrove is found in places, indicating that parts of the formation were deposited at sea level, and marine intercalations have long been known in the upper part of the formation (e.g., the "*Tongrien inférieur*" of Mayer-Eymar, 1895, 1896).

One marine mammal is known from the Gebel Qatrani Formation. This is a good skull and associated ribs of a sirenian from Quarry O in the upper part of the formation at the same level as Quarry I (level shown in Fig. 52). However, it is not from one of the marine intercalations, which probably indicates that Eocene sirenians were occasionally found in the lower reaches of rivers as they are today.

PROGRADATION OF ENVIRONMENTS

It is impossible to interpret the sequence of environments observed in the Eocene of Fayum without simultaneously considering the effect of progradation. Progradation is the normal condition on passively subsiding continental margins when the rate of supply of bioclastic and terrigenous sediment exceeds the rate of accommodation due to subsidence. This causes depositional environments to move seaward, and a generally northward progression of paleoenvironments across Egypt toward Tethys indicates that progradation was the normal condition here during much of the early Cenozoic. In terms of position of the sea-land interface at the shoreline, progradation is functionally equivalent to regression, and the early Cenozoic history of Tethys in Egypt is consequently largely a record of regression.

Progradation means that depositional environments generally move seaward through time. As observed in the Cenozoic of Egypt, earlier paleoenvironments are generally more marine and later paleoenvironments are generally more continental. Intermediate paleoenvironments should be found in intermediate positions geographically. The general succession is as follows, with the continental Gebel Qatrani Formation (Bowen and Vondra, 1974; Bown and Kraus, 1988) at the top:

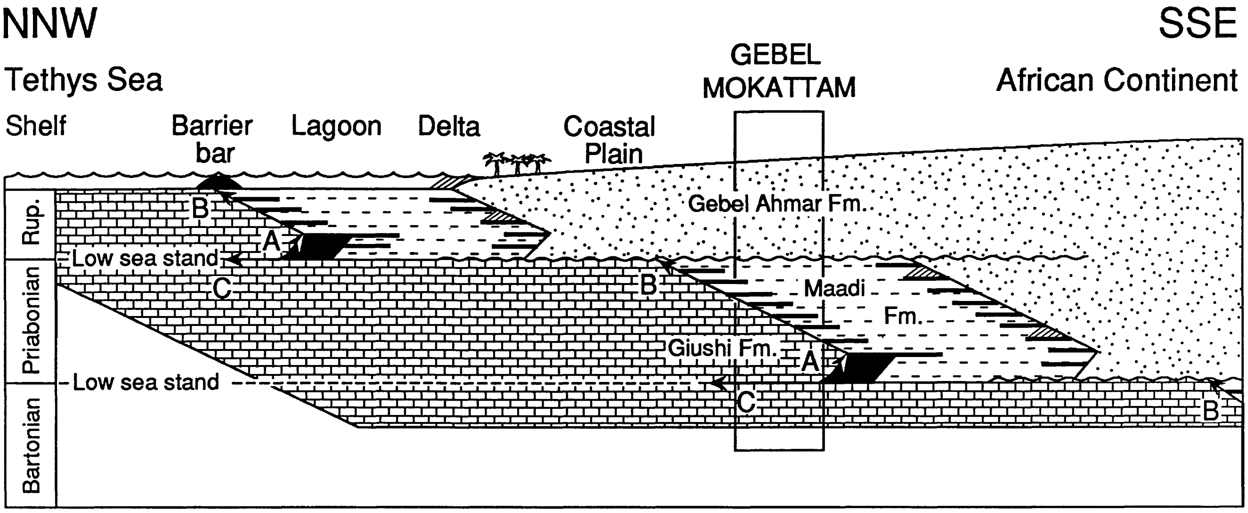


FIG. 55—Idealized sea level sequence stratigraphic model constructed to explain deposition of shallow marine formations observed in middle and late Eocene of northern Egypt (compare with Fig. 56). Succession of formations observed at Gebel Mokattam is shown in box. Model is NNW-SSE transect perpendicular to the southern Tethys - northern Africa coastline with open shallow shelf, barrier bar, lagoon, delta front, and coastal plain facies. Barrier bar and lagoonal sediments and non-lagoonal delta front sediments represent alternate environments and would not have been deposited simultaneously in the same area. Cycles of sea level change depositing successive sequence tracts are shown with uppercase letters: A, marine transgression due to rapid isostatic sea level rise that exceeds regression due to progradation; B, normal regression due to progradation on slowly subsiding passive continental margin; C, major regression due to isostatic sea level fall. Giushi Formation includes highstand and lowstand systems tracts that accumulated during Bartonian and probably early Priabonian time (middle-to-late Eocene) in open shallow shelf environments. Maadi Formation includes highstand systems tracts that accumulated during Priabonian time (late Eocene) in lagoonal environments (black lines represent hard beds deposited on margins of inner and outer lagoon). Note that sloping delta front deposits are not recorded at Gebel Mokattam. Barrier bars or beaches protecting Maadi lagoon were not preserved during regression due to bar erosion associated with progradation on slowly subsiding passive continental margin. Gebel Ahmar Formation includes continental systems tracts that accumulated during Rupelian time (early Oligocene) in riverine environments on prograding delta plains. Vertical exaggeration here is on the order of 100×.

7. Continental Gebel Qatrani Formation
6. Delta front and delta distributary deposits of the Dir Abu Lifa Member
5. Oxygenated shallow inner-lagoon shelf with hard beds of the Temple Member
4. Low energy deeper water of the Harab Member
3. Oxygenated shallow outer-lagoon shelf with hard beds of the Umm Rigl Member
2. Barrier bar deposits of the Birket Qarun Formation
1. Shallow open shelf environments of the Gehannam Formation

This sequence of ancient environments observed vertically in Fayum is the same as the sequence of environments observed in a transect from the Mediterranean Sea across Lake Burullus and onto the Nile Delta today. There is open ocean (equivalent to the Eocene Gehannam Formation) on the seaward side of the barrier bars and beaches (Birket Qarun Formation) enclosing Lake Burullus, and this lagoon has a shallow energized and oxygenated outer part (Umm Rigl Member), a deeper central part (Harab Member), and a shallow energized and oxygenated inner part (Temple Member). There is also an inner margin dominated by terrigenous sedimentation (Dir Abu Lifa Member) equivalent to occasional delta front deposition we might expect from lateral migration of the Rosetta branch of the Nile to debouch where Lake Burullus used to be. Much of the surface of the Nile Delta is aerially exposed and continental (Gebel Qatrani Formation).

By this interpretation three of the Qasr el-Sagha members represent different environments within a lagoon. The fourth member is deltaic, which is incompatible with a lagoonal environment because a rapid influx of clastics would soon fill any lagoon. Lagoonal and deltaic sedimentary environments alternate along the marine front of the Nile delta today (Fig. 1), and this was probably true on the Eocene coastline as well.

A dynamic model showing Egyptian Eocene paleoenvironments and their progradation, integrated with major cycles of sea level change, is illustrated in Figures 55 and 56. The model was developed to explain

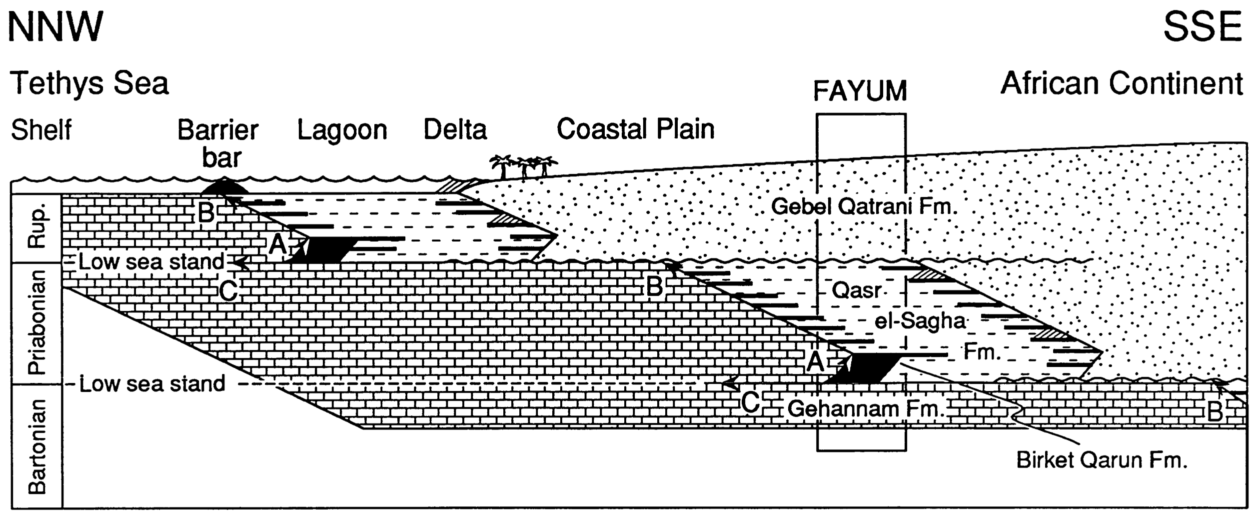


FIG. 56—Idealized sea level sequence stratigraphic model constructed to explain deposition of shallow marine formations observed in Eocene of northern Egypt (compare with Fig. 55). Succession of formations observed in Fayum is shown in box. Model is NNW-SSE transect perpendicular to the southern Tethys - northern Africa coastline with open shallow shelf, barrier bar, lagoon, delta front, and coastal plain facies. Barrier bar and lagoonal sediments and non-lagoonal delta front sediments represent alternate environments and would not have been deposited simultaneously in the same area. Cycles of sea level change depositing successive sequence tracts are shown with uppercase letters: A, marine transgression due to rapid isostatic sea level rise that exceeds regression due to progradation; B, normal regression due to progradation on slowly subsiding passive continental margin; C, major regression due to isostatic sea level fall. Gehannam Formation includes highstand and lowstand systems tracts that accumulated during Bartonian and Priabonian time (middle-to-late Eocene) in open shallow shelf environments. Birket Qarun Formation shown in black is a barrier bar transgressive systems tract that accumulated at beginning of Priabonian time (late Eocene) and was buried during isostatic sea level rise. Qasr el-Sagha Formation includes highstand systems tracts that accumulated during Priabonian time (late Eocene) in lagoonal environments (black lines represent hard beds deposited on margins of inner and outer lagoon). Sloping delta front deposits (shown with sloping lines and representing, e.g., the Dir Abu Lifa Member) build out from shore and may obliterate or completely fill lagoons (not shown here). Gebel Qatrani Formation includes continental systems tracts that accumulated during Rupelian time (early Oligocene) in riverine environments on prograding delta plains. Vertical exaggeration here is on the order of 100×.

how Fayum formations were related to each other as depositional facies in space and through time (Fig. 56). The model yields predictions about facies and unconformities to be expected at Gebel Mokattam (Fig. 55), which was a little farther seaward during the Eocene (this is inferred from the WSW-ENE trend of the ancient shoreline documented, for example, by the outcrop trend of barrier bars of the Birket Qarun Formation). Formations, facies, and unconformities at Gebel Mokattam have not yet been studied in detail to see whether they corroborate the new model, but I expect that this dynamic sequence stratigraphic model will explain the distribution of facies there better than previous static 'layer cake' models.

Figure 56 shows how sedimentary facies are related to each other offshore-onshore, how these are related vertically, and how low sea stands offshore propagate as erosional unconformities onshore. Marine shelf environments shallow landward, and one usually encounters either a barrier bar and lagoon or an active delta front in moving onshore. This can be seen today, for example, in traversing the Mediterranean and Lake Burullus to reach the continental top of the Nile Delta, or in moving from the Mediterranean across the active delta front of the Rosetta branch of the Nile. Shelf sediments are characteristically dominated by carbonates. Lagoons may include four distinct environments: a sheltering coarse clastic (sand) barrier bar or beach, an outer shallows (with both carbonates and fine clastics), a central deep (fine clastics), and an inner shallows (carbonates and fine clastics). Delta fronts include terrigenous coarse and fine clastics. In places in Fayum, shelf sediments of the Gehannam Formation grade laterally into barrier sediments of the Birket Qarun Formation, and other lateral transitions will probably be discovered as they are sought.

The Dir Abu Lifa Member of the Qasr el-Sagha Formation is deltaic, reflecting deposition in the most landward marine environments, with a strong influx of terrigenous clastics. This probably represents an alternate transect intersecting a Rosetta-like active delta with delta-front deposits. Extensive hard limestones like Blanckenhorn's beds II-6 and II-8 (e.g., Fig. 32) in the Dir Abu Lifa Member may be interdeltaic shelf carbonates deposited when delta clastics were diverted elsewhere. The Dir Abu Lifa Member is overlain by continental clastics of the Gebel Qatrani Formation, marking the end of a major phase of marine deposition in Egypt.

Finally, propagation of low sea stands offshore into unconformities onshore helps to explain why the Gehannam-to-Birket Qarun transition is so different from the Qasr el-Sagha to Gebel Qatrani transition even though both are thought to be associated with major eustatic low sea stands. The former transition includes evidence of shoreline facies (especially mangrove), and shoreline facies would be expected in the Qasr el-Sagha-to-Gebel Qatrani transition too if it was a continuous smooth transition from marine to continental sedimentation. Absence of mangrove at the top of the Qasr el-Sagha Formation and at the base of the Gebel Qatrani Formation is consistent with this contact being a major unconformity. Mangrove remains are present in places higher in the Gebel Qatrani Formation (Bown and Kraus, 1988, p. 31), and these probably grew during intervals of high sea stand flooding otherwise continental environments.

VII

MARINE MAMMALS AND LOCALITIES

In the nineteenth and early twentieth centuries, fossil vertebrates were collected opportunistically as they were found at Gebel Mokattam, usually by workers quarrying stone for building and other purposes. Schweinfurth (1883) mentioned that quarriers never failed to offer shark teeth (*lisân* or "tongue" stones) to tourists, and one can safely assume that mammals were known to have monetary value as well. Some were purchased by geologists, paleontologists, and museum representatives, which means these can have had little accompanying locality or stratigraphic information. The type specimens of *Eotherium aegyptiacum* Owen (1875), *"Manatus" coulombi* Filhol (1878), *Protocetus atavus* Fraas (1904a), *"Mesocetus" schweinfurthi* Fraas (1904a), *Protosiren fraasi* Abel (1907), *Eotherium (Eosiren) abeli* Sickenberg (1934), and *Eotherium majus* Zdansky (1938) may all have been acquired this way. In contrast, most marine mammal specimens from Fayum were discovered in place in the field and collected by professionals, so their localities and stratigraphic levels are better known.

Type specimens and published type localities of Egyptian Eocene Cetacea and Sirenia, listed in Tables 1 and 2, are discussed in the order in which they were described. Few are as well documented as one would like, but most are known sufficiently to place a type within a formation, constrain its age, and permit some interpretation of paleoenvironment.

Barnes and Mitchell (1978) published the most recent review of Egyptian Eocene Cetacea. Domning et al. (1982) reviewed type localities of Egyptian Eocene Sirenia. It was standard practice at the time to regard the Bartonian stage/age as late Eocene. In preparing this summary, I have studied original specimens of all of the existing Egyptian Eocene cetacean types in Cairo, London, Berlin, Munich, and Stuttgart, and I have seen sirenian types in Cairo, London, and Stuttgart.

CETACEA

The first specimens of Eocene cetaceans collected from Egypt were found by G. Schweinfurth on the island of Geziret el-Qarn in Birket Qarun. These were described by Dames (1883a,b), and the collection is now in the Museum für Naturkunde in Berlin. It includes at least three species, including *Prozeuglodon atrox* and *Basilosaurus isis*, which are best known from the Gehannam and Birket Qarun formations of Wadi Hitan. All of Schweinfurth's Geziret el-Qarn specimens were found in the second highest bed on the island (Fig. 27), which Beadnell (1905) regarded as part of the Birket Qarun Formation. As discussed in Chapters III and IV, this is here interpreted as the uppermost bed of the Gehannam Formation. In either case, the age of the collection is probably earliest Priabonian (the uppermost Gehannam Formation in this area is probably Priabonian in age—*fide* Abdou and Abdel-Kireem, 1975; Haggag, 1990).

The first cetacean species named from Egypt was *Zeuglodon osiris* described by Dames (1894), based on a specimen collected by Schweinfurth in 1886 at his *Zeuglodonberge* or *☿-Berge* locality *"12½ km im Westen vom alten Tempelbau"* [Qasr el-Sagha temple]. The species is here placed in a new genus *Saghacetus* (see Table 1, footnote 3). Schweinfurth (1886, p. 139) described the type locality as being in his AAAβ zone (Fig. 5). Blanckenhorn described it as being in his II-5a zone (Fig. 19). Several attempts in recent years to relocate the hill or hills called Zeuglodonberg(e) have all failed, not because there are no hills yielding *Saghacetus* 12½ km or so west of Qasr el-Sagha temple but rather because there are many. The type locality must be at or somewhere near Garet el-Esh. A very good partial skeleton of *Saghacetus* has been found there in Blanckenhorn's zone II-4 (see Fig. 32) rather than II-5a, meaning that the exact level yielding the type is uncertain. However, there is no question that the type came from the Temple Member of the Qasr el-Sagha Formation or that its age is late Priabonian.

Stromer (1903a,b) described the archaeocete specimens found during his 1902 expedition to Egypt with Blanckenhorn. These included a good skull of *Saghacetus osiris* (since destroyed) from a hard bed in Blanckenhorn's zone II-5a between Gebel Hameier (Fig. 15) and Korallenhügel (Fig. 16) north of Dimeh. In addition, Stromer (1903b) named a new species, *Zeuglodon zitteli*, based on fragmentary remains he collected at Zeuglodonberg (Figs. 18, 19; these were first identified as *Zeug-*

lodon osiris in Blanckenhorn, 1903, p. 391). The type specimen of *Zeuglodon zitteli* is a fragmentary rostrum and three articulated cervical vertebrae (illustrated by Stromer, 1903b, figs. 1 and 2). These are said to have come from the same stratigraphic interval as the type of *Saghacetus osiris*, possibly from the same locality, and they are indistinguishable from comparable remains of *S. osiris*.

Zeuglodon isis (now *Basilosaurus isis*, see Gingerich et al., 1990) was named by Beadnell in Andrews (1904, p. 214). Andrews described the best specimen, a dentary, giving its total length as 83 cm and stating that this "may be taken as the type," thus making the name available. Andrews (1904) gave the type locality as "Birket-el-Qerun beds" of Fayum. Beadnell (1905, p. 44) added that the type came from "cliffs near the west end of the lake." The type is figured in Andrews (1906, fig. 78). Beadnell's (1905) section of the Birket Qarun Formation at the west end of lake Birket Qarun is shown in Figure 25. The type specimen of *Basilosaurus isis* may have come from the top of the Gehannam Formation, from the Birket Qarun Formation, or even conceivably (but improbably) from what is here called the lower part of the Qasr el-Sagha Formation. Whether the specimen came from the Gehannam Formation or the Birket Qarun Formation at the west end of Birket Qarun matters little as the age of the type is likely to be earliest Priabonian in either case (the uppermost Gehannam Formation in this area is probably Priabonian in age—*fide* Abdou and Abdel-Kireem, 1975; Haggag, 1990).

Fraas (1904a, pp. 200-201, interpreted with the help of E. Stromer) gave stratigraphic levels for the type specimens of *Protocetus atavus* and *Mesocetus schweinfurthi* (the latter was moved to *Eocetus* by Fraas, 1904b). Both came from Gebel Mokattam. According to Fraas, the type of *P. atavus* came from Schweinfurth's (1883) bed A1e, said to be equivalent to Mayer-Eymar's horizon Ia and Blanckenhorn's Gizehensis bed I-2, and it was found 3 m above the lowest bed with bony fish and sharks. There are some inconsistencies in Gebel Mokattam sections measured by different authors, and Blanckenhorn's reference section for the lower Mokattam stage was at Wadi el-Sheikh rather than Gebel Mokattam. Consequently, Schweinfurth's section is probably the best to use for reference in interpreting Fraas' stratigraphic information. The precise locality where the type was found is unknown, but it may have been Schweinfurth's locality XII near the old grave-mosque known as Gama-Tingiye. The likely position of the type of *Protocetus atavus* in the Lower Building Stone Member of the Mokattam Formation is shown with a diamond in Figure 5. This interval is probably middle Lutetian in age (Fig. 52). *Protocetus* is distinctly primitive among Egyptian archaeocetes in retaining a protocone on upper molars and in retaining a sacral vertebra with articular surfaces for the pelvis. This stage of evolution is consistent with a middle Lutetian age.

The type skull of *Eocetus schweinfurthi* came from about 8 meters below the upper boundary of the lower Mokattam in a hard gray-white limestone above a *Schizaster* bed. This is full of mollusks and small nummulites, like the upper part of Schweinfurth's zone A1a and Blanckenhorn's zone I-5 (Fraas, 1904a, p. 201). The likely position of the type of *Eocetus schweinfurthi* in the Giushi Formation is shown with a diamond in Figure 5. This interval is probably Bartonian in age (Fig. 52). The most distinctive specimen of *Eocetus* described by Fraas (1904a) is an upper molar retaining three roots and a well developed (if worn) protocone cusp. The molar presumably came from the same stratigraphic interval as the type skull, and it indicates that *Eocetus* was significantly more primitive and thus probably older (early Bartonian?) than any specimens known to date from Wadi Hitan.

Prozeuglodon atrox was named by Andrews (1906), based on a type skull and lower jaw collected by Beadnell from "Birket-el-Qurun beds" in "a valley about 12 kilometers W.S.W. of the hill called Gar-el-Gehannem" (Andrews, 1906, p. 255). This valley is Zeuglodon Valley, or what is here called Wadi Hitan [Valley of Whales]. The type specimen of *P. atrox* retains deciduous premolars, showing that it was a juvenile, and subadult specimens indistinguishable from the type of *P. atrox* are common in both the Gehannam and Birket Qarun formations in Wadi Hitan. Beadnell (1905) did not always distinguish the Gehannam and Birket Qarun formations lithologically and they overlap some in time. Thus the age of the type specimen of *P. atrox* may be either latest Bartonian or earliest Priabonian.

Dart (1923) named three archaeocete species from Fayum based on brain size and form as evidenced by endocasts. These are problematical because Dart had no first-hand knowledge of Fayum stratigraphy nor any knowledge of fossil preservation (and distortion) there. Dart's understanding of type localities and age of the fossils he studied came either second-hand from Andrews, who published an accompanying note on the skulls from which Dart's endocasts were taken (written some seventeen years after completing his study of Fayum mammals; see Andrews, 1923), or third-hand from Beadnell via Elliot Smith over a period of almost twenty years. In recent years we have collected some forty archaeocete endocasts from the Gehannam, Birket Qarun, and Qasr el-Sagha formations, in various states of preservation, and these provide some basis for rational interpretation of the systematic position of Dart's species.

Zeuglodon sensitivus is the first species named by Dart (1923, p. 618), and the type is an endocast said to have come from "the Egyptian Fayum at the locality known as the Gar-el-Gehannem" (*fide* Beadnell as-told-to Elliot

Table 1. Type specimens and type localities of Eocene Cetacea described from Egypt.

Genus and species	Author	Type	Type locality	Inf. int.[1]
1. *Zeuglodon osiris* [here placed in new genus *Saghacetus*[3]]	Dames 1894	MNB[2] 28388 [Berlin 16]	☿-Berge 12½ km im Westen vom alten Tempelbau, AAAβ [Schweinfurth (1886, p. 139), upper Qasr el-Sagha Fm.]	F
2. *Zeuglodon zitteli* [synonym of *Saghacetus osiris*]	Stromer 1903	UISPM 'Mn.3'	Gleichen Horizont und demselben Fundort [as Berlin 16] [upper Qasr el-Sagha Fm.]	F
3. *Zeuglodon isis* [now placed in *Basilosaurus* Harlan]	Beadnell[4]	CGM 10208	Birket Qarun cliffs near west end of lake [loc. from Beadnell (1905, p. 44), Birket Qarun Fm.]	D
4. *Protocetus atavus*	Fraas 1904	SMNS 11085	Mokattam, Schweinfurth A1e ≈ Blanckenhorn I-2 [top of Lower Building Stone Mbr. of Mokattam Fm.]	A
5. *Mesocetus schweinfurthi* [now placed in *Eocetus* Fraas]	Fraas 1904	SMNS 10986	Mokattam, Schweinfurth A1a = Blanckenhorn I-5 [Giushi Fm.]	C
6. *Prozeuglodon atrox*	Andrews 1906	CGM 9319	Birket Qarun beds 12 km WSW of Garet Gehannam [Birket Qarun Fm.]	D
7. *Zeuglodon sensitivus* [synonym of *Saghacetus osiris*]	Dart 1923	NHML 12123	Fayum, "Garet Gehannam" [see text, prob. from upper Qasr el-Sagha Fm. near Qasr el-Sagha]	F
8. *Zeuglodon intermedius* [synonym of *Prozeuglodon atrox*]	Dart 1923	NHML 10173	Fayum, possibly Birket Qarun beds at west end of lake [*fide* Andrews (1923, p. 648); Birket Qarun Fm.]	D
9. *Zeuglodon elliotsmithii* [synonym of *Saghacetus osiris*]	Dart 1923	NHML 12066 [cast]	Qasr el-Sagha beds north of Birket Qarun [see Elliot Smith, 1903; Andrews, 1906, p. 236]	F
10. *Prozeuglodon stromeri* [now placed in *Dorudon*]	Kellogg 1928	UISPM 'Mn.9' [destroyed]	Feinkörnigem graugrünlichem Sandstein der Saghastufe, Fayum [Stromer (1908, p. 110); u. Qasr el-Sagha Fm.]	F

[1]Informal faunal interval designation, explained in text.
[2]Abbreviations are as follows: CGM - Cairo Geological Museum, Cairo; MNB - Museum für Naturkunde der Humboldt-Universität, Berlin; NHML - Natural History Museum, London; SMNS - Staatliches Museum für Naturkunde, Stuttgart; UISPM - Universitäts-Institut und Staatssammlung für Paläontologie und Historische Geologie, Munich.
[3]**Saghacetus** new genus, type species *Zeuglodon osiris* Dames 1894; differs from *Dorudon* and all other archaeocetes in having thoracic vertebrae normally proportioned but posterior lumbars and anterior caudals distinctly long in comparison to centrum height and breadth. *Saghacetus osiris* is easily recognized as the smallest archaeocete known from Fayum, and it is only known from the upper Qasr el-Sagha Formation. Two specimens with associated skulls, dentaries, and good axial skeletons have been prepared (University of Michigan 83905 and 97550). These and other specimens will be described in a later publication.
[4]In Andrews (1904): this was published in the May issue of *Geological Magazine* for 1904 and evidently predates publication of *Protocetus atavus* and *Mesocetus* [*Eocetus*] *schweinfurthi* in Fraas (1904a)

Smith as-told-to Dart; see Dart, 1923, p. 616). This type is one of the best natural endocasts ever collected in Fayum because it retains excellent surface detail and appears to be free from compression or other distortion. The quality of the endocast by itself suggests preservation on a lime-rich hard bed in the Temple Member of the Qasr el-Sagha Formation. Dart gave the volume of this endocast as 490 cc (Dart, 1923, p. 634), which is virtually identical to the value of 480 cc he gave for "*Zeuglodon*" *osiris*. None of the many endocasts preserved in Wadi Hitan is this small. Beadnell (1905, p. 39) mentioned that poorly preserved skeletons of *Zeuglodon isis* are fairly common in the Gehannam Formation near Garet Gehannam; however, that species has much larger endocasts (on the order of 2100 cc) and specimens at Garet Gehannam are so poorly preserved that it is unlikely any was ever considered worth collecting. Dart's type of *Zeuglodon sensitivus* is almost certainly an endocast of *Saghacetus osiris*, differing from others of the species in being full grown and exceptionally well preserved, and it probably came from the Temple Member of the Qasr el-Sagha Formation somewhere along the Qasr el-Sagha escarpment.

Zeuglodon intermedius is the second species named by Dart (1923, p. 629). This was based on an artificial endocast made from a skull described briefly by Andrews (1923). The type skull appears to be adult because the occiput is high and narrow, the rostrum is long and narrow, the frontal shield is broad, cranial sutures are closed, and premolar alveoli are adult in conformation. Dart (1923) gave the endocranial volume as 785 cc, which is in the range of *Prozeuglodon atrox*. Andrews (1923) reported the total length of the skull as 550 mm, but Kellogg (1936, p. 246) independently measured this as 795 mm, which again is within the range of *P. atrox*. Regarding the type locality, Andrews (1923, p. 648) wrote that the type skull:

> seems from the nature of the matrix to have been obtained from the Birket-el-Qurun beds at the western end of the lake from an horizon intermediate between those from which the other species were found. This, however, in the absence of definite information from the collector is not certain.

Dart's endocranial volume, Kellogg's skull length, and Andrews' inferred stratigraphic interval and geographic locality are consistent in indicating that *Zeuglodon intermedius* is a junior synonym of *Prozeuglodon atrox*.

Zeuglodon elliotsmithii is the third species named by Dart (1923, p. 625), and the type is a natural endocast described by Elliot Smith (1903). Dart studied a plaster copy of the original endocast (now lost?), and the copy Dart studied is in the Natural History Museum, London. Elliot Smith (1903) stated that this specimen was found by Beadnell in 1902 at "the same locality" as the partial skull of *Zeuglodon osiris* described and illustrated by Andrews (1901, 1906), that is, in the Qasr el-Sagha beds north of Birket Qarun (Andrews, 1906, p. 236). Dart (1923) gave the endocranial volume of this specimen as 310 cc, which is smaller than the endocranial volume of adult specimens of the smallest species, *S. osiris*, known from Fayum, and the type of *Z. elliotsmithii* is almost certainly an artificially compressed endocast, a weathered endocast, or a subadult endocast of *Saghacetus osiris*.

The last archaeocete species named from Fayum is *Prozeuglodon stromeri* Kellogg 1928, later moved to *Dorudon* (Kellogg, 1936, p. 203). The type specimen is Munich 9 [Mn. 9, destroyed], which Stromer (1908, p. 110) had earlier identified as *Zeuglodon osiris*. According to Stromer, the specimen consisted of:

> *weissliche Reste eines nicht ausgewachsenen Individuums aus feinkörnigem, graugrünlichem, weichem Sandstein der Saghastufe*
>
> [whiteish remains of an immature individual from fine-grained, gray-green, soft sandstone of the Qasr el-Sagha stage]

Many of the characteristics Kellogg (1936) listed as differences from *Saghacetus osiris* are characteristics that distinguish subadult from adult individuals, but comparable molar measurements (Kellogg, 1936, p. 206) show *Dorudon stromeri* to have been about 50% larger than *Saghacetus osiris* in most linear dimensions (and new specimens show the two species to have had differently proportioned lumbar and caudal vertebrae). The type specimen of *Dorudon stromeri* came from the Temple Member of the Qasr el-Sagha Formation and it is thus late Priabonian in age.

To summarize, one archaeocete genus and species, *Protocetus atavus*, is known from the middle Lutetian of Egypt. Another genus and species, *Eocetus schweinfurthi*, is known from the Bartonian. Two genera and species, *Basilosaurus isis* and *Prozeuglodon atrox*, have been named from the Bartonian-Priabonian transition, and two species, *Saghacetus osiris* and *Dorudon stromeri*, are known from the late Priabonian.

SIRENIA

Richard Owen (1875) named the first Eocene sirenian described from Egypt, *Eotherium aegyptiacum*, based on a specimen presented by a Dr. Grant of Cairo. Palmer (1899) noted that *Eotherium* was preoccupied and placed this in the new genus *Eotheroides*. The type included fragments of the basicranium and a well preserved endocranial cast. This was found in:

> the white, compact, fine-grained, calcareous stone of the Nummulitic Eocene Tertiary period, now quarried extensively in the Mokattam cliffs, south of Cairo, for the buildings in progress in the modern part of that city.

The type of *E. aegyptiacum* is almost certainly from the Lower Building Stone Member of the Mokattam Formation, and it may have been found at or near Schweinfurth's locality XII (Gama-Tingiye). Fraas (1904a, p. 201) mentioned *Eotherium aegyptiacum* Owen as coming from 4 m above the level of *Protocetus atavus*, but it is not clear whether he was referring to Owen's original type or to referred specimens collected later. The probable position of the type specimen of *Eotheroides aegyptiacum* in the Lower Building Stone Member of the Mokattam Formation is shown with a diamond in

Table 2. Type specimens and type localities of Eocene Sirenia described from Egypt.

Genus and species	Author	Type	Type locality	Inf. int.[1]
1. *Eotherium aegyptiacum* [now placed in *Eotheroides* Palmer]	Owen 1875	NHML[2] 46722	White nummulitic limestone of Mokattam cliffs [L. Building Stone Mbr. of Mokattam Fm.]	**A**
2. *Manatus coulombi* [indet. or synonym of *Protosiren fraasi*?]	Filhol 1878	MNHN	Carrières de Mokattam prés du Caire [Mokattam Fm.]	**A or B**
3. *Eosiren libyca*	Andrews 1902	CGM 10054	Qasr el-Sagha beds, Fayum [upper Qasr el-Sagha Fm.]	**F**
4. *Protosiren fraasi*	Abel 1907	CGM 10171	Mokattam Hills, probably same as type of *E. aegyptiacum* [*fide* Andrews (1906, p. 204), LBS, Mokattam Fm.]	**A**
5. *Archaeosiren stromeri* [synonym of *Eosiren libyca*?]	Abel 1913	SMNS	Westlich von Dimeh, Fayum, Horizont 5a der obern Mokattamstufe [upper Qasr el-Sagha Fm.]	**F**
6. *Eotherium (Eosiren) abeli* [synonym of *Protosiren fraasi*?]	Sickenberg 1934	UISPM [destroyed]	Unter Mokattam "hinter den Khalifengräbern" [Mokattam Fm.]	**A or B**
7. *Eotherium majus* [synonym of *Eotheroides aegyptiacum*?]	Zdansky 1938	CGM?	Niveau "Baustein" des Gebel Mokattam Ost von Kait Bey [Mokattam Fm.]	**A or B**

[1]Informal faunal interval designation, explained in text.
[2]Abbreviations are as follows: CGM - Cairo Geological Museum, Cairo; MNHN - Muséum National d'Histoire Naturelle, Paris; NHML - Natural History Museum, London; SMNS - Staatliches Museum für Naturkunde, Stuttgart; UISPM - Universitäts-Institut und Staatssammlung für Paläontologie und Historische Geologie, Munich.

Figure 5. This, like the type of *Protocetus atavus*, is probably middle Lutetian in age (Fig. 52).

Manatus coulombi was named by Filhol (1878) based on three teeth from the Mokattam quarries near Cairo. According to Filhol (1878, p. 124):

Les dents de Manatus *qui y ont été trouvées ont été rencontrées à cinq mètres de profondeur. La portion supérieure du sol était formé par l'agglomération de nummulites avec oursins et coquilles marines. C'est sous cette couche qu'ont été découverts divers débris de mammifères.*

[The teeth of *Manatus* found there have been found at a depth of five meters. The upper part of the soil was formed by an agglomeration of nummulites with marine echinoids and mollusk shells. Beneath this bed have been found various remains of mammals.]

Filhol mentioned a number of invertebrates, including "*Conoclypeus*" and *Cerithium giganteum*, but it is not clear that these came from the same level as the sirenian. *Cerithium* is a form-genus applied to high-spired, turreted, nonumbilicate, variously sculptured gastropods. Oppenheim (1903-1906) considered Mokattam *Cerithium giganteum* to belong in *Cerithium* (*Campanile*) *lachensis* Bayan. Whatever name is used, this species is distinctive in being very large (possibly 50 cm or more in height when complete). Fraas (1867, p. 144) considered *Cerithium giganteum* to be the most conspicuous mollusk in the building stone of Cairo, and recognized a distinct zone for it (Chapter II). The type of *Manatus coulombi* undoubtedly came from the Mokattam Formation, but it may have come from either the Lower or Upper Building Stone. The teeth are relatively small (the largest lower molar measures 15 × 11 mm), but otherwise little can be said about them.

The type specimen of *Eosiren libyca* named by Andrews (1902) is a nearly complete skull collected from Qasr el-Sagha beds north of Birket Qarun (Andrews, 1906). This is almost certainly from the Temple Member of the Qasr el-Sagha Formation and it is late Priabonian in age.

The name *Protosiren fraasi* was first published as a *nomen nudum* by Abel (1904), which explains how Fraas

(1904) was able to indicate that this species came from the same stratigraphic level as the type of *Protocetus atavus*, but Abel provided no diagnosis or illustration, nor did he designate a type specimen. Abel's (1907) study is taken as the first valid publication of *Protosiren fraasi* (following Sickenberg, 1934, p. 43; and Domning et al., 1982, p. 36). In the latter study, Abel made the Cairo Geological Museum skull illustrated by Andrews (1906, fig. 66) the type. According to Andrews (1906, p. 204), this came from "limestones of the Mokattam Hills" and "probably the same [horizon] as ... the type of *Eotherium aegyptiacum*." The mandible described with this skull (Andrews, fig. 67) has since been compared with *Eotheroides aegyptiacum* (Domning et al., 1982), reinforcing the idea that *Eotheroides aegyptiacum* and *Protosiren fraasi* occur together in the upper part of the Lower Building Stone Member of the Mokattam Formation. Thus the age of the type specimen of *P. fraasi* is probably middle Lutetian.

Priem (1907) described a good mandible of *Protosiren fraasi* from Gebel Mokattam sent to him by P. Teilhard, then professor at the *Collège de la Ste-Famille* in Cairo. Priem indicated (p. 417) that this, like most of the collection made by Teilhard, came from the "*couches supérieures du Mokattam*," which evidently means that the specimen did not come from the Lower Building Stone of the Mokattam Formation, as the type did, but rather probably from the Upper Building Stone (or conceivably from what are today called Giushi and Maadi formations). The specimen has been important in comparisons made by Sickenberg (1934) and Domning et al. (1982), and it is unfortunate that its provenance is so poorly known.

Domning et al. (1982, p. 55 and fig. 34) described a mandible of *Protosiren* sp. said to come from the late Eocene Qasr el-Sagha Formation of Fayum. This specimen is actually from the Gehannam Formation or the Birket Qarun Formation of Wadi Hitan (Zeuglodon Valley), and it is latest Bartonian (middle Eocene) or earliest Priabonian (late Eocene) in age. *Protosiren* is not known from the Qasr el-Sagha Formation.

Abel (1913, p. 307) named a new sirenian genus and species *Archaeosiren stromeri*, based on two Stuttgart specimens, one a skull (lacking the lower jaw) with most of the axial skeleton, and the other an isolated thoracic vertebra. Abel ranked the specimens by completeness, but here again he did not provide a diagnosis or illustration, nor did he explicitly state that the more complete specimen is the type. Sickenberg (1934, p. 130) regarded *Archaeosiren stromeri* as a *nomen nudum*, but paradoxically used the species name and credited it to Abel (Sickenberg synonymized *Archaeosiren* with *Eotherium*). Further, Sickenberg considered Abel to have provided enough information to identify a specimen to which the name belonged. Whether *Archaeosiren stromeri* dates from Abel (1913) or Sickenberg (1934) need not concern us here. Abel (1913) states that the type came from "*Horizont 5a der oberen Mokattamstufe*" west of Dimeh in Fayum, that is, Blanckenhorn's zone II-5a (see Figs. 15-18, 20, 32). The type specimen of *Archaeosiren stromeri* is late Priabonian in age, and this species is probably a synonym of *Eosiren libyca*.

Sickenberg (1934, p. 34) named a new species *Eotherium (Eosiren) abeli* based on an isolated upper molar (right M^2) from the lower Mokattam "*hinter den Khalifengräbern*" [behind the graves of the caliphs]. The graves of the caliphs are in the region in front of Gebel Mokattam known as El-Khalifa or Qaitbai [Kait Bey], north and east of the Cairo Citadel (Schweinfurth, 1883; Geological Survey of Egypt, 1983). This locality information is ambiguous, but it probably means that the specimen came from the Mokattam Formation, making it Lutetian in age (Fig. 52). An isolated tooth is weakly diagnostic at best, but the small size of the type of *E. abeli* suggests that it may possibly be an upper molar of *Protosiren fraasi*.

The last species of Eocene sirenian named from Egypt, *Eotherium majus* described by Zdansky (1938), is also based on an isolated upper molar. This was found by J. Cuvillier "*im Niveau des 'Bausteines' des Gebel Mokattam O. von Kait Bey*" [in the level of the 'Building Stone' of Gebel Mokattam east of Kait Bey]. The repository of the type is unknown, but Cuvillier and Zdansky were both lecturers at the Geological Institute, Cairo University, and possibly the type is there. The locality information is ambiguous, but it probably means that the specimen came from the Mokattam Formation, making it Lutetian in age (Fig. 52). The large size of the type of *E. majus* suggests that it may possibly be an upper molar of *Eotheroides aegyptiacum*.

To summarize, there are clearly two sirenian genera and species, *Eotheroides aegyptiacum* and *Protosiren fraasi*, known from the middle to late Lutetian at Gebel Mokattam. One of these genera, *Protosiren* sp., has been reported from the late Bartonian or early Priabonian at Wadi Hitan in Fayum (and new collections there include *Eotheroides*). An additional genus and species, *Eosiren libyca*, is known from the late Priabonian in Fayum.

AGES AND PALEOENVIRONMENTS

Marine mammals are known from seven time intervals in the Paleogene of Egypt. For ease of reference, these are designated informally **A** through **G**. Ages of **A-C** are based to some degree on the stage of evolution of cetaceans and sirenians coming from these intervals, but **D-G** are based on independent evidence discussed in Chapter V. Six of these intervals are Eocene and one is

Oligocene. The oldest interval (**A**, see Tables 1 and 2) is probably middle Lutetian in age and it has yielded the type specimens of *Protocetus atavus*, *Eotheroides aegyptiacum*, and *Protosiren fraasi*. All are from Gebel Mokattam, and all inhabited open marine shallow shelf environments.

The next two intervals (**B** and **C**) are the least well known in terms of age and fauna. Interval **B** is probably late Lutetian and it includes sirenians questionably synonymized with *Eotheroides aegyptiacum* and *Protocetus fraasi*. Interval **C** is probably early Bartonian and it includes the type and referred specimens of *Eocetus schweinfurthi*. All specimens from intervals **B** and **C** came from Gebel Mokattam. All inhabited marine shallow shelf environments, possibly with more restricted circulation and greater chemical precipitation of evaporites than seen in **A**.

The next interval (**D**) is known from the Birket Qarun escarpment north of the west end of lake Birket Qarun, and it is becoming very well known as a result of ongoing work in Wadi Hitan. This is latest Bartonian and earliest Priabonian in age, straddling the Bartonian-Priabonian low sea stand. It includes the type and many referred specimens of *Basilosaurus isis* and *Prozeuglodon atrox*, and it includes specimens referred to *Eotheroides* sp. and *Protosiren* sp. The paleoenvironment is a shallow marine shelf with evidence of restricted circulation and chemical precipitation of evaporites in the form of celestite (strontium sulfate). The cetaceans are more advanced dentally and probably postcranially than those known before, while the sirenians appear very similar to those from **A** and **B** at Gebel Mokattam.

The lower part of the Qasr el-Sagha Formation (Umm Rigl Member, interval **E**) yields rare cetaceans and fragmentary sirenians of early Priabonian age, but none has been described to date.

The uppermost Eocene interval (**F**) is late Priabonian in age, and this is the interval yielding described mammals that is most distinctive environmentally. Much of the Qasr el-Sagha Formation is dominated by sediments deposited in shallow lagoonal environments bounded offshore by barrier bars. We can further infer from the model in Figures 55 and 56 that the part of the Qasr el-Sagha Formation that interval **F** represents, the Temple Member, was deposited along the inner shore of a lagoon or lagoons. Here both the cetaceans and sirenians appear to be different than those found elsewhere. *Saghacetus osiris*, *Dorudon stromeri*, and *Eosiren libyca* are presently known only from Temple Member lagoonal sediments.

The only Oligocene locality yielding a marine mammal (in what might be called interval **G**) is Quarry O in the upper part of the Gebel Qatrani Formation. This has yielded a skull and partial skeleton of a sirenian that has not yet been described or identified to genus. This is a marine mammal but it was found in continental riverine deposits, indicating that Egyptian sirenians probably inhabited rivers to some degree in the Oligocene.

It is impossible to make any real comparative interpretation of changing environments of cetaceans and sirenians because mammal-bearing intervals at Gebel Mokattam are older than those in Fayum, and they sample environments in deeper water farther offshore. Thus they do not permit comparison of either the same environment at different times or different environments at the same time.

All of the Eocene sirenians considered here are found in marine sediments where *Ophiomorpha* and *Callianassa* are common. Callianassids are frequently associated with seagrass habitats (McCoy and Heck, 1976), and this provides additional, if indirect, evidence that the Eocene sirenians of Egypt probably fed on seagrasses too (Domning, 1981; Domning et al., 1982). Seagrass may have been part of the hard bed succession discussed in Chapter VI.

TAXON LONGEVITY

It is possible to make a limited comparison of Egyptian Eocene cetaceans and sirenians in terms of taxon longevity. No cetacean genus or species appears in more than one of the informal time intervals employed here, whereas the same sirenian genera and possibly species range through intervals **A-D**. Based on this evidence, cetaceans appear to have been evolving more rapidly than sirenians in the latter part of the Eocene.

VIII

CONCLUSIONS AND PROSPECTUS

Eocene and Oligocene sedimentary rocks and depositional environments of northern Egypt are best interpreted in a dynamic stratigraphic context. The dynamic model proposed here has two components: (1) episodic change in eustatic sea level, superimposed on (2) normal progradation of depositional facies on a passive continental margin. The sea of interest is Tethys, the continental margin is the northern margin of Africa, and the shoreline between them trended, generally, WSW-ENE across what is now northern Egypt. This trend, in part coincidentally, is also the trend of the best studied outcrops of Eocene and Oligocene sediments in Fayum and in the desert surrounding Gebel Mokattam east of Cairo.

The most important changes in sedimentary facies on passively subsiding continental margins are seen in going offshore-onshore (or vice versa) rather than along the shore line, and much of the difficulty in understanding Fayum and Gebel Mokattam stratigraphy has come because many of the best outcrops are not perpendicular to the ancient shoreline but rather lie parallel to it. Further, these outcrops are generally eroded from the "back" (i.e., from the continental side), meaning that the present outcrop distribution of sedimentary facies is reversed from the original distribution of facies (offshore-onshore transects appear reversed), making the pattern of facies relationships more difficult to recognize.

Figures 55 and 56 in Chapter VI show idealized reconstructions of sedimentary facies in NNW-SSE transects perpendicular to shoreline. These are dynamic in combining sea level change with progradation. They are idealized in the sense that consideration of sea level change has been limited to episodes of major change, progradation has been assumed to proceed at a constant rate, and local structural influences (as at Abu Roash) have been ignored.

Figure 56 was constructed to show the vertical distribution of sedimentary facies observed in Fayum where facies and formations are best exposed, and to show how the vertical distribution of facies relates to their offshore-onshore distribution. The extent to which the same model explains vertical and offshore-onshore distributions of facies at Gebel Mokattam (Figure 55) is largely unknown, and further study east of Cairo will provide an important test of the general model, hopefully leading to refinement.

Marine mammals, cetaceans and sirenians, are relatively common as fossils in nearshore deposits at Gebel Mokattam and in Fayum. These are often well preserved and very informative about evolutionary stages represented. It is impossible at present to make any real comparative interpretation of changing environments of cetaceans and sirenians because mammal-bearing intervals at Gebel Mokattam are older than those in Fayum, and they sample environments in deeper water farther offshore. They do not, at present, permit comparison of evolution in different environments through time. However, it is also true that much of the Eocene in Egypt remains to be prospected for marine mammals. Blanckenhorn (1900) reported finding *Zeuglodon* teeth at Wadi el-Sheikh in the Eastern Desert (Fig. 8) and marine mammals have been reported elsewhere in Egypt, but such leads have seldom been pursued. Finding new cetaceans and sirenians in new environments and new time intervals is largely a matter of effort—fossils are undoubtedly there to be collected.

Archaeocetes were widely distributed and evolved rapidly in the Eocene. Consequently, cetacean fossils have considerable potential for broad-scale stratigraphic correlation within Egypt and between Egypt and other parts of the world. Eocene cetaceans and sirenians are also interesting because the two groups document a major evolutionary transition in the history of mammals, the transition from life on land to life in the sea, which took place in parallel in the two groups.

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Gebel el Ahmar
der rothe Berg
Höchste Spitze 380
Weg zum versteinerten Wald und zum Moses-Brunnen
330
Loc. XIII.
Haus Ruine
280
Loc. XVI.
Austern 180 Breccie
Loc. XV.
Loc. XIII.
alter Bahndamm
Loc. VI.
Kalköfen
grauer recenter kalkiger Sandstein
220
Loc. XIV.
Ringbahn von der Abbassieh nach Heluan
wahrer Nord.
Steinbruchs-Depot-Häuser
Steinkarrenwege
Loc. V.
Sandgrube
Hütten
Reservoir
Hütten
Mausoleum Kansuve el Ghuri
Sogenannte Chalifen Gräber
Pulverkammer
Pulverfabri
Wasserthürme der Compagnie des eaux
Spitze 61,168 Meter
Basis 43,786
Meereshöhe
Gama Schech Galal
Hohe Schutt
Windmüh
Bab el Nasr
Geologisch-topographische Karte
des Westabhangs des Mokattam bei Cairo
nach eigenen Vermessungen
entworfen von
G. SCHWEINFURTH
1883.
Maafsstab = 1: 25,000.
0 100 200 300 400 500 600 700 800 900 1000 Meter.