Santonian-Campanian biostratigraphy of the Kalaat Senan area (West-Central Tunisia)

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Abstract: The Santonian-Campanian (S/C) transition in the Kalaat Senan area is well exposed in the Assila Wadi (OA) section and consists of marls with indurate glauconitic levels towards the base. Standard Mediterranean ammonite biozonations could not be applied to this section because the biomarkers are absent. However, planktonic foraminiferal biozonation is more reliable for indicating the S/C boundary, and here we propose to use the last appearance datum of *Dicarinella asymetrica* as the index marker of this boundary. A high-resolution quantitative analysis of the planktonic foraminifera of the OA section allows us to define the main bioevents across the S/C transition interval and to specify the S/C boundary. The section reveals that the extinctions across the transition interval occurred among species with a trochospiral keeled test and free portici of the genera *Dicarinella* and *Marginotruncana*. In fact, the dicarinellids eventually became extinct and the last appearance of the index species *Dicarinella asymetrica* defines the S/C boundary, whereas the marginotruncanids suffered a gradual extinction and several species crossed the boundary. Representative taxa of the genera *Globotruncanita* and *Globotruncana* first occurred in the uppermost part of the Santonian. These bioevents indicate a major but gradual planktonic foraminiferal turnover during the S/C transition, and may be related to adaptive changes and intraspecific competition. Because dicarinellids and marginotruncanids lived in tropical-subtropical oceanic realms, they seem to have been less able to adapt during the environmental changes associated with the transition; they were progressively replaced by more evolved globotruncanids belonging to the genera *Globotruncana* and *Globotruncanita*. This major turnover may have been initiated by an increase in temperatures succeeding a maximum flooding stage of a transgressive period. These oceanic conditions appear to have been favorable for radiation of the globotruncanids and heterohelicids.

Key words: Santonian/Campanian boundary, biostratigraphy, planktonic foraminifera, Kalaat Senan, Tunisia

1. Introduction

Since the 1995 Meeting on Cretaceous Stages in Brussels, a number of studies have contributed to further improve the knowledge of biostratigraphic characteristics of the different stages and their boundaries (Gale et al., 1995; Hancock and Gale, 1996). As a result, diverse biozones based on different fossil groups (ammonites, belemnites, inoceramids, planktonic and benthic foraminifera, radiolarians, and calcareous nannofossils) have been correlated. Despite discrepancies relating to the methodology used and sampling resolution that led to controversies, there has been a marked improvement in the characterization of some of the stages and their boundaries (Salaj, 1980; Bellier, 1983; Caron, 1985; Robaszynski and Caron, 1995; Arz, 1996; Rami et al., 1997; Rami, 1998; El Amri and Zaghbib-Turki, 2005). In addition to biostratigraphic correlations, several studies further established a calibration between proposed biozones and the magnetostratigraphic scale, and most

recently an absolute age of 83.6 ± 0.2 Ma has been assigned to the Santonian/Campanian (S/C) boundary (Gradstein et al., 2012).

The S/C transition interval has been studied in many sections in Tunisia, e.g., El Kef (Nederbragt, 1991, 1993; Jarvis et al., 2002), Fguira Salah (Salaj, 1980), Aïn Settara (Arz, 1996), Kalaat Senan (Robaszynski, 1999; Robaszynski et al., 2000), and elsewhere, e.g., Alamedilla (Arz, 1996), Navarra and Alava in Spain (Küchler and Wagreich, 2002), Lipnik-Kije in Poland (Remin, 2004), the New Jersey coastal plain in the United States (Georgescu, 2006), Seaford Head in England (Hampton et al., 2007), and the Waxahachie Dam Spillway in Texas (Gale et al., 2008), but the Global Boundary Stratotype Section and Point (GSSP) has yet to be chosen by the International Subcommission on Cretaceous Stratigraphy. Moreover, the criteria that should be used to characterize the boundary have not been formally stated yet.

Although published paleomagnetic data relating to the Upper Santonian–Lower Campanian remain equivocal,

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magnetostratigraphy has potentially more universal chronostratigraphic value to resolve the debate. Gradstein et al. (2004) placed the S/C boundary above the C34N/C33R. However, Gradstein et al. (2012) noted that the base of the Campanian is coeval with the base of C33R. According to the same authors, the S/C boundary identified by the last occurrence (LO) of *D. asymetrica* lies a little above paleomagnetic inversion and reversal zone C34N/C33R.

These results are supported by input from various taxonomic groups from the Santonian–Campanian transition series successions (e.g., inoceramids, ammonites, echinoids, crinoids, planktonic foraminifera, calcareous nannofossils). These fossil groups have provided diverse criteria for defining the S/C boundary.

Based on ammonites of the Tethyan realm, the boundary is initially defined by the first appearance datum (FAD) of *Placenticeras bidorsatum* (de Grossouvre), but according to Hancock and Gale (1996), this extremely rare species is not a practical marker.

The base of the Campanian Stage has also been defined by the LO of texanitinids (Robaszynski et al., 2000) and by the first occurrence (FO) of *Scaphites hippocrepis* (latest form) from the Narrava and Alava sections in Spain (Küchler and Wagreich, 2002).

On the other hand, in the North American Western Interior Sea, the S/C boundary coincides with the base of the *Scaphites leei* III biozone (Cobban et al., 2006; Gale et al., 2008, Gradstein et al., 2012).

Pelagic crinoids have also been found suitable for defining the S/C boundary. It has been defined to coincide with the LO of *Marsupites testudinarius* (Hancock and Gale, 1996; Robaszynski, 1999; Gradstein et al., 2004; Remin, 2004; Robaszynski et al., 2005; Hampton et al., 2007; Gale et al., 2008; Melinte-Dobrinescu and Bojar, 2010; Gradstein et al., 2012). The first appearance of *Uintacrinus anglicus* is also used to define the proximity of the boundary (Gale et al., 2008).

The presence of *Marsupites laevigatus* in the Micraster bed in the Gosau Group in Austria is considered a criterion of the S/C boundary (Wagreich et al., 2010).

Calcareous nannofossils used to characterize the boundary are as follows: stratigraphic level just below the FOs of either *Arkhangelskiella cymbiformis* (Burnett, 1998) or *Broinsonia parca parca* (Hancock and Gale, 1996, p. 104; Robaszynski, 1999, p. 162).

The FO of *A. cymbiformis* in the Fizesti section (Romania) is below the S/C boundary (Melinte-Dobrinescu and Bojar, 2010). In the Navarra section (Spain), Küchler and Wagreich (2002) further placed the boundary within CC17, equivalent to the *Calculites obscurus* (Deflandre) biozone. This biozone is subdivided into subzones CC17a and CC17b using the *Calculites* cf. *obscurus* and *Calculites obscurus* morphotypes, respectively. Hampton et al. (2007)

also confirmed that the boundary is best placed just above the first appearance of *Calculites obscurus*. Hence, the S/C transition is marked by successive appearances of *Calculites obscurus* and *Aspidolithus parcus parcus* (Stradner), which indicate respectively the upper part of the Santonian and the base of the Campanian (Ogg and Ogg, 2004). According to Gardin et al. (2001), the base of the Campanian coincides with the LO of *A. parcus parcus*.

A morphological lineage from *A. parcus expansus*, *A. parcus parcus*, and *A. parcus constrictus* characterized by a reduction of a central-plate area characterizes the uppermost Santonian-basal Campanian (Crux, 1982; Gardin et al., 2001; Bey et al., 2012). According to Wagreich et al. (2010), the first appearance of curved *Lucianorhabdus cayeuxii* together with common *Calculites obscurus* is an event indicating the proximity of the S/C boundary.

On the basis of planktonic foraminifera, Wonders (1980) defined the S/C boundary coinciding with the transition from the *Globotruncana elevata*/*Marginotruncana carinata*. However, according to Sigal (1952), *Marginotruncana carinata* is a junior synonym of the *Globotruncana asymetrica* (=*Dicarinella asymetrica*) concurrent biozone to the *Globotruncana elevata* partial range zone.

Salaj (1980) suggested instead that the S/C boundary coincides with the boundary between the *Globotruncana fornicata manaurensis* and *Globotruncana arca arca* s.s. biozones. Similarly, Peryt (1980) selected the *Globotruncana arca* biozone to represent the first foraminiferal biozone of the Campanian Stage. According to Bellier (1983) and Gradstein et al. (2004), the S/C boundary is indicated by the last appearance datum (LAD) of *Dicarinella asymetrica*. Gale et al. (1995), in accordance with Robaszynski et al. (1984, 2000), defined this boundary as being associated with the first appearance of *Globotruncanita elevata*, and Arz (1996) further characterized it by the FO of *Pseudoguembelina costulata* and the LO of *Dicarinella asymetrica*. Robaszynski (1999) specified that the upper Santonian coincides with the *Sigalia deflaensis* biozone, and the lower part of the Campanian stage is distinguished by the *Ventilabrella eggeri* biozone.

According to Wagreich et al. (2010), the base of Campanian is placed after the FO of *Globotruncanita elevata* but before the LO of *Dicarinella asymetrica*.

Robaszynski and Caron (1995) based on ammonites, Premoli Silva et al. (1998) based on stable isotopes, and Petrizzo (2000, 2002, 2003) based on magnetostratigraphy discussed the foraminiferal species range across the S/C transition and placed the S/C boundary in the upper part of the *Dicarinella asymetrica* biozone at the C34N/C33R boundary.

In this paper, we revise the S/C transition in the Assila Wadi (OA) section, from the Kalaat Senan area (central Tunisia), previously studied by Robaszynski et al. (2000).

Samples previously collected by these authors from the upper part of the Santonian–lower part of the Campanian interval (As285–As418 in Robaszynski et al., 2000, p. 376) are widely spaced (5 m apart) and cannot provide detailed biostratigraphy despite the richness of the planktonic foraminiferal fauna. Thus, we attempt to provide high-resolution semiquantitative foraminiferal data that will permit the identification of the S/C boundary in the section. The area includes good and continuous Cretaceous outcrops, many of which were previously studied by Pervinquière (1903, 1907), Thomas (1909), Berthe (1949), and Burollet (1956).

A geological map of the area (1/50,000 scale), prepared by Lehotsky et al. (1978), is useful for locating suitable exposures for study, and various biostratigraphic studies have been carried out in the area (e.g., Robaszynski, 1999; Robaszynski et al., 2000). The S/C transition interval in the OA section has been studied previously for its ammonites, inoceramids, planktonic foraminifera, and calcareous nannofossils (Robaszynski et al., 2000), but the reliance placed on regular 5-m sampling intervals has hindered biochronological resolution. We now provide detailed species ranges with quantitative data in order to improve the foraminiferal biozonation and characterize the main bioevents of the S/C transition interval.

2. Geographical and geological setting

The Santonian-Campanian transition series studied at the OA section is located about 16 km from Kalaat Senan village in the southern border of the "Jugurta table" sculpted within the *Nummulites*-rich Eocene limestones. The Eocene series and the adjacent Cretaceous-Paleocene sequences constitute the flank of the westernmost anticlinal structure close to the Algerian frontier. These structures are part of the central Atlas, where the folds trend mainly NE-SW and are cut by several grabens filled with Cenozoic deposits (Burollet, 1956; Lehotsky et al., 1978; Ben Ferjani et al., 1990). The studied section is about 50 km southeast of the GSSP established for the K/Pg boundary (El Kef section). It is close (~4 km) to the Aïn Settara section that also comprises a complete Cretaceous–Paleogene transitional succession (Arenillas et al., 2000; Luciani, 2002) (Figure 1).

3. Material and methods

Our study has focused on 60 m of the OA section (using a new sampling set), in the interval between samples As365 and As425 (Figure 2) reported by Robaszynski et al. (2000). This interval includes the transition from the Santonian to the Campanian, and it is in the upper part of the El Kef formation (Fournié, 1978). This succession is well exposed in the section, which is easily accessible by the road from Tajerouin to Majouba, and then over the

bridge of Oum Zâtar Wadi. From there one takes the trail to Sidi Bou Haraoua Marabout for a distance of about 2 km to reach the Assila Wadi.

At the OA section, the lower part of the succession is composed of soft marls 1–10 m thick with thin (10–20 cm) intercalated deposits of lithified marls and clayey limestones. Between 10 and 27 m from the base, the succession becomes increasingly richer in glauconitic grains, which may form distinct beds of up to 50 cm thick (Figure 2). The upper part of this section (between 27 m to 60 m from the base of the section) is composed of soft marls intercalated by resistant marl and clayey limestone.

Throughout this interval we have collected a total of 60 samples (A1–A60) at regular intervals of 1 m. The sediments were washed over 2 Afnor sieves (100 μm and 500 μm) and then dried in an oven at a moderate temperature (40 °C). The washed residues contained rich assemblages of diverse microfossils, and an Otto microsplitter was used to subdivide the washed residues in available parts containing at least 300 specimens in each fraction to establish relative abundances. The planktonic foraminifera were identified using the Ellis and Messina catalogue online and other appropriate published works on Cretaceous foraminifera (e.g., Robaszynski et al., 1984; Caron, 1985). The semiquantitative data are based on counts of approximately 300 specimens.

4. Biostratigraphy

Across the studied interval deposition at the OA section, 3 foraminiferal biozones are distinguished.

1- Dicarinella asymetrica biozone (TRZ), Author: Postuma (1971)

This total range zone is defined by the FAD and LAD of the nominate taxon and corresponds to the middle Santonian-late Santonian (Robaszynski et al., 1984; Caron, 1985; Robaszynski and Caron, 1995; Premoli Silva and Sliter, 1995; Robaszynski et al., 2000; Puckett, 2005; Sari, 2006). In the OA section we have investigated only the uppermost part of this biozone, which corresponds to the upper part of the Santonian Stage. The bed within, which is observed as the LO of this taxon to indicate the top of the biozone, is placed at 19 m above the base of the studied series.

2- Globotruncanita elevata/Globotruncana arca biozone (CRZ)

We propose *Globotruncanita elevata* and *Globotruncana arca* to nominate the first biozone of the Campanian Stage, because the 2 nominated species are equally abundant. This concurrent biozone (CRZ) is defined as the interval from the LO of *Dicarinella asymetrica* at the base to the FO of *Globotruncana ventricosa* at the top. From the LO of *Dicarinella asymetrica* typical specimens of *Globotruncanita elevata* and *Globotruncana arca* dominate the globotruncanids; therefore, it becomes difficult to
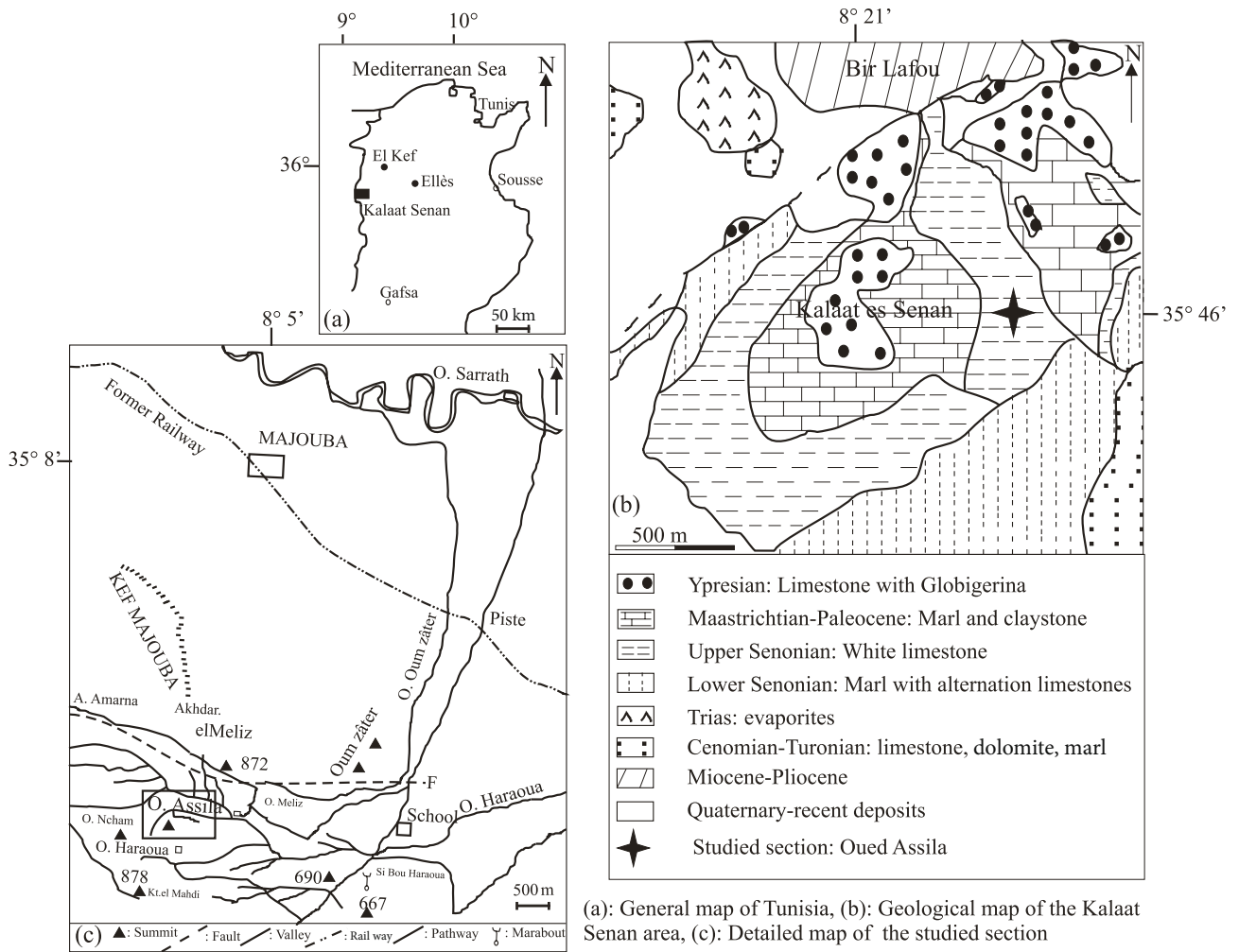
Figure 1. Geographic location of the studied section.

(a): General map of Tunisia, (b): Geological map of the Kalaat Senan area, (c): Detailed map of the studied section

Legend:
- Ypresian: Limestone with Globigerina
- Maastrichtian-Paleocene: Marl and claystone
- Upper Senonian: White limestone
- Lower Senonian: Marl with alternation limestones
- Trias: evaporites
- Cenomian-Turonian: limestone, dolomite, marl
- Miocene-Pliocene
- Quaternary-recent deposits
- Studied section: Oued Assila

(c) ▲: Summit ⟋: Fault ⌣: Valley ⋯: Rail way ⟋: Pathway ⅄: Marabout

favor one or another species to nominate the relevant zone. It is synonym of the *G. elevata* PRZ (Robaszynski et al., 1984; Caron, 1985; Robaszynski and Caron, 1995; Premoli Silva and Sliter, 1995; Robaszynski et al., 2000) and of the *Globotruncana arca* biozone (IZ) of Salaj and Samuel (1963). This biozone indicates the lower part of the Campanian Stage.

3- *Globotruncana ventricosa* biozone (IZ), Author: Dalbiez (1955)

This interval zone, adopted by Wonders (1980), Robaszynski et al. (1984), Caron (1985), Robaszynski and Caron (1995), and Premoli Silva and Sliter (1995), is characterized by the FO of *Globotruncana ventricosa* at the base and by the FO of *Globotruncanita* (*Radotruncana*) *calcarata* at the top. This biozone indicates the middle Campanian. Recently, Petrizzo et al. (2011) have proposed the *Contusotruncana plummerae* biozone for indicating the middle Campanian because of the rarity of *Globotruncana ventricosa* at the base of the interval zone.

5. Stratigraphic distribution and abundance of planktonic foraminifera

All of the samples from the section yielded rich assemblages of well-preserved planktonic foraminifera including small, biserial heterohelicids (e.g., *Heterohelix pulchra*, *H. globulosa*) and large multiserial heterohelicids (e.g., *Ventilabrella eggeri*, *V. glabrata*), trochospiral keeled (e.g., *Marginotruncana*, *Globotruncana*, and *Globotruncanita*) and unkeeled (*Costellagerina*, *Hedbergella*) taxa, and the rare planispiral *Globigerinelloides* (Figure 3). Small heterohelicids dominate the assemblages in all the samples studied.

The lower part of the succession (A1–A20) corresponds to the upper part of the *Dicarinella asymetrica* biozone and shows that the dicarinellids and marginotruncanids are not abundant. The first group is represented only by one species (i.e. *Dicarinella asymetrica*). The second group is more diverse (high species richness if we compare it to species richness of the genus *Dicarinella*).

187

Formation	Stage	Biozone	Samples (As) Robaszynski et al. (2000)	Samples (A)	Lithology	Description
Kef	middle part of the Campanian	*Globotruncana ventricosa* (IZ)	425, 420	60, 55		soft marls with resistant marl interbeds
	lower part of Campanian	*Globotruncanita elevata/Globotruncana arca* (CRZ)	415, 410, 405	50, 45, 40		soft and resistant marl alternations
				30		soft marls and clayey limestone alternations
			394, 389	25		marls rich in glauconite
	upper part of Santonian	*Dicarinella asymetrica* (TRZ)	384, 380, 375, 370, 365	20, 15, 10, 5, 1		soft and resistant marl alternations, some layers contain glauconite

10 m

● glauconite　∙ ∙ ∙ ∙ ∙ marl　▭ resistant marl and clayey limestone

Figure 2. Lithologic description of the Wadi Assila section.

	Kef			Formation
Upper Santonian	Lower Camanian		Middle Campanian	Age
Dicarinella asymetrica	*Globotruncanita elevata/Globotruncana arca*		*G. ventricosa*	Biozone
	Sample (A)			
	Lithology			

Species ranges chart (Lithology and biozones at top; species listed at right):

- *Heterohelix pulchra*
- *Heterohelix glabrans*
- *Heterohelix reussi*
- *Heterohelix globulosa*
- *Heterohelix navarroensis*
- *Ventilabrella eggeri*
- *Ventilabrella glabrata*
- *Planoglobulina manuelensis*
- *Marginotruncana undulata*
- *Globotruncanita elevata*
- *Contusotruncana fornicata*
- *Hedbergella delrioensis*
- *Globigerinelloides ultramicrus*
- *Pseudotextularia nuttalli*
- *Marginotruncana marginata*
- *Marginotruncana sinuosa*
- *Globotruncana obliqua*
- *Globotruncana caliciformis*
- *Hedbergella simplex*
- *Marginotruncana pseudolinneiana*
- *Dicarinella asymetrica*
- *Costellagerina pilula*
- *Heterohelix labellosa*
- *Globotruncana manaurensis*
- *Archaeoglobigerina blowi*
- *Heterohelix moremani*
- *Marginotruncana coronata*
- *Marginotruncana schneegansi*
- *Marginotruncana tarfayaensis*
- *Marginotruncana renzi*
- *Marginotruncana sigali*
- *Archaeoglobigerina cretacea*
- *Heterohelix carinata*
- *Ventilabrella alpina*
- *Contusotruncana patelliformis*
- *Rugoglobigerina* aff. *macrocephala*
- *Globotruncana* cf. *arca*
- *Globotruncana arca*
- *Globotruncana orientalis*
- *Globotruncana mariei*
- *Globotruncana bulloides*
- *Globotruncana linneiana*
- *Pseudoplanoglobulina austinana*
- *Contusotruncana* aff. *walfishensis*
- *Globotruncanita stuartiformis*
- *Contusotruncana plummerae*
- *Globotruncanita insignis*
- *Globotruncana ventricosa*

Legend (left margin):
- ● Glauconite
- Marls
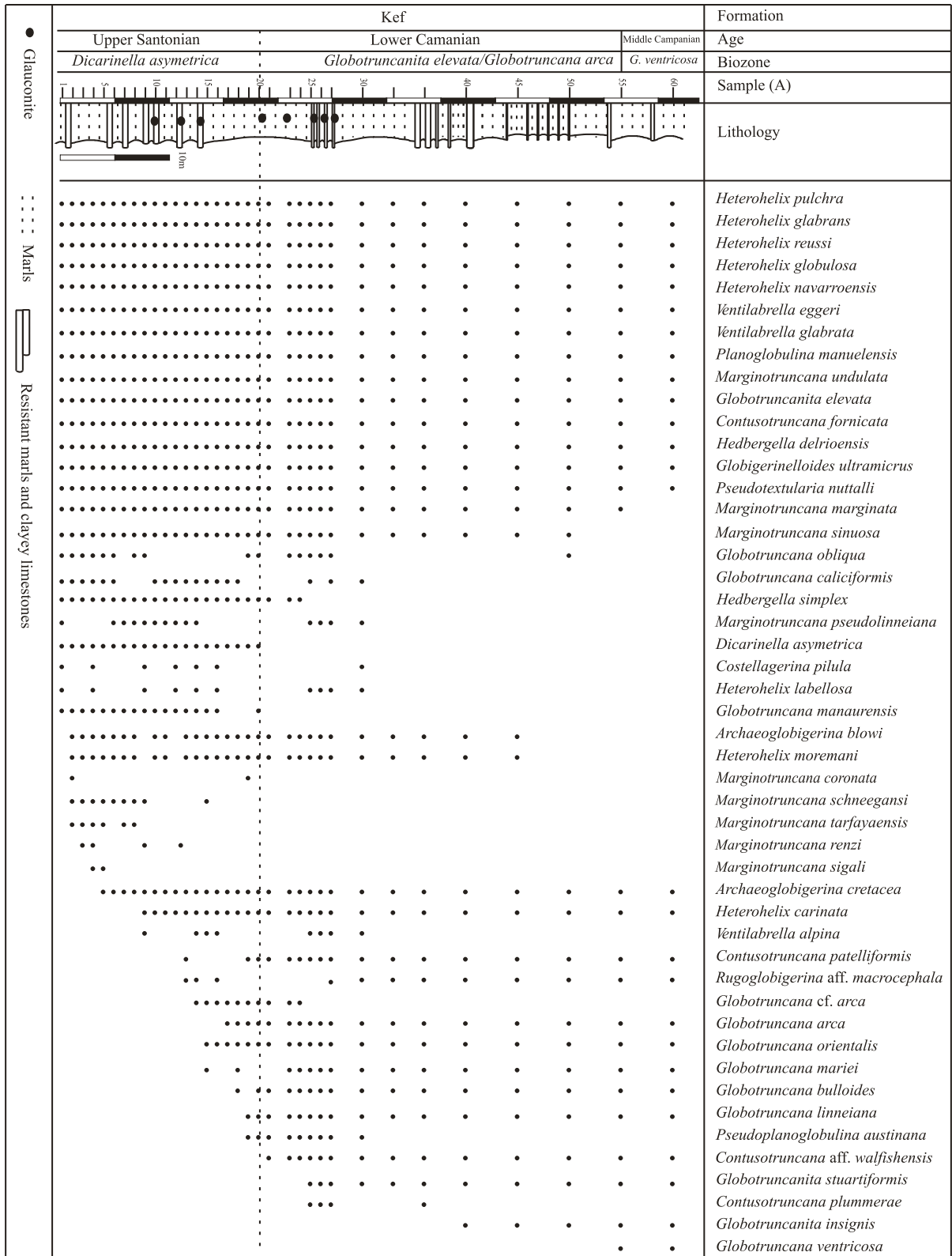- Resistant marls and clayey limestones

Figure 3. Species ranges of planktonic foraminifera at the Wadi Assila section.

Both are replaced by the globotruncanids through the remainder of the section. The LO of *Dicarinella asymetrica* was recorded in sample A20. *Globotruncanita elevata* occurs at the base in sample A1. Scarce specimens closely related to *Globotruncana arca* occur beginning at sample A14, while more frequent typical morphotypes are observed in sample A17. *Contusotruncana patelliformis* appears in sample A13 in the upper part of the Santonian, while *Globotruncana orientalis* and *Globotruncana mariei* are present in sample A15, 5 m below the LO of *Dicarinella asymetrica*. The large heterohelicids display low diversity. *Ventilabrella eggeri*, *V. glabrata*, and *Planoglobulina manuelensis* occur at the base (sample A1) of the section, in the upper Santonian. *Ventilabrella alpina* is present in sample A9, 11 m below the Santonian/Campanian boundary here designated as characterized by the LO of *Dicarinella asymetrica*. *Globotruncana linneiana* and *G. bulloides* occur in sample A19.

Contusotruncana patelliformis first appears in sample A21, and *Contusotruncana plummerae* appears 4 m above in sample A25, which corresponds to the lower part of the Campanian stage. *Globotruncanita insignis* appears in sample A40. This species is considered a direct descendant of *Globotruncana stuartiformis* (Falzoni and Petrizzo, 2011). The FO of *Globotruncana ventricosa* is towards the top of the section, in sample A55.

The S/C transition interval shows a major turnover of planktonic foraminifera that affected particularly dicarinellid and marginotruncanid taxa, as *Dicarinella asymetrica* disappeared as well as most species of *Marginotruncana*. As pointed out earlier, the disappearance of dicarinellids (e.g. *Dicarinella primitiva*, *D. concavata*) predated the S/C boundary below the studied interval (see El Amri, 2008). In the OA section (Figures 3 and 4), the number of species as well as the number of individuals of *Marginotruncana* declined, although *M. undulata*, *M. sinuosa*, *M. pseudolinneiana*, and *M. marginata* persist into the lower part of the Campanian. Taxa such as *M. tarfayaensis*, *M. renzi*, *M. schneegansi*, *M. coronata*, and *M. sigali* disappear below the S/C boundary.

Above the boundary, *Globotruncana*, *Globotruncanita*, and *Contusotruncana* became diversified. However, at the OA section the upper part of the Santonian is characterized by the coexistence of *Dicarinella asymetrica*, *Globotruncana* cf. *arca*, *Globotruncana orientalis*, *Globotruncana bulloides*, *Globotruncana linneiana*, and *Globotruncana mariei*. At the base of the Campanian stage, after the extinction of *Dicarinella asymetrica*, the genus *Contusotruncana* becomes more diverse and associated with typical *Globotruncana arca*.

Semiquantitative data reveal an abundance of Heterohelicidae compared with other forms of planktonic foraminifera, especially *Heterohelix globulosa*, *H. glabrans*, and *H. pulchra*. The other groups are less abundant (Figures 4 and 5).

Throughout the *Globotruncanita elevata*/ *Globotruncana arca* concurrent biozone, representatives of *Globotruncana* and *Globotruncanita* become more frequent and diverse; those of *Contusotruncana* thrived and some acquired a higher trochospiral test than *C. fornicata* (e.g., *C. patelliformis*). In the lower part of the Campanian, particularly close to the base of the *Globotruncanita elevata*/*Globotruncana arca* biozone, an obvious increase in relative abundance of trochospiral keeled forms (e.g., *Globotruncanita elevata*, *Contusotruncana patelliformis*) regarded as intermediate and deeper water morphotypes is observed. This increase is concurrent with a slight decrease in numbers of surface species. Through the *Globotruncanita elevata*/*Globotruncana arca* biozone, *Heterohelix* remains dominant, its relative abundance being close to 60% of the assemblages (Figures 4 and 5).

Globotruncana arca is more common (>10%) than other species of the genus. Large heterohelicids and keeled globotruncanid morphotypes increase in relative abundance at the S/C boundary (Figure 5).

6. Discussion

Comparing our results with those of Robaszynski et al. (2000) regarding FOs and LOs of many planktonic foraminifera species, e.g., the LO of *D. asymetrica*, FO of *G. arca*, and FO of *G. ventricosa*, discrepancies are noted (Figure 6). We consider that the LO of *Dicarinella asymetrica* is an important event marking the S/C boundary. It is correlated with many other bioevents noted in studies of crinoids, ammonites, and calcareous nannofossils (Figure 7). In our material, the LO of undoubted *D. asymetrica* (Figure 8) is 5 m above the level recorded by Robaszynski et al. (2000).

Regarding *Globotruncana arca*, a few specimens were identified at the uppermost Santonian (A17). Scarce specimens that may be confused with *G.* cf. *arca* were recorded below (A14) the LO of *D. asymetrica*, but showing free portici as in *Marginotruncana* species. According to Robaszynski et al. (2000), the first appearance of *G. arca* was further below (~20 m lower than our sample A17). The FO of *G. ventricosa* is 15 m above that plotted by Robaszynski et al. (2000) (Figure 6). According to Robaszynski and Mzoughi (2010), the first forms close to *Globotruncana ventricosa* are present in the Haraoua bar overlying the Assila member in the Ellès section, but in the Kalaat Senan section the first forms close to this species are present below the Assila member (As404 equivalent to 1 m below sample A40: in Figure 8b, p. 376). In Tunisian sections, the Assila member is the first member of the Campanian stage and the Haraoua member is the second member.
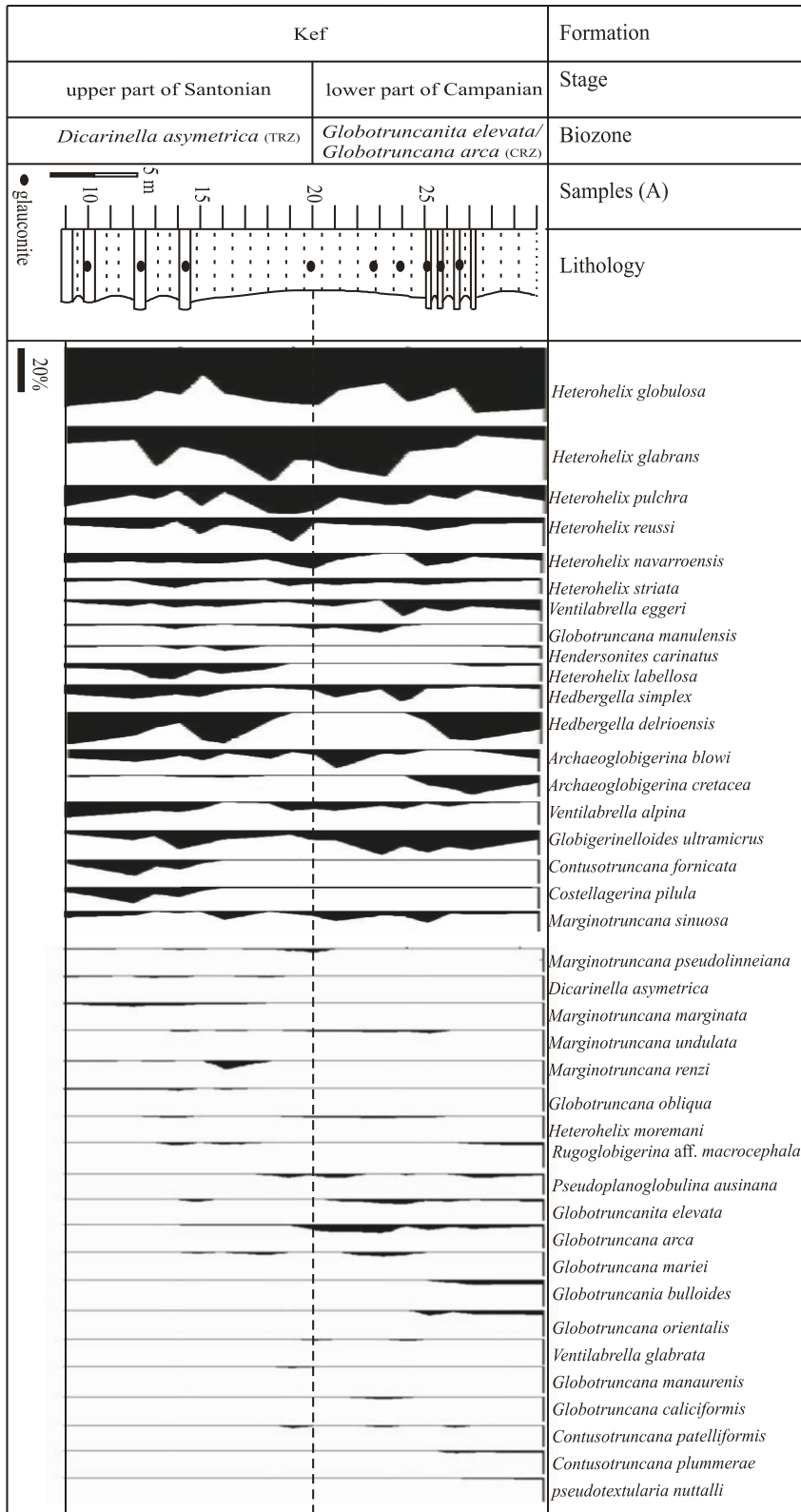
Kef		Formation
upper part of Santonian	lower part of Campanian	Stage
Dicarinella asymetrica (TRZ)	*Globotruncanita elevata/ Globotruncana arca* (CRZ)	Biozone
		Samples (A)
		Lithology

Heterohelix globulosa

Heterohelix glabrans

Heterohelix pulchra

Heterohelix reussi

Heterohelix navarroensis

Heterohelix striata

Ventilabrella eggeri

Globotruncana manulensis

Hendersonites carinatus

Heterohelix labellosa

Hedbergella simplex

Hedbergella delrioensis

Archaeoglobigerina blowi

Archaeoglobigerina cretacea

Ventilabrella alpina

Globigerinelloides ultramicrus

Contusotruncana fornicata

Costellagerina pilula

Marginotruncana sinuosa

Marginotruncana pseudolinneiana

Dicarinella asymetrica

Marginotruncana marginata

Marginotruncana undulata

Marginotruncana renzi

Globotruncana obliqua

Heterohelix moremani

Rugoglobigerina aff. macrocephala

Pseudoplanoglobulina ausinana

Globotruncanita elevata

Globotruncana arca

Globotruncana mariei

Globotruncania bulloides

Globotruncana orientalis

Ventilabrella glabrata

Globotruncana manaurenis

Globotruncana caliciformis

Contusotruncana patelliformis

Contusotruncana plummerae

pseudotextularia nuttalli

Figure 4. Relative abundance of planktonic foraminifera species at the Wadi Assila section.
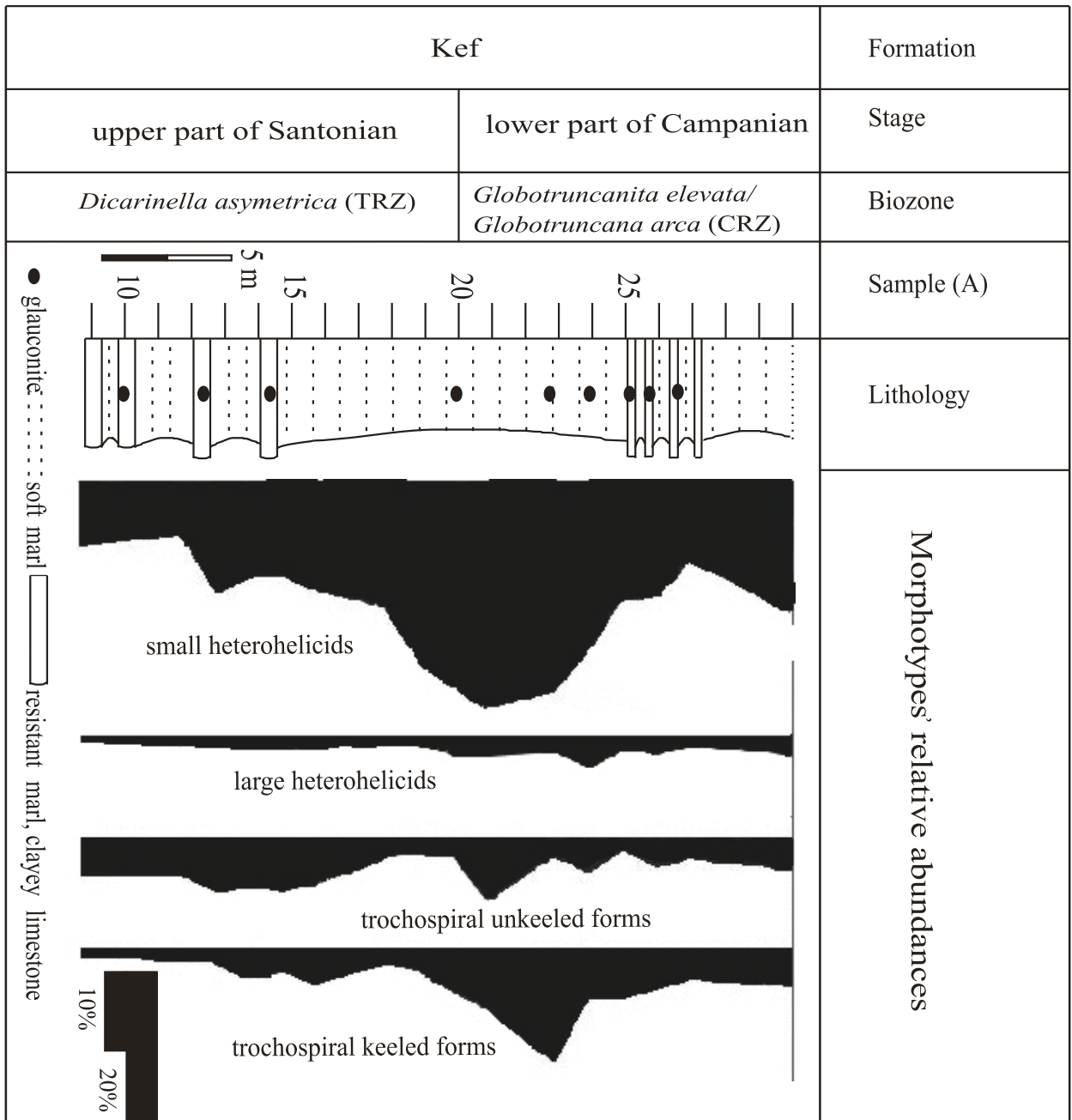
Figure 5. Relative abundance of planktonic foraminiferal morphogroups at the Wadi Assila section.

Representatives of *Marginotruncana* disappear gradually. The LOs of 5 species are observed (e.g., *M. sinuosa*, *M. tarfayaensis*) through a 10-m-thick interval below the LO of the *D. asymetrica* biohorizon. However, 3 species belonging to this genus persist above this biohorizon. Thus, *M. pseudolinneiana* last occurs in sample A30 and *M. marginata* (Figure 9) in sample A55, while *M. undulata* is still present in sample A60 at the top of the studied section. According to Robaszynski et al. (2000),

all species belonging to *Marginotruncana* disappeared at As374, equivalent to our sample A10.

At the OA section the high abundance of small heterohelicids and the extinction of the latest *Dicarinella* and of several species of *Marginotruncana* are simultaneous with diversification within the genera *Globotruncana*, *Globotruncanita*, *Planoglobulina*, and *Ventilabrella*, whereas some species of *Marginotruncana* persist in the lower and middle part of the Campanian Stage. These
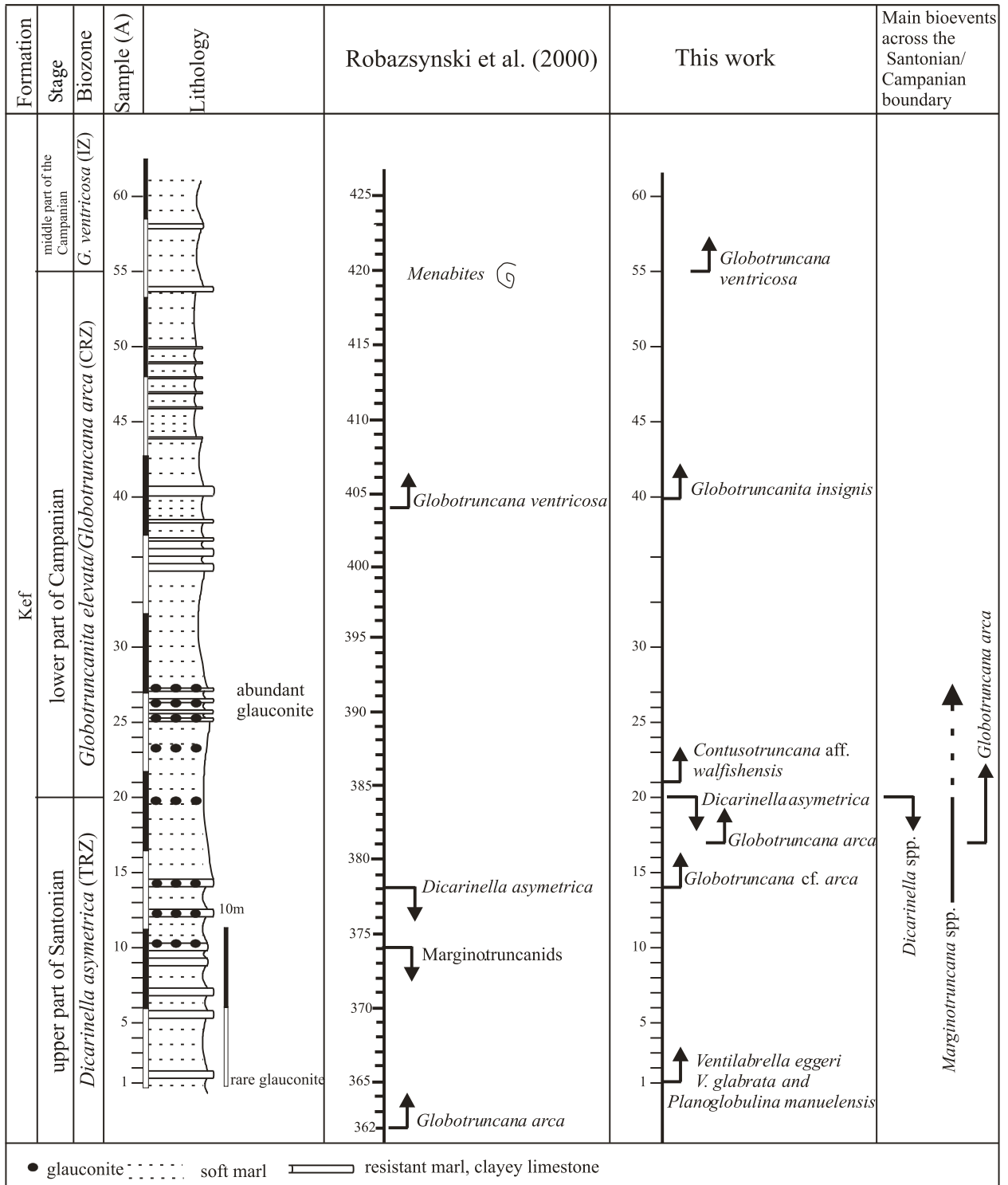
Figure 6. Bioevents observed at Wadi Assila section and comparison with those in Robaszynski et al. (2000).

observations are in agreement with that noted at the Alamedilla section located in southern Spain (Arz, 1996). Indeed, regarding the Santonian-Campanian transition, at this Spanish section, the author noticed an increase in relative abundance of surface dwellers (~41% to ~55%) and of deeper photic mass water dwellers (~5.5% to ~13.5%), probably due to a rise of the global sea level. The base of the Campanian stage is marked by a high abundance of

upper part Santonian	lower part Campanian	Stage
C34N	C33R	Magneto-stratigraphy
(Ogg and Ogg, 2004)		

upper part Santonian	lower part Campanian	Stage
Marsupites testudinarius (Hancock and Gale, 1996; Gradstein et al., 2004;Robaszynski et al., 2005; Gale et al., 2008)	*Uintacrinus anglicus* (Gale et al., 2008)	Crinoids

upper part Santonian	lower part Campanian	Stage
Scaphites hippocrepis (Küchler and Wagreich, 2002)	*Placenticeras bidorsatum* (Gale et al., 1995; Robaszynski, 1999; Gradstein et al., 2004)	Ammonites
Texanitinids (Robaszynski et al., 2000)		

upper part Santonian	lower part Campanian	Stage
Aspidolithus parcus parcus (Ogg and Ogg, 2004)	*Calculites obscurus* (Küchler and Wagreich, 2002; Remin, 2004; Hampton et al., 2007) *Broinsonia parca parca* (Hancock and Gale, 1996; Robaszynski, 1999)	Calcareous nannofossils

upper part Santonian	lower part Campanian	Stage
D. asymetrica (Bellier, 1983; Robaszynski and Caron, 1995; Ogg and Ogg, 2004; this work) *D. asymetrica* (Petrizzo, 2002; Gale et al., 2008)	*Gt. elevata* (Gale et al., 1995; Ogg and Ogg, 2004) *Gt. elevata* (This work) *G. arca* (This work)	Planktonic foraminifera

Figure 7. Bioevents observed by different authors across the Santonian-Campanian transition interval based on several groups (crinoids, ammonites, calcareous nannofossils, and planktonic foraminifera).
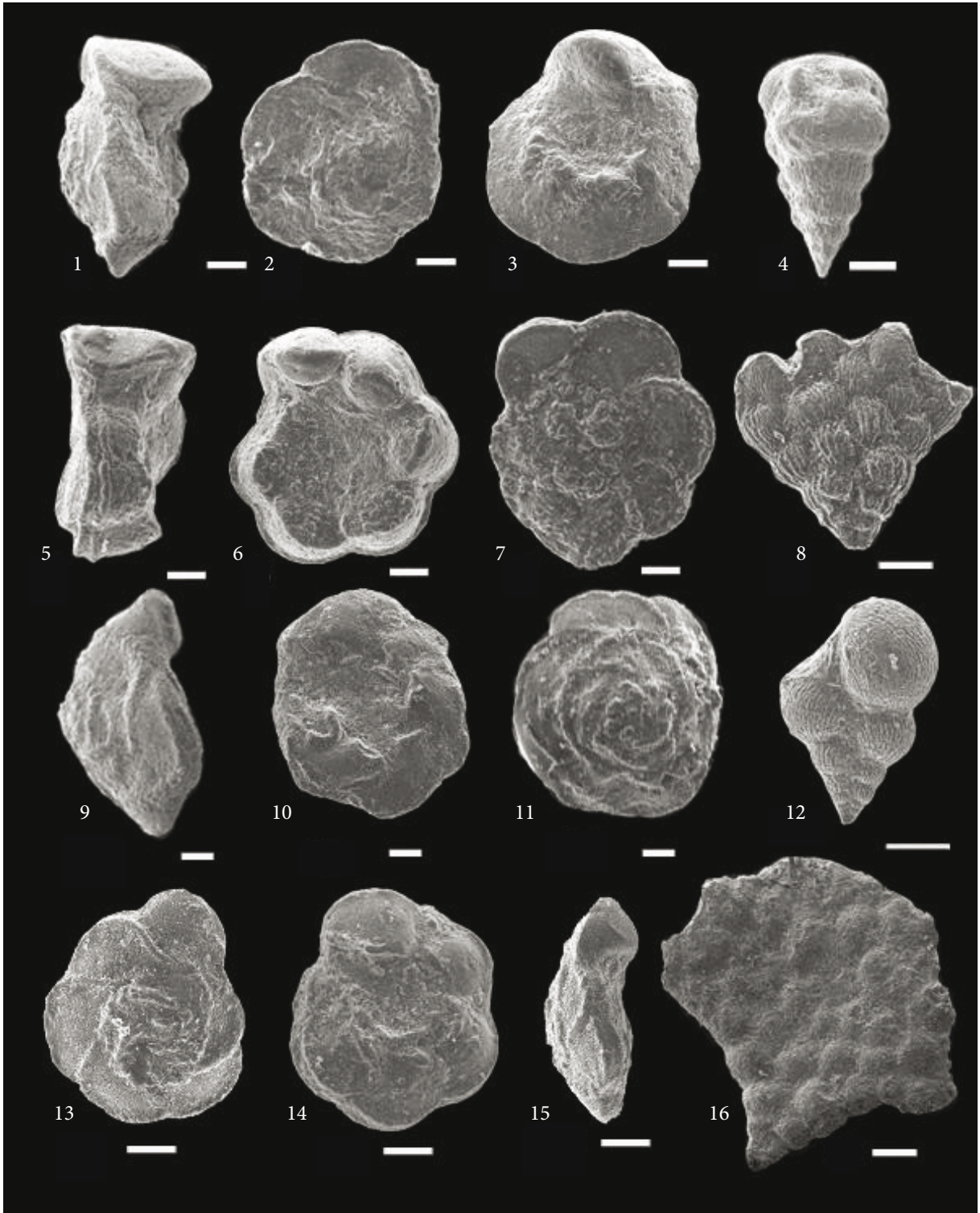
Figure 8. 1, 2, 3: *Globotruncanita elevata* (A7); 4: *Pseudotextularia nuttalli* (A9); 5, 6, 7: *Dicarinella asymetrica* (A9); 8: *Ventilabrella eggeri* (A7); 9, 10, 11: *Contusotruncana patelliformis* (A55); 12: *Heterohelix globulosa* (A12); 13, 14, 15: *Globotruncana orientalis* (A12); 16: *Planoglobulina manuelensis* (A24). Scale bars = 100 μm.
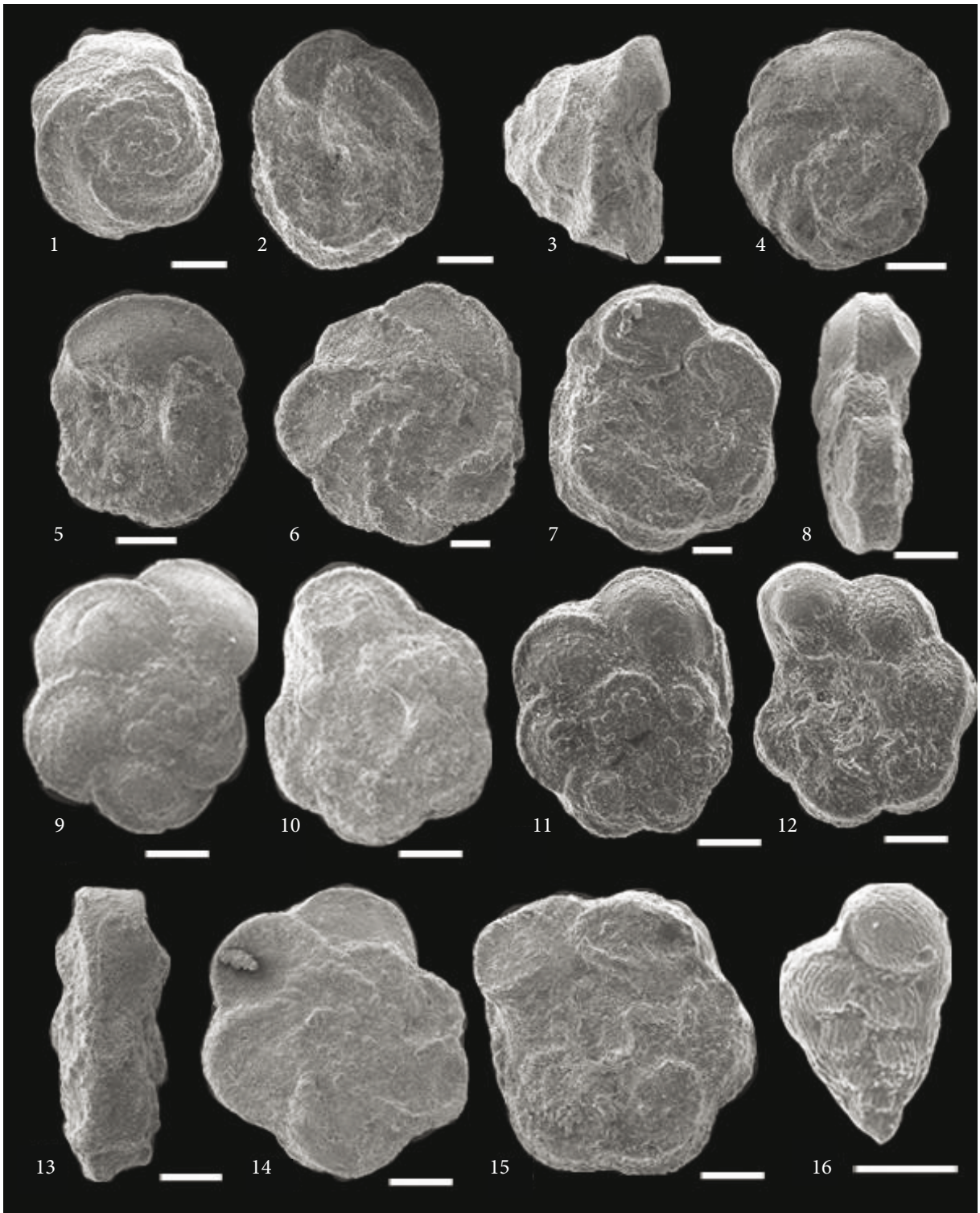
Figure 9. 1, 2, 3: *Contusotruncana* aff. *walfishensis* (A55); 4, 5: *Contusotruncana plummerae* (A25); 6, 7: *Globotruncana* cf. *arca* (A19); 8, 9, 10: *Marginotruncana marginata* (A9); 11, 12: *Globotruncana bulloides* (A25); 13, 14, 15: *Globotruncana linneiana* (A25); 16: *Hendersonites carinatus* (Cushman, 1938) (A55). Scale bars = 100 μm.

Heterohelix globulosa (30%: Figure 4). These results are correlated to those observed in the Tercis-les-Bains section in France (Arz, 1996). However, the same author noticed a higher relative abundance of heterohelicids (~45%) at the Tercis-les-Bains section, with dominance of *Heterohelix globulosa*. Nederbragt (1991), working at the Mellègue Wadi section in northern Tunisia, noted that across the Santonian-Campanian transition, the relative abundance of *Heterohelix globulosa* exceeds 40%.

Across the Santonian-Campanian transition and in the lower part of the Campanian stage, large heterohelicids (*Ventilabrella eggeri*, *Planoglobulina manuelensis*) prospered. Simultaneously, small and biserial heterohelicids increased. Their relative abundance exceeds 50% (Figure 5).

The increase in relative abundances of small biserial heterohelicids taxa is inferred to show an expansion of oxygen minima (Boersma and Premoli Silva, 1989; Premoli Silva and Sliter, 1999) and high productivity (MacLeod et al., 2001).

In our opinion, this increase of small heterohelicids implies a rather warmer climate. This warming is demonstrated by Arthur et al. (1985) and Clarke and Jenkyns (1999) based on oxygen isotopes during the Santonian-Campanian transition, which corresponds to a transgressive period according to Haq et al. (1987) and Miller et al. (2005).

These diverse bioevents were documented at many localities: e.g., El Kef (Nederbragt, 1991) and Alamedilla (Arz, 1996). They testify to a major turnover that would be induced by a global pulse of climate warming with temperature increase of 2–3 °C (Steuber et al., 2005) initiated across the Santonian-Campanian transition. From the Santonian-Campanian boundary, temperatures were rising. This assumption is supported by the increase of $\delta^{13}C$ according to Melinte-Dobrinescu and Bojar (2010).

Consequently, this turnover favored more performing specialists in the deeper warm mass water that adopted the "k" paleoecological strategy. It is commonly accepted that small biserial planktonic foraminifera favored surface-dwelling water habits.

This turnover was made in favor of species having coalescent portici (*Globotruncanita* species) and tegilla (*Globotruncana* species). It could be related to a best adaptation to the paleoclimatic change corresponding to an increase in temperature and/or trophic influx (nutrients).

The marginotruncanids and dicarinellids thriving during the Coniacian-Santonian period have free portici. Many of them are also assigned to be subtropical to tropical specialists (Petrizzo, 2002). Some marginotruncanids (e.g., *M. marginata*, *M. pseudolinneiana*, and *M. coronata*) are common in temperate latitudes (Pożaryska and Peryt, 1979; Peryt, 1980). The disappearance of dicarinellids

and gradual decline of marginotruncanids during the Santonian-Campanian transition are documented worldwide (e.g., Arz, 1996; Premoli Silva and Sliter, 1999; Petrizzo, 2000, 2003).

The dicarinellid and globotruncanid morphology may be correlated with recent globorotaliids, which are assigned to be specialists of tropical to subtropical warm oceans like their Cenomanian homologues (i.e. *Rotalipora* spp.) considered by Hart (1999).

According to Caron and Homewood (1982), Hart (1999), and Premoli Silva and Sliter (1999), keeled species lived in deeper water from water depths of about 100–200 m, where species increased in number and acquired their most significant morphological characteristics.

The diversification of species showing ornamentation (*Rugoglobigerina* aff. *macrocephala*), an increase of the number of chambers (*Planoglobulina manuelensis*, *Ventilabrella eggeri*), and a high trochospire (*Contusotruncana* aff. *walfishensis*: see Figure 9: 1, 2, 3) observed across the Santonian-Campanian transition may be related to an additional biotic response to an increase in temperature.

7. Conclusions

Because biomarker *Marsupites testudinarius* is absent at the OA section (Robaszynski et al., 2000), the *Dicarinella asymetrica* LAD is suggested to be the appropriate criterion to identify the S/C boundary in the Tethyan realm.

The dicarinellids that appeared since the upper Cenomanian and prospered during the Turonian-Coniacian interval knew a gradual disappearance; with the LO of *Dicarinella asymetrica* they eventually disappeared. Across the Santonian-Campanian transition interval major turnover was initiated. Consequently, the index species *Dicarinella asymetrica* did not cross the S/C boundary as defined here. Many species of *Marginotruncana* also became extinct. However, a few of them crossed the S/C boundary as defined here and persisted later through the early Campanian (e.g., *Marginotruncana marginata*, *M. undulata*). In contrast, large heterohelicids (*Ventilabrella eggeri*, *Planoglobulina manuelensis*, and *Pseudotextularia nuttalli*), globotruncanids belonging to *Globotruncana* (e.g., *G. orientalis*, *G. bulloides*, *G. mariei*, *G. linneiana*, and *G. arca*), to *Globotruncanita* (e.g., *Gta. elevata*, *Gta. insignis*, *Gta. stuartiformis*), and to *Contusotruncana* (e.g., *C. patelliformis*) thrived close to the S/C boundary. These various responses of planktonic foraminiferal species may be related to a global increase in temperature.

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Appendix 1. List of planktonic foraminifera cited in the text with author attributions and dates.

Archaeoglobigerina blowi Pessagno 1967

Archaeoglobigerina cretacea (d'Orbigny 1840)

Costellagerina pilula (Belford 1960)

Contusotruncana fornicata (Plummer 1931)

Contusotruncana patelliformis (Gandolfi 1955) (Figure 8: 9, 10, 11)

Contusotruncana plummerae (Gandolfi 1955) (Figure 9: 4, 5)

Contusotruncana aff. *walfishensis* (Figure 9: 1, 2, 3)

Dicarinella asymetrica (Sigal 1952) (Figure 8: 5, 6, 7)

Dicarinella concavata (Brotzen 1934)

Dicarinella primitiva (Dalbiez 1955)

Globigerinelloides ultramicrus (Subbotina 1949)

Globotruncana arca (Cushman 1926)

Globotruncana cf. *arca* (Figure 9: 6, 7)

Globotruncana bulloides (Vogler 1941) (Figure 9: 11, 12)

Globotruncana caliciformis (de Lapparent 1918)

Globotruncana fornicata manaurensis Gandolfi 1955

Globotruncana linneiana (d'Orbigny 1839) (Figure 9: 13, 14, 15)

Globotruncana mariei Banner and Blow 1960

Globotruncana obliqua Herm 1965, not a junior synonym of *G. linneiana* (see Appendix 2)

Globotruncana orientalis El Naggar 1966 (Figure 8: 13, 14, 15)

Globotruncana ventricosa White 1928

Globotruncanita insignis (Gandolfi 1955)

Globotruncanita elevata (Brotzen 1934) (Figure 8: 1, 2, 3)

Globotruncanita stuartiformis (Dalbiez 1955)

Hedbergella delrioensis (Carsey 1926)

Hedbergella flandrini Porthault 1970

Hedbergella simplex (Morrow 1934)

Hendersonites carinatus (Cushman 1938), previously *Heterohelix carinata* (Figure 9: 16)

Heterohelix globulosa (Eherenberg 1840) (Figure 8: 12)

Heterohelix labellosa Nederbragt 1991

Heterohelix moremani (Cushman 1938)

Heterohelix navarroensis Loeblich 1951

Heterohelix pulchra (Brotzen 1936)

Heterohelix reussi (Cushman 1938)

Marginotruncana carinata (Dalbiez 1955)

Marginotruncana coronata (Bolli 1945)

Marginotruncana schneegansi (Sigal 1952)

Marginotruncana marginata (Reuss 1845) (Figure 9: 8, 9, 10)

Marginotruncana renzi (Gandolfi 1942)

Marginotruncana sigali (Reichel 1949)

Marginotruncana sinuosa Porthault 1970

Marginotruncana pseudolinneiana Pessagno 1967

Marginotruncana tarfayaensis (Lehmann 1962)

Marginotruncana undulata (Lehmann 1963)

Planoglobulina manuelensis (Martin 1972) (Figure 8: 16)

Pseudotextularia nuttalli (Voorwijk 1937) (Figure 8: 4)

Pseudoguembelina costulata (Cushman 1938)

Pseudoplanoglobulina austinana (Cushman 1938)

Sigalia deflaensis (Sigal 1955)

Ventilabrella alpina De Klasz 1953

Ventilabrella eggeri Cushman 1928 (Figure 8: 8)

Ventilabrella glabrata Cushman, 1938

Appendix 2. Systematic taxonomic remarks.

Globotruncanita insignis (Gandolfi 1955)

1955- *Globotruncana rosetta insignis* Gandolfi in Gandolfi, p. 67, pl. 6,

1984- *Globotruncana insignis* Gandolfi in Robaszynski et al., p. 199, pl. 12, figs. 1–3,

2011- *Globotruncanita insignis* (Gandolfi 1955), Falzoni and Petrizzo, figs. 4.3, 4.10–4.11, 5.2–5.3, 5.7–5.8.

This species is similar to *Globotruncanita elevata*. It differs from it by spiral side that is entirely conical while in *Globotruncanita elevata* only the central part is conical. This species is regarded as a direct descendant of *Globotruncanita stuartiformis* (Falzoni and Petrizzo, 2011).

Globotruncana obliqua Herm 1965

Globotruncana obliqua was commonly regarded as a junior synonym of *Globotruncana linneiana*. Basically, *G. obliqua* differs from the latter by the imbricate chambers observed in the side view. We are in agreement with Georgescu (2006) that *G. obliqua* is considered as a valid species.

Appendix 3. Statistic table.

Species	A9	A12	A13	A14	A15	A16	A18	A19	A20	A21	A23	A24	A25	A26	A27	A30
H. globulosa	186	177	84	93	54	84	120	90	75	42	36	74	96	75	180	105
H. glabrans	54	45	78	39	51	54	123	54	45	42	52	34	45	39	24	24
H. pulchra	69	33	27	9	42	12	63	48	33	12	20	26	18	27	12	27
H. reussi	21	36	21	6	33	12	27	39	6	6	8	12	24	18	15	9
H. navarroensis	30	27	18	18	21	18	12	18	21	6	0	0	24	18	9	12
H. striata	9	6	12	18	9	6	3	12	6	6	4	6	12	9	9	3
V. eggeri	3	21	6	15	12	12	6	3	6	6	0	22	15	21	18	18
P. manuelensis	3	0	3	0	3	6	3	0	0	0	0	0	6	9	6	9
He. carinatus	3	3	3	9	3	0	3	3	6	3	8	2	0	0	0	0
H. labellosa	3	3	0	6	0	9	0	0	0	0	0	0	0	0	0	3
Hd. simplex	12	21	27	30	12	18	12	0	0	0	0	0	0	0	6	3
Hd. delrioensis	27	45	21	18	24	9	6	6	6	12	4	24	6	6	3	6
Ar. blowi	108	81	30	21	60	60	18	0	0	0	0	0	18	54	81	30
Ar. cretacea	24	39	18	9	21	6	18	3	6	18	4	6	0	0	0	15
V. alpina	3	0	0	3	3	3	0	0	0	0	0	0	18	24	51	12
Gs. ultramicrus	51	36	18	21	15	0	3	15	9	9	4	10	3	9	3	0
C. fornicata	9	30	9	36	27	15	12	6	12	9	24	20	42	30	51	15
Cg. pilula	12	51	12	18	6	0	0	0	0	0	0	0	0	0	0	0
M. sinuosa	18	12	0	3	0	15	0	3	6	9	4	6	21	3	6	3
M. pseudolinneiana	6	3	0	6	3	0	6	6	9	0	0	0	0	0	0	0
D. asymetrica	3	0	6	3	0	0	3	0	0	0	0	0	0	0	0	0
M. marginata	6	27	9	9	6	6	0	0	0	0	0	0	0	0	0	0
M. undulata	0	3	0	6	3	3	3	3	3	3	4	4	12	0	0	0
M. renzi	3	0	3	0	0	27	0	0	0	0	0	0	0	0	0	0
G. obliqua	6	9	3	9	0	3	0	0	0	0	0	0	0	0	0	0
H. moremani	0	0	3	6	0	0	0	3	3	3	4	4	6	0	0	0
R. aff. *macrocephala*	0	0	0	6	0	3	0	0	0	0	0	0	0	0	3	6
Ps. austinana	0	0	0	0	3	0	9	12	6	9	0	6	3	6	21	9
Gt. elevata	0	0	0	0	12	0	3	0	0	3	8	14	6	9	6	9
G. arca	0	0	0	0	3	3	3	3	12	12	16	4	18	9	21	6
G. mariei	0	0	0	0	3	0	9	0	0	0	8	4	0	0	0	0
G. bulloides	0	0	0	0	0	0	0	0	0	0	0	0	0	12	27	15
G. orientalis	0	0	0	0	0	0	0	0	0	0	0	0	15	6	15	12
V. glabrata	0	0	0	0	0	0	0	0	3	0	0	4	0	0	0	0
G. manaurensis	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0
G. caliciformis	0	0	0	0	0	0	0	0	0	0	4	2	0	0	0	0
C. patelliformis	0	0	0	0	0	0	0	9	3	0	4	2	0	9	3	3
C. plummerae	0	0	0	0	0	0	0	0	0	0	0	0	0	9	6	6
Ps. nuttalli	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
Total number	669	708	411	417	429	384	465	339	276	210	216	286	408	402	579	363