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CAMPANIAN–MAASTRICHTIAN FORAMINIFERAL STRATIGRAPHY AND PALAEOENVIRONMENT OF THE LOWER TAR MEMBER IN THE WADI TAR SECTION, WESTERN SIRTE BASIN (LIBYA)

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Abstract: Upper Campanian–Maastrichtian sections on the western flank of the Hun Graben in the Western Sirte Basin (WSB) are displaying two major type facies based on the foraminiferal assemblages. The first one indicates open-marine to outer-shelf conditions, and is represented by numerous bathy-pelagic planktonic foraminiferal species referable to the *Radotruncana calcarata, Globotruncana aegyptiaca* and the lower part of the *Gansserina gansseri* Zone (all late Campanian).The second type facies indicates an inner-shelf environment and is represented in the middle-upper part of the *Gansserina gansseri* Zone (early Maastrichtian) and *Racemiguembelina fructicosa* (late Maastrichtian) dominated by epi-pelagic planktonic and large benthic foraminifers. Large benthic foraminiferal index species *Siderolites calcitrapoides* Lamarck and *Omphalocyclus macroporus* (Lamarck) occur in abundance by the middle–late Maastrichtian. Correlation between planktonic foraminiferal zonation and large benthic foraminiferal zonation is given. An open-marine to outer-shelf environment passed into shallower marine conditions during the late Campanian–early Maastrichtian to late Maastrichtian, then a slight deepening and again shallowing is noticed.

Key words: Southern Tethys, Western Sirte Basin, Lower Tar Member, foraminifera, biostratigraphy, palaeoenvironment, late Campanian–Maastrichtian.

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INTRODUCTION

The Sirte Basin is located in the north-central part of Libya (Fig. 1). It is a basin characterized by a series of platforms and deep troughs containing several oil and gas fields. Depositional history of the Sirte Basin started in the Early Cretaceous time, which has been related to the tectonic evolution of the North African passive continental margin. The history of the Sirte Basin had been spanning the Cretaceous and Palaeogene times. It had been influenced by several marine transgressions and several rifting phases induced by the deformation of the North African continental margin. The relative sea-level changes and the tectonics might have greatly influenced the accomodation space, especially over the Western Sirte Basin (WSB) during the Palaeogene.

Because of the numerous oil and gas fields, the geological history of the WSB was the subject of numerous studies (Berggren, 1963; Jordi and Lonfat, 1963; Furst 1964; Gohrbandt, 1966; Goudarzi, 1970; Conley, 1971; Barr and Weegar, 1972; Bezan, 1996). Its structural geology was the core of the publications of Klitzsch (1970, 1971), Anketell and Kumati (1991b), Abadi and Van Dijk (1993), Anketell (1996), Schröter (1996), Van Dijk and Eabadi (1996) and Knytl *et al*. (1996). Sedimentology and depositional history of the basin have been studied by Selley (1967, 1968, 1969, 1971), Williams (1972), Gumati and Kanes (1985) and Anketell and Kumati (1991a). Biostratigraphy of the Cretaceous carbonates of the Sirte Basin has benefitted from a relatively rich bibliography. Some of the prominent papers on biostratigraphy are: Berggren (1969), Barr (1972), Barr and Berggren (1980), Eliagoubi and Powell (1980), Shakoor and Shagroni (1984), Butt (1986), Salaj and Nairn (1987), Tmalla (1992, 1996), Tawadros (2001, 2012), Hallett (2002), Tshakreen *et al*. (2002), Salaj (2003), and Tshakreen and Gasiński (2004).

The Late Cretaceous sediments outcropping in the Wadi Tar Al Kair on the western flank of Hun Graben (WBS) are representing the south-western Tethyan biogeographic realm they have been investigated for their foraminiferal assemblages. The Late Cretaceous sediments of the WSB have

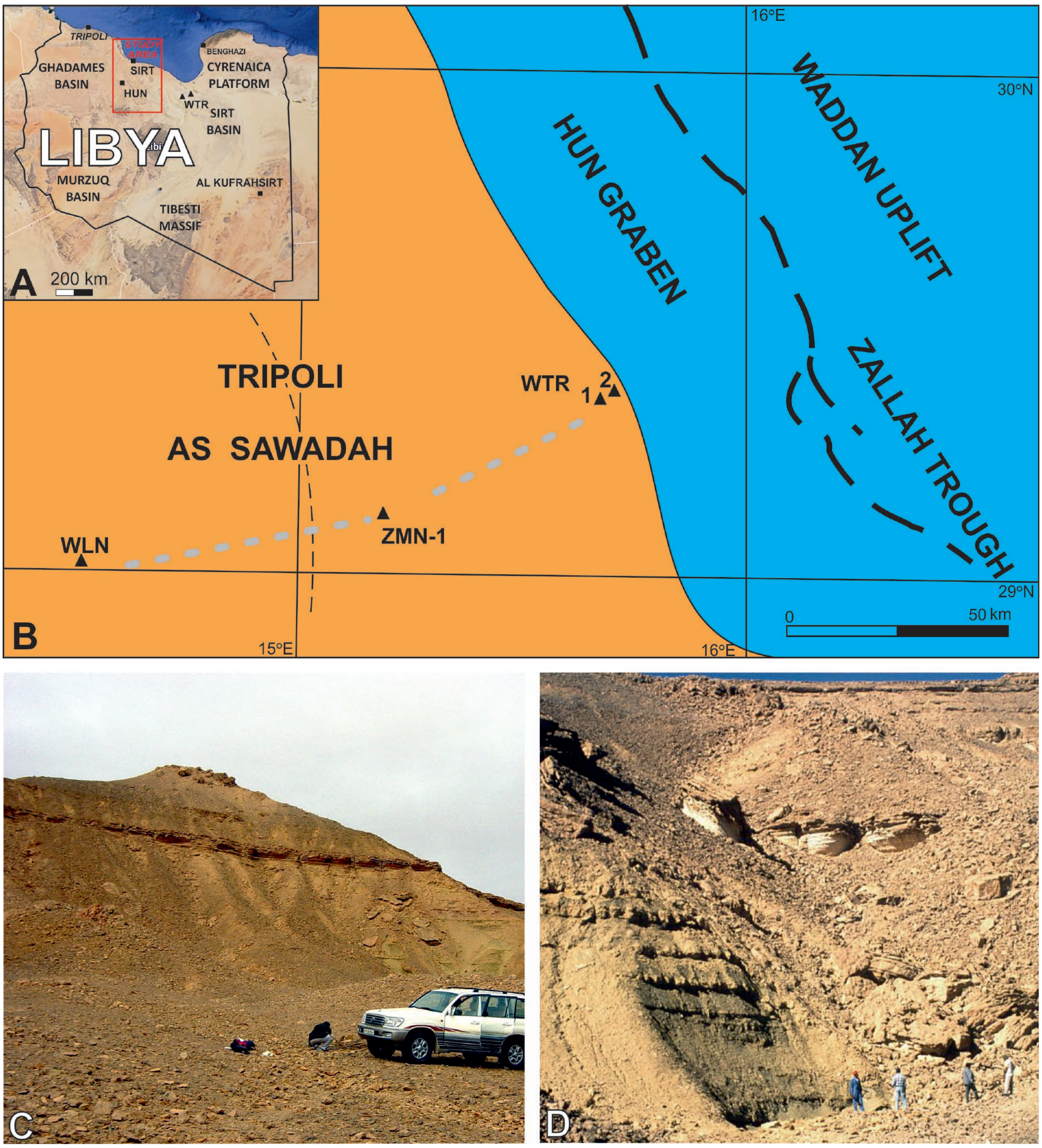

Fig. 1. Location map of the study area and views of the studied outcrops . **A.** Sketch map of Libya. **B.** Geological sketch map of the Western Sirte Basin including the investigated sections WTR 1 and WTR 2 at Wadi Tar Al Kair (western flank of Hun Graben). **C.** Outcrop view of the WTR 1 section at Wadi Tar Al Kair. **D**. Outcrop view of the WTR 2 section at Wadi Tar Al Kair.

been the core of a two-fold micropalaeontological analysis: most precise biostratigraphy and contribution of data for a comprehensive interpretation of the basin bathymetry.

GEOLOGICAL SETTING OF THE AREA

The Sirte Basin is located within the North African passive continental margin as an inland extension of the Gulf of Sirte. Its geological history is related to the tectonic evolution of the North African continental margin (Klitzsch, 1971; Jongsma *et al*., 1985; Anketell and Kumati, 1991a, b; Guiraud and Maurin, 1992; Anketell, 1996). Poly-phased extensional tectonics initiated the formation of the Sirte Basin in the Early Cretaceous time, and divided the basin into a succession of NW-SE trends of platforms and troughs (Fig. 1).

The Western Sirte Basin, as one of the largest sedimentary basins in North Africa, forms a broad NW-trending embayment. To the present day, it is open to the Mediterranean Sea to the north, and bounded by the Tripoli Asswada Arch to the west and by the Cyrenaica Platform to the east (Fig. 1). Essentially the basin consists of several NW- to SE-trending structural highs alternating with adjacent troughs as the result of extensional tectonics (cf., Conant and Goudarzi, 1967; Goudarzi, 1970).

Several attempts have been made by tectonics specialists to characterize the relationships between the North African plate motion and rifting within the Western Sirte Basin but the subject is still controversial (Anketell, 1996). According to Westaway (1996), the Western Sirte Basin is an active oblique-extensive area that can be regarded as an internal deformation of the African Plate adjusting its motion in a N-NE ward direction relative to Eurasia.

The Lower Tar Member, as the uppermost member of the Al Gharbiyeh Formation, is the core of the present study (Figs 2, 3) and was formerly included in the Zimám Formation (also called the Zmam Formation).The latest formation, which name was introduced by Jordi and Lonfat (1963), was composed of three members which from oldest to youngest are the Lower Tar, Upper Tar and Had members. The type sections of these members are located on the western flank of the Hun Graben (Fig. 1). Previous important studies on the Zimám Formation had been performed by Jordi and Lonfat (1963), Furst (1964), and Shakoor and Shagroni (1984). These latter considered the Socna Mollusc Bed as a key unit within the lower portion of the Upper Tar Member. However, Furst (1964) included the Socna Mollusc Bed as a separate unit. These studies considered the base of the Socna Mollusc Bed as the boundary between the Upper Cretaceous and Paleocene. The above stratigraphic scheme and its modifications have been used not only within the SW Western Sirte Basin (Shakoor and Shagroni, 1984) but also outside the Western Sirte Basin. Further to the revision of the Cretaceous sections, the Lower Tar Member was incorporated into the Al Gharbyeh Formation (cf., Hallett and Clark-Lowes, 2016).

In the studied locations, the Lower Tar Member consists of calcareous claystone, mudstone, shale and siltstone interbedded with calcarenites. The calcarenite layers contain abundant shells of bivalves, gastropods and echinoid tests. This concentration of fossils gives rise to shell lag deposits that can be interpreted as storm layers. The thickness and frequency of the fossiliferous calcarenite layers increase upward in the sections (Figs 2, 3).

The lower boundary of the Lower Tar Member is not exposed in the study area and the upper boundary is located at the base of the Socna Mollusc Bed. This upper boundary has been traditionally considered as the Cretaceous-Palaeogene boundary (Jordi and Lonfat, 1963; Furst, 1964; Bar and Weegar, 1972). No micropalaeontological evidence for the Cretaceous-Palaeogene boundary in surface sections has ever been found so far. However, some authors (e.g., Eliagoubi and Powell, 1980) postulated an early to mid-Maastrichtian age for the Lower Tar Member with characteristic foraminiferids.

MATERIAL AND METHODS

Studies had been carried out on the Lower Tar Member in the Western Sirte Basin (WBS) within the frame of Project WSB no. 2383. Fieldwork was part of a joint study by Petroleum Research Centre Libya (now LPI) and Teknica Petroleum Services Ltd. (Canada) team members during the 1998 and 1999 field seasons in the Western Sirte Basin area (Fig. 1). The stratotype section of the Lower Tar Member is the surface sections of Wadi Tar Al Kair, all situated on the western flank of the Hun Graben (coordinates 29° 22’ N, 15° 42’ E, sections WTR1, WTR2).

The Wadi Tar Al Kair sections (WTR1, WTR2) are displaying more than 35 m of Campanian-Maastrichtian sediments (LTM and Socna beds). Thirty-five samples, each 200 g weight were processed to retrieve foraminifera within the scope of searching of planktonic index taxa susceptible to frame a standard planktonic zonation as well as for palaeobathymetric estimation.

Marlstones and limestones samples had been disintegrated by successive cycles of heating-and-freezing in Glauber’s salt. Some very soft samples were only soaked. The residue was washed through a set of sieves (65μm and 100μm in diameter). From each samples all specimens were collected and foraminiferal assemblages were quantitatively analysed for palaeoecological interpretation (see Fig. 4). Specimens were identified under stereoscopic and SEM microscopes. Thin sections were processed to observe the inner structures of shallow-water large benthic foraminifers.

RESULTS

The examined sediments are containing rich assemblages of relatively well preserved planktonic foraminifers, all characterized by the dominance of heterohelicids, globigerinelloidids, hedbergellids, rugoglobigerinids, globotruncanids, and globotruncanelloids. The benthic foraminifers, especially the large ones, are numerous in the middle and upper parts of the studied sections. Composition changes in the foraminiferal assemblages are shown in Figures 2 and 4, while selected species of planktonic and benthic foraminifers are illustrated in Figures 5 and 6. A brief description of these changes is given below.

Samples WTR1-1 – WTR2-7 contain diversified assemblages with keeled taxa, including: *Globotruncana aegyptiaca* Nakkady, *Globotruncana arca* (Cushman), *Globotruncana bulloides* Vogler, *Globotruncana falsostuarti* Sigal, *Globotruncana rosetta* (Carsey), *Globotruncana ventricosa* (White), *Globotruncana subspinosa* Van Hinte, *Globotruncana stuarti* (Lapparent), *Gansserina gansseri* (Bolli), *Contusotruncana contusa* (Cushman), *Contusotruncana fornicata* (Plummer), pseudo-keeled taxa such as *Globotruncanella havanensis* (Voorwijk), and globular morphotypes consisting of *Globotruncanella* sp. and non-keeled *Hedbergella holmdelensis* Olsson, *Heterohelix striata* (Ehrenberg), *Heterohelix globulosa* (Cushman), *Globigerinelloides prairiehillensis* Pessagno, *Planoglobulina* sp., *Rugoglobigerina macrocephala* Brönnimann, *Rugoglobigerina rugosa* (Plummer), *Rugoglobigerina scotti* (Brönnimann), *Archaeoglobigerina blowi* Pessagno (Figs 2, 4–6). These assemblages differ from that of the overlying strata (WTR2-8) with a high number of trochospiral forms, mainly rugoglobigerinids *Rugoglobigerina rugosa* (Plummer), *Rugoglobigerina macrocephala* Brönnimann, (Figs 2, 4, 6, 7). Further up

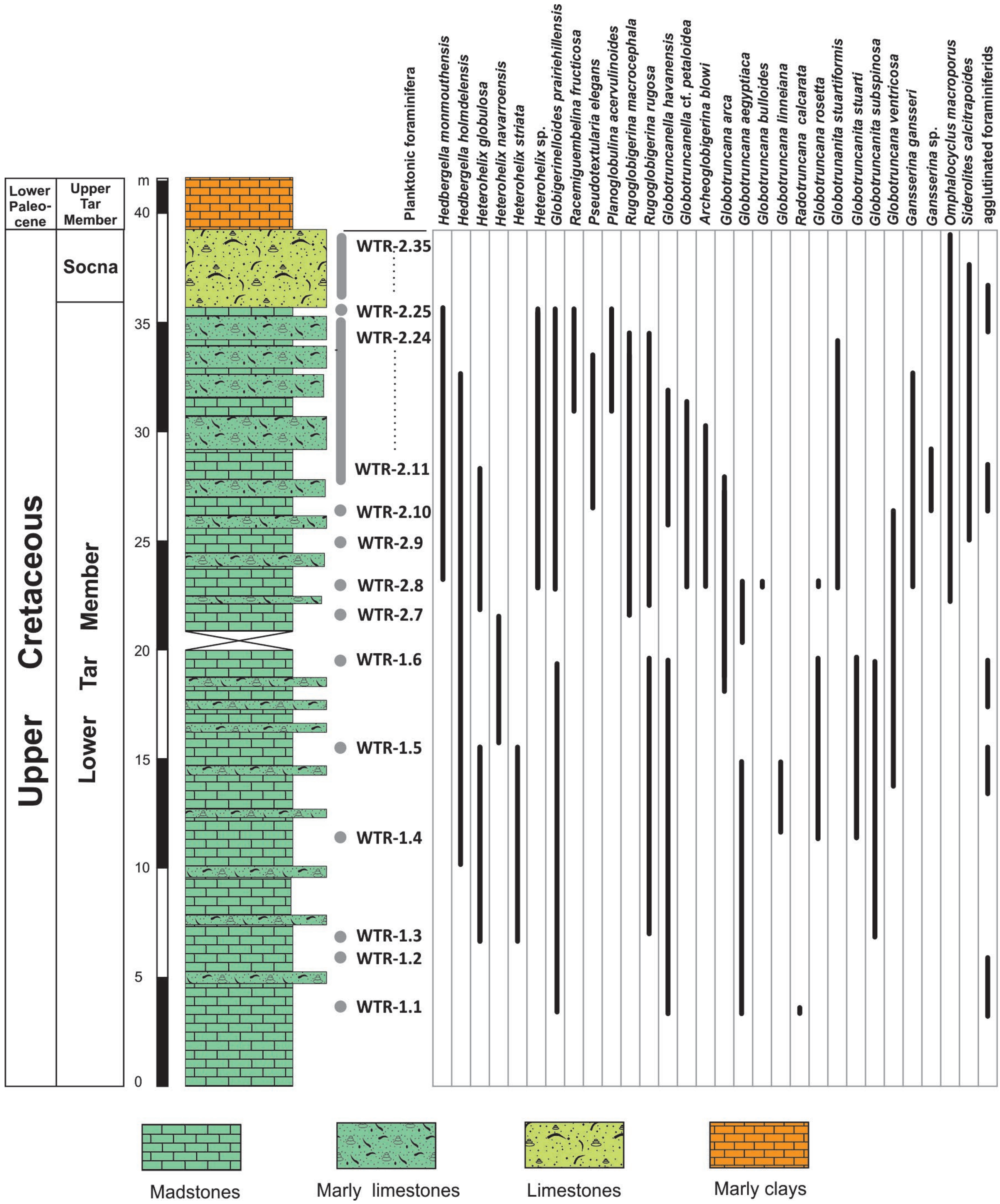

Fig. 2. Composite stratigraphic column of surface sections WTR 1 and WTR 2 at Wadi Tar Al.

in the profile (WTR2-9–WTR2-10) significant faunal changes are observed in the benthic and planktonic foraminiferalassemblages: i.e., the dominance of large benthic calcareous, lamellar foraminifera (LBF), *Siderolites calcitrapoides* Lamarck, *Omphalocyclus macroporus* (Lamarck) (Figs 2, 4, 6, 7) then the dominance of globular heterohelicids and rugoglobigerinids, and finally the disappearance of planktonic keeled forms and rugoglobigerinids. Small benthic calcareous foraminifers and agglutinated foraminifers are also worth noticing.

The higher part of the studied section is solely characterised by benthic foraminiferids and globular heterohelicids, e.g., *Racemiguembelina fructicosa* (Egger), the index taxa for *Racemiguembelina fructicosa* Zone, rugoglobigerinids and the disappearance of planktonic keeled forms and a lower number of rugoglobigerinids.

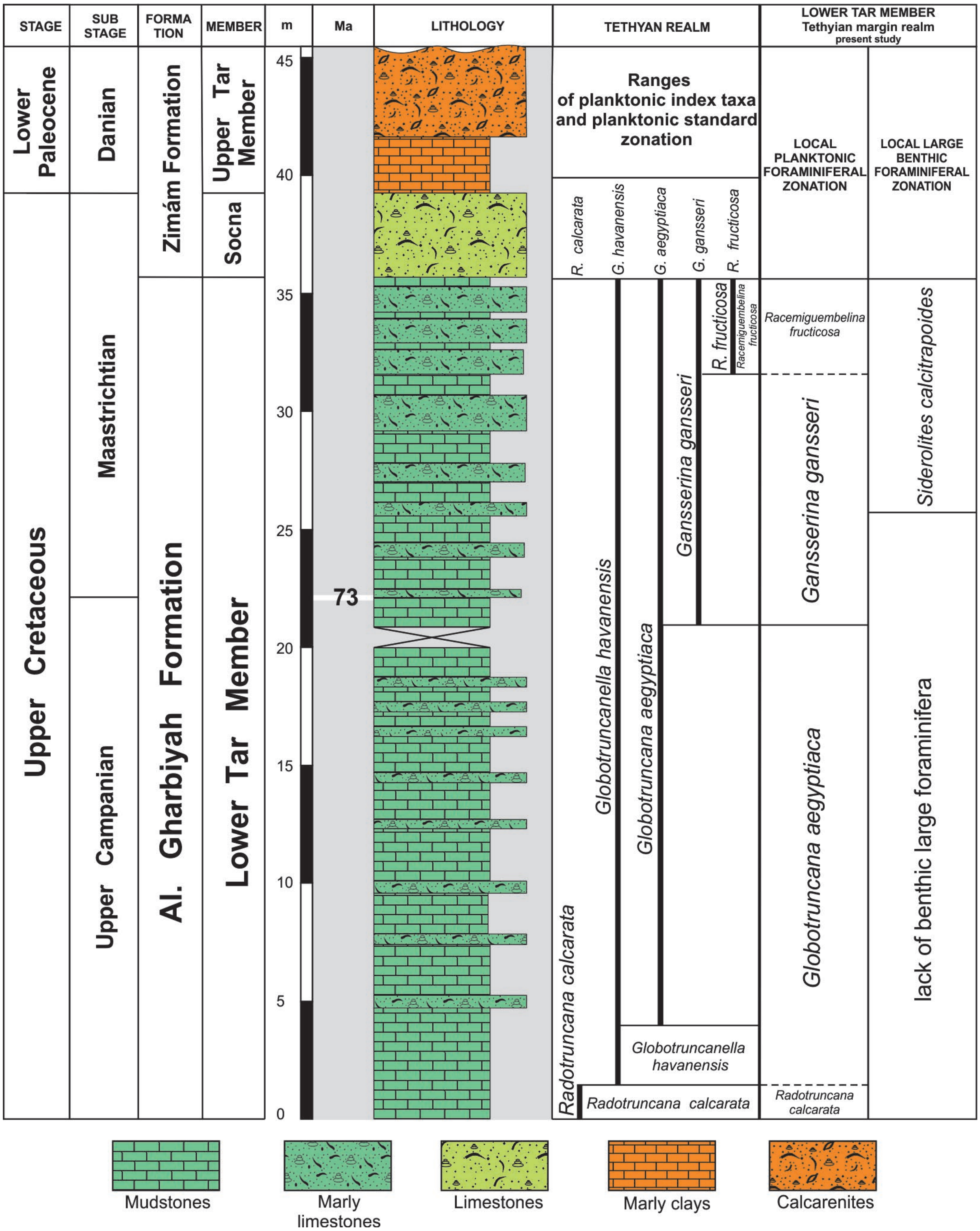

Fig. 3. Composite stratigraphic column of surface section on the western flank of the Hun Graben. Range of planktonic foraminifera. Correlation between planktonic foraminiferal zonation and large benthic foraminiferal zonation .

The foraminiferal assemblages from the highest part of the section are displaying a very low diversity with globular (non-keeled) planktonic forms, mainly heterohelicids and globigerinelloidids, and some benthic forms (WTR2-11––WTR2-25). All the samples above WTR2-25 are characterized by the occurrence of single LBF (*Siderolites calcitrapoides* Lamarck, *Omphalocyclus macroporus* (Lamarck) in very bad state of preservation, and no planktonic foraminiferid has been retrieved so far. *Globotruncana aegyptiaca* and *Gansserina gansseri* are commonly found in samples from the Lower Tar Member sections. *Radotruncana* cf. *calcarata* occurs as a single specimen in sample WTR1 and its bad state of the preservation do not allow a precise designation. *Globotruncana aegyptiaca*occurs in sample WTR1-2 and persists upwards. The *Gansserina gansseri* occurs in sample WTR2-7 and is present in the overlying strata (Fig. 2).

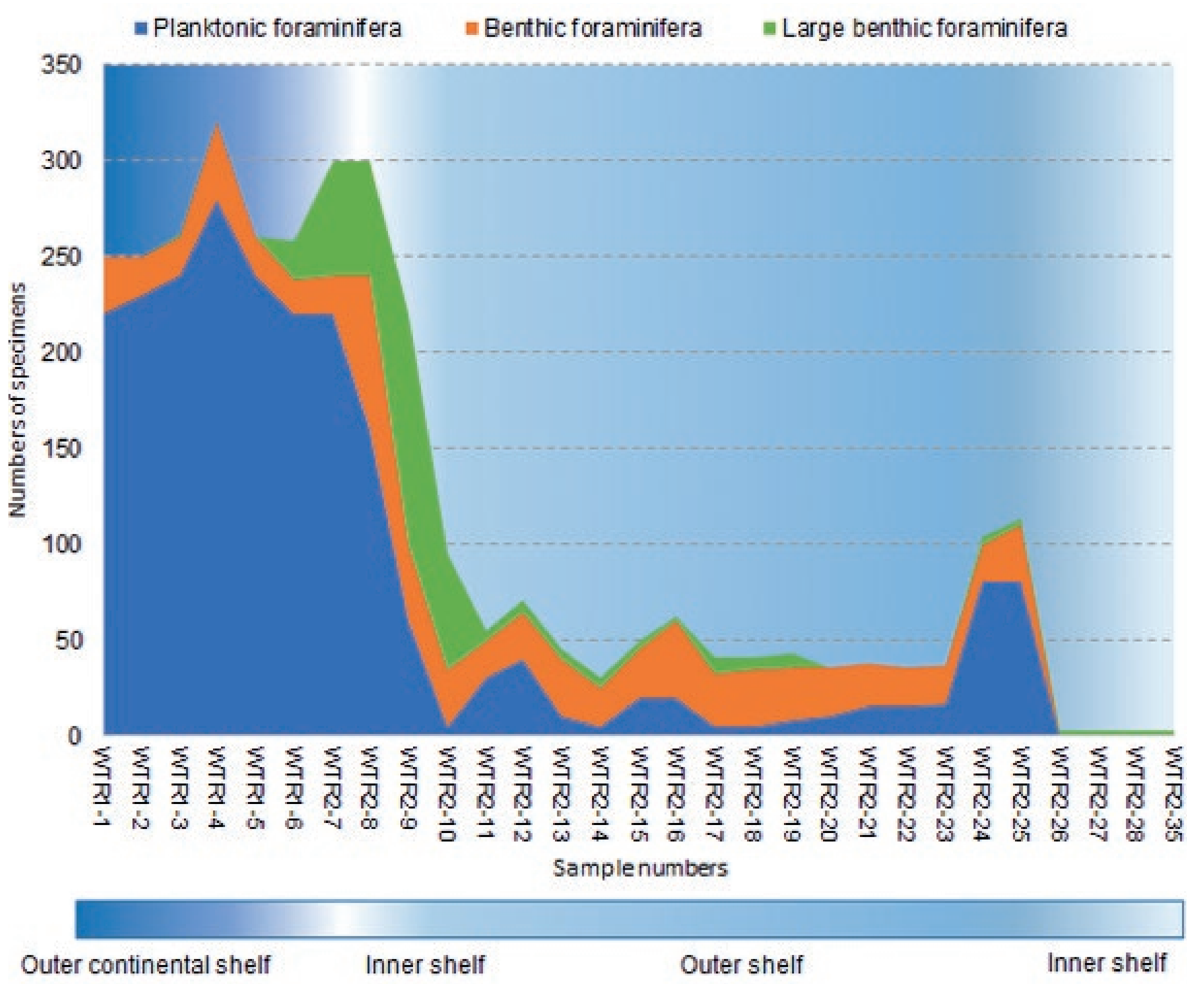

Fig. 4. Vertical fluctuations of foraminiferal assemblage composition and of estimated palaeo-depths, mainly based on appearance of large benthic shallow-water foraminiferids.

INTERPRETATIONS

Planktonic foraminiferal biostratigraphy

In the following, we are using the standard planktonic foraminiferal zonations proposed by Caron (1985), Robaszyński and Caron (1995), Ogg *et al.* (2004, 2012) and Premoli-Silva and Verga (2004). Planktonic foraminifera of the studied sections comprising planktonic foraminifera taxa that are important biostratigraphical markers, particularly in the Tethyan Realm, and correlation with the standard planktonic foraminiferal zonation are possible, however sometimes difficult because of the bad preservation or single occurrence of the taxa.

The top of the *Radotruncana calcarata* Total Range Zone (late Campanian) is identified thanks to the occurrence of the zonal index species in sample WTR 1-1. The concept of the *Radotruncana calcarata* Zone (late Campanian) is largely discussed by Robaszyński *et al.* (2000), Robaszyński and Mzoughi (2010) and Voigt *et al*. (2010, 2012). Recognized in Tercis (GSSP; Landes, France), in the Bottaccione and Contessa sections (Apennines Italy) as well as in the spectacular sections in North Africa (e.g., at El Kef, Tunisia), the *R. calcarata* Zone is defined by the total stratigraphic range of *R. calcarata*, which is considered as globally synchronous. Notwithstanding, at Tercis, the *R. calcarata* Zone is based only on the occurrence of two poorly-preserved specimens, and we must keep in mind that the total range of this zone might possibly not be recorded in full. Most micropalaeontologists working on the North African sections are considering that the Campanian ends with the upper limit of the *Radotruncana calcarata* Zone (cf. Robaszyński and Mzoughi, 2010). According to them, *R. calcarata* appears in the upper part of the ammonite *Nostoceras* (*B.*) *polyplocum* Zone and becomes extinct below the *Nostoceras hyatti* Zone, which is well below the Campanian-Maastrichtian boundary. In sample WTR1-1, the first and single occurrence of *R.* cf. *calcarata* is noted (Fig. 2). Therefore, the recognition of this zone should be treated with some caution.

One would assume that samples WTR1-2 to WTR1-6 represent *the Globotruncana aegyptiaca* Zone (late Campanian) and samples WTR2-7-WTR2-11 represent the

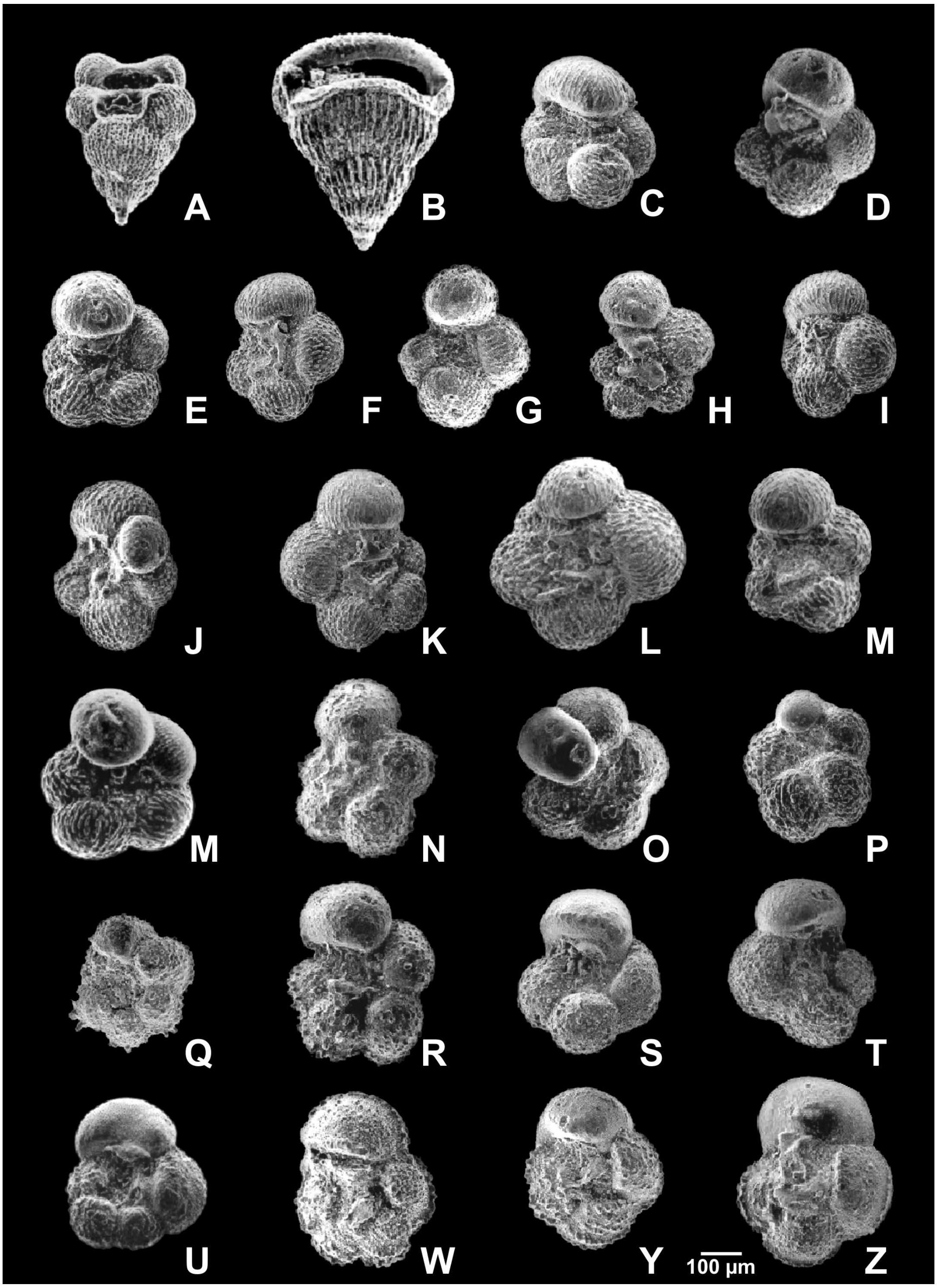

Fig. 5. SEM images of Upper Cretaceous significant planktonic foraminifera from the studied interval. **A.** *Heterohelix planata* (Cushman), sample WTR2-10; **B.** *Pseudotextularia elegans* (Rzehak), WTR2-14; **C.** *Rugoglobigerina macrocephala* Brönnimann, sample WTR2-24; **D.** *Rugoglobigerina macrocephala* Brönnimann,WTR1-6; **E**. *Rugoglobigerina rugosa* (Plummer), sample WTR2-24; **F.** *Rugoglobigerina rugosa* (Plummer), sample WTR2-11; **G.** *Rugoglobigerina rugosa* (Plummer), sample WTR2-17; **H.** *Rugoglobigerina rugosa* (Plummer), sample WTR2-19; **I.** *Rugoglobigerina rugosa* (Plummer), sample WTR2-18; **J.** *Rugoglobigerina rugosa* (Plummer), sample WTR2-15; **K.** *Rugoglobigerina rugosa* (Plummer), sample WTR2-23; **L.** *Rugoglobigerina rugosa* (Plummer), sample WTR2-22; **Ł.** *Rugoglobigerina rugosa* (Plummer), sample WTR2-25; **M.** *Rugoglobigerina rugosa* (Plummer), sample WTR2-25; **N.** *Rugoglobigerina* cf. *scotti* (Brönnimann), sample WTR.2-17; **O.** *Rugoglobigerina* sp., WTR1-5; **P.** *Rugoglobigerina* sp., sample WTR1-4; **Q.** *Globotruncanella* cf. *citae* (Bolli), sample WTR2-7; **R.** *Globotruncanella havanensis* (Voorwijk), WTR1-1; **S.** *Archaeoglobigerina blowi* Pessagno, sample WTR2-8; **T.** *Archaeoglobigerina* cf. *blowi* Pessagno, sample WTR2-11; **U.** *Archaeoglobigerina* cf. *cretacea* Pessagno, sample WTR2-11.

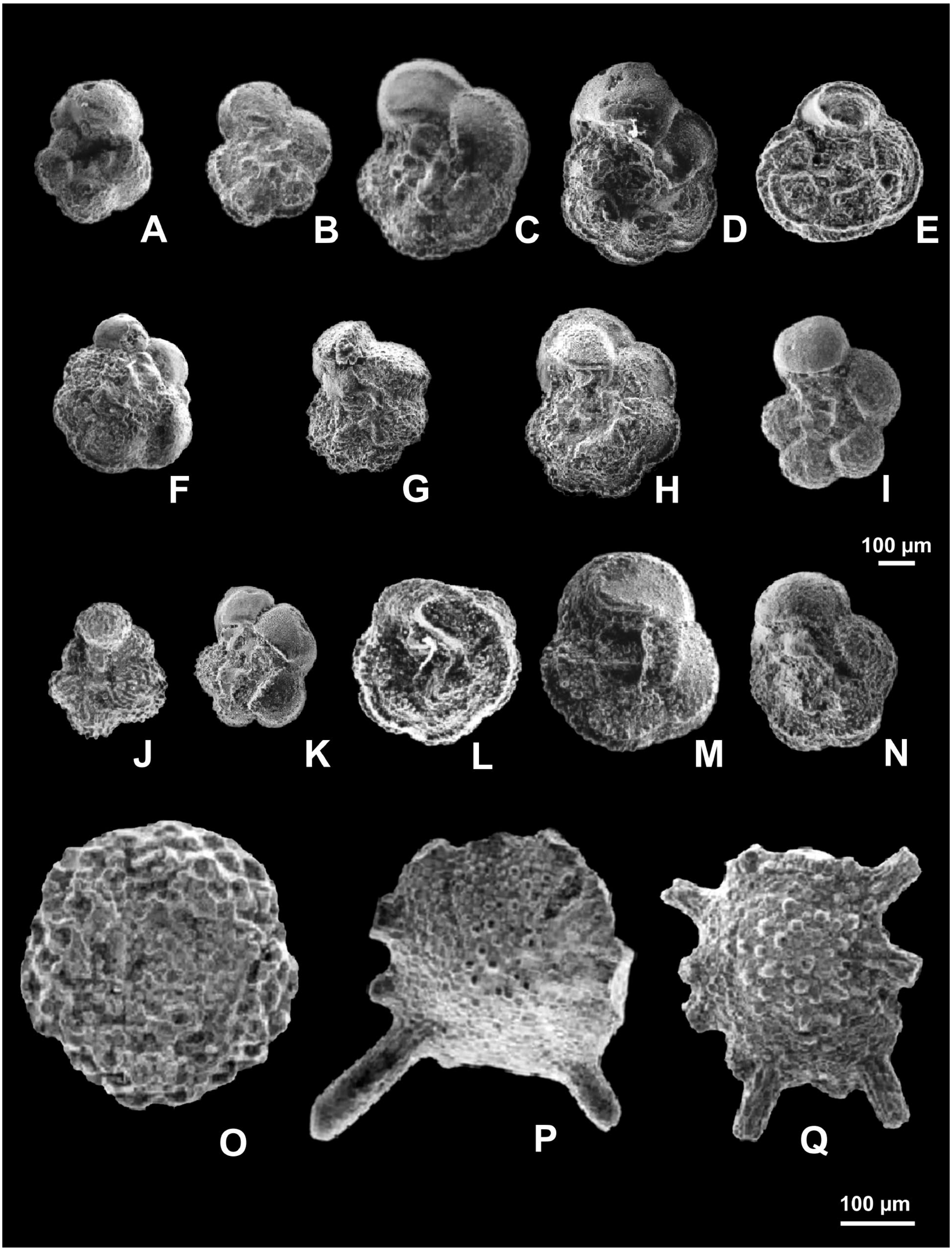

Fig. 6. SEM images of Upper Cretaceous significant planktonic and large benthic foraminifera from the studied interval. **A.** *Globotruncana* cf. *bulloides* Vogler, sample WTR1-1; B. *Globotruncana arca* (Cushman), sample WTR1-1; **C**. *Rugoglobigerina macrocephala* Brönnimann, sample WTR2-24; **D.** *Globotruncana bulloides* Vogler, sample WTR1-1; **E.** *Globotruncana bulloides* Vogler, sample WTR1-6; **F.** *Globotruncana falsostuarti* Sigal, sample WTR1-6; **G.** *Rugoglobigerina rugosa* (Plummer), sample WTR2 -17; **H.** *Globotruncana ventricosa* (White), sample WTR1-1; **I.** *Globotruncanella havanensis* (Voorwijk), sample WTR1-1; **J.** *Rugoglobigerina rugosa* (Plummer), sample WTR2-15; **K.** *Gansserina gansseri* (Bolli), sample WTR2-9; **L.** *Rosita contusa* (Cushman), sample WTR2-7; **M.** *Rosita fornicata* (Plummer), sample WTR1-4; **N.** *Abathomphalus* sp. WTR2-25; **O.** Isolated species of *Omphalocyclus;* **P.** Isolated species of *Siderolites;* **R.** Isolated species of *Siderolites.*

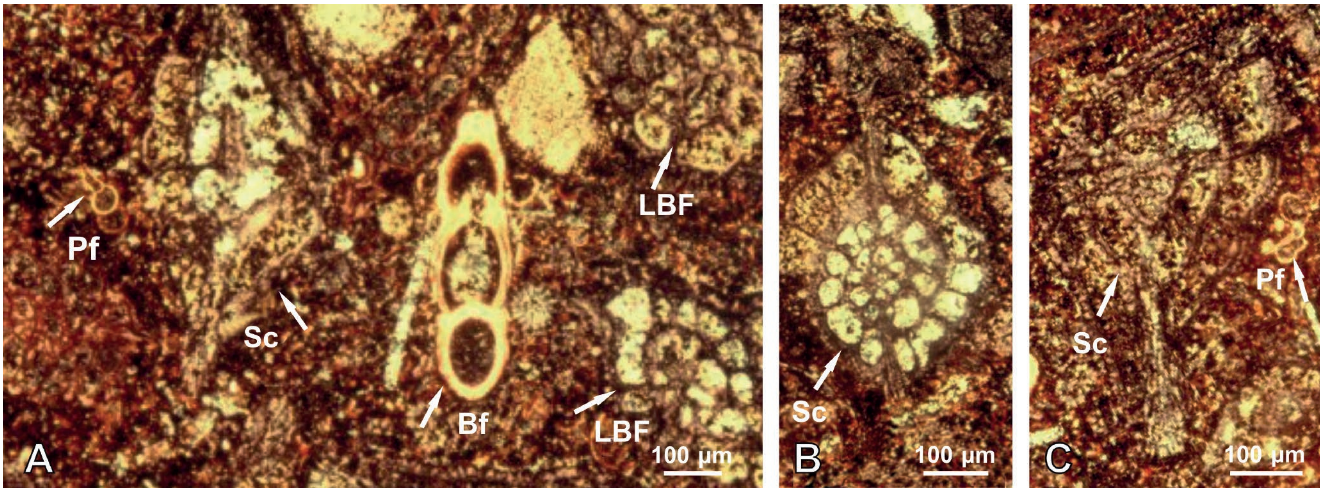

Fig. 7. Microphotographs of thin section. **A.** Pf – planktonic foraminifer*Hedbergella* sp.axial section; Sc– *Siderolites* sp. large benthic foraminifer, oblique section; Bf – benthic calcareous forms *Nodosaria* sp., axial section; LBF – part of large benthic foraminifer, oblique section; LBF– part of large benthic foraminifer, oblique section, WTR 2-10. **B.** Sc – *Siderolites calcitrapoides* large benthic foraminifer, oblique section, WTR2-11. **C.** Sc – *Siderolites sp.* large benthic foraminifer – oblique section; Pf –planktonic form *Archaeoglobigerina* sp.– axial section, WTR2-9

Gansserina gansseri Zone. The *Globotruncana aegyptiaca* Zone (interval zone) between the first occurrence (FO) of the nominal species and the FO of *Gansserina gansseri.* The lower boundary of the zone is at the top of the first quarter of chron 32 R2 (Premoli Silva and Sliter, 1994). The top is at the FO of *Gansserina gansseri*.

Gansserina gansseri, index species of the *Gansserina gansseri* Interval Zone (late Campanian–early Maastrichtian), starts to occur in sample WTR2-7 and is present in the overlying strata (Fig. 2). The lower boundary of this zone is the FO of the index species in the high part of chron 32 N2 (Premoli Silva and Sliter, 1994). The top of this zone is marked by the FO of *Abathomphalus mayaroensis* (Bolli) (Robaszyński *et al*., 1984; Caron, 1985). The Lower Tar Member was assigned to Maastrichtian on the basis of ammonites *Nostoceras magdadiae* Lefeld and Uberna, 1991 and *Baculites* sp. (Lefeld and Uberna, 1991). However, Salaj and Nairn (1987) previously suggested a late Campanian–Maastrichtian age. According to Cretaceous microfossil biostratigraphy (Bralower *et al*., 1995; Robaszyński and Caron, 1995; Machaniec, 2002; Gasiński and Uchman, 2009, 2011; Ţabără *et al.,* 2017), the stratigraphic range of the *Gansserina gansseri* Zone spans across the Maastrichtian–Campanian boundary, which has been dated as approximately 71.3 My (Fig. 3). Taking into consideration integrated geomagnetic polarity and stratigraphic time scale for the Cretaceous Period (Gradstein *et al*., 1994; Gradstein and Ogg, 2004; Ogg *et al*., 2004, 2012), the Campanian-Maastrichtian boundary was situated within the Lower Tar Member (Fig. 2). According to the current time scale, the *Globotruncana aegyptiaca* Zone belongs entirely to the late Campanian stage (Gradstein *et al*., 1994; Ogg *et al*., 2004, 2012). Therefore, the lower part of the Lower Tar Member exposed in the type locality at Wadi Tar is of Campanian age rather than of Maastrichtian age as formerly proposed.

A worth mentioning fact about the stratigraphic record of the uppermost Cretaceous strata at the western margin of the Western Sirte Basin is that the latest Maastrichtian nominal index species, *Abathomphalus mayaroensis* has not been found in the surface outcrops. All the samples collected above sample WTR2-25 appear to be barren of planktonic foraminiferids. Although there could be several reasons for this dearth of youngest Cretaceous planktonic, the most likely one, consistent with the sedimentological observations, is that being a hiatus at the peak of the Cretaceous regression. The most plausible explanation of the absence of index taxa *Abathomphalus mayaroensis* is the bathymetry, because this species is bathypelagic, thus absent in shallower areas of the basin (Farouk, 2014; Kędzierski *et al.,* 2015). Another argument is the fact that *A. mayaroensis* is seldom found in tropical areas (Premoli-Silva and Verga, 2004; Abdallah and Obaidalla, 2013).

The present study evidences that the Lower Tar Member section in the type localities at the Wadi Tar belongs in the lower part to the late Campanian (*Radotruncana calcarata*, *Globotruncana aegyptiaca* zones and lower part of the *Gansserina gansseri* Zone), and the upper part belongs to the middle–late Maastrichtian (*Gansserina gansseri* Zone, *Racemiguemelina fructicosa* Zone, Fig. 3).

Large benthic foraminiferal biostratigraphy

Large benthic foraminifers recorded in the Wadi Tar section [*Siderolites calcitrapoides* Lamarck and *Omphalocyclus macroporus* (Lamarck)], have a stratigraphic value (Robles-Salcedo *et al.,* 2013, 2018), which indicate the middle–late Maastrichtian (Fleury *et al.,* 1985; Caus, 1988; Abdelghany, 2003; Caus *et al.,* 2010).

PALAEOECOLOGY

Analyses of foraminiferal assemblage compositions provided first-order data to precise the biostratigraphic and palaeobathymetric estimations and the direction of palaeoslope inclination based on models proposed respectively for planktonic foraminifers (e.g., Sliter, 1972; Sliter and Baker, 1972; Olsson and Nyong, 1984; Gasiński, 1997, 1998) and for large benthic foraminifers (e.g., Hottinger, 1983, 1997, 2006; Hallock and Glenn, 1986; Hohenegger, 1994, 1995, 1996, 2009; Machaniec *et al*., 2011; Robles-Salcedo *et al.*, 2013, 2018).

Palaeobathymetric estimation based on recent foraminiferids and analyses of basic literature have been proposed by Hemleben *et al.* (1989). According to current conventions, the ratio of planktonic to benthic species gives an indication of the open ocean versus near shore habitat of the foraminifera at the time of skeletal deposition. Similar restrictions on species survival and abundance have been found in fossil sediments (e.g., Eicher and Worstell, 1970; Douglas, 1972; Sliter, 1972; Sliter and Baker, 1972; Boersma and Shackleton, 1981; Caron and Homewood, 1983; Leckie, 1987).

Sedimentary environmental changes on the western flank of the Hun Graben are clearly visible in the vertical fluctuations of the foraminiferal assemblage compositions in the Lower Tar Member. Quantitative relationships between planktonic and benthic foraminiferids, and shallow marine fossils, in the Lower Tar Member, are shown in Fig. 4. There are significant differences in the fossil content between the lower and upper portions of the Lower Tar Member.

The lower portion, from samples WTR1-1 to WTR1-7 (*Radotruncana calcarata*, *Globotruncana aegyptiaca* and *Gansserina gansseri* zones), is dominated by highly diversified bathypelagic planktonic foraminiferids (globotruncanids). In contrast, the upper portion of the Lower Tar Member, from samples WTR2-11 to WTR2-25 (*Gansserina gansseri*, *Racemiguembelina fructicosa* zones) contains the epipelagic planktonic foraminiferids and a relatively large amount of benthic forms. Between the lower and the upper parts of the section lies a middle interval represented by samples WTR2-8 to WTR2-10 (*Gansserina gansseri* Zone), which contains a high number of shallow water microfossils with an even proportion of planktonic and benthic forms.

These differences in the vertical distribution are interpreted in terms of bathymetric variations and, hence, different depositional environments. The lower part of the Lower Tar Member (late Campanian, *Radotruncana calcarata*, *Globotruncana aegyptiaca* and lower part of *Gansserina gansseri* zones; samples WTR1-1–WTR1-7) had been most likely deposited in an open-marine to outer-shelf environment of considerable water depth. This is supported by the predominance of keeled planktonic foraminiferids which belong to the bathypelagic morphotypes (Figs 5, 6). The upper part of the Lower Tar Member (Maastrichtian, upper part of the *Gansserina gansseri* and *Racemiguembelina fructicosa* planktonic foraminiferal zones; *Siderolites calcitrapoides* large benthic foraminifera Zone; samples WTR2-8 to WTR2-10-25) had been probably deposited in a shallower environment. This is indicated by a high proportion of large benthic foraminifers typical of carbonate platform environments within the photic zone.

Quantitative and qualitative studies of planktonic foraminifers documented foraminiferal changes that can be used as a proxy tool for sea-level changes for the late Campanian and Maastrichtian in the studied area, from open-marine to littoral areas (Fig. 4). The latest Cretaceous regression could have caused a diminution of the water capacity over the slope and shelf and, hence, probably drove the extinction of bathy-pelagic species.

Additionally, an intermediate environment had developed between the open-marine to outer-shelf and the inner-shelf environments. The existence of such an environment is strongly supported by the foraminiferal assemblages of samples WTR2-8 to WTR2-10 (Figs 2, 4–7).

These assemblages consist of approximately equal proportions of pelagic and benthic foraminiferids, with a large amount of shallow large benthic foraminifers. Such mixed assemblages can be interpreted as allochthonous shallow water foraminiferids assemblages transported into a deeper pelagic environment by density currents.

Foraminiferids from the Lower Tar Member of the Zimám Formation were previously studied and used for stratigraphic and environmental interpretations (Eliagoubi and Powell, 1980). Our results and subsequent interpretations differ from this early opinion. Eliagoubi and Powell (1980) proposed two assemblage zones within the Lower Tar Member; namely, the *Globotruncana fornicata* Zone and the younger *Globotruncana conica* Zone. This latter was subdivided into the *Globotruncana* (*Gansserina*) *gansseri* Subzone and the *Globotruncana contusa* Subzone. When analyzing the alternations of the pelagic and shallow water assemblages of foraminiferids in the Lower Tar Member, Eliagoubi and Powell (1980, p. 151) postulated tectonically driven changes of sea-level as a main key factor upon sedimentation.

According to them, open-marine conditions favouring the accumulation of planktonic forms had been punctuated by intervals of pronounced shallowing where few planktonic forms are preserved. Locally, at the top, the *Globotruncana conica* Zone at Dur Talah and near the middle of the same zone at Wadi Tar, the sudden abundance of shallow-water, higher-energy, benthic forms from the euphotic zone (*Omphalocyclus* and *Siderolites*) clearly indicate a return to fault-controlled shallowing of the basin. The presence of these benthic foraminiferids associated with sea-grass is indicative of a clear, oligotrophic shallow-water setting, with a maximum depth of 15–30 m (Caus *et al*., 2016; Hart *et al*., 2016). The presence of *Siderolites* is the mere piece of evidence of shallow-water environments, mainly carbonates, of tropical to subtropical platforms (Robles-Salcedo *et al*., 2013).

The changes in the pelagic and shallow-water assemblages, especially the co-occurrence of shallow-water fossils with planktonic ones in the same samples, can also indicate a possible redeposition and not only a shallowing. Mobilization of foraminiferal ooze and its distribution by dilute suspension currents have been documented from many deep-water marine settings. Tectonic influence on the redeposition process is very likely but does not imply necessarily a significant shallowing of the depositional environment in the middle part of the Lower Tar Member as postulated Eliagoubi and Powell (1980).

The shallowing of the depositional environment of the Lower Tar Member was rather gradual and consistent with the global regression recorded at the end of the Cretaceous Period. This does not require to interpret them in terms of tectonically-driven relative sea-level changes. The transition from the Cretaceous to the Palaeogene is marked in the Western Sirte Basin by regressive deposits coinciding with a major, worldwide regression (Hallam, 1963; Ager, 1981; Haq *et al.*, 1987; Haq, 2014).

CONCLUSIONS

The Lower Tar Member exposed in the stratotype sections of Wadi Tar Al Kair in the Western Sirte Basin spans four standard planktonic foraminiferal zones, i.e. the *Radotruncana calcarata* Zone, *Globotruncana aegyptiaca* Zone (late Campanian), the *Gansserina gansseri* Zone (late Campanian–middle Maastrichtian) and *Racemiguembelina fruticosa* and one standard large benthic foraminiferal zone on the basis of the index species *Siderolites calcitrapoides* for the middle–late Maastrichtian.

Changes in the foraminiferal assemblages, especially the presence of the large benthic foraminifers, supports a positive correlation between benthic assemblage composition and intensity of shallowing.

The highest sea-level is located in the late Campanian. Large benthic foraminifera are mere evidence of inner-shelf palaeo-depths in Maastrichtian. A significant shallowing is inferred in the middle/late Maastrichtian, followed by a deepening and again shallowing in the late Maastrichtian on the western margin of the Sirte Basin.

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