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Carbonate Platform to Basin Transition along an Upper Cretaceous to Lower Tertiary Syrian Arc Uplift, Galala Plateaus, Eastern Desert of Egypt

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ABSTRACT

Biostratigraphic and facies analyses were made on Upper Campanian to Lower Eocene strata along a 58-kilometer-long dip transect across the Northern and Southern Galala plateaus, west of the Gulf of Suez. The analyses enabled us to reconstruct the evolution of a platform–slope–basin transition that is roughly parallel with the trend of the plateaus. We interpret individual sedimentary cycles as processes of a southward-prograding carbonate platform that developed along a branch of the Syrian Arc Fold Belt. The Northern Galala area was a structural high as shown by hiatuses spanning Late Cretaceous (Coniacian) to Early Paleocene times. To the south, carbonate platform progradation is evident from the Late Campanian onward. Late Cretaceous platform-derived slope deposits interfinger with basinal chalks and calcareous shales farther south. Early Tertiary carbonates were deposited in platform, slope, and basin settings. The evolution of the platform–slope–basin transition is documented by the changing large-scale depositional geometry. The evolution occurs within sedimentary sequences that are interpreted by means of a high-resolution biostratigraphic framework. The facies architecture reflects the evolution from a rimmed shelf (Late Cretaceous) to a distally steepened ramp (latest Cretaceous to Paleocene) and eventually to a homoclinal ramp (Early Eocene). The reconstruction of the imprint of fluctuating sea levels on the sedimentary record has been used to establish comparisons with age-equivalent cycles from neighboring regions.

INTRODUCTION

Several authors have studied the stratigraphy and sedimentology of the outcropping Upper Cretaceous–lower Tertiary succession in the Eastern Desert of Egypt. They are, for example, Awad and Abdallah, 1966; Abdel Kireem and Abdou, 1979; Bandel and Kuss, 1987; Bandel et al., 1987; Hendriks et al., 1987; and Kuss and Leppig, 1989). Interpretations of the synsedimentary tectonics of the Upper Cretaceous-Paleocene carbonate-dominated strata in the northern part (Galala area) are found in Kuss (1992) and Moustafa and Khalil (1995). They form the basis for further detailed investigations by Kulbrok (1996), Gietl (1998) Scheibner et al. (2000), and Scheibner et al. (in press)

This study summarizes the results of biostratigraphic and lithofacies investigations of the carbonate-dominated Upper Campanian–Lower Eocene strata along a platform–slope–basin transect across the Galala plateaus west of the Gulf of Suez (Figure 1). It also evaluates the implications for deposition along a structural uplift and reconstructs the cyclic organization of the sedimentary successions within the time-slices of the Late Cretaceous and the Paleocene to Early Eocene. Several factors controlled sedimentation on the shallow-water shelves in the north and in the slope-transitions to an adjacent basin farther south. The most important are erosion of elevated areas (siliciclastic input), carbonate platform sedimentation (biosedimentary input), and sea-level fluctuations (accommodation space). They vary in time and space and interact to have diverse depositional effects. In contrast to the pre-Upper Campanian and post-Paleocene successions, sedimentation in the Late Cretaceous–Paleocene–Early Eocene interval may not have been influenced by synsedimentary tectonic processes. This hypothesis is supported by sequence stratigraphic interpretations of age-equivalent strata from a Syrian Arc uplift in neighboring Sinai (Lüning, Kuss et al., 1998).

The north-northwest-trending Gulf of Suez developed as a result of Miocene rifting. It is bordered by sharp scarps. The younger tectonic structures crosscut the depositional architecture and sedimentary structures of the Cretaceous-Paleogene succession along faults that extend farther west for several

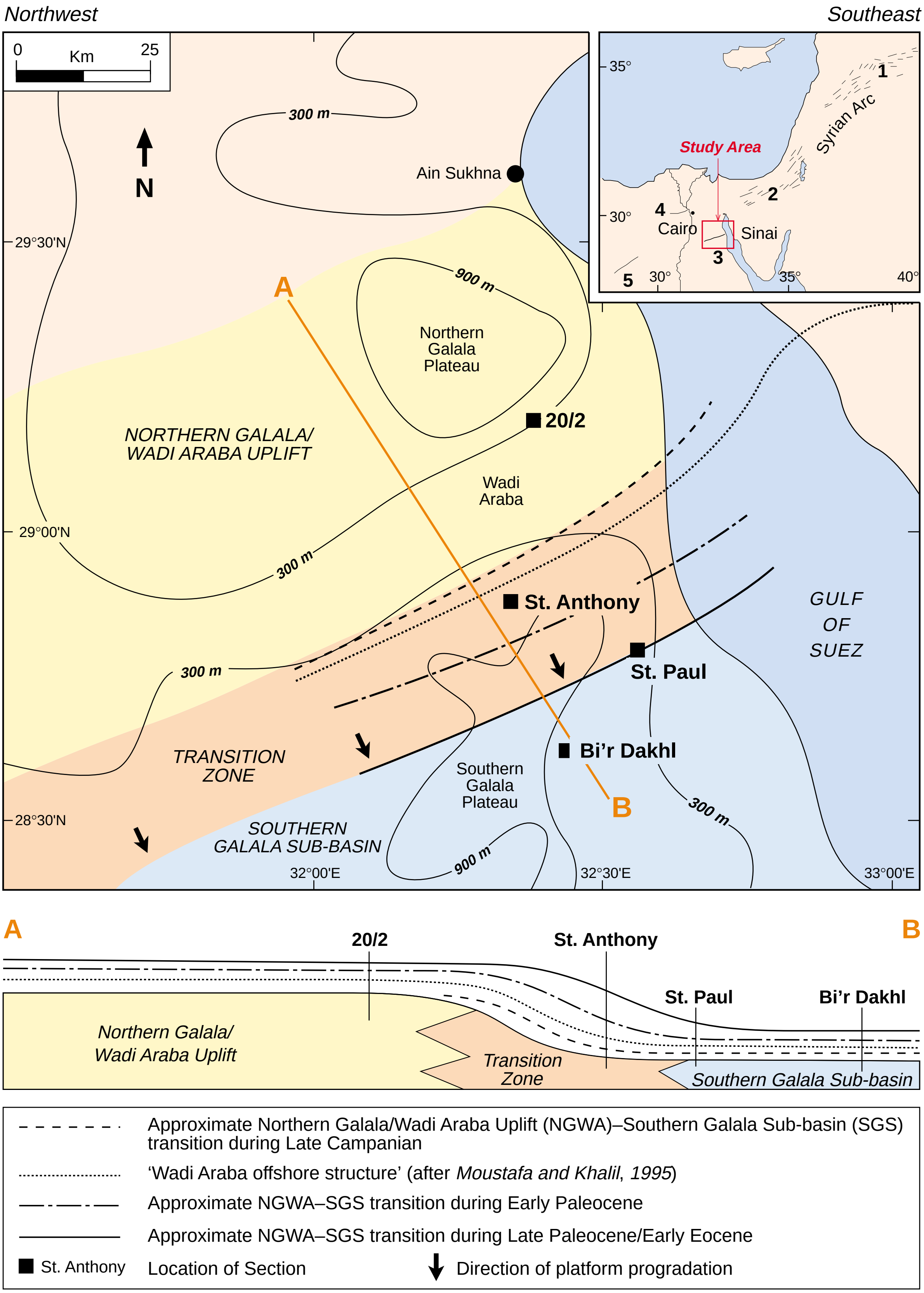


Figure 1: The Galala area, part of a Syrian Arc fold in the Eastern Desert near the western coast of the Gulf of Suez. [Inset shows Syrian Arc and location of Galala area: 1 = Palmyrid Fold Belt; 2 = Areif el Naqa anticline in the Negev-Sinai Fold Belt; 3 = Northern Galala/Wadi Araba Uplift; 4 = Abu Roash; 5 = Bahariya Uplift/Western Desert]. During Late Cretaceous–Paleogene times, the platform to basin transitions formed approximately parallel to the Galala trend and shifted southward, as indicated by the time lines along transect A–B. Black squares show the locations of the four key sections: 20/2, St. Anthony, St. Paul, Bi'r Dakhl (Figure 5).

tens of kilometers. Rift-related tectonism has been the cause of local weathering and alteration of the underlying Paleogene strata. For example, Miocene salts favor the dolomitization of the older strata and may leach away microfossils. Major rift-related and rotated fault blocks characterize the present-day geomorphology of plateaus, plains and wadis (Figure 1).

MATERIAL AND METHODS

During several field seasons in northeastern Egypt between 1993 and 1998, about 45 stratigraphic sections were logged on either side of the Gulf of Suez, most of them along the northern, eastern, and southern rims of the Galala plateaus. The work has been documented by Kulbrok (1996), Gietl (1998) and Scheibner et al. (2000). About 550 hand specimens of limestones for thin-section studies and 600 samples of chalk and calcareous shales (for investigations on washed microfossils) were collected.

In this study, we concentrate on four key sections (Figure 1) to demonstrate the lithologic and stratigraphic variations from north to south (Figure 2) that reflect a platform–slope–basin transition in the Eastern Desert (Figure 3). The key sections are:

- *Section 20/2*: Late Cretaceous uplift and Paleocene platform sedimentation of the Southern Galala Formation.
- *St. Anthony Section*: southward-prograding slope deposition of the Late Cretaceous St. Anthony Formation, and Paleocene platform-to-slope deposits of the Southern Galala Formation.
- *St. Paul Section*: Late Cretaceous basinal sediments of the uppermost Sudr Formation and the Dakhla Formation and Paleocene slope-to-basin deposits of the Southern Galala Formation.
- *Bi'r Dakhl Section*: Paleocene basin sediments of the Dakhla Formation, Sudr Formation, and Late Paleocene–Early Eocene slope-to-basin deposits of the Southern Galala Formation interfingering with the basinal Esna Formation.

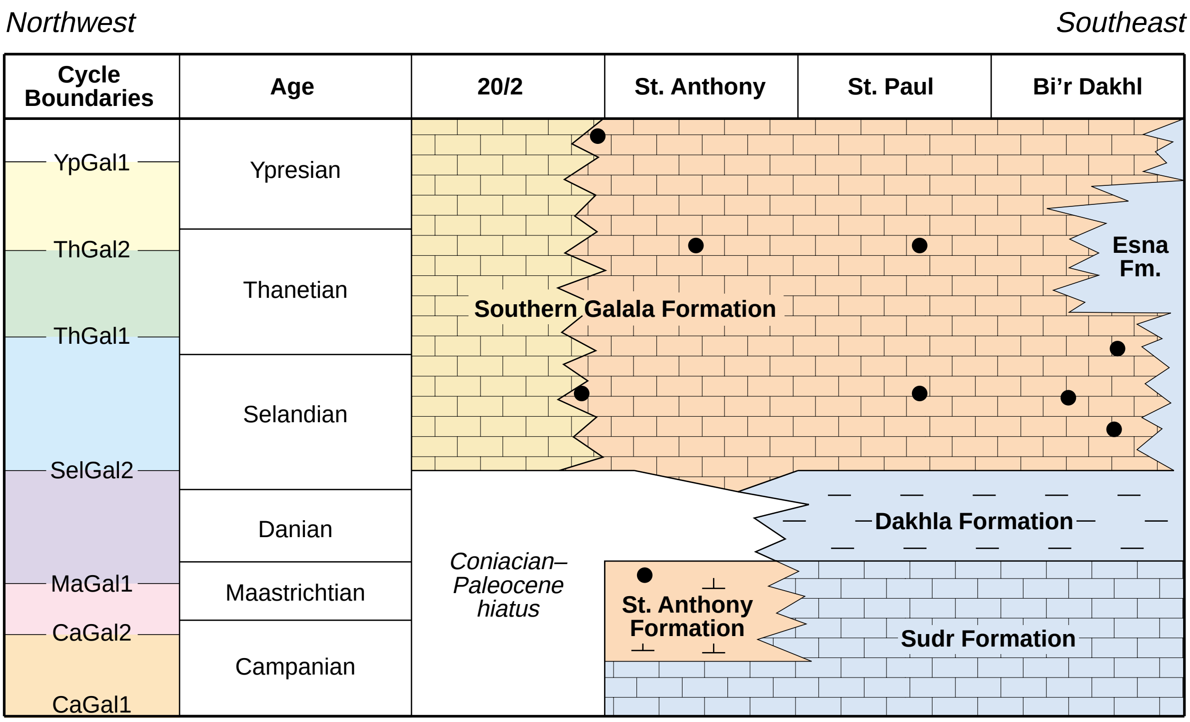


Figure 2: The Late Campanian (Late Cretaceous)–Ypresian (Early Eocene) formations of the four key sections to illustrate lithofacies changes from NW to SE within a stratigraphic time frame (see Figure 1 for locations). *Color key for formations*: yellow = platform deposits of the Uplift (20/2); orange = slope deposits of the Transition Zone (St. Anthony and Southern Galala formations); blue = basin deposits of the Sub-basin (Sudr, Dakhla and Esna formations). *Black dots* indicate synsedimentary reworking within the limestones.

The biostratigraphic and lithostratigraphic data are used to correlate these sections and to illustrate the large-scale depositional architecture of the sedimentary sequences. These data form the basis of our regional interpretations of uplift, erosion, sedimentation, and renewed subsidence, marked by the southward shifting Transition Zone (Figure 1). Cycle-boundaries are indicated by variations in water depths that allow for the reconstruction of relative changes in sea level. They form the basis for sequence stratigraphic interpretations combined with the evaluation of facies and microfacies, field observations of sedimentary structures, vertical stacking patterns, and microfaunal compositions. For more details, refer to Gietl (1998), Scheibner et al. (2000), and Scheibner et al. (in press).

GEOLOGIC SETTING

Surface sections on the Northern and Southern Galala plateaus consist mainly of clastic sedimentary rocks of late Paleozoic to Early Cretaceous age, and predominantly carbonate strata of the Late Cretaceous to Paleogene (Bandel and Kuss, 1987). Their gross architecture reflects a southward-thinning, wedge-like pile of sediments that were deposited during marine transgressions that came mainly from the north onto the African-Arabian Shelf (Kuss and Bachmann, 1996). Locally, in the Late Cretaceous, structural highs affected the sedimentary successions to form islands along the Northern Galala / Wadi Araba Uplift.

The complex uplifts and domal anticlines of the Syrian Arc Fold Belt were formed during the closure of the Neo-Tethys (Stampfli et al., 1995), as a consequence of the convergence of the African and Eurasian plates. Northeastern Egypt, situated at the northern edge of the African-Arabian Craton, was affected during Late Cretaceous to early Tertiary times by east-northeast-oriented dextral wrench faulting. This resulted in transpressive movements and the inversion of the Late Triassic–Liassic half-grabens that cut east-northeastward across the northern rim of the African-Arabian Plate.

The Syrian Arc can be traced from Syria to the central Western Desert of Egypt, via Sinai and the northern part of the Eastern Desert (Figure 1, inset). It is composed of the Palmyride and Sinai-Negev fold belts, both having similar lithologic and structural characteristics (Shahar, 1994). The Galala plateaus represent a major branch of the Syrian Arc in the Eastern Desert, characterized by Late Cretaceous uplift in the north and subsidence farther to the south (Figure 1). In contrast to various Syrian Arc localities in Egypt and neighboring areas, the Galala plateaus exhibit a unique Late Cretaceous to Early Paleogene carbonate-dominated platform-to-slope succession. This is comparable to other island-like Tethyan elevations rimmed by carbonate platforms, such as the Bakony Mountains of Hungary (Haas, 1999), Maiella in Italy (Eberli et al., 1994), and Sicily (Camoin et al., 1988).

Folding and / or uplift of the Syrian Arc began in post-Cenomanian times (Aal and Lelek, 1994) and reached its acme during the Late Cretaceous. However, diverse ages for the peak deformation exist based on studies in other regions. For example:

- Moustafa and Khalil (1995) reported an early Late Senonian age of major uplift as indicated by surface and subsurface data from localities in northeast Egypt.
- Lüning, Kuss et al. (1998) gave evidence of a major Late Campanian–Early Maastrichtian uplift, based on micropaleontologic studies on exposures in Sinai.
- Bosworth et al. (1999) assumed a major pre-Campanian compressive deformation event based on surface and subsurface data from the southern Gulf of Suez.

We cannot define exactly the onset of uplift in the Galala plateaus because of later erosion, but their rise is obvious during pre-Late Campanian times when the uplift affected the depositional processes on their southern flank.

The area under investigation can be divided into the following three east-northeast-striking facies belts (Figure 1):

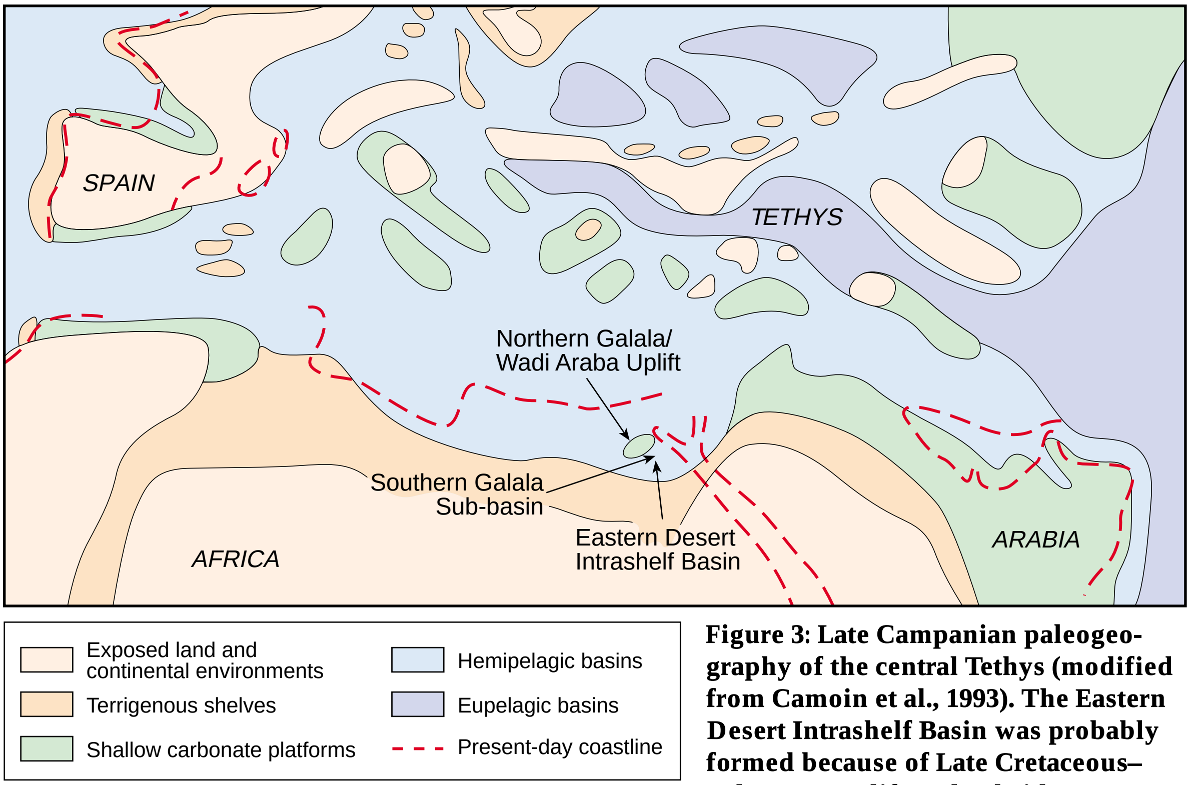


Figure 3: Late Campanian paleogeography of the central Tethys (modified from Camoin et al., 1993). The Eastern Desert Intrashelf Basin was probably formed because of Late Cretaceous–Paleogene uplift and subsidence.

- The **Northern Galala/Wadi Araba Uplift** in the north is characterized by long-lasting hiatuses (if Upper Cretaceous deposits are present at all, they are mainly dolomitized). The overlying carbonate platform deposits of latest Paleocene age interfinger with slope deposits of the Transition Zone farther south.

- The **Transition Zone** is characterized by Upper Cretaceous to Paleogene slope deposits. It is composed of the Upper Campanian–Lower Paleocene St Anthony Formation and the Late Paleocene to Early Eocene Southern Galala Formation (see Figures 1 and 2, and discussion in Scheibner et al. (in press)). The slope sediments were formed in the transition to the Southern Galala Sub-basin.

- The **Southern Galala Sub-basin** was formed in the Late Campanian by the Northern Galala / Wadi Araba Uplift and represents the northern part of the Eastern Desert Intrashelf Basin (Figure 3). The interfingering of Late Paleocene–Early Eocene slope and basin deposits is seen in the Sub-basin (Bi'r Dakhl Section, Figure 2; and Scheibner et al., in press). Sedimentary wedges prograding southward from the Northern Galala / Wadi Araba Uplift led to an increase in loading and subsidence in the Sub-basin. The Late Cretaceous to Early Tertiary evolution of the Sub-basin was closely connected to the development of the Eastern Desert Intrashelf Basin. The Sub-basin's configuration became apparent in the Paleocene, as shown by paleobathymetric estimates (Speijer and van der Zwaan, 1994; Scheibner et al., 2000).

The Late Cretaceous boundary between the Northern Galala / Wadi Araba Uplift and the Southern Galala Sub-basin coincides with the separation between deformed and undeformed pre-Campanian strata. It is well exposed along the northern scarp of the Southern Galala Plateau, for example near the St. Anthony Section (Figure 1; see also Bandel and Kuss, 1987). At this location, an angular unconformity separates steeply south-dipping Turonian–Lower Campanian units of the Northern Galala / Wadi Araba Uplift from moderately south-dipping to nearly horizontally bedded Upper Campanian–Maastrichtian to Lower Eocene strata of the Southern Galala Sub-basin. Biostratigraphic evidence of a paleostructural elevation in the north and its long duration is illustrated by hiatuses ranging in age from post-Turonian to Late Paleocene (see Section 20 / 2, Figure 6). The east-northeast-trending Northern Galala / Wadi

Araba Uplift influenced the Late Cretaceous–Paleogene sedimentation processes in the area. Consequently, they are characterized by a gently south-dipping carbonate platform that rims the Uplift in the north and interfingers with transitional slope sediments and with hemipelagic deposits of the Sub-basin farther south. Based on the work of Kuss and Kulbrok (1995), the following three major southward-prograding carbonate-platform systems can be distinguished with respect to their large-scale sedimentary architecture (Figure 4):

- The Late Campanian / Maastrichtian rimmed shelf.
- The Paleocene distally steepened ramp.
- The Early Eocene homoclinal ramp.

Late Cretaceous Platform-to-Basin Configuration

The tectonically induced topography strongly affected sedimentation during the Late Cretaceous. Whereas long intervals of non-deposition prevailed in the central part of the Northern Galala / Wadi Araba Uplift, Upper Campanian fine-grained mixed siliciclastic and carbonate sediments of the St. Anthony Formation accumulated in the Transition Zone. The sediments represent the foreslope of a rimmed carbonate shelf that fringed the Uplift (Figure 4). Carbonate-secreting shallow-water benthic organisms are present in proximal slope deposits on the southern edge of the Uplift. They occur in a Late Campanian lowstand wedge and in Early Maastrichtian shallow-water limestones within the St. Anthony Formation at the St. Anthony Section (see Figure 6 and Figure 7a(ii)). The regional distribution of these slope deposits follows an east-northeast trend parallel to the 'Wadi Araba offshore structure' of Moustafa and Khalil (1995). This structure has been mapped farther east from subsurface data and coincides with the southern boundary of the Northern Galala / Wadi Araba Uplift (Figure 1). Syrian Arc inversion tectonics in this area resulted in a steeply south-dipping margin that reflects the topography of a Late Campanian–Early Maastrichtian rimmed carbonate shelf (compare platform models of Burchette and Wright, 1992; Handford and Loucks, 1993).

The succeeding Maastrichtian units of the St. Anthony Formation are composed of siliciclastic carbonates. They correlate with major areas of non-deposition to the north (Northern Galala / Wadi Araba Uplift) and open marine chalk-calcareous shale intercalations of the Sudr Formation farther south in the Southern Galala Sub-basin (Figure 4). The lateral extent and duration of the Late Cretaceous carbonate shelf that rimmed the Uplift and extended into the Sub-basin is difficult to estimate because of later erosion. Moreover, a more than 10-kilometer-wide segment of the former platform is missing due to subsequent erosion of the present-day Wadi Araba (Figures 1 and 4). However, the lowstand deposits of the St. Anthony Formation in the St. Anthony Section and age-equivalent basinal sedimentary rocks of the Sudr Formation farther south enable rough estimates to be made. The lowstand deposits are about 180 meters (m) thick and consist of wedge-like units of sediments that include slumps and slides (Figure 7a(iii)). They pass into chalks and calcareous shales that are about 60 m thick in the St. Paul Section 14 km farther south (Figures 6, 7b) where no imprints of major sedimentary disturbances were observed. A stratigraphic model predicts a Late Cretaceous carbonate shelf more than 100 m thick that may have rimmed the southern edge of the Northern Galala / Wadi Araba Uplift (Figure 4). The model assumes a time interval of 2.3 to 2.5 million years and a shelf-to-basin profile inclined 1.3º to 8.5° to the south.

There is little evidence of any latest Maastrichtian–Early Paleogene shallow-water carbonates in the Transition Zone. Their absence might be due to the mainly siliciclastic nature of the sedimentation or to a latest Maastrichtian–Early Paleocene marine regression.

Paleogene Platform to Basin Configuration

The gross architecture of the Late Cretaceous rimmed platform gradually changed to a Paleogene ramp-basin transition, seen as step-wise, southward-prograding successions (Figure 4). The distally steepened Paleocene carbonate ramp evolved into an Early Eocene homoclinal ramp (Gietl, 1998). Shallow-water limestones of the Southern Galala Formation were deposited on a gently south-dipping carbonate ramp. They crop out on the Northern Galala / Wadi Araba Uplift and interfinger with slope deposits in the Transition Zone and with basinal sediments (Esna Formation) of the Southern Galala Sub-basin (Figure 2). Evidence for these transitions is found in planktonic foraminiferal zone P4-P5

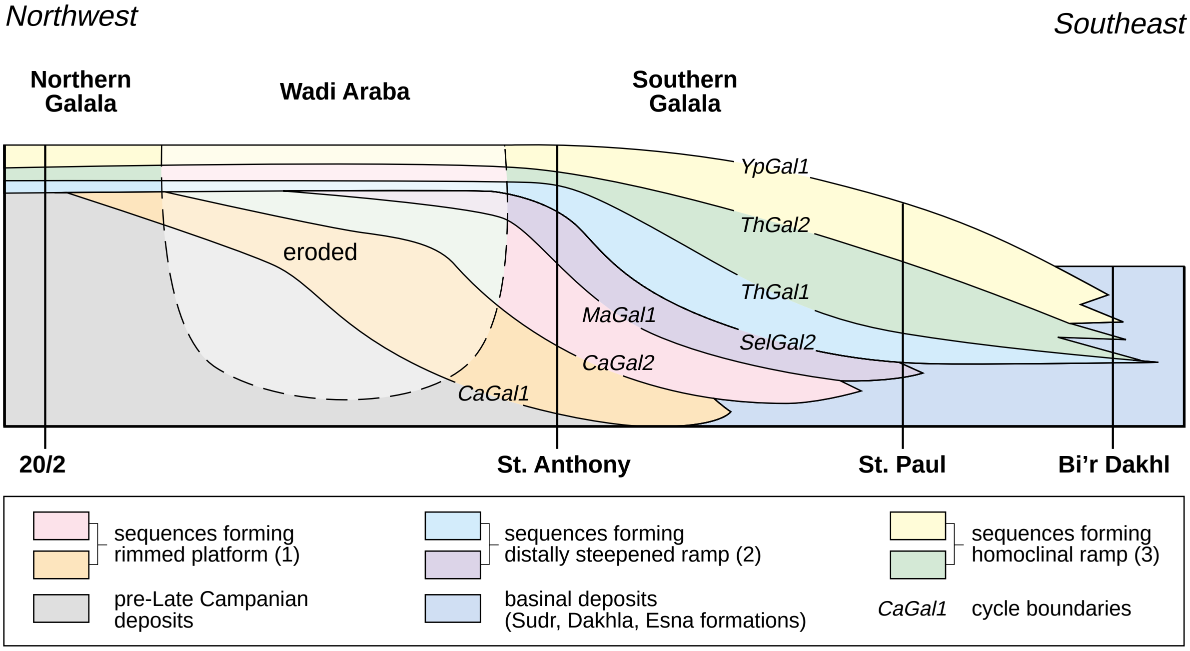


Figure 4: Schematic cross-section of Late Cretaceous–Paleogene sedimentary sequences to demonstrate the stratigraphic evolution of three carbonate platforms at the Northern Galala/Wadi Araba uplift: (1) rimmed shelf; (2) distally steepened ramp; and (3) homoclinal ramp.

(Figure 5). In this interval, the proximal slope deposits of the Southern Galala Formation in the St. Anthony Section include debris flows (see Figure 7a(i)) and interfinger with slope deposits about 14 km to the south (near St. Paul)(see Figure 7b). They also have intertonguing relationships with basin sediments of the Esna Formation in the Bi'r Dakhl Section, 12 km farther south (see Figure 7c). The distribution and facies of the Lower Eocene carbonates in the Uplift and Transition Zone indicate a homoclinal ramp morphology (Figure 4). The morphological model is also supported by evidence of thickness changes, the sequence geometries, and coevally increasing occurrences of local build-ups and shoals in the shallow ramp areas (Kuss, 1992; Kulbrok, 1996; Gietl, 1998).

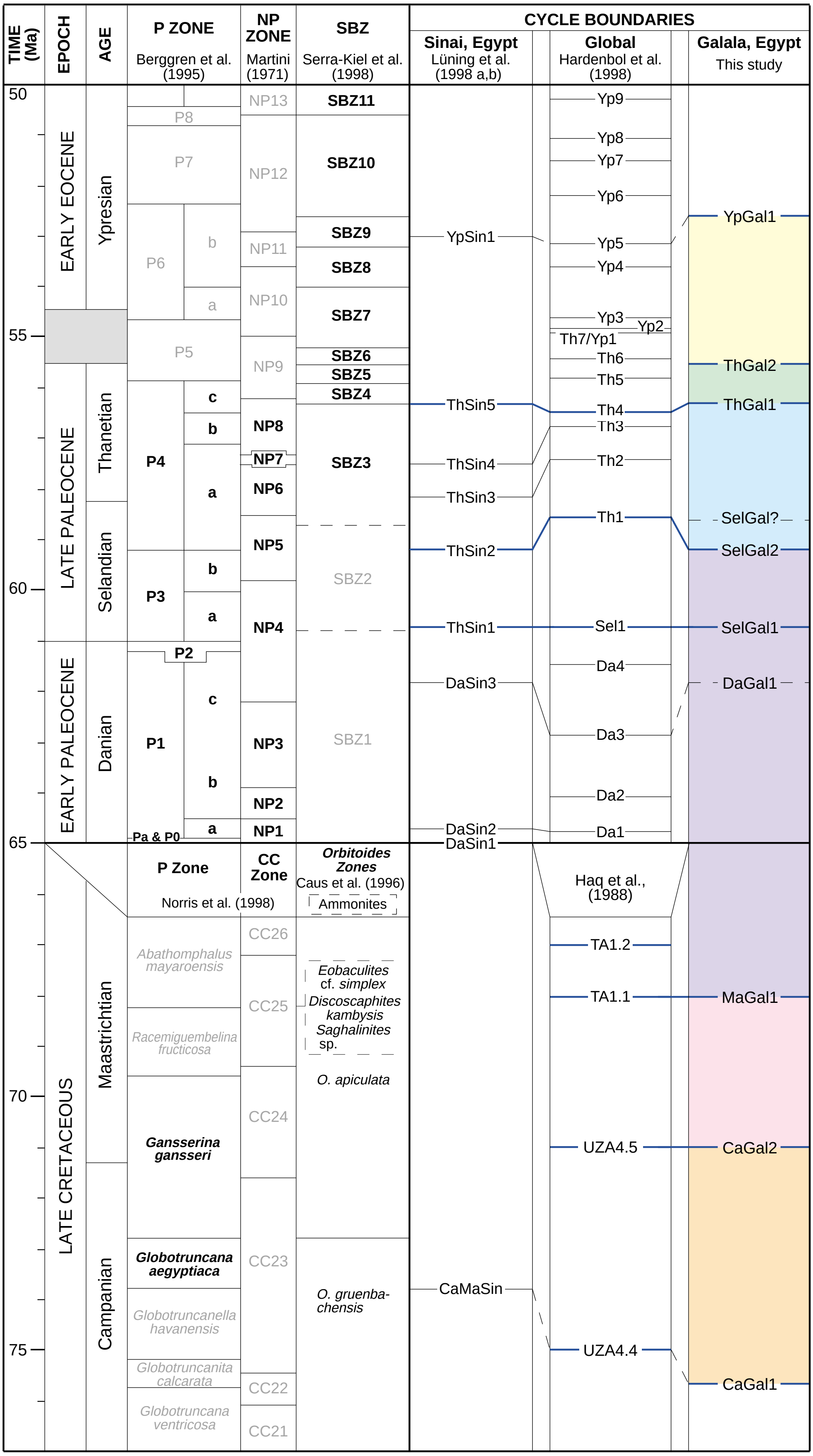
BIOSTRATIGRAPHY

Late Campanian–Maastrichtian

Biostratigraphic subdivisions of the Late Cretaceous deposits in the study area (Figure 5) are mainly based on planktonic (Norris et al., 1998) and benthic foraminifera (Caus et al., 1996). Supplementary data are provided by a few ammonites and are compared with range-zones given by Ward and Kennedy (1993). Detailed descriptions and illustrations of the local biozones are given by Abdel Kireem and Abdou (1979), Kuss (1986), and Kulbrok (1996).

The lack of Late Cretaceous biostratigraphic data for most of the Northern Galala / Wadi Araba Uplift is either due to the absence of strata of that age or, if they do exist, to strong diagenetic alteration. Only at its southernmost edge in the Transition Zone to the Southern Galala Sub-zone, are mainly hemipelagic sediments present (St. Anthony Section). The isolated microfossils are for the most part poorly preserved owing to the presence of silty-sandy intercalations and frequent dolomitization (Abdallah and Eissa, 1966; Kuss, 1986). Microfossil preservation improves southward and Maastrichtian planktonic foraminifera occur in the mostly hemipelagic succession of chalk and calcareous shales of the Southern Galala Sub-zone at St. Paul.

According to the biozonal scheme of Kulbrok (1996), the Upper Cretaceous succession in the St. Anthony Section of the Transition Zone starts with Campanian chalk of the late *Globotruncana ventricosa*-


TIME (Ma)
EPOCH
AGE
P ZONE
Berggren et al. (1995)
NP ZONE
Martini (1971)
SBZ
Serra-Kiel et al. (1998)
CYCLE BOUNDARIES
Sinai, Egypt
Lüning et al. (1998 a,b)
Global
Hardenbol et al. (1998)
Galala, Egypt
This study
50
55
60
65
70
75
EARLY EOCENE
LATE PALEOCENE
EARLY PALEOCENE
LATE CRETACEOUS
Ypresian
Thanetian
Selandian
Danian
Maastrichtian
Campanian
P8
P7
P6
b
a
P5
P4
c
b
a
P3
b
a
P2
P1
c
b
a
Pa & P0
NP13
NP12
NP11
NP10
NP9
NP8
NP7
NP6
NP5
NP4
NP3
NP2
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SBZ11
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SBZ5
SBZ4
SBZ3
SBZ2
SBZ1
YpSin1
ThSin5
ThSin4
ThSin3
ThSin2
ThSin1
DaSin3
DaSin2
DaSin1
Yp9
Yp8
Yp7
Yp6
Yp5
Yp4
Yp3
Yp2
Th7/Yp1
Th6
Th5
Th4
Th3
Th2
Th1
Sel1
Da4
Da3
Da2
Da1
YpGal1
ThGal2
ThGal1
SelGal?
SelGal2
SelGal1
DaGal1
P Zone
Norris et al. (1998)
CC Zone
Orbitoides Zones
Caus et al. (1996)
Ammonites
Haq et al., (1988)
Abathomphalus mayaroensis
Racemiguembelina fructicosa
Gansserina gansseri
Globotruncana aegyptiaca
Globotruncanella havanensis
Globotruncanita calcarata
Globotruncana ventricosa
CC26
CC25
CC24
CC23
CC22
CC21
Eobaculites cf. simplex
Discoscaphites kambysis
Saghalinites sp.
O. apiculata
O. gruenba-chensis
CaMaSin
TA1.2
TA1.1
UZA4.5
UZA4.4
MaGal1
CaGal2
CaGal1

Globotruncanita calcarata zones (Figure 5). The chalk is overlain by dolomitic calcareous shale of the Upper Campanian *Globotruncanella havanensis* to *Globotruncana aegyptiaca* zones intercalated with several silt-sandstone and marly limestone units. They contain larger benthic foraminifera of *Orbitoides gruenbachensis* and *Siderolites calcitrapoides* from the lower part of the *G. aegyptiaca* biozone, and *O.* cf. *apiculata* from the lower part of the *Gansserina gansseri* zone. However, no evidence exists for age-equivalent calcareous shales to the south in the St. Paul and Bi'r Dakhl sections. In these areas, the Upper Cretaceous calcareous shales contain planktonic microfauna of the late *G. gansseri* zone to *Abathomphalus mayaroensis* zone.

Limestones intercalated with calcareous shales of the lower part of the *G. gansseri* zone are found only in the St. Anthony Section. They contain the larger benthic foraminifera of *Orbitoides* sp. and *Omphalocyclus macroporus*. In this section, the overlying marly siltstones contain the ammonite taxa *Saghalinites* sp. and *Discoscaphites kambysis* together with the baculite *Eobaculites* cf. *simplex* (J.K. Kennedy, University of Oxford, 1996, oral communication). *Saghalinites* sp. indicates a Late Maastrichtian age (Ward and Kennedy, 1993). The zonal marker species of the latest Maastrichtian *Abathomphalus mayaroensis* chronozone are missing from most of northeastern Egypt (see discussion in Luger et al., 1998), including the St. Anthony Section. However, evidence for the *Kassabiana falsocalcarata* subzone is found in several sections of the Southern Galala Sub-basin (Masters, 1984). The subzone coincides with the upper part of the *A. mayaroensis* biozone according to Luger et al. (1998).

Paleocene–Early Eocene

Most biostratigraphic studies of the Paleocene-Early Eocene succession in the Galala area were made on the mainly chalky and shaly facies from the southern part of the Southern Galala Sub-basin. Examples are Strougo et al. (1992), Faris (1994), Kulbrok (1996), Scheibner et al. (2000), and Scheibner et al. (in press). Biozones are based on studies of planktonic foraminifera (P-Zones) by Berggren et al. (1995) and nannoplankton (NP-Zones) by Martini (1971) (Figure 5). Only a few contributions deal with the shallow-water calcareous shales and limestones of the Transition Zone and the Uplift area farther north. In these areas, work by Kuss and Leppig (1989), Gietl (1998), and Boukhary et al. (1998) are based on larger foraminifera using criteria from Hottinger (1960) for alveolinids and by Schaub (1981) for nummulitids. Serra-Kiel et al. (1998) revised the correlation of Paleogene planktonic and shallow-water benthic zones and introduced the concept of 'shallow benthic zones' (SBZ of Figure 5). In Figure 5, following zonation was used for the units of the four key sections:

- Biozones P1–P4 of the standard Paleocene–Early Eocene biozones (Berggren et al., 1995) are determined from hemipelagic deposits of the St. Paul and Bi'r Dakhl sections, in accordance with the data of Strougo et al. (1992). The biostratigraphic record of shallow-water deposits commences with redeposited limestones of the latest SBZ2, sandwiched between calcareous shales of the P3-P4 boundary (Scheibner et al., 2000).

- First occurrences of autochthonous ramp carbonates of the Northern Galala / Wadi Araba Uplift occurred locally in the late SBZ3 (Gietl, 1998) but in most areas their deposition began in SBZ4 or P4c. Shallow-water limestones of the SBZ5–SBZ10 zones (equivalent to basin sediments of P5–P6) are present at several localities on the Uplift (Kuss and Leppig, 1989; Gietl, 1998) and in the Transition Zone farther south (St. Anthony Section, Figure 6).

Figure 5: Stratigraphy and cycle boundaries of Late Campanian to Early Eocene strata in the Galala area. The time scale adopted for the three left-hand columns is based on Norris et al. (1998) and relies on Gradstein et al. (1995) for Cretaceous datums and Berggren et al. (1995) for the Paleocene-Eocene datums. Age estimates for most of the Late Cretaceous calcareous nannofossil and planktonic foraminiferal datums were taken from Erba et al. (1995). Bold characters and numbers in the fourth, fifth, and sixth columns refer to determined biozones; gray characters and numbers relate to inferred biozones. Comparisons of cycle boundaries are based on absolute ages; mismatches are due to different biostratigraphic concepts used by various authors (see discussion in text). Colors as for Figures 2.

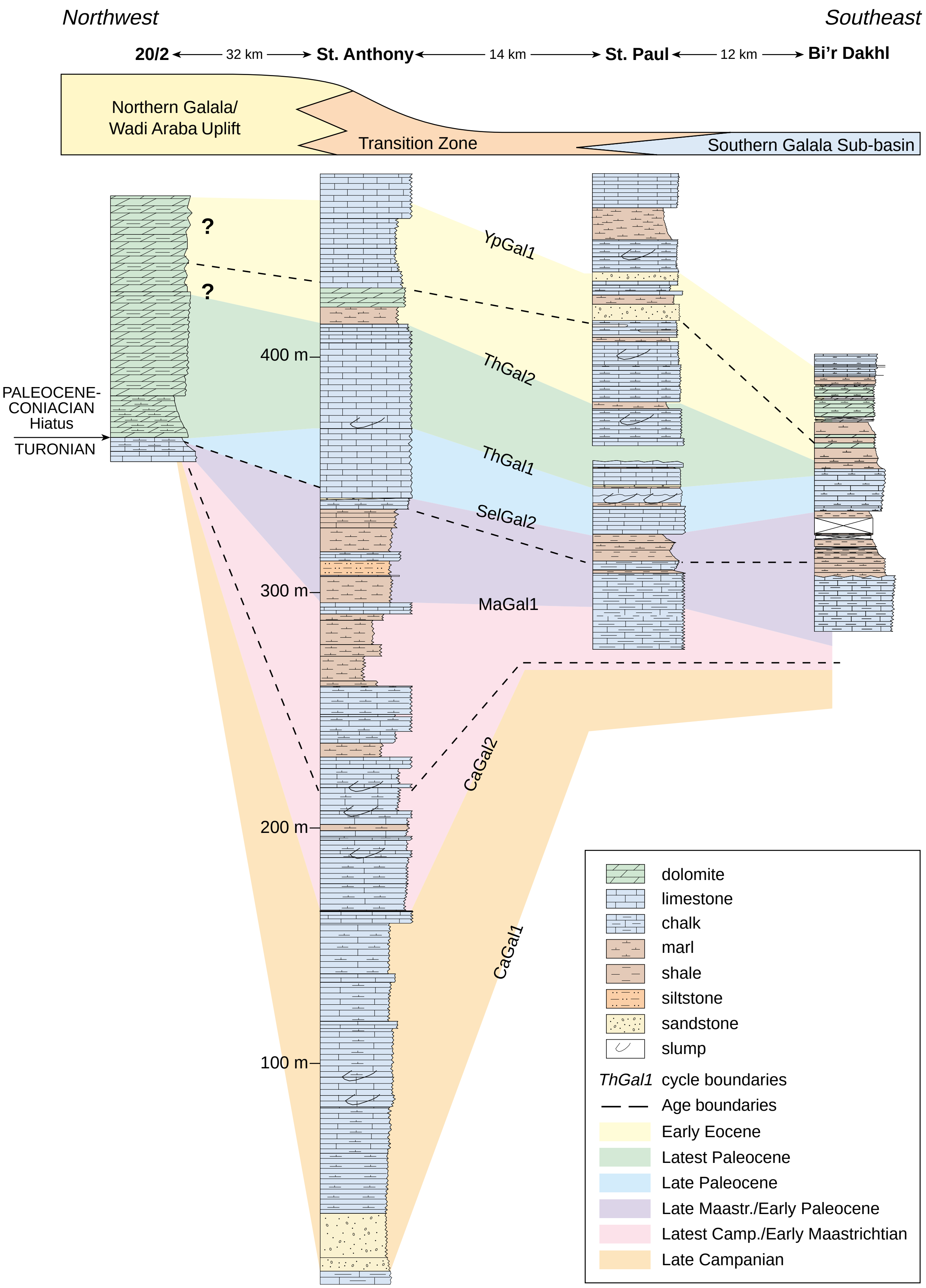

Figure 6: Stratigraphic correlation and cycle boundaries of the four Late Cretaceous–Paleogene key sections (key section St. Paul is a composite profile). Hiatuses, lithologic variations, and thickness variations are due to paleogeographic differences between the Uplift, Transition Zone, and Sub-basin (see schematic section at top). The distances between sections refer to their position on transect A–B (Figure 1).

SEDIMENTARY FACIES, CYCLES, AND SEA-LEVEL CHANGES

The integration of the sedimentologic and stratigraphic data from the four stratigraphic sections has enabled us to attribute the vertical and horizontal facies distribution to changing environments that are essentially controlled by variations in water depths. Comparisons with regional age-equivalent sea-level fluctuations occur in Sinai (Lüning, Kuss et al., 1998; Lüning, Marzouk and Kuss, 1998), and Israel (Lewy, 1990). They support the definition and correlation of lithofacies along the transect from the Northern Galala / Wadi Araba Uplift to the Southern Galala Sub-basin. They enable the reconstruction of the internal geometries and architectures of the lithofacies with respect to changes in depositional conditions (Figures 4 and 7). Detailed descriptions of Late Cretaceous-Paleogene macro- and microfacies, including descriptions of shallow-water biota are found in Bandel and Kuss (1987), Kuss and Leppig (1989), Kuss (1986; 1992), Kuss and Herbig (1993), Kulbrok (1996), and Gietl (1998). Cretaceous-Paleogene sea-level fluctuations from deeper ramp-basinal areas of Southern Galala were reported by Kulbrok (1996) and recently re-studied by Scheibner et al. (2000). We have concentrated on characteristics such as foraminiferal data (planktonic / benthonic ratio) or sedimentological interpretations that are relevant to water-depth estimates and the reconstruction of regional fluctuations in sea level.

Paraconformities and discontinuities occur at various levels within each section and are used for the interpretation of sequence boundaries. A major hiatus is present in Section 20 / 2 (Figure 6) spanning the Coniacian to Late Paleocene interval. Although we cannot estimate the lower and upper boundaries of this hiatus on an exact biostratigraphic scale, a long-lasting period of non-deposition and / or erosion due to uplift is concluded from regional observations. Another important hiatus is possibly present in the St. Anthony Section near the Maastrichtian-Paleocene boundary, but again the exact biostratigraphic evidence is missing. Discontinuities of much shorter duration in slope areas are indicated by the penecontemporaneous reworking of sediments (Scheibner et al., 2000). The same is true in areas that are more basinal where the absence of individual sub-zones suggests an incomplete stratigraphic record.

Upper Cretaceous

Upper Cretaceous rocks are exposed only on the southernmost edge of the Northern Galala / Wadi Araba Uplift (St. Anthony Section, Figure 6). The basal part of the St. Anthony Section consists of Campanian chalk-calcareous shale intercalations and massive chalk that reflect deep-neritic outer-shelf sedimentation. Farther north, there is no stratigraphic evidence of Upper Cretaceous rocks, which suggests that most parts of the Northern Galala area were above sea level in Late Campanian–Early Maastrichtian times. Similarly, no age-equivalent sediments are to be found in outcrops to the south.

The Campanian chalk in the St. Anthony Section is truncated disconformably by the chaotic Upper Campanian units of the St. Anthony Formation. The Formation contains olistoliths, south-verging slumps, and debris flows composed of intercalations of bioclastic limestone, sandstone, and siltstone (Figure 6, and Figure 7a(iii)). We interpret the base of this unit to be a sequence boundary (CaGal1, Figure 5). It may be correlated with the CaMaSin boundary in southeastern Sinai (Lüning, Kuss et al., 1998) and with unconformities in the vicinity of the Campanian-Maastrichtian boundary described from Israel (Almogi-Labin et al., 1990; Lewy, 1990). These Upper Campanian strata contain redeposited shallow-water biota, such as orbitoids and green algae together with corallinaceans and planktonic foraminifera. This assemblage of organisms that originally lived in shallow-platform to deeper-shelf environments favors the model of a rimmed carbonate shelf situated at the southern edge of the elevated Northern Galala swell (Figure 4). The platform morphology can also be deduced from the sedimentary structures, facies characteristics, and the relatively short distance between platform and slope deposits.

In the St. Anthony Section, the reworked sediments sandwiched between CaGal1 and CaGal2 (Figure 6) are interpreted as a southward-prograding low-stand wedge resulting from falling sea level during the Late Campanian (lowermost *Globotruncanita calcarata* zone) (Figure 5). We assume that the subaerial exposure of the elevated areas farther north, hitherto covered by the sea, included the Northern Galala / Wadi Araba Uplift. This uplifted area formed an island with (at present unexposed) Upper Cretaceous carbonate platform deposits that prograded southward along its southern coast. In the St. Paul and Bi'r Dakhl sections, rocks of that age are also not exposed (Figure 6). However, there is

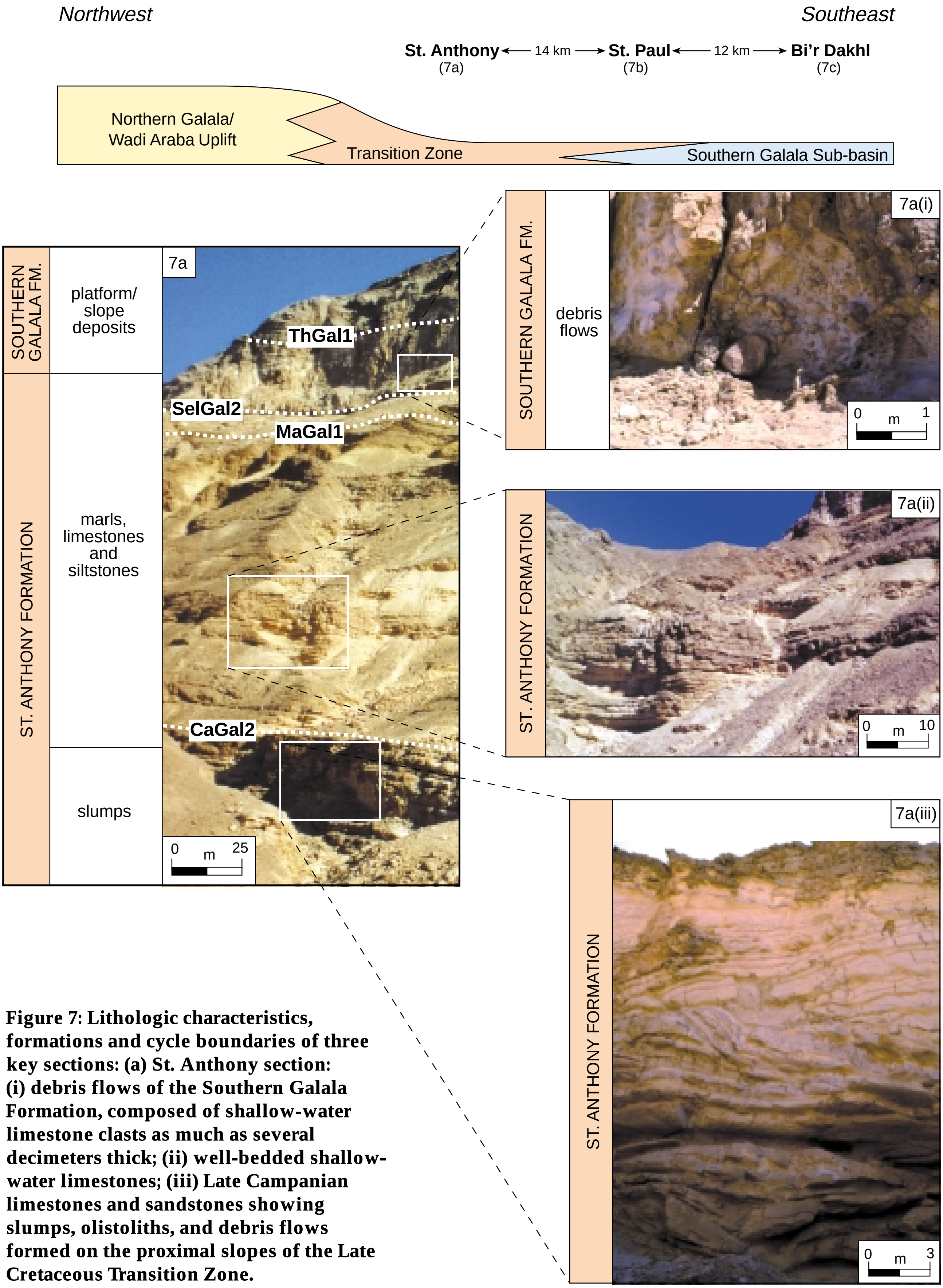

Figure 7: Lithologic characteristics, formations and cycle boundaries of three key sections: (a) St. Anthony section: (i) debris flows of the Southern Galala Formation, composed of shallow-water limestone clasts as much as several decimeters thick; (ii) well-bedded shallow-water limestones; (iii) Late Campanian limestones and sandstones showing slumps, olistoliths, and debris flows formed on the proximal slopes of the Late Cretaceous Transition Zone.

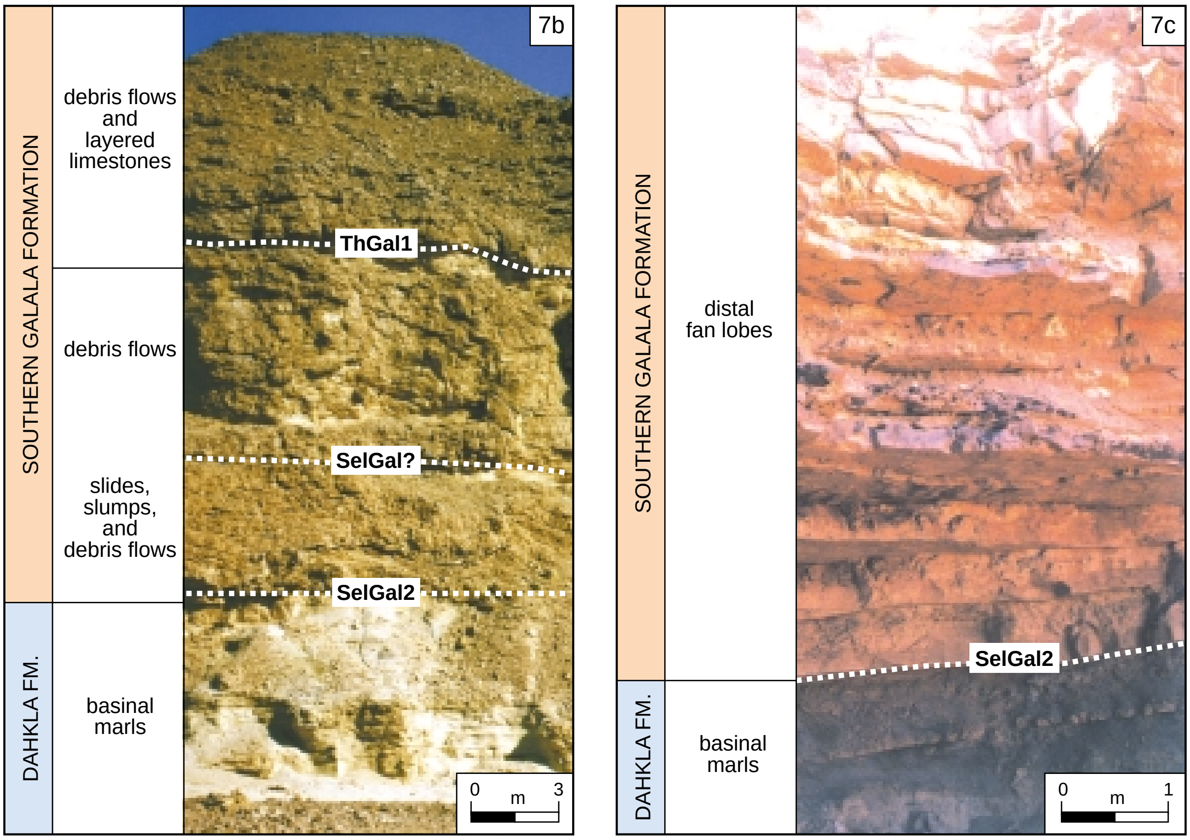

Figure7: (b) St. Paul; and (c) Bi'r Dakhl.

evidence of correlation with hemipelagic chalk / marl successions in the Eastern Desert Intrashelf Basin (Figure 3) to the south (Bandel et al., 1987).

In the St. Anthony Section and farther south, a Late Campanian rise of sea level is indicated by the presence of hemipelagic calcareous shales of the upper *Globotruncana aegyptiaca* zone (Kulbrok, 1996). Conspicuous facies changes characterize the cycle boundary CaGal2 at the top of the *G. aegyptiaca* zone (comparable to UZA4.5 of Haq et al., 1988). Mixed siliciclastic limestones containing omphalocyclids and reworked shallow-water biota occur above the CaGal2 boundary. They indicate a second interval of southward-prograding shallow-water deposits (Figure 7a(ii)) that were laid down on the now exposed carbonate platform to the north. They are overlain by neritic carbonates of the *G. gansseri* zone and by Lower Maastrichtian calcareous shales of the late *Gansserina gansseri–Abathomphalus mayaroensis* zones (Kulbrok, 1996). Cycle boundary MaGal1 (equivalent to TA1.1 of Haq et al. (1988)) coincides with the onset of siliciclastic- dominated sediments. In contrast, there is no evidence of shallow-water deposition in the Upper Maastrichtian chalk of the Sudr Formation in the Southern Galala Sub-basin (St. Paul and Bi'r Dakhl sections, Figure 6).

The exact reconstruction of the Late Cretaceous uplift history in the Northern Galala-Wadi Araba area is further complicated by the poor stratigraphic record (for example, Section 20/2, Figure 4). Nevertheless, we can assume a long interval of uplift on the basis of hiatuses (also reported in neighboring areas), that range in age from post-Turonian to pre-Late Paleocene (see Shahar, 1994).

Paleocene–Early Eocene

Evidence of regional fluctuations in sea level is present in sediments of the Paleogene ramp that covered parts of the Northern Galala-Wadi Araba area, as well as in slope-basin successions farther south.

The first lowstand of the Early Paleocene and its corresponding sequence boundary DaGal1 (Figure 5) were interpreted by Kulbrok (1996) and may coincide with DaSin3 of eastern Sinai (Lüning, Marzouk and Kuss, 1998). The same authors reported two earlier Paleocene sea-level falls, also known from outcrops in the Nile Valley (Speijer and Schmitz, 1998), but not discernible in the Galala plateaus. Cycle boundary SelGal1 was recognized to the northeast of the Gulf of Suez on sedimentologic evidence (Kulbrok, 1996). It may coincide with a mid-NP4 benthic peak described from Gebel Oweina by Speijer and Schmitz (1998) and from east Sinai (ThSin1) by Lüning, Marzouk and Kuss (1998), and may be comparable with Sel1 of Hardenbol et al. (1998).

The Late Paleocene (NP5–NP9) slope section in the northern part of the Southern Galala Sub-basin (St. Paul Section) provides evidence of three phases of ramp progradation. At least two of the phases can be equated with falls in sea level (Scheibner et al., 2000). In the Bi'r Dakhl Section, thin equivalents of the prograding ramp deposits interfinger with basinal calcareous shales of the Dakhl Formation (Figure 7c). The succession indicates that the Sub-basin was fed with carbonates derived from the south-prograding Paleogene ramp (Figure 3). A pronounced fall in sea level in the middle of the NP5 zone (SelGal2) correlates with a sequence boundary recognized from the northern Gulf of Suez (Kulbrok, 1996) and from Sinai (ThSin2 of Lüning, Marzouk and Kuss (1998)). Furthermore, Lüning, Marzouk and Kuss (1998) gave evidence of its synchronicity with Th1 of Hardenbol et al. (1998), which suggests that SelGal2 may be a candidate as a global cycle boundary (Figure 5). A second phase of ramp progradation described from the northern part of the Sub-basin by Scheibner et al. (2000) could reflect a cycle boundary. However, it cannot be correlated with other regional descriptions and it may be related to the sea-level fall that caused SelGal2 (Figure 5). Cycle boundary ThGal1 coincides with a phase of ramp progradation in the northern part of the Sub-basin, interpreted as being the result of a major fall in sea level. Evidence comes from the relationship of the SBZ4 interval (Scheibner et al., 2000) with the ThSin5 boundary of Lüning, Marzouk and Kuss (1998) from east Sinai and Th4 of Hardenbol et al. (1998). In contrast, it was not possible to prove the presence of sequence boundaries ThSin3 and ThSin4 of Lüning, Marzouk and Kuss (1998) in the Sub-basin or in the Oweina area (Speijer and Schmitz, 1998) to the south.

Fluctuations in sea level on the latest Paleocene–Early Eocene ramp are indicated by lateral and vertical facies changes supported by the distribution of facies-relevant alveolinids (Gietl, 1998). Cycle boundary ThGal2 from the basal SBZ6 (Figure 5) may correspond to a mid-NP9 sea-level signal from the same interval in eastern Sinai. Productivity controls or hiatuses, however, cannot be excluded here as possible causes of variations in planktonic-benthonic ratios (Lüning, Marzouk and Kuss, 1998). The exact age of the later YpGal1 cycle boundary (basal SBZ10/P6-P7 boundary interval) is difficult to determine because of poor stratigraphic resolution based on alveolinids in the ramp carbonates. YpGal1 may be equivalent to the YpSin1 sequence boundary, the determination of which is also difficult (Lüning, Marzouk and Kuss, 1998) because of the diachronous character of the lithologic boundaries.

COMPARISON WITH OTHER REGIONS OF SYRIAN ARC DEFORMATION

The deformational history of the Syrian Arc is difficult to unravel because of the marked changes in the intensities of deformation in time and space. For example, few major phases of uplift represent peaks of deformation that are comparable from one area to another. Nevertheless, they help in understanding the geodynamic processes that acted along the northern rim of the African-Arabian Plate, and give clues that help in the elucidation of the neighboring southeastern Mediterranean Plate puzzle. Sharar (1994) estimated a 400- to 600-m uplift during the Late Turonian–Eocene in the Sinai-Negev Fold Belt. Hirsch et al. (1995) reconstructed initial, main, and late phases of compression pulses for the Negev Fold Belt from the Coniacian to the Miocene. Based on continent-wide comparisons, Guiraud and Bosworth (1996) assumed several Late Cretaceous compressive events but they rejected the model of a long-lasting compressional regime. Their interpretation was of Late Santonian deformation and Campanian rifting, followed by compression phases during the Late Maastrichtian and in the Miocene (Aquitanian-Burdigalian and Tortonian times). On a wider regional scale, the relationship of Syrian Arc tectonics to Late Cretaceous African deformational events is presently unknown (Bosworth et al., 1999) because of the absence of exact stratigraphic evidence for the respective intervals of deformation.

The first evidence of Late Cenomanian–Turonian compression between the northeastern part of the African-Arabian Plate and the Eurasian Plate seems to predate initial uplift in the Syrian Arc. The collision zone is flanked by an ophiolite belt of Late Cretaceous age that extends from Cyprus to Oman. Post-Cenomanian compression regimes are described from Turkey and Oman by Collins and Robertson (1997) and by Patton and O'Connor (1988). The compressions correlate with the first inversion movements in the Syrian Arc system (Moustafa, 1988) that began in Early Turonian times along older deep-seated extensional faults. An example is at Abu Roash in Egypt (location 4 on inset map, Figure 1). In the Negev, Honigstein et al. (1988) reconstructed a major Late Turonian–Early Santonian tectonic phase based on short-distance thickness changes and biostratigraphically well-constrained onlap patterns.

A good reference area for several Late Cretaceous–Paleogene uplift phases is the Areif el Naqa anticline in northeastern Sinai (location 2 on inset map, Figure 1). The anticline is part of the southern branch of the Syrian Arc (Lüning, Kuss et al., 1998). Lateral facies changes and thickness changes are linked to the anticlinal geometry and reflect Coniacian–Santonian basin inversion (Bartov et al., 1980). Age-equivalent tectonic activity was described from other localities of northern Sinai, where Upper Coniacian sediments are missing (Lewy, 1975) while, at the same time, central Sinai was covered by the sea. Similar results (although poorly constrained by biostratigraphy) are based on interpretations of seismic profiles. The profiles show evidence of Late Cretaceous to Oligocene onlap against synsedimentary rising anticlines in the Negev-Sinai Fold Belt (Ayyad and Darwish, 1996) and the Palmyride Fold Belt (Chaimov et al., 1992).

The culmination of Syrian Arc movements at Areif el Naqa during Late Campanian to Early Maastrichtian times may be coeval with uplift in the Northern Galala area. The movements are documented by reworked sandstones and silicified limestones that accumulated on the flanks of the Areif el Naqa anticline while the crest was exposed above the level of the Late Cretaceous sea. A similar situation prevailed in other Syrian Arc anticlines of Sinai and the Negev. In contrast, the Late Campanian to Maastrichtian deposits of the Northern Galala / Wadi Araba Uplift were formed in an adjacent carbonate platform setting (Figures 3 and 4).

Similar carbonate platforms rimmed the Northern Galala / Wadi Araba Uplift during Paleocene to Eocene times (Figure 3). Age-equivalent rocks in the Areif el Naqa anticline are composed of hemipelagic marls and chalks gently inclined relative to the underlying folded Late Cretaceous deposits (Lüning, Kuss et al., 1998). This Late Paleocene angular unconformity is present elsewhere in Sinai (Moustafa and Khalil, 1995) and in northern Negev (Zur et al., 1995). A major uplift phase in the Gulf of Suez region was described by Patton et al. (1994). It commenced in the Late Paleocene and it may be coeval with the second phase of ramp progradation at sequence boundary SelGal? (Figure 5) of the Northern Galala / Wadi Araba Uplift.

IMPLICATIONS FOR THE HYDROCARBON POTENTIAL

The Late Campanian to Early Eocene shallow-water limestones of the Galala plateaus contrast with age-equivalent lithologies described from most of the other areas of uplift in the Syrian Arc. For example, chalky, shaly and marly rocks occur at Abu Roash near Cairo (Moustafa, 1988), at Areif el Naqa in eastern Sinai (Lüning, Kuss, et al., 1998), and are interpreted from subsurface seismic data (Ayyad and Darwish, 1996). Slumps, thin silt-sand intercalations, stratigraphic discontinuities or onlap patterns indicate gravity flows from submarine slopes or islands that, however, are not rimmed by Galala-type carbonate platforms.

Cretaceous–Tertiary platform carbonates that were deposited on the southern shores of the Neo-Tethyan Ocean (Figure 3) contain significant hydrocarbon resources. Many of the carbonates are important reservoirs with porosities due to the interplay of primary, secondary and later diagenetic alterations, or they are source rocks formed mainly during marine transgressions. Kerogen-rich limestones often develop in intrashelf basins, such as the Late Aptian–Cenomanian of the Sinai ramp (Kim et al., 1999) or the productive Cenomanian-Turonian platform deposits of the Arabian Gulf (Alsharhan and Nairn, 1994). Similarly, the Late Cretaceous–Early Tertiary carbonates of the Northern Galala / Wadi Araba

Uplift contain source-rock facies that are characterized by laminated argillaceous and shaley lime-mudstones and wackestones. If the down-faulted Galala-type sediments in the Gulf of Suez are similar, we may expect to find mature organic-rich carbonate deposits there that were formed in intrashelf basins of the Late Campanian–Eocene carbonate platforms. For example, the source rock of the Zafarana field in the Gulf of Suez is probably composed of organic-rich Senonian-Eocene carbonate deposits.

CONCLUSIONS

The stratigraphic evolution of the Upper Cretaceous–Paleogene succession of the Galala plateaus in the Eastern Desert of Egypt was controlled by a Syrian Arc Uplift that defined the subsequent basin-and-swell morphology. During Late Campanian times, the Northern Galala / Wadi Araba Uplift was formed, as indicated by southward-prograding slope deposits of a Transition Zone that links the Uplift with the Southern Galala Sub-basin of the Eastern Desert Intrashelf Basin (Figure 1). The Sub-basin is the result of the southward prograding Late Cretaceous–Paleogene sedimentary wedges of the Transition Zone causing loading and subsequent subsidence. The slope deposits of the Transition Zone interfinger with neritic and hemipelagic sediments of the Sub-basin. The successive Paleogene sequences are evidence for a gradual southward movement of the Transition Zone (Figure 1).

The platform to basin transition of the Galala area is reflected in the facies architecture (Figure 4) and the sedimentologic and paleoecologic variations. It is controlled mainly by the interplay of uplift and subsequent erosion, re-deposition, biogenic sedimentation, and sea-level changes. An analysis of the prograding depositional geometry of the Uplift margin and of the slope deposits of the Transition Zone reveal changing margin morphologies that evolved spatially and temporally into each other. Consequently, the Late Cretaceous rimmed platform is followed by a distally steepened Paleocene ramp and overlain by an Early Eocene homoclinal ramp (Figure 4). Only the slope deposits of the Transition Zone give evidence of the now eroded Upper Cretaceous carbonate shelf. On a regional scale, rare occurrences of well-bedded shallow-water carbonates may be equivalent to the Early Paleocene carbonate platform in the Galala area. Carbonate production resumed in most parts of the Galala Uplift during Late Paleocene times and resulted in the deposition of massive carbonates.

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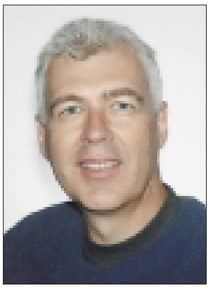

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