Planktonic foraminiferal biostratigraphy and paleoecology of Upper Cretaceous deposits from the Palmyride Region, Syria

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ABSTRACT

This study represents a detailed micropalaeontological investigation of the composition and diversity of planktonic foraminiferal assemblages from the upper Turonian to Maastrichtian interval of two deep exploration wells (Al Mahr-1 and Palmyra-1) in the Palmyride area of Syria. In combination with lithostratigraphic analysis, this detailed biostratigraphic study provided important new palaeoecological and palaeoclimatic interpretations and insights into the nature of deposition along the northern passive margin of Gondwana during the Late Cretaceous.

The investigated strata belong to three lithostratigraphic units (from base to top): the upper part of the Judea Formation (upper Turonian–lowermost Santonian), the Soukhne Formation (Santonian–lower Campanian), and the Shiranish Formation (upper Campanian–Maastrichtian). The results represent the first detailed determination of planktonic foraminifera from the Palmyride region. The presence of rich and diverse foraminiferal associations enabled the establishment of the following nine late Turonian to Maastrichtian biostratigraphic zones, based on documented index-taxa and/or the entire microfossil assemblages: I) Biozone I; II) Biozone II; III) Biozone III; IV) Contusotruncana plummerae Zone; V) Biozone IV; VI) Globotruncanella havanensis Zone; VII) Pseudoguembelina palpebra Zone; VIII) Racemiguembelina fracticosa Zone; and IX) Abathomphalus mayaroensis Zone. The late Turonian to early Campanian foraminiferal assemblages (biozones I–IV) are dominated by opportunistic taxa (r-strategists) and suggest a generally fluctuating subtropical climate and deposition in outer shelf environments. The well-preserved and highly diversified late Campanian to Maastrichtian foraminiferal assemblages (biozones V–IX) imply the presence of a well-stratified water column, tropical to subtropical climate, and deposition in outer shelf to upper bathyal environments. A decrease in the number of globotruncanid species during the late Maastrichtian indicates a less stratified water column and unfavourable environmental conditions for K-strategists.

The common occurrence of phosphate grains in the Soukhne Formation (Santonian–lower Campanian) represents an important indicator of specific geological and palaeoenvironmental conditions, such as oxygen deficiency, upwelling and transgression. These conditions support the interpretation of the domination by opportunistic planktonic foraminiferal taxa (heterohelicids and muricohedbergellids) in Biozone II.

Keywords: Planktonic foraminifera, Biostratigraphy, Phosphatic grains, Upper Turonian–Maastrichtian, Palmyride region, Syria

1. INTRODUCTION

The Palmyride area is part of the northern Arabian platform (Fig. 1). The Arabian platform was located on the northern passive margin of Gondwana bordering the Tethys Ocean for most of the Phanerozoic. The Palmyride fold belt was established at the site of an inverted Mesozoic rift basin and
developed as a linear trough genetically related to the Levantine margin rift system, which formed along a Gondwana Proterozoic suture zone (BREW, 2001). Ongoing extension produced a 6 km thick and 200 km laterally extensive Palaeozoic and Mesozoic sedimentary succession (BREW, 2001). Tectonic evolution of the area has been strongly influenced by geological activity along the Arabian plate boundaries: the Dead Sea transform fault to the west, the Bitlis suture and East Anatolian fault to the north, and the Zagros suture to the east (Fig. 1).

This study focuses on the Upper Cretaceous (upper Turonian–Maastrichtian) succession from two deep exploration wells Al Mahr-1 and Palmyra-1, and was aimed at age determination and correlation (litho- and biostratigraphic) of strata based on their microfossil assemblages (mainly planktonic and some benthic foraminifera). Planktonic foraminifera have been abundant in most oceanic environments since their appearance in the Middle Jurassic and are the most commonly used microfossil group for biostratigraphic zonation and reconstruction of past sea surface-water conditions and palaeoclimate (HEMLEBEN et al., 1989; MURRAY, 1991).

Many studies have focused on biostratigraphic evolution of Cretaceous planktonic foraminifera (e.g., ROBASZYN-SKI et al., 1984; 2000; CARON, 1985; SLITER, 1989; ROBASZYN-SKI & CARON, 1995; PETRIZZO, 2003; PREMOLI SILVA & VERGA, 2004; SARI, 2006, 2009; BABAZADEH et al., 2007; HUBER et al., 2008; PETRIZZO et al., 2011; GARDIN et al., 2012). Previous biostratigraphic investigations of the Upper Cretaceous deposits in the Palmyride area were undertaken on material from deep exploration wells by LUČIĆ (2001), STANKOVIĆ et al. (2003; 2005), and DACER et al. (2007), but not in a great detail.

The main purpose of this paper is to establish planktonic foraminiferal zonation of the upper Turonian–Maastrichtian succession of the Palmyride area based on the microfossil assemblages and/or index taxa present in order to improve palaeoenvironmental interpretations of deposition in the Palmyride basin during the late Cretaceous. The biostratigraphic zonation is compared with the regional Tethyan zo-
nation. Documenting variations in planktonic foraminiferal assemblages and any associated lithological changes are critical for making paleoecological and palaeoceanographic interpretations. Santonian to early Campanian sediments rich in phosphate grains are examined here as an important indicator of specific geological and palaeoenvironmental conditions. The data obtained are compared to those from other coeval regional successions in order to establish the significance of the Palmyride strata, as part of the Arabian platform, for better understanding of the sedimentary evolution of the broader Tethyan region and its response to global environmental changes.

2. GEOLOGICAL SETTING

Regionally the investigated area is also known as the Hayan exploration block (Fig. 1), which is located in the Palmyride area, an intracontinental transpressive mountain range (LUČIĆ, 2001). The Palmyrides represent the most distinct tectonic and structural unit in central Syria as a zone of subdued topography that extends from the Dead Sea Fault Zone to the west, and disappears to the east at the Euphrates Graben or depression (Fig. 1). The Palmyrides are 400 km long and 100 km wide, stretching southwest–northeast across Syria with a maximum altitude of around 1300 m (LUČIĆ & FORŠEK, 2000; BREW, 2001; BREW et al., 2001; HERNITZ KUČENJAK et al., 2006; WOOD, 2011).

In the Palmyride area, Mesozoic deposits of Early Triassic to Late Cretaceous age were observed in all deep wells (LUČIĆ et al., 2002). Unlike the Upper Triassic and Jurassic deposits (maximum 700 m thick), which can either exhibit substantially reduced thickness (to 200 m minimum) or be absent in some places due to erosion or non-deposition, the Cretaceous strata are present throughout the region (approx. 800 m thick). The oldest deposits exposed on the surface are Upper Triassic evaporites interbedded with shales. Jurassic deposits are represented by different varieties of carbonate rocks, and Lower Cretaceous deposits consist of dolomites and limestones with rare interbeds of anhydrite and shale. In the Late Cretaceous there was a deepening of the depositional system, which resulted in the deposition of shales and marly limestones with a gradual increase in the amount of marl up-section (PONIKAROV, 1966a, b; LUČIĆ et al., 2002).

For the purpose of the Syrian Petroleum Company (SPC), the investigated Upper Cretaceous succession is subdivided into three lithostratigraphic units (Figs. 2, 3): 1) the upper part of the Judea Formation (upper Turonian–lowerest Santonian); 2) the Soukhne Formation (Santonian–lower Campanian); and 3) the Shiranish Formation (upper Campanian–Maaschichtian); (MOUTY & AL­MALEH, 1983). The Judea Formation is represented by limestones and dolomitic limestones with thin intercalations of yellow to brownish yellow marl. The Soukhne Formation is characterized by calcareous horizons in the lower part, and by clayey limestones, marls and phosphatic deposits in the upper part. Argillaceous limestones, marls, chert and ovoid calcareous concretions (10–30 cm in diameter) are present in the Shiranish Formation.

3. MATERIAL AND METHODS

The foraminiferal study is based on analyses of 81 samples of Upper Cretaceous deposits obtained as drill cuttings from two deep exploration wells (Al Mahr-1 and Palmyra-1) drilled in the Hayan exploration block in the Palmyride area. Samples of drill cuttings from mud samples were collected every 5–10 metres. Most of the analyzed samples contain very well preserved planktonic and benthic foraminifera.

Samples for micropaleontological analyses were disaggregated in tap water and diluted with hydrogen peroxide, then washed through 63 μm, 125 μm, and 160 μm sieves, dried and examined on an Olympus SZX16 stereomicroscope. Representative aliquots of approximately 300 planktonic foraminiferal specimens were counted for quantitative planktonic foraminiferal analyses. The term “dominant” was used for species that constitute more than 10% of the planktonic foraminiferal assemblage, whereas the terms “common”, “fewand”, “rare” refer to species comprising 3–10%, 1–3%, and <1% of the assemblage, respectively. Plankton/benthic ratios were determined for each biozone on at least 300 specimens from the entire foraminiferal assemblages in >63 μm grain fraction and were used for palaeoecologic and palaeoenvironmental interpretations.

Micropaleontological investigation was focused on the vertical distribution, diversity and composition of mainly planktonic and less abundant benthic foraminiferal assemblages (Figs. 2–3) according to GAWOR­BIEDOWA (1984), LOEBLICH & TAPPAN (1988), ISMAIL (1992), BOLLI et al. (1994), LY & KUHNT (1994), KAIHO (1998), PREMOLI SILVA & VERGA (2004), ISMAIL et al. (2007), HAMPTON et al. (2007), and GASINSKI & UCHMAN (2009). The presence of rich and diverse foraminiferal associations enabled biostatigraphic zonation of the Upper Turonian to Maaschichtian deposits based on documented index-taxa and/or the entire microfossil assemblages. Standard planktonic foraminiferal zonation after ROBASZYNSKI et al. (1984), CARON (1985), ROBASZYNSKI & CARON (1995), PREMOLI SILVA & SLITER (1994), ROBASZYNSKI et al. (2000), PREMOLI SILVA & VERGA (2004), SARI (2006, 2009), HUBER et al. (2008), OGG et al. (2008), PETRIZZO et al. (2011) and PÉREZ­RODRÍGUEZ et al. (2012) have been used. A zonal sheme which emphasizes the lowest (LO) and the highest occurrences (HO) of index taxa and/or selected species in microfossil associations has been applied.

Phosphatic grains of the Soukhne Formation deposits were also analyzed using SEM back-scattered electron imaging (BSE) and energy dispersive X-ray analysis (EDX). The semi-quantitative X-ray elemental mapping of P, F, Cl
Figure 2: Stratigraphic column of the Al Mahr-1 exploration well showing stratigraphic distribution of planktonic foraminifera (Formation names after SPC – Syrian Petroleum Company).

Biozones:

I (Late Turonian–Early Santonian)
II (Middle–Late Santonian)
III (Early Campanian)
IV Globotruncana plummerae Zone (Early–Middle Campanian)
V (Late Campanian)
VI Globotruncanella havanensis Zone (Late Campanian)
VII Pseudoguembelina palpebra Zone (Late Campanian)
VIII Racemiguembelina fructicosa Zone (Late Campanian–Early Maastrichtian)
IX Abathomphalus mayaroensis Zone (Late Maastrichtian)
Figure 3: Stratigraphic column of the Palmyra-1 exploration well showing stratigraphic distribution of planktonic foraminifera (Formation names after SPC – Syrian Petroleum Company).

Biozones:

I (Late Turonian–Early Santonian)
II (Middle–Late Santonian)
III (Early Campanian)
IV Globotruncana plummerae Zone (Early–Middle Campanian)
V (Late Campanian)
VI Globigerinoides havanensis Zone (Late Campanian)
VII Pseudoguembelina palpebra Zone (Late Campanian)
VIII Racemiguembelina fructicosa Zone (Late Campanian–Early Maastrichtian)
IX Abathomphalus mayaroensis Zone (Late Maastrichtian)
Figure 4: Correlation between the two exploration wells (Al Mahr-1, Palmyra-1) showing planktonic biozones and lithology.
and Ca was performed using a FEI Quanta 450 SEM with EDAX TEAM EDS at Smith College (Northampton, Massachusetts, USA).

4. BIOSTRATIGRAPHY

Biostratigraphic subdivision of the investigated Upper Cretaceous successions is based on planktonic foraminifera. Stratigraphic ranges of the identified microfossil assemblages indicate a late Turonian to Maastrichtian age. Stratigraphic relationships between the identified planktonic foraminiferal species are shown in Figs. 2 and 3, whereas the lithostratigraphic and biostratigraphic biozonation correlation between Al Mahr-1 and Palmyra-1 are presented in Fig. 4.

The upper Turonian to lowermost Santonian deposits contain planktonic and benthic foraminiferal assemblages characteristic of this stratigraphic range. These poorly diversified microfossil assemblages have equal proportions of small benthic and planktonic foraminifera. The Santonian to lower Campanian strata, on the other hand, are characterized by a moderately diversified microfossil assemblage with increased abundance and diversity of planktonic foraminifera, and the absence of nominal taxon/zonal markers. High diversity microfossil assemblages with a dominance of planktonic foraminifera and well-preserved index taxa are present in the upper Campanian to upper Maastrichtian deposits.

Previous studies of late Cretaceous planktonic foraminifera from the Palmyrides only generally indicated the age of the deposits (STANKOVIĆ et al., 2003, 2005; DACER et al., 2007). Biostratigraphy of the upper Turonian to Maastrichtian successions from the Al Mahr-1 and Palmyra-1 wells is correlated with the existing and well-established planktonic foraminiferal zonation for the Tethyan realm (ROBASZYNSKI & CARON, 1995; ROBASZYNSKI et al., 2000; PREMOLI SILVA & SLITER, 2004). Fig. 5. Since the zonal markers are very rare or absent, alternative planktonic foraminiferal assemblages as well as the whole planktonic foraminiferal association enable application of standard biozonation (ROBASZYNSKI et al., 1984; CARON, 1985; SLITER, 1989; PREMOLI SILVA & SLITER, 1994; ROBASZYNSKI & CARON, 1995; ROBASZYNSKI et al., 2000; PREMOLI SILVA & VERGA, 2004; CHACON et al., 2004; HUBER et al., 2008; SARI, 2009; PETRIZZO et al., 2011; PEREZ-RODRIGUEZ et al., 2012).

Nine biozones have been identified in the upper Turonian to Maastrichtian succession: Biozone I, Biozone II, Biozone III, IV Contusotruncana plummerae Zone, Biozone V, VI Globotruncanella havanensis Zone, VII Pseudoguembelina palpebra Zone, VIII Rouseiniquelmisica Zone, and IX Abathomphalus mayorensis Zone. A list of taxa together with author names and year of publication are provided in the Appendix. All of the diagnostic species and some additional taxa typical of the studied foraminiferal assemblages are illustrated in Figs. 6–9.

Biozone I (Figs. 6A–D)

Age. Late Turonian–Early Santonian

Interval. Al Mahr-1 (185–210 m, Figs. 2 and 4), Palmyra-1 (180–200 m, Figs. 3, 4)

Assemblage characteristics. As index taxa were not observed, the lowest occurrence (LO) of Contusotruncana fornicata and Globigerinelloides bollii has been used to define the lower boundary of this Zone. This biozone may correspond to the Dicarinella concavata Zone (PREMOLI SILVA & SLITER, 1994; ROBASZYNSKI & CARON, 1995; ROBASZYNSKI et al., 2000; PREMOLI SILVA & VERGA, 2004; SARI, 2006, 2009).

The foraminiferal assemblage of this interval is composed of rare non-keeled planktonic foraminifera with a wide stratigraphic range: Archaeoglobigerina blowi, A. cretacea (Figs. 6C, D), Whiteinella balthica, Whiteinella sp., Dicarinella sp. (Fig. 6A) and Marginotruncana sp. (Fig. 6B). In the middle of the biozone Muricochederbergella holmdelensis and Pseudotextularia nuttalli have their lowest occurrence.

The most abundant species in the assemblage are Heterohelix reussii, H. moremani, and H. globulosa, comprising 38% of the total planktonic foraminiferal association. Biozone I is also characteristic by very common Pseudotextularia nuttalli, Muricochederbergella holmdelensis, Muricochederbergella flandrii, marginotruncanids and whiteinellids. In addition, the following small calcareous benthic foraminifera are present and account for up to 50% of the total foraminiferal association: Bulimina ovulum, Gyroidinoides globosus, Bulimina sp., Gavellinela sp. (Figs. 9A, B), Lenticulina sp., and Nodosaria sp.

Lithology and palaeoenvironment. Brownish grey to grey limestone (mudstone/wackestone to foraminiferal wackestone), dolomitic limestone and marl with equal proportions of planktonic and calcareous benthic foraminifera indicate accumulation within outer shelf environments.

Biozone II (Figs. 6E–I)

Age. Middle–Late Santonian

Interval. Al Mahr-1 (150–185 m, Figs. 2 and 4), Palmyra-1 (140–180 m, Figs. 3, 4)

Assemblage characteristics. Because of the absence of a zonal marker, the lower boundary of this Zone is defined approximately by the LO of Globotruncanella hovanniana, whereas the upper boundary coincides with the disappearance of all dicarinellids and whiteinellids. This biozone may correspond to the Dicarinella asymetria Zone (PREMOLI SILVA & SLITER, 1994; ROBASZYNSKI & CARON, 1995; ROBASZYNSKI et al., 2000; PREMOLI SILVA & VERGA, 2004; SARI, 2006, 29).

The first half of Biozone II is characterized by the LO of several new taxa such as Globotruncanella bulloides, G. hilli, G. arca, Hendersonites carinatus, Heterohelix striata, H. punctulata, H. planata, Globigerinelloides prairiehillerensis and G. subcarinatus. Dominant species in this Zone are Heterohelix globulosa and H. reussi (Fig. 6I), while Pseudotextularia nuttalli and Heterohelix punctulata are very common. The following planktonic foraminifera continue from the underlying zone: Archaeoglobigerina blowi (Figs. 6E, F), A. cretacea, Contusotruncana fornicata (Figs. 6G, H), Globigerinelloides bollii, Muricochederbergella holmdelensis and Marginotruncana sp. Globotruncanella arca, G. bulloides, and G. linneiana range throughout Biozone II but are
Figure 5: Proposed biozonation for the Upper Cretaceous succession and stratigraphic range of selected species of the Palmyride region compared with the zonal schemes for Tethys (ROBASZYNSKI and CARON, 1995; PREMOLI SILVA & VERGA, 2004). Timescale was adapted from OGG et al. (2008), and sea-level curve is from HAQ et al. (1987). Grey area indicates the presence of phosphate grains.

<table>
<thead>
<tr>
<th>Biozone</th>
<th>Age</th>
<th>Interval</th>
<th>Lithology and palaeoenvironment</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>Early Campanian</td>
<td>Al Mahr-1 (120–150 m), Palmyra-1 (115–140 m)</td>
<td>Foraminiferal mudstone/wackestone, marl, dolomitic limestones with phosphate grains.</td>
</tr>
<tr>
<td>III</td>
<td>Early Campanian</td>
<td>Al Mahr-1 (120–150 m), Palmyra-1 (115–140 m)</td>
<td>Foraminiferal mudstone/wackestone, marl, dolomitic limestones with phosphate grains.</td>
</tr>
<tr>
<td>IV</td>
<td>Early Campanian</td>
<td>Al Mahr-1 (120–150 m), Palmyra-1 (115–140 m)</td>
<td>Foraminiferal mudstone/wackestone, marl, dolomitic limestones with phosphate grains.</td>
</tr>
<tr>
<td>V</td>
<td>Early Campanian</td>
<td>Al Mahr-1 (120–150 m), Palmyra-1 (115–140 m)</td>
<td>Foraminiferal mudstone/wackestone, marl, dolomitic limestones with phosphate grains.</td>
</tr>
<tr>
<td>VI</td>
<td>Early Campanian</td>
<td>Al Mahr-1 (120–150 m), Palmyra-1 (115–140 m)</td>
<td>Foraminiferal mudstone/wackestone, marl, dolomitic limestones with phosphate grains.</td>
</tr>
<tr>
<td>VII</td>
<td>Early Campanian</td>
<td>Al Mahr-1 (120–150 m), Palmyra-1 (115–140 m)</td>
<td>Foraminiferal mudstone/wackestone, marl, dolomitic limestones with phosphate grains.</td>
</tr>
<tr>
<td>VIII</td>
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<td>Al Mahr-1 (120–150 m), Palmyra-1 (115–140 m)</td>
<td>Foraminiferal mudstone/wackestone, marl, dolomitic limestones with phosphate grains.</td>
</tr>
<tr>
<td>IX</td>
<td>Early Campanian</td>
<td>Al Mahr-1 (120–150 m), Palmyra-1 (115–140 m)</td>
<td>Foraminiferal mudstone/wackestone, marl, dolomitic limestones with phosphate grains.</td>
</tr>
</tbody>
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**Proposed Biozonation**

Biozone I (Figs. 6J–N)

**Age.** Early Campanian

**Interval.** Al Mahr-1 (120–150 m, Figs. 2 and 4), Palmyra-1 (115–140 m, Figs. 3, 4)

**Assemblage characteristics.** The main characteristics of the microfossil assemblage is the disappearance of margi- notruncanids at the base of this biozone while *Pseudoguembelia costulata* has its lowest occurrence. Rugoglobigerina rugosa first occurs in the middle part of Biozone III, whereas *Heterohelix ruessi* has its highest occurrence (HO). This bi-

**Figure 6:**

- **Figure 6A:** Diagram showing the stratigraphic position of selected species in Biozone I.
- **Figure 6B:** Diagram showing the stratigraphic position of selected species in Biozone II.
- **Figure 6C:** Diagram showing the stratigraphic position of selected species in Biozone III.
- **Figure 6D:** Diagram showing the stratigraphic position of selected species in Biozone IV.
- **Figure 6E:** Diagram showing the stratigraphic position of selected species in Biozone V.
- **Figure 6F:** Diagram showing the stratigraphic position of selected species in Biozone VI.
- **Figure 6G:** Diagram showing the stratigraphic position of selected species in Biozone VII.
- **Figure 6H:** Diagram showing the stratigraphic position of selected species in Biozone VIII.
- **Figure 6I:** Diagram showing the stratigraphic position of selected species in Biozone IX.
Figure 6: SEM photomicrographs of selected planktonic foraminifera observed in Biozone I (A–D), Biozone II (E–I), Biozone III (J–N) and Contusotruncana plummerae Zone (Biozone O, P). A Dicarinella sp., Palmyra-1, interval 190–200 m. B Marginotruncana sp., Al Mahr-1, interval 190–200 m. C, D Archaeoglobigerina cretace (C), and detail of the wall texture (D), Al Mahr-1, interval 185–190 m. E, F Archaeoglobigerina blowi (E), and detail of the wall texture (F), Palmyra-1, interval 160–170 m. G Contusotruncana fomicata, Al Mahr-1, interval 155–160 m. H Heterohelix reussi, Palmyra-1, interval 140–150 m. I Heterohelix globulosa, Palmyra-1, interval 130–140 m. K, L Muricohedbergella holmdelensis, Palmyra-1, interval 120–130 m. M, N Heterohelix striata (M), and detail of the wall texture (N), Al Mahr-1, interval 120–130 m. O, P Contusotruncana plummerae, Palmyra-1, interval 100–110 m.
Dominant species in the planktonic foraminiferal assemblage are *Hendersonites carinatus*, *Heterohelix striata*, *H. punctulata* and *Pseudotextularia muttalli*, while *Globigerinelloides bollii* is very common. In addition, the microfossil assemblage contains the following planktonic foraminifera that continue from Biozone II: *Globotruncanita elevata*, *G. arca*, *G. subcarinatus*, *Laeviheterohelix dentata*, *G. hilli*, *G. arca*, *Globotruncanita stuartiformis*, *Heterohelix globulosa* (Fig. 6J), *H. planata*, *Globigerinelloides prairiehillensis*, *G. subcarinatus*, *Muricochedergerella holmdelensis*, and *Muricochedergerella* sp. Specimens of the genus *Heterohelix* remain diverse and constitute the most abundant group in the microfossil association with 47% of the planktonic foraminiferal assemblage. Most of the calcareous benthic foraminifera that persisted from the underlying Biozone II, and comprise up to 35% of the microfossil assemblage, include *Bulimina ovulum*, *Bulimina sp.* (Fig. 9E), *Gyroidinoides globosus*, *Lenticulina rotulata*, *Lenticulina sp.*, and *Oridosalis sp.*

**Biozone IV: *Contusotruncanana plummerae* Zone (Figs. 6O, P, 7A, B)**

**Definition.** Stratigraphic interval from the LO of *Contusotruncanana plummerae* to the LO of *Radotruncanella calcarea* (PETRIZZO et al., 2011)

**Age.** Early to Middle Campanian

**Interval.** Al Mahr-1 (85–120 m, Figs. 2 and 4), Palmyra-1 (80–115 m, Figs. 3, 4)

**Assemblage characteristics.** Beside the LO of the zonal marker *Contusotruncanana plummerae* (Figs. 6O, P) the lower boundary of this biozone is also characterized by the LO of *Hendersonites carinatus* and by the first occurrence of *Laeviheterohelix glabrans*, *Muricochedergerella moumoutnoushis* and *Heterohelix navarroensis*.

The planktonic foraminiferal assemblage is similar to that in Biozone III. However, planktonic foraminifera are more abundant and the overall number of species increased. The dominant species include *Heterohelix striata, H. planata, Pseudoguembelina costulata* and *Pseudotextularia muttalli*. In addition, the assemblage is characterized by common *Muricochedergerella holmdelensis*, *M. moumoutnoushis*, *Globigerinelloides bollii* (Fig. 7A), *G. subcarinatus* and *Heterohelix globulosa*. Other species in this Zone include: *Archaeoglobotherioides* (Fig. 7B), *A. cretacea, Contusotruncanana fornicata, Globotruncanana arca, G. bulloides, G. linneiana, G. hilli, Globotruncanita stuartiformis, Heterohelix punctulata, Globigerinelloides prairiehillensis, Muricochedergerella* sp. and *Rugoglobigerina rugosa*. Representatives of the genus *Heterohelix* decrease in abundance to 32%, whereas pseudoglobalbeldinids increase in diversity as well as in abundance and can account for up to 10.5% of the total assemblage.

The amount of calcareous benthic foraminifera decreases to 30% of the assemblage. The most common taxa include *Bulimina ovulum*, *Gavelinella monterelesis* (Fig. 9C), *Gyroidinoides globosus*, *Lenticulina rotulata*, *Lenticulina* sp. (Fig. 9F), *Gavelinella sp.*, *Gyroidinoides* sp., and *Cibicides* sp.

**Biozone V (Figs. 7C–G)**

**Age.** Late Campanian

**Interval.** Al Mahr-1 (80–85 m, Figs. 2 and 4), Palmyra-1 (75–80 m, Figs. 3, 4)

**Assemblage characteristics.** Since the zonal marker is very rare and generally poorly preserved, the base of Biozone V is marked by the LO of *Laeviheterohelix dentata, Globotruncanella havanensis* and *Globotruncanella stuartii*. This biozone may correspond to the *Radotruncanella calcarea* Zone (ROBASZYNSKI & CARON, 1995; PREMOLI SILVA & SLITER, 1994; ROBASZYNSKI et al., 2000; PREMOLI SILVA & VERGA, 2004; SARI, 2006, 2009; HUBER et al., 2008).

The species *Heterohelix labellosa* appears in the middle part of Biozone V. The planktonic foraminiferal assemblage of this Biozone is abundant and highly diversified. Most planktonic foraminifera persist from the underlying Biozone IV, including *Archaeoglobotherioides* (Fig. 7E, F), *G. bulloides, G. linneiana, G. hilli, Heterohelix globulosa, H. navarroensis, H. planata, H. punctulata, H. striata, Globigerinelloides bollii, G. prairiehillensis* (Fig. 7G), *G. subcarinatus*, *Laeviheterohelix glabrans, Muricochedergerella holmdelensis, M. moumoutnoushis, Muricochergerella* sp., *Pseudoguembelina costulata, Pseudotextularia muttalli* (Fig. 7C), and *Rugoglobigerina rugosa* (Fig. 7D). The genus *Heterohelix* constitutes 38% of the assemblage and remains the most abundant group in the planktonic association. In comparison with previous biozones, the diversity of Biozone V increases and the total number of planktonic foraminifera reaches 27 species.

Small benthic foraminifera comprise less than 20% of the assemblage and include *Bolivina incrassatae*, *Gavelinella monterelesis*, *Gavelinella sp.*, *Gyroidinoides globosus*, *Lenticulina rotulata*, *Lenticulina* sp., *Neoflabeolina reticulata*, *Serovaina complanata*, and *Cibicides* sp.

**Lithology and palaeoenvironment.** Argillaceous limestone (wackestone) and marl, as well as calcareous marble with abundant planktonic foraminifera (70%) indicate outer shelf to upper bathyal depositional environments.

**Biozone VI: *Globotruncanella havanensis* Zone (Figs. 7H–J)**

**Definition.** Partial range Zone from the LO of *Globotruncanella havanensis* to the LO of *Pseudoguembelina palpebra* (HUBER et al., 2008)
Age. Late Campanian

Interval. Al Mahr-1 (70–80 m, Figs. 2 and 4), Palmyra-1 (65–75 m, Figs. 3, 4)

Assemblage characteristics. The zonal marker Globotruncanella havanaensis (Fig. 7H) is relatively rare, while species Pseudoguembelina excolata, Planoglobulina carseya and Rugoglogiberina hexacamerata have their lowest occurrence at the base of the Biozone IV.

The following planktonic foraminifera continue from the underlying Biozone V: Archaeoglobigerina blowi, A. cretacea, Contusotruncana fornicata, Globotruncanella arca, G. buloides, G. linneiana, G. hilli, Globotruncanita stuartiformis, G. stuarti, Heterohelix globulosa, H. navarroensis (Figs. 7I, J), H. planata, H. punctulata, H. striata, Globigerinelloides bollii, G. prairiehilli, G. subcarinatus, Laevigohelix globulosa, L. dentata, Muricoherdbergella holmdelensis, M. mounmothensis, Muricoherdbergella sp., Pseudoguembelina costulata, Pseudotextularia mutti, and Rugoglogiberina rugosa. In the middle of the biozone Globotruncanella petaloidea, Rugoglogiberina macrocephala and Guembelitria turrita have their LO. Species of genus Heterohelix remain the most abundant group in the micro-fossil assemblage with 37.5% representation. Globotruncanids increase in diversity (8 species) and abundance (13.5%), and become an important component of the planktonic assemblage. In addition, small benthic foraminifera comprise 15% of the total fauna and include Bolivina incrassata, Gavelinella monterelensis, Gavelinella sp., Gyroidinoides globosus, Lenticulina rotulata, Lenticulina sp., Neofulvetes reticulata, Serovaina complanata, Cibicidoides sp. (Fig. 9H), and an agglutinated form Spiroplectamina sp. (Fig. 9G).

Lithology and palaeoenvironment. Marl and argillaceous limestone (mudstone/wackestone) with abundant planktonic foraminifera (85%) suggest outer shelf to upper bathyal depositional environments.

Biozone VII: Pseudoguembelina palpebra Zone (Figs. 7K–P, 8A)

Definition. Partial range Zone from the LO of Pseudoguembelina palpebra to the LO of Racemiguelinbelina fructicosa (HUBER et al., 2008)

Age. Late Campanian–Early Maastrichtian

Interval. Al Mahr-1 (35–70 m, Figs. 2 and 4), Palmyra-1 (30–65 m, Figs. 3, 4)

Assemblage characteristics. Pseudoguembelina palpebra (Fig. 7N) is consistently present in this biozone. The first occurrence of Globotruncanella pschadae, Pseudoguembelina kempensis and Racemiguelinbelina powelli is recorded in the lower part of this biozone. Gansserinera gansseri (Figs. 7O, P) is present, but very rare, throughout this interval. Very common species in the assemblage include Heterohelix globulosa, Pseudoguembelina costulata (Fig. 7M), Heterohelix striata, and H. navarroensis. Common species include Heterohelix labellosa, Pseudoguembelina excolata, Pseudotextularia mutti, and Rugoglogiberina rugosa (Figs. 7L, 8A). Other representative species are Archaeoglobigerina blowi, A. cretacea, Contusotruncana fornicata, Globotruncanara arca, G. buloides, G. linneiana, G. hilli, Globotruncanella havanaensis, G. petaloidea, Globotruncanita stuarti, G. stuartiformis, Guembelitria turrita, G. cretacea, Heterohelix planata, H. punctulata, Globigerinelloides bollii, G. prairiehilli, G. subcarinatus, Laeviheterohelix dentata, L. glabrana, Muricoherdbergella holmdelensis, M. mounmothensis, Muricoherdbergella sp., Planoglobulina carseya, Rugoglogiberina hexacamerata (Fig. 7K), and R. macrocephala. The middle part of Biozone VII is characterized by the lowest occurrence of Abathomphalus intermedius, Globotruncanella minuta and Globotruncanita petterisi, while Globigerinelloides bollii become extinct. The upper part of this Biozone is also characterized by the lowest occurrences of Pseudotextularia intermedia and Globotruncanita conica. In comparison with Biozone VI, biodiversity significantly increases throughout Biozone VII and reaches the maximum of 41 species. This increase is partly related to speciation of globotruncanids, (represented by 12 species). The genus Heterohelix remains the dominant group with 34% abundance, whereas pseudoguembeliniids remarkably increase up to 17%. Globotruncanids, despite numerous species, represent 15% of the planktonic foraminiferal population.

Among calcareous benthic foraminifera the most common taxa are: Bolivina incrassata, Bolivinoides miliaris, Gavelinella monterelensis, Gavelinella sp., Gyroidinoides globosus, Lenticulina rotulata (Fig. 9J), Lenticulina sp., Neofulvetes reticulata (Fig. 9I), Oridorsalis umbonatus, Serovaina complanata, Cibicidoides sp., Nodosaria sp., and agglutinated Spiroplectamina sp. The proportion of small benthic foraminifera significantly decreases and they make up only 10% of the microfossil assemblage.

Lithology and palaeoenvironment. Marl and argillaceous limestone (mudstone/wackestone) with high proportions of planktonic species (up to 90%) imply continuous deepening of this marine realm and deposition in outer shelf to upper bathyal environments.

Biozone VIII: Racemiguelinbelina fructicosa Zone (Figs. 8B–E)

Definition. Partial range Zone from the LO of Racemiguelinbelina fructicosa to the LO of Abathomphalus mayeroensis (HUBER et al., 2008; PEREZ-RODRÍGUEZ et al., 2012)

Age. Early Maastrichtian

Interval. Al Mahr-1 (30–35 m, Figs. 2 and 4), Palmyra-1 (25–30 m, Figs. 3, 4)

Assemblage characteristics. Beside the nominate species Racemiguelinbelina fructicosa (Fig. 8E). Planoglobulina acervulinae and Pseudotextularia elegans are also recorded for the first time in the lower part of this biozone. In the same horizons Contusotruncana fornicata and C. plummerae have their HO. Dominant species in the assemblage are Heterohelix globulosa, H. striata and H. navarroensis. Common species include Rugoglogiberina rugosa and R. macrocephala. The planktonic foraminiferal assemblage is similar to that in Biozone VII (41 species) and consists of the following species: Abathomphalus intermedius, Archae-
Figure 7: SEM photomicrographs of selected planktonic foraminifera observed in Contusotruncana plummerae Zone (Biozone IV, A, B), Biozone V (C–G), Globotruncanella havanensis Zone (Biozone VI, H–J) and Pseudoguembelina palpebra (Biozone VII, K–P). A Globigerinelloides bollii, Al Mahr-1, interval 95–100 m. B Archaeoglobigerina blowi, Al Mahr-1, interval 85–90 m. C Pseudotextularia nuttalli, Al Mahr-1, interval 80–85 m. D Rugoglobigerina rugosa, Al Mahr-1, interval 80–85 m. E F Globotruncanca arca (E), and detail of the wall texture (F), Palmyra-1, interval 75–80 m. G Globigerinelloides prairiehillensis, Palmyra-1, interval 75–80 m. H Globotruncanella havanensis, Palmyra-1, interval 65–70 m. I J Heterohelix navarroensis (I), and detail of the wall texture (J), Palmyra-1, interval 60–65 m. K Rugoglobigerina hexacamerata, Al Mahr-1, interval 65–70 m. L Rugoglobigerina rugosa, Al Mahr-1, interval 65–70 m. M Pseudoguembelina costulata, Al Mahr-1, interval 60–65 m. N Pseudoguembelina palpebra, Palmyra-1, interval 50–60 m. O Pansserina gansseri, Al Mahr-1, interval 45–50 m (O), and Palmyra-1, interval 40–50 m (P).
oglobigerina blowi, A. cretacea, Contusotruncana fornicata, Gansserina gansseri, Globotruncanella arca, G. bulloides, G. linneiana, G. hilli, Globotruncanella havanensis, G. minuta, G. petaloidea (Fig. 8B), Globotruncanita conica, G. stuarti, G. stuartsformis (Figs. 8C, D), G. pettersii, G. prachtihelissa, G. subcarinatus, L. megabulbifer dentata, L. gibrans, Murico hedbergella holmdelensis, M. monmouthensis, M. monterelensis, Planoglobulina carseyae, Pseudo globigerinoides costulata, P. exocolata, P. kempensis, P. palpebra, Pseudotextularia muttallii, P. intermedia, Rugoglobigerina hexacamerata, and Racemigembeelia powelli. Representatives of the genus Heterohelix increase in abundance to 38%, and rugoglobigerinids are more common here than in the underlying biozones and make up to 14% of the planktonic foraminiferal association. Pseudo globelminids that reached a peak in the previous biozone drop in abundance to 8%, and globotruncanids also decrease in occurrence towards the top of Biozone VII.

Small benthic foraminifera comprise less than 10% of the assemblage and include Bolivina incrassata, Gavelinella monterelensis, Gavelinella sp., Gyroidinoides globosus, Lenticulina rotulata, Lenticulina sp., Neoflabelligerina reticulata, Stensioeina pommerana (Figs. 8K, L), Cibicidoides sp., and agglutinated species Gaudryina laevigata.

Lithology and palaeoenvironment. Marl and argillaceous limestone (mudstone/wackestone) contain a high proportion of rich and very well preserved planktonic foraminifera suggesting deposition in upper to middle bathyal environments.

Biozone IX: Abathomphalus mayarensis Zone (Figs. 9F–P)

Definition. Interval Zone from the LO of the nominal taxon to the extinction of most of the Cretaceous planktonic foraminifera (PREMOLI SILVA & SLITER, 1994; ROBASZYNSKI & CARON, 1995; ROBASZYNSKI et al., 2000; PREMOLI SILVA & VERGA, 2004; CHACON et al., 2004)

Age. Late Maastrichtian

Interval. Al Mahr-1 (10–30 m, Figs. 2 and 4), Palmyra-1 (5–25 m, Figs. 3, 4)

Assemblage characteristics. The zonal marker Abathomphalus mayarensis (Figs. 8F, M, N) is represented by a few specimens. Very common species in the planktonic foraminiferal assemblages include Heterohelix globulosa, H. striata, Rugoglobigerina rugosa, Heterohelix navarroensis, H. planata and Muricohedbergella monmouthensis, while common species include Heterohelix labellosa, Globotruncanella arca, Rugoglobigerina macrocephala and Muricohedbergella holmdelensis. This very well preserved and highly diverse assemblage also contains other species such as Globotruncanella hilli, Globotruncanella havanensis, G. minuta, G. petaloidea, G. pschade, Globotruncanita conica (Fig. 8P), G. stuarti, G. stuartsformis (Figs. 8K, L), G. pettersi, G. prachtihelissa, Heterohelix punctulata, Pseudo globelminidae exocolata (Figs. 8G, H), P. kempensis, P. palpebra, Pseudotextularia elegans (Figs. 8I, J), P. intermedia, P. muttallii, Planoglobulina carseyae, and Rugoglobigerina hexacamerata.

A large overturn in planktonic fauna occurred within Biozone IX due to the extinction and disappearance of many species at the base of the biozone, including: Archaeoglobigerina blowi, A. cretacea, Globotruncanella bulboides and Globigerinelloides prachtihelissa. Furthermore, species such as Abathomphalus intermedius (Fig. 8O), Gansserina gansseri, Globotruncanella linneiana, Pseudo globelminidae costulata and Racemigembeelia powelli become rare and then disappear in the middle part of Biozone IX. Species of the genus Heterohelix remain the dominant group in the planktonic assemblage with the same abundance of 36%, whereas globotruncanids and rugoglobigerinids have almost the same abundance as in the underlying Biozone VIII. The very high overall diversity (40 species) of Biozone IX, although somewhat lower than in Biozone VIII, dramatically decreases at the end of the zone when most planktonic foraminiferal species become extinct. Only a few species such as Muricohedbergella holmdelensis, M. monmouthensis and G. monterelensis become agglutinated forms Gaudryina laevigata (Fig. 9O) and Spiropectammina sp.

Lithology and palaeoenvironment. Marl, argillaceous limestone (mudstone/wackestone) and slightly dolomitized argillaceous limestone (foraminiferal wackestone) contain rich and very well preserved foraminiferal assemblages (plankton/benthos ratio is 94:6), suggesting a persistent open-marine influence and deposition in upper to middle bathyal environments.

5. INTERPRETATION AND DISCUSSION

This detailed study of the Late Turonian–Maastrichtian planktonic and benthic foraminiferal assemblages provides the basis for biostratigraphic and palaeoenvironmental interpretations of the successions examined. A total of 56 planktonic foraminiferal species belonging to 20 different genera have been identified. Abundant and moderately to highly diverse and generally well preserved planktonic foraminiferal assemblages enabled biozonation and identification of the following biozones: Biozone I, Biozone II, Biozone I, IV Contusotruncanella plummerae Zone, Biozone V, VI Globotruncanella havanensis Zone, VII Pseudo globelminidae palpebra Zone, VIII Racemigembeelia fruticosa Zone and IX Abathomphalus mayarensis Zone. Identification of possible stratigraphic gaps in the Upper Cretaceous successions examined here was very difficult because the drill cuttings were sampled every 5–10 metres. According to BREW (2001), the Upper Cretaceous strata succession of the Palmyride area is characterized by progressively deeper water environments. Evidence for some minor compression and uplift has been documented for the latest Cretaceous of this area, together with an associated minor sedimentary hiatus at the Creta-
Figure 8: SEM photomicrographs of selected planktonic foraminifera observed in the Pseudoguembelina pulpebra Zone (Biozone VII, A) Racemiguembelina fructicosa Zone (Biozone VIII, B–E) and Abathomphalus mayaroensis Zone (Biozone IX, F–P). A Rugoglobigerina rugosa, Palmyra-1, interval 40–50 m. B Globotruncanella petaloidea, Al Mahr-1, interval 30–35 m. C Globotruncanita stuartiformis (C), and detail of the wall texture (D), Al Mahr-1, interval 30–35 m. E Racemiguembelina fructicosa, Palmyra-1, interval 25–30 m. F Abathomphalus mayaroensis, Al Mahr-1, interval 30–35 m. G, H Pseudoguembelina exco- lata (G), and detail showing wall texture (H), Palmyra-1, interval 20–25 m. I, J Pseudotextularia elegans (I), and detail showing wall texture (J), Palmyra-1, interval 20–25 m. K, L Globotruncanita stuartiformis, Al Mahar-1, interval 20–25 m. M, N Abathomphalus mayaroensis, Al Mahar-1, interval 15–20 m (M), and Palmyra-1, interval 10–20 m (N). O Abathomphalus intermedius, Palmyra-1, interval 10–20 m. P Globotruncanita conica, Palmyra-1, interval 10–20 m.
correspond to the Figs. 2–5 and 10) is moderately preserved. This biozone may stratigraphic hiatus in that area.

The foraminiferal assemblage of Biozone I (late Turonian–early Santonian, upper part of the Judea Formation; Figs. 2–5 and 10) is moderately preserved. This biozone may correspond to the *Dicarinella concavata* Zone, and is characterized by the LO of *Gobigerinelloides bollii* and *Contusotruncana fornicata*, as well as by abundant *Heterohelix russii*, *H. globulosa* and *H. moremani*. Opportunistic (*r*-strategists) biserial taxa heterohelicids and globular archeoglobigerinids (*PREMOLI SILVA & SLITER*, 1999; *PETRIZZO*, 2002, 2003) are important components in this biozone. The dominant species *Heterohelix globulosa* inhabits subsurface levels in the water column (*ABRAMOVICH et al.*, 2003). Domination of opportunistic biserial heterohelicids and other genera with simple morphology (*Muricochedugella, Pseudotextularia, Archeoglobigerina* and *Whiteinella*), which comprise up to 87% of the total planktonic foraminiferal assemblage, indicate palaeoceanographic conditions favorable for opportunistic (*r*-strategy) organisms, such as a high productivity ocean with generally cooler but fluctuating climate, well developed oxygen minimum zone, common up-wellings and cyclic eutrophinations of the surface water (*BOERSMA & PREMOLI SILVA*, 1989; *NEDERBRAGT et al.*, 1998; *PETRIZZO*, 2002).

On the other hand, the occurrence of K-strategists (*Dicarinella* and *Marginotruncana*), although present in a smaller percentage in the planktonic assemblage, indicates warm stable episodes with oligotrophic oceanic conditions and well developed water column stratification, which are favourable for these two groups with more complex test architecture (*PETRIZZO*, 2002). Almost equal proportions of small benthic and planktonic foraminifera in limestones (mudstone/wackestone to foraminiferal wackestone) and marl suggest deposition in outer shelf environments (*OLSSON & NYONG*, 1984; *BOERSMA*, 1988; *MURRAY*, 1991; *GRÄFE*, 2005).

The most important characteristic of Biozone II (middle–late Santonian, the Soukhne Formation; Figs. 2–5 and 10) is the highest level of speciation of planktonic foraminifera. This Biozone is determined by the first appearance of several new taxa including *Globotruncana linneiana*, *G. arca*, *G. bulloides*, *G. hilli*, *Hendersonites carinatus*, *Heterohelix planata*, *H. punctulata*, *H. striata*, *Globigerinelloides praeriehilensis*, and *Globotruncana stuartiformis*, which may suggest the *Dicarinella asymmetrica* Zone. The foraminiferal assemblage is moderately diverse and better preserved relative to biozone I. Heterohelicids experienced speciation during this Biozone; their abundance increased to 46.5%, and they remained a dominant group until the end of the Cretaceous. As opportunistic planktonic foraminifera heterohelicids inhabit more nutrient-rich waters and are indicators of cooler and unstable environments (*NEDERBRAGT*, 1991; *NEDERBRAGT et al.*, 1998; *PETRIZZO*, 2002). Their speciation is most likely induced by a somewhat cooler but variable climate and anoxic events during the middle Santonian. Beside heterohelicids, other small-sized forms with simple test-morphology, such as *muricochedugellids, archeoglobigerinids* and *globigerinelloids*, are very common in the planktonic assemblage. All of these groups belong to opportunistic taxa that have a great reproductive potential in eutrophic and somewhat mesotrophic environments with a very well developed oxygen minimum layer (*NEDERBRAGT*, 1991). Small-sized heterohelicids indicate expansion of the oxygen minimum zone (OMZ) due to increased surface water productivity and depletion of oxygen in subsurface waters by oxidation of organic carbon (*LECKIE*, 1987; *LECKIE et al.*, 1998; *KELLER & PARDO*, 2004; *PARDO & KELLER*, 2008; *ASHKENAZI-POLIVODA et al.*, 2011). Heterohelicidae were found to be very common in most of the OMZ suggesting high productivity and/or some tolerance to subsurface oxygen depletion (*ASHKENAZI-POLIVODA et al.*, 2011). In addition, abundant phosphate grains in the upper part of this zone, support the interpretation that Biozone II was characterized by high palaeoproductivity, relatively constant and high food supply and moderate increase in bottom water aeration. Very high productivity during this biozone was supported by a fluctuating climate and up-welling cycles, which brought nutrient-rich water into the environments inhabited by heterohelicids and upper-middle bathyal benthic foraminifera. At the upper boundary of Biozone II all dicarinellids and whiteinellids became extinct. The proportion of planktonic species increased and reached up to 60% of the microfossil assemblage present in foraminiferal mudstone/wackestone, marl and dolomitic limestones that represent an open marine, most probably outer shelf environments (*OLSSON & NYONG*, 1984; *BOERSMA*, 1988; *MURRAY*, 1991; *GRÄFE*, 2005).

Biozone III (early Campanian, the Soukhne Formation; Figs. 2–5 and 10) is marked by the disappearance of margonotrunceans in its base and by the LO of *Pseudoguembelina costulata* and *Rugloglobigerina rugosa*. This planktonic assemblage may correspond to the *Globotruncanina elevata* Zone. Planktonic and benthic foraminiferal assemblages are rich and moderately well preserved. The proportion of planktonic species reaches up to 65% and indicates further deepening of this realm (*BOERSMA*, 1988; *MURRAY*, 1991; *GRÄFE*, 2005; *DARVISHZAD & ABDOLALIPOUR*, 2009). The most common species are opportunistic (*r*-strategists) taxa: *Hendersonites carinatus*, *Heterohelix punctulata*, *H. striata* and *Pseudotextularia nuttalli*. Although characterized by different deposits, i.e., limestone (foraminiferal mudstone/wackestone) and calcareous marl, relative to Biozone II, the deposition of these strata continued within the same open marine, probably outer shelf settings.
Phosphate grains are very common in dolomitic limestones from the upper part of Biozone II in Al Mahr-I (Figs. 2 and 4), and in the uppermost part of Biozone II and the lowermost part of Biozone III in Palmyra-I (Figs. 3, 4). Abundant phosphate grains generally indicate some very specific geological and palaeoenvironmental conditions, such as oxygen deficiency, upwelling conditions, and transgressive intervals (HAQ et al., 1987; REISS, 1988; ALMOGI-LABIN et al., 1993; WIDMARK & SPEIJER, 1997; JARVIS et al., 2002; PUFHAL et al., 2003; SOUDRY et al., 2006; ASHKENAZI-POLIVODA et al., 2011). It is possible that such palaeoenvironmental conditions, especially upwelling, increased food supply and primary production in the surface and subsurface marine environments, and thus also indirectly affected higher production and domination of opportunistic (r-strategists) planktonic foraminiferal species during Biozones II and III.

The lowest occurrence of Laeviheterohelix glabrans and Muricohedbergella monnouthensis and rare Contusotrupancana smallae in the planktonic foraminiferal assemblage of Biozone IV (middle–late Campanian, the Shiranish Formation; Figs. 2–5 and 10) suggest the Contusotrupancana smallae Zone. This biozone has been appointed by PETRIZZO et al. (2011) for the lower–middle Campanian of tropical and subtropical areas because of the difficulties in using the first occurrence datum of Globotruncanella ventricosa in low latitude successions from the Tethyan Realm. Species of the genus Heterohelix dominated in the previous Biozone III but decrease to 32.5% in Biozone IV, whereas the abundance of two genera Muricohedbergella and Pseudoguembelina significantly increases up to 15% and 10.5%, respectively. Although the opportunistic (r-strategists) species are still dominant, the specialized taxa (K-strategists) such as globotruncanids (PREAMOLI SILVA & SLITER, 1999; PETRIZZO, 2002; DUBICKA & PERYT, 2012) increase in the overall number of species and also slightly increase in abundance within this planktonic assemblage. This indicates mesotrophic to more oligotrophic environmental conditions that are favorable for keeled globotruncanids. The well-preserved foraminiferal assemblage and high proportion of planktonic foraminifera (70%) in the argillaceous limestones marl and calcareous marls of Biozone IV suggest an open marine, probably outer shelf to upper bathyal environment (BOERSMA, 1988; MURRAY, 1991; GRÄFE, 2005).

The lowest occurrence of planktonic foraminifera Laeviheterohelix dentata, Globotruncanella havanaensis and Globotruncanita stuartii in Biozone V (late Campanian, the Shiranian Formation; Figs. 2–5 and 10) may suggest the Radotruncanca calcarea Zone. The well-preserved foraminiferal assemblage is rich, diverse and has an increased number of K-strategists (keeled globotruncanids; PREMOLI SILVA & SLITER, 1999). Globotruncanids have a complex test morphology and usually inhabit the subsurfacewater column (PETRIZZO, 2002; ABRAMOVICH et al., 2003; DUBICKA & PERYT, 2012), which implies good stratification of the water column and a tropical to subtropical climate during the late Campanian (LECKIE, 1989; HUBER et al., 1995; DARVISHZAD & ABDOLALIPOUR, 2009). Deposits and sedimentary settings remain the same as for Biozone IV, i.e., deep-water marine environments.

The zonal marker Globotruncanella havanaensis is relatively rare in Biozone VI (late Campanian, the Shiranish Formation; Figs. 2–5 and 10), and the base of this Biozone is indicated by the LO of Pseudoguembelina excolata, Plagnoglobulina carseyae and Rugoglobigerina hexacamerata. The foraminiferal assemblage is rich and well preserved. Although the opportunistic group heterohelicids stay dominant group in the planktonic assemblage with 37.5% abundance, K-strategists, such as keeled globotruncanids, become an important component in the planktonic foraminiferal assemblage with 9 species and 13.5% abundance. These point to stable environmental conditions, such as an oligotrophic ocean with a tropical to subtropical climate, well stratified water column, stable thermocline and other favourable palaeoenvironmental parameters for r/K and K-selected group of planktonic foraminifera (LECKIE, 1989; MURRAY, 1991; DARVISHZAD & ABDOLALIPOUR, 2009). Abundance of species from the genus Globigerinelloides and Muricohedbergella (r-selected forms) show inverse trends in comparison with the previous biozones and decrease to 7.5% and 6%, respectively (Fig. 10). The proportion of planktonic species increased and reached up to 85% of the microfossil assemblage present in marl and argillaceous limestone (mudstone/wackestone) that represent an open marine, outer shelf to upper bathyal environments (OLSSON & NYONG, 1984; BOERSMA, 1988; MURRAY, 1991; GRÄFE, 2005).

The Pseudoguembelina palpebra Zone (Biozone VII, late Campanian–early Maastrichtian, the Shiranian Formation; Figs. 2–5 and 10) is characterized by the LO of P. palpebra, which is consistently found throughout the interval in moderate abundance. Also, the lowest occurrence of Globotruncanella pschadai, Pseudoguembelina kempensis and Racemiguembelina powelli is recorded in the lower part of this biozone. Gansserina gansseri is very rare and poorly preserved in the investigated samples, and therefore P. palpebra serves as a better zonal marker for the uppermost Campanian, as also reported by HUBER et al. (2008) from subtropical North Atlantic (Blake Nose). The planktonic foraminiferal assemblage of Biozone VII is rich, very well preserved and in comparison with Biozone VI, biodiversity throughout this interval significantly increases (to 41 species). Opportunistic representatives of the genus Heterohelix are still the dominant group in the planktonic assemblage with 34% abundance. Also, the genus Pseudoguembelina, known as a successful surface and subsurface dweller in tropical and subtropical open ocean (NEDERBRAGT, 1989; HUBER, 1992; ABRAMOVICH et al., 2003), significantly increased in abundance up to 17%. Species of the genus Pseudoguembelina are strongly photosymbiotic and their expansion is related to favourable palaeoecological conditions in the Late Cretaceous ocean, such as the presence of warm and oligotrophic surface ocean waters (D’HONDT & ZACHOS, 1998; ABRAMOVICH et al., 2003). The proportion of planktonic foraminifera accounts for up to 90% of the microfossil assemblages found in marl and argillaceous lime-
The lowest occurrence of planktonic foraminifera Plano- 
globulina acervulinoides and Peudotextularia elegans in 
association with the rare zonal marker Racemiguembelia 
fructicosa, is indicative of Biozone VIII (early–late Mas-
trichtian, the Shiranish Formation; Figs. 2–5 and 10). This 
biozone is characterised by a diverse and very well preserved 
planktonic foraminiferal assemblage with 41 species, similar 
to that from Biozone VII. Rugoglobigerinids increased in 
abundance and reached up to 14% of the assemblage, while 
representatives of the genus Heterohelix still dominate the 
assemblage with 38%. Species of the genus Rugoglobigerina 
habit surface and subsurface habitats (ABRAMOVICH et 
al., 2003), and are known as symbiotic organisms (D’HONDT 
in this biozone is likely supported by good water column 
stratification and opening of new niches favourable for all 
groups of planktonic foraminifera. Many subsurface dwel-
ers, such as several species of the genus Globotruncanidae, 
acquired adaptation to the thermocline habitat (ABRAMOV-
ICH et al., 2003). All of these changes correspond very well 
to the documented global sea level fluctuations and alter-
ning cooler and warmer periods in the early to late Maa-
strichtian (HAQ et al., 1987; Fig. 5). During Zone VIII the sedi-
mentary setting was a deep sea environment (upper bathyal), 
as a result of further deepening of this sedimentary realm. 

The planktonic foraminiferal assemblage of the latest 
Cretaceous Abathomphalus mayaroensis Zone (Biozone IX, 
late Maastrichtian, the Shiranish Formation; Figs. 2–5 and 10) is 
very similar to those in Biozone VIII and is rich in the 
overall number of species (39) as well as in the number of 
individuals. An important characteristic of this biozone is 
the increased number of K-strategist species of globotrunc-
canids (15.5%), and planoglobulinids (4%), whereas rug-
globigerinids retained their abundance (14%). Some op-
portunistic species of the genus Muricochederella also 
show an increase and constitute 9% of the assemblage, while 
members of the genus Globigerinelloides (2%) decrease in 
abundance (Fig. 10). Species of the genus Heterohelix have 
an almost equal abundance (36%) compared to Biozone VIII.

Composition of the planktonic foraminiferal assemblage with 
a significantly higher percentage of K-strategist special-
ist, which inhabit subsurface and thermocline layers, indi-
cates an oligotrophic ocean with a very well stratified water 
column supported by a stable thermocline (PREMOLI 
SILVA & SLITER, 1999; PEARSON et al., 2001; ABRAM-
OVICH et al., 2003). On the other hand, the symbiont-bearing 
taxa Rugoglobigerina, Pseudoguembelina and Hetero-
helix were very well adapted to surface and subsurface 
oligotrophic ocean water (D’HONDT & ZACHOS, 1998; 
PEARSON et al., 2001; ABRAMOVICH et al., 2003). In the upper 
part of Biozone IX, the decreased numbers of glo-
botruncanid species indicate fluctuating climate, sea-level 
changes and up-welling cycles which could cause instability 
in the water column and unfavourable environmental condi-
tions for K-strategists (ABRAMOVICH & KELLER, 2002; 
HAQ et al., 1987). This high diversity abruptly decreases at 
the end of the Biozone, when most planktonic foraminiferal 
species became extinct. Marl, argillaceous limestone (mud-
stone/wackestone), and slightly dolomitized limestone (fo-
raminiferal wackestone) contain rich and very well preserved 
foraminiferal assemblages, whereas planktonic foraminifera 
reach over 90% of the entire community suggesting deposi-
tion in upper bathyal environments (BOERSMA, 1988; 
MURRAY, 1991; GRAFE, 2005; DARVISHZAD & ABDOLALIPOUR, 
2009).

The Soukhne Formation (Santonian–Early Campanian, 
Biozones II and III, Figs. 2–4) contains phosphate grains. 
Similar phosphate deposits are widespread in many parts 
of the Levantin region (i.e., Israel, Jordan, Iraq, Turkey and 
Egypt; AL MALEH & MOUTY, 1994; PUFHAL et al., 2003; 
ABED et al., 2005; BAIJUMY & TADA, 2005; SOUDRY 
et al., 2006; ASHCKENAZI-POLIVODA et al., 2011; SCH-
NEIDER-MOR et al., 2012). The phosphate deposits in Syria 
formed in response to a high-productivity upwelling regime 
that persisted on the southern margins of the Tethys during 
the Late Cretaceous (AL MALEH & MOUTY, 1994). The 
planktonic assemblages associated with phosphate grains in 
the Palmyride strata are characterized by domination of op-
portunistic (r-strategists) taxa such as the genus Heterohelix 
(Biozone II and III, Figs. 2, 3), which indicates a highly pro-
ductive photic zone (REISS, 1988; ALMOGI-LABIN et al., 
1993; WIDMARK & SPEIJER, 1997; PUFHAL et al., 2003) 
and a low oxygen environment (ASHCKENAZI-POLIVODA et 
al., 2011). The benthic assemblages found with phosphates have 
abundant specimens of the genus Bulimina, which are 
commonly documented from highly productive, 
low-oxygen settings from around the world, including for 
example South America, Morocco, Egypt, Jordan, Iraq and 
Israel (PUFHAL et al., 2003; ASHCKENAZI-POLIVODA et 
al., 2011). An additional factor that contributed to the for-
mation of phosphate was the enrichment in phosphorus 
from P-rich deep waters that upwelled in the Palmyrida Ba-
sin by currents flowing along the northern edge of the Ara-
bian platform (SOUDRY et al., 2006). Warming of the up-
welled water and the abundance of nutrients caused the 
proliferation of plankton, which assimilated, stored and con-
centrated phosphate. After the deposition of plankton, a large 
amount of phosphate dissolved and became concentrated in 
the sea-floor sediments (AL MALEH & MOUTY, 1994). 

Such high primary productivity and sea floor phospho-
genesis prevailed mainly on the southeastern Tethyan mar-
gins as a result of persistent upwelling circulation that recy-
cled dissolved phosphorus from the intermediate-depth 
waters and distributed it to the photic zone (SOUDRY et al.,
The phosphates developed during transgressive periods that promoted carbonate sediment starvation. Simple (internally homogenous) $\text{P}_2\text{O}_5$-enriched phosphate nodules probably replaced calcite nodule precursors in suboxic conditions as a result of processes that involved oceanic upwelling, exhumation and burial coupled with alternating oxic and suboxic conditions (MARSHALL-NEILL & RUFFELL, 2004). The presence of phosphate is an important indicator of oxygen deficiency, upwelling conditions, transgressive intervals, and omission surfaces (TRAPPE, 2001), and any future studies of this Cretaceous stratigraphic interval should also include detailed analyses of the associated phosphate grains.

6. CONCLUSIONS

The stratigraphic analysis of the Upper Cretaceous strata from the Palmyride area in Syria included a detailed micropalaeontological investigation of foraminiferal assemblages and rock types obtained from drill cuttings in two deep exploration wells (Al Mahr-1 and Palmyra-1).

Nine biozones have been identified in the upper Turonian to Maastrichtian succession: Biozone I, Biozone II, Biozone III, IV Contusotruncana plummerae Zone, Biozone V, VI Globotruncanella havanensis Zone, VII Pseudoguembelina palpebra Zone, VIII Raceemiguembelina fructicosa Zone, and IX Abathomphalus mayorensis Zone.

During the late Turonian to early Campanian (Biozone I to III) in the investigated Palmyride strata, domination of opportunistic taxa (Heterohelix, Globigerinelloides, Archaeoglobigerina, and Muricohedbergella) implies upwelling, low oxygen conditions and subtropical climate. On the other hand, the rich and highly diversified planktonic assemblages (Biozone IV to IX) with many K-selected taxa (i.e., ornamented keeled globotruncanids, rugoglobigerinids, planoglobulinids, pseudoguembelinids) indicate a tropical to subtropical climate and well-stratified water column during the late Campanian and into the Maastrichtian. In the upper part of Biozone IX, the decreased numbers of globotruncanid species indicate a less stratified water column and unfavourable environmental conditions for K-strategists. A dramatic faunal turnover at the end of this Biozone is marked by the extinction of most planktonic foraminifera, with only a few species (e.g., Muricohedbergella holmdelensis, M. montmouthensis and Guembelitria cretacea) present across the Cretaceous/Cenozoic boundary.

Phosphate grains are very common in dolomitic limestone of the upper part of Biozone II in Al Mahr-1 and in the uppermost part of Biozone II and lowermost part of Biozone III in Palmyra-1 (Soukhne Formation). The phosphate occurrence helps improve the late Santonian–early Campanian stratigraphic interpretation of this interval because similar deposits occur during this time period elsewhere along the southeastern margins of Tethys (Israel, Jordan, Iraq, Turkey and Egypt). The presence of phosphate in the study area indicates oceanic upwelling that caused increased food supply and influenced higher primary marine production, and thus indirectly affected higher production and domination of opportunistic planktonic foraminifera in Biozones II and III.

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REFERENCES


APPENDIX 1

List of taxa cited in the text and figure explanations, in alphabetical order according to genus

Planktonic foraminifera
Abathomphalus intermedius (BOLLI, 1951)
Abathomphalus mayaroensis (BOLLI, 1951)
Archaeoglobigerina blowi PESSIONG, 1967
Archaeoglobigerina cretacea (D’ORBIGNY, 1840)
Contusotruncana fornicata (PLUMMER, 1931)
Contusotruncana plummerae (GANDOLFI, 1955)
Dicarinella sp.
Gansserina gansseri (BOLLI, 1951)
Globigerinelloides bollii PESSIONG, 1967
Globigerinelloides prairiehillensis (PESSIONG, 1967)
Globotruncana arca (CUSHMAN, 1926)
Globotruncana bulloides (VOLGER, 1941)
Globotruncana hilli PESSIONG, 1967
Globotruncana linneiana (D’ORBIGNY, 1839)
Globotruncanella havanensis (VOORWIJK, 1937)
Globotruncanella minutula CARON & GONZALEZ DONOSO, 1984
Globotruncanella petaloidea (GANDOLFI, 1955)
Globotruncanella pschadae (KELLER, 1946)
Globotruncanita conica (WHITE, 1928)
Globotruncanita pettersi (GANDOLFI, 1955)
Globotruncanita stuarti (DE LAPPARENT, 1918)
Globotruncanina stuartiformis (DALBIEZ, 1955)
Guembelitria cretacea CUSHMAN, 1933
Guembelitria turrita NEDERBRAGT, 1990
Hendersonites carinatus (CUSHMAN, 1938)
Heterohelix globulosa (EHERNBERG, 1840)
Heterohelix labellosa NEDERBRAGT, 1990
Heterohelix navarroensis LOEBLICH, 1951
Heterohelix moremani (CUSHMAN, 1938)
Heterohelix planata (CUSHMAN, 1938)
Heterohelix punctulata (CUSHMAN, 1938)
Heterohelix reussi (CUSHMAN, 1938)
Heterohelix striata (EHERNBERG, 1840)
Laeviheterohelix dentata (STENESTAD, 1968)
Laeviheterohelix glabrans (CUSHMAN, 1938)
Marginotruncana sp.
Muricochedbergella flandrini (PORTHAULT, 1970)
Muricochedbergella holmdelensis (OLSSON, 1964)
Muricochedbergella mounmouthensis (OLSSON, 1960)
Muricochedbergella sp.
Planoglobulina casevae (PLUMMER, 1931)
Planoglobulina acervulinoidea (EGGER, 1899)
Pseudoguembelina costulata (CUSHMAN, 1938)
Pseudoguembelina excelsa (CUSHMAN, 1926)
Pseudoguembelina kempensis ESKER, 1968
Pseudoguembelina palpebra BROENNMANN & BROWN, 1953
Pseudotextularia elegans (RZEHAK, 1891)
Pseudotextularia intermedia DE KLASZ, 1953
Pseudotextularia nuttali (VOORWIJK, 1937)
Racemiguembelina fruticososa (EGGER, 1902)
Racemiguembelina powelli SMITH & PESSIONG, 1973
Rugoglobigerina macrocephala BROENNMANN, 1952
Rugoglobigerina hexacamerata BROENNMANN, 1952
Rugoglobigerina rugosa (PLUMMER, 1926)
Whiteinella balthica DOUGLAS & RANKIN, 1969
Whiteinella sp.
Benthic foraminifera
Bolivinoides draco (MARSSON, 1878)
Bolivinoides miliaris HILTERMANN & KOCH, 1950
Bolivina incrassata REUSS, 1851
Bulimina ovulum REUSS, 1844
Bulimina sp.
Cibicidoides sp.
Gaudryina laevigata FRANKE, 1914
Gavelinella monterelensis (MARIE, 1941)
Gavelinella sp.
Gyroidinoides globosus HAGENOW, 1842
Gyroidinoides sp.
Lenticulina rotulata (LAMARCK, 1804)
Lenticulina miitsteri (ROEMER, 1839)
Lenticulina sp.
Neoflabella reticulata (REUSS, 1851)
Nodosaria sp.
Oridorsalis umbonatus (REUSS, 1851)
Oridorsalis sp.
Praebulimina reussi (MORROW, 1934)
Praebulimina kickapoensis (COLE, 1938)
Seroavaina complanata (CUSHMAN & STAINFORTH, 1945)
Spiroplectammina sp.
Stensioeina pommerana BROTZEN, 1936
APPENDIX 2

Distribution of Late Cretaceous genera of planktonic foraminiferal assemblage from Al Mahr-1 and Palmyra-1 wells.

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(% BENT. FORAM. | 48.78 | 40.67 | 35.72 | 29.79 | 19.66 | 15.05 | 8.76 | 7.44 | 6.02 |